Nearshore Lake Currents Measured During Upwelling and Downwelling of the Thermocline in Lake Ontario

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ABSTRACT

The upwelling-downwelling cycles observed along the north shore of Lake Ontario have periods of about 12 to 16 days in length. Currents associated with the downwelling cycle are typically stronger. The periods of the cycles are at least a factor of 2 larger than are periods expected from cyclone movements across the Great Lakes. Although the upwelling/downwelling cycles are generally a response to the wind, this discrepancy suggests a tendency for a more wave-like periodic response.

The kinetic energy in currents near the theoretical inertial period clearly delineates a nearshore zone of about 8 km in width. Internal wave periods observed are 14 and 17 h, but no 14 h periods are observed beyond 8 km. Most of the upwelling and downwelling is confined to this zone. The sloping shore model of Csanady appears to accurately predict the extent of this zone.

1. Introduction

There have been frequent documentations of intense upwelling on the Great Lakes (Fig. 1). The location where the water first reaches the surface is usually not known, but examination of the many aerial surveys over Lakes Erie and Ontario suggest that capes such as Toronto Island (L. Ontario) and Pointe aux Pins (L. Erie) are favored locations. There is, of course, good reason to suspect cape-induced upwelling based on the conservation of vertical vorticity (Arthur, 1965), and the examples presented here (Fig. 1) do not necessarily indicate the locations where upwelling is occurring, but only the spreading of the upwelled water at the surface. Blanton and Winklhofer (1971) estimated that for the upwelling episode in Lake Erie (Fig. 1b) only about 200 km^2 is necessary to transport upwelled water upward at a velocity of 2×10^{-3} cm s^{-1}. The volume of upwelled water represented by these figures was a rough estimate of the quantity of hypolimnion (below pycnocline) waters transported to the coast during the southwest wind conditions that prevailed on 21 July 1970. This study vividