Coastal Upwelling/Downwelling Cycles in Southern Lake Superior[1]

H. J. NIEBAUER[2], THEODORE GREEN AND ROBERT A. RAGOTZKIE

Marine Studies Center, University of Wisconsin, Madison 53706

(Manuscript received 18 February 1977, in revised form 30 May 1977)

ABSTRACT

Extensive current meter, hydrographic and wind data were collected in the region of the Keweenaw Current, a strong coastal jet, during the late spring and early summer regime of Lake Superior. These data were compared with surface wind and pressure patterns over the region with the following conclusions:

1) Longshore winds associated with migrating low-pressure systems generate onshore Ekman transport and coastal downwelling. The coastal downwelling results in an intensification of the onshore internal pressure gradient, and consequently the coastal jet. Speeds of over 75 cm s^{-1} are both observed and calculated, suggesting the Keweenaw Current, at these times, is in geostrophic equilibrium.

2) Longshore winds associated with migrating high-pressure systems generate offshore Ekman transport and coastal upwelling. Upwelling velocities of 13–50 m day^{-1}, an offshore surface transport layer of 10 m, a near-shore deceleration of the Keweenaw Current and current direction fluctuations of near- and sub-inertial period are found associated with the upwelling.

The period of passage of highs (upwelling) and lows (downwelling) in July is about 4–6 days. This gives the Keweenaw Current the appearance of a pulsating coastal jet of period 4–6 days and amplitude about 60 cm s^{-1}.

1. Introduction

The Laurentian Great Lakes of North America are often regarded as large-scale models of the oceans. Strong coastal currents occur seasonally that are, in some fundamental respects, similar to ocean currents. Coastal upwelling and downwelling are also frequently observed in the Great Lakes, often in conjunction with coastal currents (e.g., Csanady, 1971). Csanady's (1972) study of currents along the north shore of Lake Ontario correlated eastward flow with upwelling (marked by a lens-shaped thermocline) and westward flow with downwelling (marked by a wedge-shaped thermocline). According to Csanady, the thermocline has an equilibrium position upon which upwelling and downwelling are superimposed. The fluctuations are driven by periodic wind impulses which cause readjustment in thermocline position and longshore (geostrophic) currents through conservation of potential vorticity. An updated review of theories of coastal currents has been given by Csanady (1975).

Coastal currents, associated with upwelling and downwelling, have also been observed in Lakes Michigan (Mortimer, 1971) and Ontario (Blanton, 1975), apparently in conjunction with quasi-geostrophic Kelvin waves propagating around the Lakes. Blanton reports cycles of upwelling/downwelling of period 12–16 days. He notes that this is at least twice the period expected if the upwelling/downwelling cycles are directly driven by winds associated with the passage of weather systems. It is during upwelling/downwelling cycles that complete water mass exchange between inshore and offshore zones can occur. Thus coastal currents, upwelling and downwelling are fundamental to understanding lake dynamics, and are of practical concern for their capability to transport nearshore pollutants. The basic physics applies as well to the continental shelf regions of the oceans.

Several studies have been made of a coastal current off the Keweenaw Peninsula in Lake Superior over the last 10 years (Ragotzkie and Bratnick, 1965; Smith and Ragotzkie, 1970; Green and Yeske, 1974; Yeske and Green, 1975). The Keweenaw Current flows eastward along the northern shore of the Keweenaw Peninsula, and can attain speeds in excess of 90 cm s^{-1} during the summer. Gilson *et al.* (1973), in a study of short-term variations in the baroclinic portion of the Keweenaw Current, observed strong wind-driven coastal upwelling and downwelling. The magnitude and frequency of both temperature and geostrophic velocity variations dramatically illustrated the need for more extensive current and temperature time series.

---

[1] Marine Studies Center Contribution No. 31.

[2] Present affiliation: Institute of Marine Science, University of Alaska, Fairbanks 99715.

In 1973, an array of current meters was moored across the Keweenaw Current off Eagle Harbor, Mich. (Fig. 1). The resulting data form the basis for this study which looks, in some detail, at the current and temperature structure of the Keweenaw Current during several upwelling/downwelling cycles. These data were acquired during the spring and early summer regime of Lake Superior (July and early August) when warm water is generally wedged against the coast and the outer edge of the Current is often marked by a very sharp horizontal temperature gradient within 10 km of shore (typically a drop from 10–12°C to about 4°C over 1–1.5 km, although gradients of 1°C per 10 m have been measured). A correlation is also made between relatively long-period fluctuations in the Current (of the order of 5 days) and pressure systems migrating over the Lake Superior region.

2. Data

The nearshore region off Eagle Harbor, Mich., in Lake Superior has been the site of the most recent (1971–4) set of measurements by the University of Wisconsin Marine Studies Center on the Keweenaw Current. Here the coastline is straight and the bottom topography regular with the bottom slope about 0.1. In addition, the Keweenaw Current flows quite near the coast, often within 1 km of shore during the spring regime. In 1973, three Aanderaa RCM-4 current meters were moored 8–9 m beneath surface buoys at 0.7, 3.5 and 6.5 km offshore (Fig. 1). Currents and temperatures were recorded every 10 min; current directions and temperatures were instantaneous readings, while current speed was derived from the summation of rotor revolutions over the 10 min. The data were subsequently averaged over $\frac{1}{2}$ h using a simple arithmetic mean and are plotted in Figs. 2, 5 and 6.

A large number of hydrographic sections were made along the buoy line. Consequently, all references to distances from shore are relative to this line. A depth of 60 m was taken as the reference level of no motion for computing geostrophic currents via the dynamic height method. Sixty meters was the depth limit of the bathythermograph, and has been commonly used as the reference level in Great Lakes hydrographic work.

Supporting wind and coastal water temperature data were collected at the Eagle Harbor lighthouse. Surface pressure maps were taken from the North American Surface Chart Series as compiled by the National Climatic Center. The data discussed are representative of a much larger set available (Niebauer, 1976).

3. Upwelling and downwelling events

Coastal temperature and current speed minima that correlate with longshore winds from the northeast (leading to offshore Ekman transport) are used to define coastal upwelling events. Coastal temperature and current speed maxima (toward the northeast) that correlate with longshore winds from the southwest (leading to onshore Ekman transport) are used to define downwelling events. The combination of these two events, which seem to occur in pairs, is considered an upwelling/downwelling cycle. Evidence for approximately six such cycles is present in the temperature and current meter data and is briefly summarized in Table 1.

The upwelling/downwelling cycles can be divided into two groups. Weak or minor (in the sense of small temperature drops and short event durations) upwelling events and strong (in the sense of strong current accelerations toward the northeast) down-

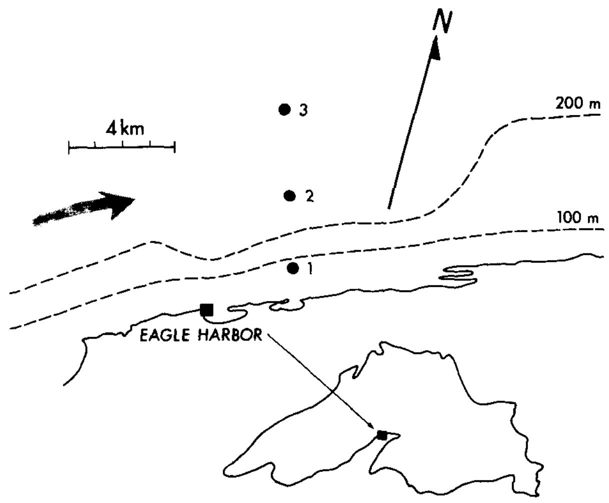

Fig. 1. Positions of the current meters (circles) along the north coast of the Keweenaw Peninsula in Lake Superior. The Eagle Harbor lighthouse is denoted by a square.

Table 1. Table of upwelling (U) and downwelling (D) events along the Keweenaw Peninsula for July 1973. Winds from 075°T are +, those from 255°T are (−). See text for explanation of 5–6 July event.

July	Average wind speed (m sec^{-1})	Wind duration (h)	Type of event
1–2	+4.0	20	U
2–5	−5.1	78	D
5–6	+1.6	14	(U)?
6–10	−4.2	86	D
11–12	+3.4	13	U
12–15	−5.6	72	D
16–17	+3.1	29	U
17–19	−3.9	55	D
20–25	+6.0	71	U
25–26	−2.5	23	D
26–27	+1.3	31	U
27–29	−4.4	49	D
29–31	+3.3	38	U

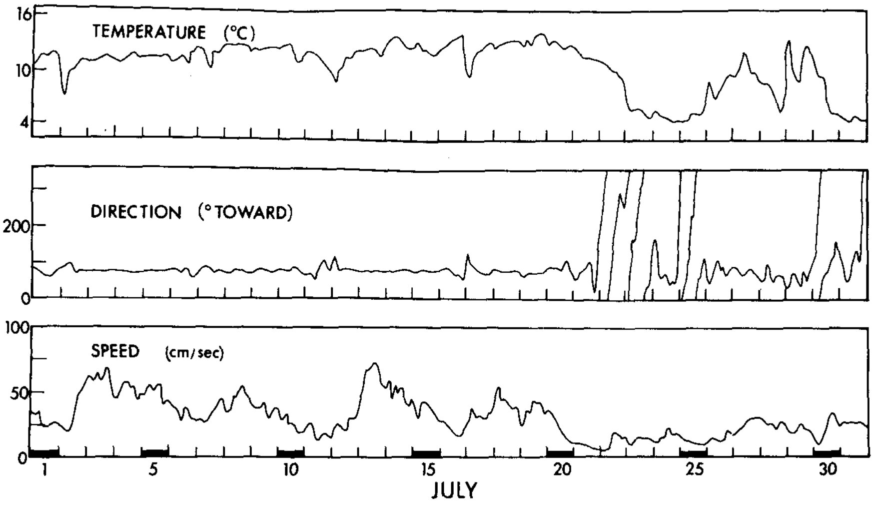

FIG. 2. Temperature, current speed and current direction at buoy 1 during July 1973 (see Fig. 1). The current meter was about 8 m below the surface. The heavy bars indicate 5-day periods.

welling events occur during approximately the first three weeks of July. The opposite is true for the last week in July, when strong upwelling and relatively weak downwelling occur. Niebauer (1976) found a similar relationship, that is, minor upwelling events and major downwelling in early July with major upwelling events and minor downwelling in later July and August, from data acquired in the same area of Lake Superior in 1972. The period of an upwelling/downwelling cycle was 4–5 days in both years.

a. Upwelling/downwelling during 1–20 July

The temperature record for the nearshore current meter (Fig. 2) shows three, and possibly four, minor coastal upwelling events coinciding with both northeasterly winds (Fig. 3 and Table 1) and with the appearance of cold water at the coast (Fig. 4). These events occur about every 5 days; on the 2nd, perhaps on the 7th, on the 12th and on the 17th. The temperature drops at 0.7 km offshore average about 3.5°C compared with 6°C at the coast. A comparison of these two temperature records with that of a water intake about 30 km west of Eagle Harbor in an effort to find evidence of internal Kelvin waves propagating along the coast was inconclusive. Such an edge wave would be expected to travel at 20–25 cm s^{-1}, covering the 30 km in 35–40 h. No such time lag was found in the temperature time series. However, the data are sparse, and much more work is needed on this subject before any firm conclusions can be drawn.

Current meter temperature records from 3.5 and 6.5 km offshore (Figs. 5 and 6) show temperature maxima coinciding with the temperature minima near the coast. This suggests offshore transport of warm nearshore water during the minor upwelling events. Warm water reached at least 3.5 km offshore on 2 and 7 July, and at least 6.5 km offshore on 12 and 17 July. The farthest offshore temperature record

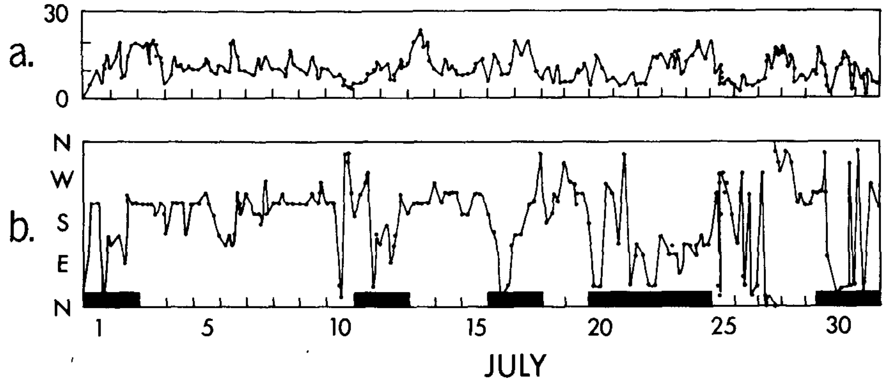

FIG. 3. Raw wind data taken each 6 h at the Eagle Harbor lighthouse during July 1973. Upwelling periods (see Fig. 4) are denoted by heavy bars. Speeds (a) are in miles per hour, directions (b) are those from which the wind blew.

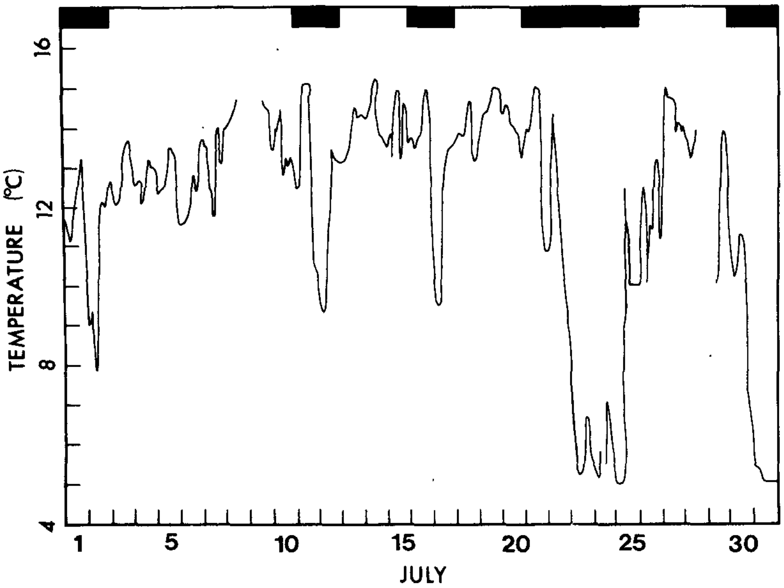

FIG. 4. Coastal water temperatures at the Eagle Harbor lighthouse during July 1973. The thermistor was located about 10 m offshore in 2–3 m of water; it did not read below 5°C. The heavy bars denote upwelling periods.

shows that the sharp thermal gradient was within 6.5 km of shore during most of 1–20 July.

The temperature records indicate a rather intense onshore temperature gradient which implies an onshore pressure gradient resulting in a force directed offshore, and a baroclinic current flowing toward the northeast during coastal downwelling events. The current meter data bear this out. All three direction records for 1–20 July average 075°T. The current direction is quite steady nearshore (standard deviations are of the order 5°) with fluctuations increasing lakeward. The nearshore direction record does, however, show short bursts of fluctuations that coincide with the minor upwelling events onshore. These bursts are about 24 h in duration and 50° (from 050–100°T) in range. The fluctuations appear to be inversely related to the speed of the current. When current speeds are high, current meanders are suppressed. When the current slackens, as during minor upwelling events, current meanders are quite obvious. Similar fluctuations are not apparent in the two offshore records (Figs. 5 and 6); this could be due to the fact that the currents at these locations are generally far less steady.

The speed record for the nearshore current meter (Fig. 2) shows a wavelike series of alternating maxima and minima during the three-week period. Speed maxima (averaging 60–75 cm s^{-1}) occur on 3, 8, 13

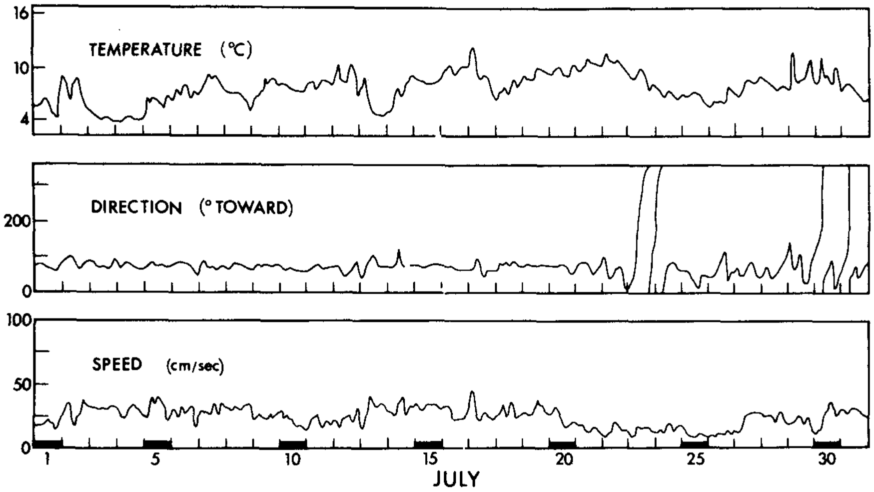

FIG. 5. As in Fig. 2 except for data from buoy 2.

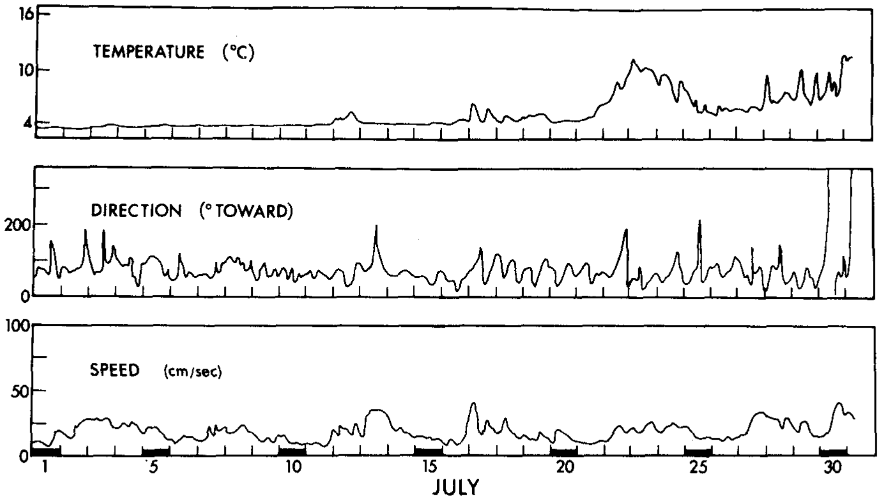

FIG. 6. As in Fig. 2 except for data from buoy 3.

and 18 July. They coincide with temperature maxima nearshore and with temperature minima offshore (down to 4°C at 3.5 km on 3–4 and 13 July). Speed maxima also coincide with a component of the wind blowing parallel to the Keweenaw coastline from the west-southwest (Fig. 3 and Table 1). These winds result in onshore Ekman transport and downwelling along the coast. Thus, speed maxima are most likely due to a combination of the intensification of the onshore pressure gradient, the concentration of longshore momentum nearshore (through onshore Ekman transport) and the surface drag from southwest winds.

Speed minima also occur about every 5 days, coinciding with the minor upwelling events. Speed minima, averaging 10–25 cm s^{-1}, occur on 2, 7, 11–12 and 16–17 July (Fig. 2). These occur at the end of gradual decelerations of the Keweenaw Current over 2–4 day periods following speed maxima. These decelerations are probably due to gradual turbulent erosion of the strong onshore pressure gradient that is generated during coastal downwelling. The gradual deceleration, combined with additional destruction of the onshore pressure gradient and offshore spreading of longshore momentum during upwelling, and surface drag due to northeast winds, help produce the speed minima. The series of alternating speed minima and maxima gives the nearshore speed record a pulsating or asymmetric wavelike form of period about 5 days and range of 35–65 cm s^{-1}.

The speed at 3.5 km offshore (Fig. 5) does not show this wavelike form so clearly. There, speeds average about 25 cm s^{-1} for the three-week period. However, higher current speeds occur on 1–2 and 16–17 July. These coincide with temperature and speed minima nearshore and temperature maxima offshore, suggesting offshore movement of both longshore momentum and warm coastal water during upwelling.

Speeds at 6.5 km offshore (Fig. 6) average 10–15 cm s^{-1} for the three-week period. The record appears to have a wavelike form, somewhat similar to the nearshore record, but reduced in magnitude. Four speed maxima are indicated. The first three, shown on 2, 7–8 and 13 July coincide with the first three speed maxima in the 0.7 km record. There is, however, little temperature structure at 6.5 km offshore, suggesting that the speed maxima are either not baroclinic or that the data were collected on the edge of the baroclinic zone. The temperature and speed maxima at 6.5 km offshore on 16–17 July coincide with temperature and speed minima at 0.7 km offshore and a temperature and speed maxima at 3.5 km offshore. During this event, both longshore momentum and warm coastal water appear to have been carried to at least 6.5 km from shore.

b. Upwelling/downwelling events for 21–31 July

While downwelling events dominated the coastal zone off Eagle Harbor for 1–20 July with relatively weak upwelling events, the opposite is true for 21–31 July. Major upwelling events (coastal temperature drops of 7–10°C lasting of the order of 3 days) occur on 22–25 July and 29 July–1 August. A minor upwelling event occurs on 28 July. Relatively weak downwelling (maximum current speeds of order 25 cm s^{-1}) events occur on 25–26 and 27–29 July. The general qualitative features of the upwelling and downwelling events are essentially the same as during 1–20 July, with three exceptions.

First, the average temperature of the offshore water is higher during this period due to summer heating, indicating that the Lake is approaching the summer regime. By 1 August the Lake surface is everywhere above 4°C. In the summer regime, the Keweenaw Current is no longer bound to the north by the thermal gradient (it has disappeared) and the current widens to at least 10 km offshore. The speed records (Figs. 2, 5 and 6) appear to support this with nearly identical current speeds to 6.5 km offshore for almost the entire period 21–31 July. Second, during minor upwelling events, warm surface water from near the coast was carried offshore as illustrated by temperature maxima in the 3.5 km record (Fig. 5). This also holds for the major upwelling events. However, following the temperature maximum at 3.5 km, during major events (e.g., on 22–25 July) the temperature starts to decrease while strong upwelling is indicated nearshore. This suggests that cooler upwelled water moved offshore, and reached at least 3.5 km on 22–25 and 30–31 July. Finally, where weak current direction fluctuations coincided with minor upwelling events during 1–20 July, full anticyclonic motion occurs during 21–31 July coinciding with the major upwelling events. This periodic motion is also reflected in the temperature records. Spectrum analysis of the temperature and current meter data in the 5–25 h period range (Niebauer, 1976) suggests that most of the energy is near the local inertial period of 16.2 h. However, significant energy appears in periods as short as 10 h in both current and temperature records. This energy is probably associated with internal Poincaré waves (see e.g., Mortimer, 1971); the fundamental barotropic seiche period for Lake Superior (8 h) is too short to account for these energy peaks.

4. The relation to atmospheric pressure systems

The characteristics of the Keweenaw Current as outlined in Section 3 have been interpreted as a series of alternating upwelling and downwelling events occurring along the Keweenaw Peninsula. These events appear to be driven by longshore winds associated with a series of alternating high and low pressure systems passing north of Lake Superior.

a. Downwelling associated with a low-pressure system

We consider the case of the low-pressure system passing northwest and north of Lake Superior on 11–13 July (Fig. 7). This low was more intense than other examples for 1–20 July, but not atypical. It is associated with the best-documented downwelling event. Wind circulation around the low is counterclockwise, generally along the isobars, but somewhat toward the low-pressure center. This causes a strong wind component (observed winds of 10 m s^{-1} from 225°T, with gusts to 22 m s^{-1} on 13 July) to blow parallel to the Keweenaw Peninsula from the west-southwest resulting in onshore Ekman transport and coastal downwelling. Fig. 8 shows temperature cross sections before and during the passage of the low-pressure system. [Actually, the data for Fig. 8a were acquired just as the minor upwelling event of 11–12 July began. The temperature data from the 0.7 km mooring (Fig. 2) show that the 9°C isotherm in Fig. 8a subsequently rises to less than 10 m depth early on 12 July.] The maximum change in temperature during the transition from upwelling to downwelling is not demonstrated. However, these are the

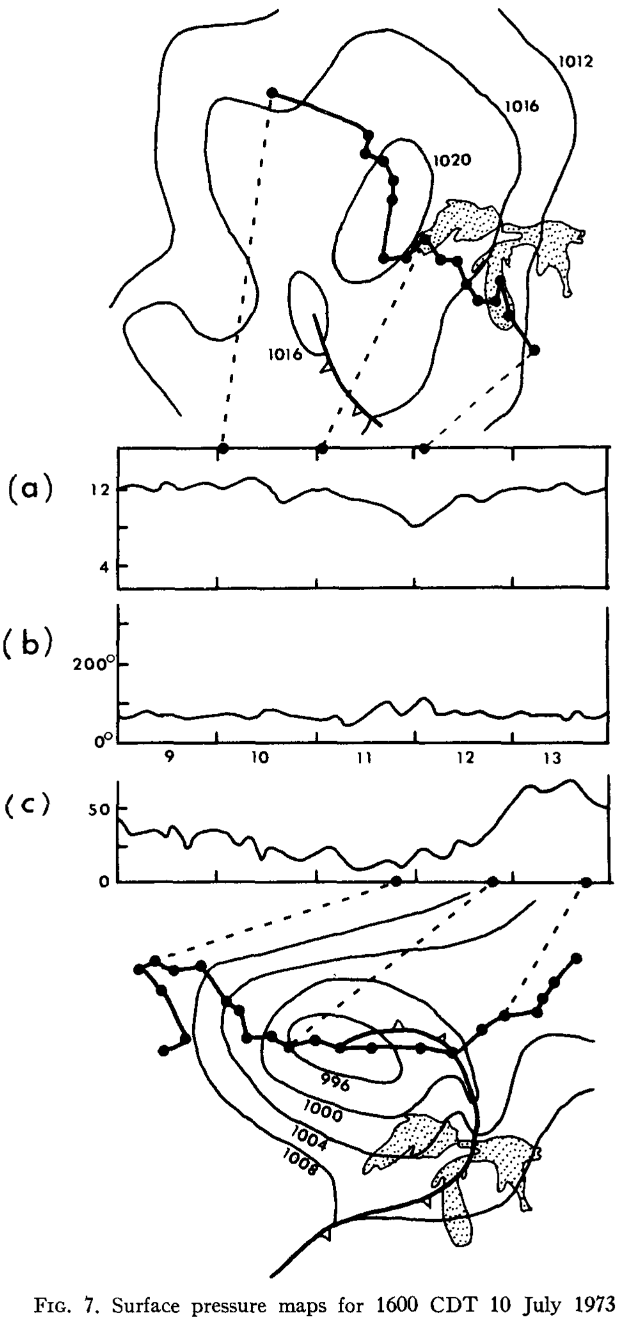

Fig. 7. Surface pressure maps for 1600 CDT 10 July 1973 (top) and 2000 CDT 12 July 1973 (bottom). These are associated with the upwelling/downwelling cycle of 10–15 July. Dots denote 3 h positions of the centers of high and low pressure. Pressures are in millibars. Concurrent currents and temperatures measured at buoy 1 are also shown: (a) temperature (°C); (b) current direction (direction toward); (c) current speed (cm s^{-1}).

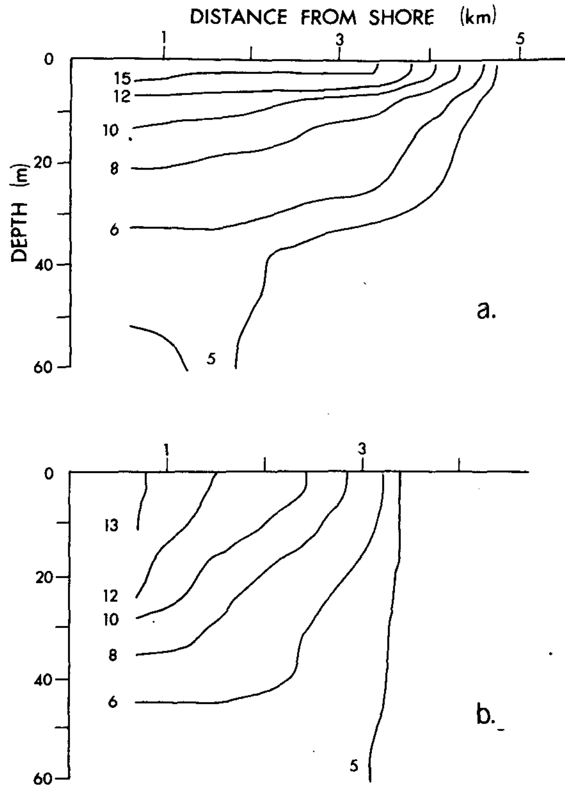

FIG. 8. Temperature (°C) cross sections off Eagle Harbor along the buoy line (Fig. 1). Data were taken each 0.5 km. (a) 1800 CDT 11 July; (b) 1400 CDT 13 July.

only antecedent hydrographic data available for comparison.

Prior to downwelling, warm surface water, as illustrated in Fig. 8 by the 8–15°C isotherms, lies within 20 m of the surface out to about 4 km offshore. This water is forced shoreward and downward along the coast during downwelling. The 8–13°C isotherms rotated downward onshore, producing a wedge-shaped thermocline. The 14–15°C water moved further onshore, out of the region where data were acquired. Cold water was transported onshore behind the warm water as illustrated by the successive positions of the 5°C isotherm. The time series plots of temperature for 11–13 July in Figs. 2, 5 and 6 are consistent with the temperature cross sections and vividly illustrate the downwelling event.

The current acceleration associated with the tilted isotherms is illustrated in the current cross sections computed by the dynamic method (Fig. 9). The level of no motion of 60 m can be questioned as Fig. 8 suggests temperature structure below 60 m. The maximum acceleration occurred at a little over 1 km offshore. On 11 July the calculated current was 15 cm s^{-1} at 1 km offshore; it rose to over 65 cm s^{-1} by 13 July, which correlates very well with the observed nearshore current (Fig. 2). The comparison of the measured and calculated current speeds suggests the longshore current was very nearly in geostrophic equilibrium.

Relatively strong low-pressure systems north of the Lake were found to correlate with the strong downwelling events of 1–20 July. Relatively weak low-pressure systems were found to correlate with the weak downwelling events of 21–31 July. The period of passage for the low-pressure systems was 4–6 days. This compares with a 20-year of 6.3 days in June (Reitan, 1974) and a 3–6 day spectral estimate from ten years of data at Duluth, Minn. (Oort and Taylor, 1969).

b. Upwelling associated with a high-pressure system

We consider now the case of the high pressure system passing north of Lake Superior on 19–24 July (Fig. 10). The anticyclonic circulation results in a component of the wind blowing parallel to the Keweenaw coastline from the east-northeast that causes offshore Ekman transport. The result is the strong coastal upwelling illustrated in Figs. 2 and 4–6.

The intensity of this high-pressure system is typical of all the high-pressure systems in July, with the exception of that associated with the 6–7 July upwelling event. However, high-pressure systems occur-

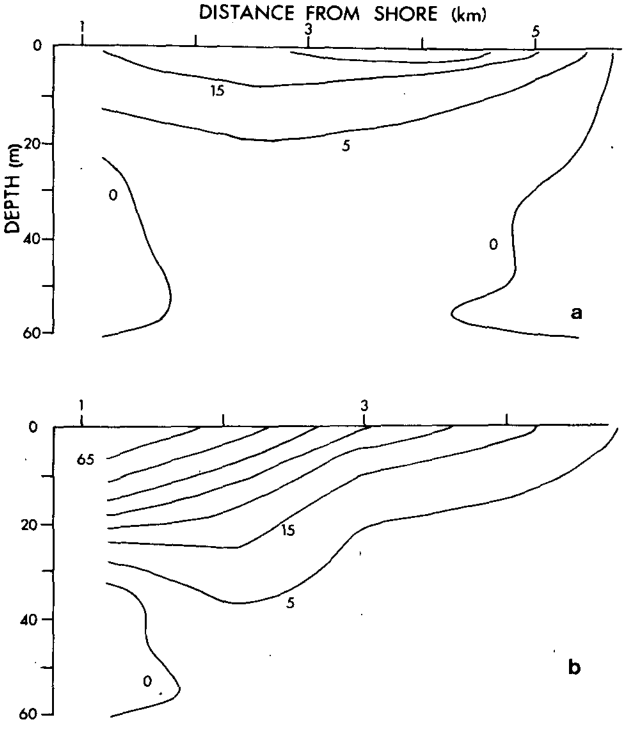

FIG. 9. Geostrophic current calculated from dynamic heights along the buoy line (Fig. 1). Speeds are positive toward the northeast. The level of no motion was taken to be at 60 m. (a) 1800 CDT 11 July; (b) 1400 CDT 13 July. Contours are shown in 10 cm s^{-1} intervals, starting at 5 cm s^{-1}.

ring during 1–20 July passed over the area in less than 48 h. Those occurring during 21–31 July had a duration of around 4–5 days, allowing the east-northeasterly winds far more time to generate offshore Ekman transport, resulting in major upwelling. Fig. 10 shows that the high of 19–24 July was north of Lake Superior for about 5 days, and actually retrograded at one point. The apparent minor upwelling event of 6–7 July is illustrated by the current variation rather than the temperature variation (Fig. 2). In this case, a very weak high was located north of Lake Superior, squeezed between strong low-pressure systems on 2–4 and 7–9 July. The result was very weak upwelling that would have been overlooked if only the temperature record had been considered.

Fig. 11 shows temperature cross sections just before and during the upwelling event of 19–24 July. A wedge-shaped thermocline was associated with the downwelling of 17–19 July. Water of temperature 15°C was on the surface nearshore, and the 5°C isotherm rose from 60 m deep nearshore to the surface about 7–8 km offshore. By about 5 days later, the 15°C water had been forced offshore of the array and water of temperature less than 5°C was at the surface to about 1 km offshore. The thermocline was then lens-shaped.

The variation in temperature over this 5-day period (Fig. 12) shows an upwelling region 4–5 km wide and at least 60 m deep nearshore. Upwelling velocities (calculated from isotherm movement) average about 15×10^{-3} cm s^{-1} (13 m day^{-1}) with maximum values of 60×10^{-3} cm s^{-1} occurring near the coast. For comparison, upwelling velocities of 35×10^{-3} cm s^{-1} occur along the north shore of Lake Superior (Ragotzkie, 1974), and velocities of 7.0×10^{-3} cm s^{-1} occur in the coastal ocean (Smith *et al.*, 1966).

The 0°C isotherm forms a small tongue-shaped pattern (the tip of the tongue is marked by the solid arrow). Similar and often more marked patterns were found by Niebauer (1976) from data collected during three other upwelling/downwelling cycles in 1972 and 1973. The tip of the tongue appears to be a pivot point about which the flow changes from vertical to horizontal. Water shoreward of this point is upwelling. Lakeward and above this point, the flow is horizontal and directed offshore. These motions are indicated by the shaded arrows. It appears that the depth of offshore transport is of order 10 m. Offshore currents as measured by the current meters, calculated from the movement of surface isotherms, and calculated Ekman transport, all fall in the 3–5 cm s^{-1} range.

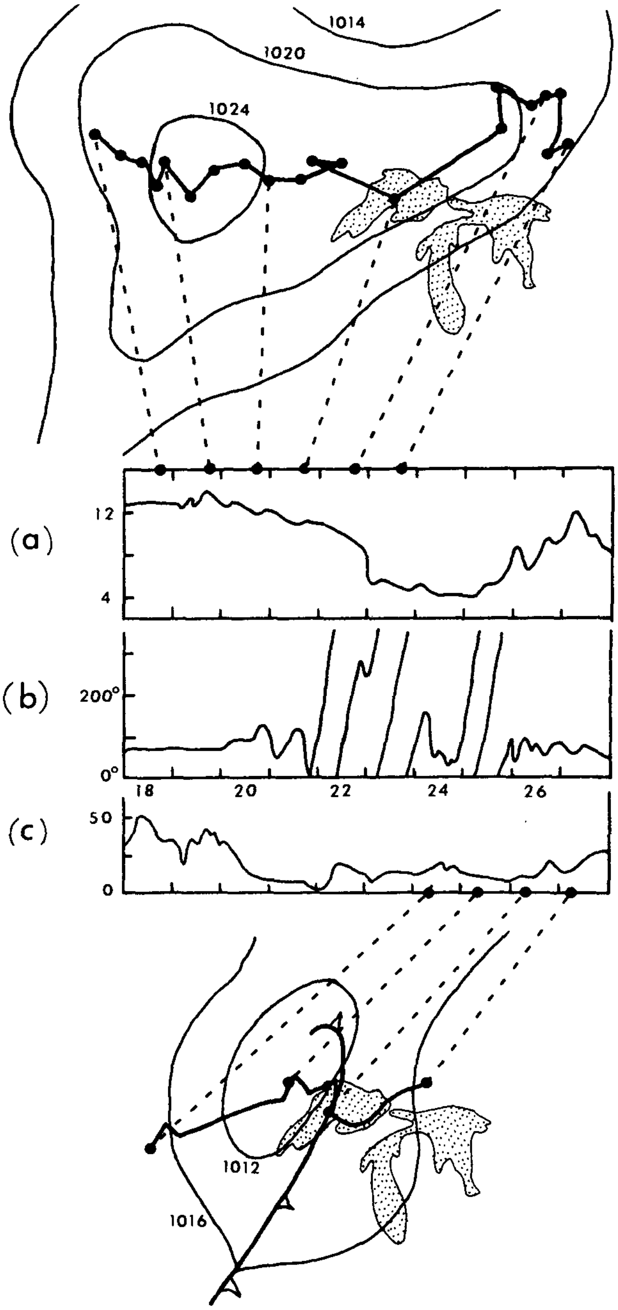

FIG. 10. Surface pressure maps for 0100 CDT 20 July (top) and 0700 CDT 25 July (bottom), associated with the upwelling/downwelling cycle of 20–26 July. The notation is as in Fig. 7.

Baroclinic geostrophic velocities indicate the transformation of the current from eastward from up to 50 cm s^{-1} on 19 July (Fig. 13) to essentially no motion (and slight countercurrents of 5 cm s^{-1} or less) by 24 July. These latter velocities do not agree very well with the current meter records. It is suggested that as upwelling progresses the horizontal (baroclinic) pressure gradient disappears and the current is no longer in geostrophic equilibrium. It is speculated that the ensuing adjustment to ageostrophic conditions gives rise to the inertial oscillations during upwelling events (Fig. 2).

5. Summary

Current meter, hydrographic and wind data were collected in the region of a strong coastal jet during

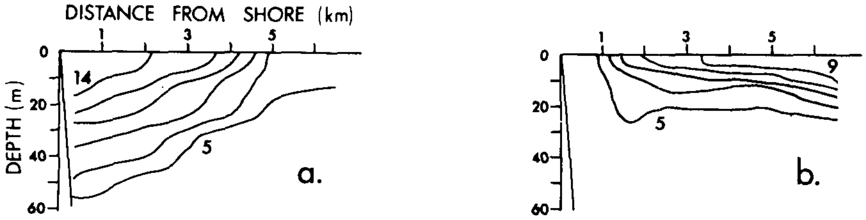

FIG. 11. Temperature cross sections off Eagle Harbor (Fig. 1). (a) 2000 CDT 19 July; (b) 2000 CDT 24 July. Except where noted, only even isotherms are shown in (a).

the late spring and early summer regime of Lake Superior. These data were compared with surface pressure patterns over the area with the following conclusions:

1) Longshore wind components associated with passing low-pressure systems cause onshore Ekman transport and coastal downwelling along the Keweenaw Peninsula. This results in an intensification of the onshore pressure gradient associated with the Keweenaw Current, which in turn causes the Current to intensify. Speeds of over 75 cm s^{-1} toward 075°T are both recorded and calculated suggesting that the Keweenaw Current, at these times, is in geostrophic (baroclinic) equilibrium.

2) Longshore wind components associated with passing high-pressure systems north of Lake Superior cause offshore Ekman transport and coastal upwelling. Cool upwelled water along the coast and warmer surface water offshore are found associated with average coastal upwelling velocities of 15×10^{-3} cm s^{-1}, an offshore Ekman transport layer of about 10 m and offshore surface layer velocities of 3–5 cm s^{-1}. Coastal upwelling is also found to be associated with a nearshore deceleration of the Keweenaw Current and current direction fluctuations of near and sub-inertial period. It is suggested that the deceleration of the Current is due to a combination of the destruction of the cross-shore horizontal pressure gradient during upwelling, winds blowing in the opposite direction from which the Current flows, and longshore momentum being forced offshore by Ekman transport. Whether the upwelling process causes the Current to cease, or to dissipate by being spread over the coastal zone, or to be forced offshore as a coherent jet is not yet fully understood.

The period of passage of highs and lows in July is about 4–6 days. Thus, alternating upwelling and downwelling occurs about every 4–6 days giving the Keweenaw Current the appearance of a pulsating coastal jet of period 4–6 days and range about 60 cm s^{-1}.

ACKNOWLEDGMENTS

This research has been supported by the National Science Foundation under Grant 33140.

We thank Professor F. Scarpace, Drs. R. Terrell and L. A. Yeske, Leo Racewicz, skipper of the *Tina Marie,* David Ward, Steve Worley, Bill Sasse, John Gilson, the Koop family of Eagle Harbor, and the

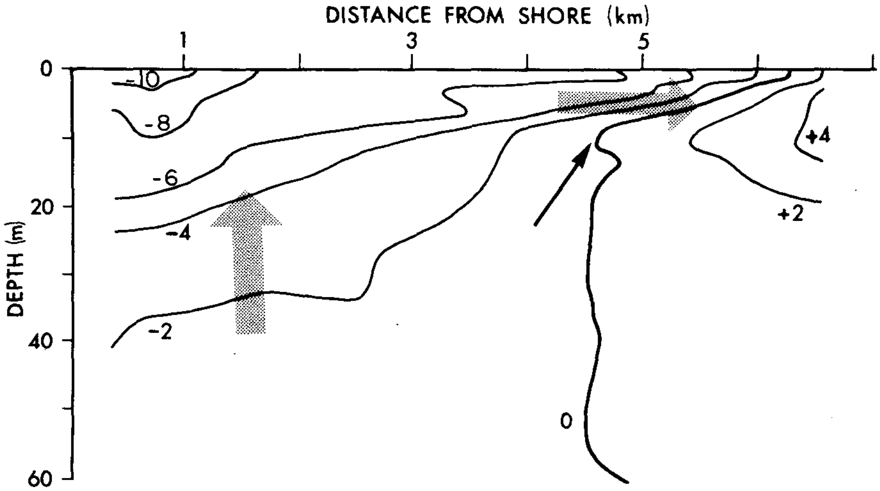

FIG. 12. Temperature differences (°C) between 1900 CDT 20 July and 2000 CDT 24 July (latter minus former). The solid arrow denotes a supposed transition from vertical to horizontal flow discussed in the text; light arrows show inferred water motions.

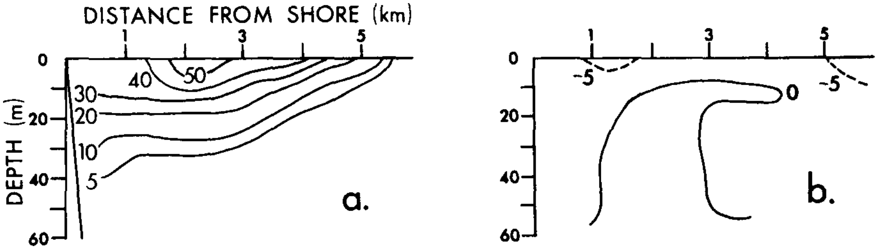

FIG. 13. Geostrophic currents calculated from dynamic heights along the buoy line (Fig. 1), as in Fig. 9: (a) 2000 CDT 19 July; (b) 2000 CDT 24 July.

entire ground crew at Eagle Harbor without whose help this research could not have been undertaken. Special thanks goes to James Bucholtz, who fabricated a great deal of the equipment and instruments used in four years of experiments. Thanks also go to Professors T. Royer and J. Colonell who critically read the manuscript.

REFERENCES

Blanton, J. O., 1975: Nearshore lake currents measured during upwelling and downwelling of the thermocline in Lake Ontario. *J. Phys. Oceanogr.*, **5**, 111–124.

Csanady, G. T., 1971: On the equilibrium shape of the thermocline in a shore zone. *J. Phys. Oceanogr.*, **1**, 263–270.

——, 1972: The coastal boundary layer in Lake Ontario: Part II: The summer-fall regime. *J. Phys. Oceanogr.*, **2**, 168–176.

——, 1975: Hydrodynamics of large lakes. *Annual Reviews of Fluid Mechanics*, Vol. 7, Annual Reviews, Inc., 357–386.

Gilson, J. E., T. Green, III and H. J. Niebauer, 1973: Short-term variation in the baroclinic flow of a coastal current. *Abstracts 16th Conf. Great Lakes Res.*, 85 pp.

Green, T., and L. A. Yeske, 1974: Surface kinetic energy transfers in the Keweenaw Current. Contrib. No. 24, Marine Studies Center, University of Wisconsin, 50 pp.

Mortimer, C. H., 1971: Large-scale oscillatory motions and seasonal temperature changes in Lake Michigan and Lake Ontario, Part I, Text. Special Rep. No. 12, Center for Great Lakes Studies, University of Wisconsin-Milwaukee, 111 pp.

Niebauer, H. J., 1976: Wind driven coastal upwelling in Lake Superior. Ph.D. thesis, University of Wisconsin-Madison, 264 pp.

Oort, A. H., and A. Taylor, 1969: On the kinetic energy spectrum near the ground. *Mon. Wea. Rev.*, **97**, 623–636.

Ragotzkie, R. A., 1974: Vertical motions along the northern shore of Lake Superior. *Proc. 17th Conf. Great Lakes Res.*, 456–461.

——, and M. Bratnick, 1966: Infrared temperature patterns on Lake Superior and inferred vertical motions. Tech. Rep. No. 27, Dept. of Meteorology, University of Wisconsin-Madison, 9 pp.

Reitan, C. H., 1974: Frequencies of cyclones and cyclogenesis for North America, 1951–1970. *Mon. Wea. Rev.*, **102**, 861–868.

Smith, N. P., and R. A. Ragotzkie, 1970: A comparison of computed and measured currents in Lake Superior. *Proc. 13th Conf. Great Lakes Res.*, 969–977.

Smith, R. L., J. G. Pattullo and R. K. Lane, 1966: An investigation of the early stage of upwelling along the Oregon coast. *J. Geophys. Res.*, **71**, 1135–1140.

Yeske, L. A., and T. Green, III, 1975: Short-period variations in a great lake coastal current by aerial photogrammetry. *J. Phys. Oceanogr.*, **5**, 125–135.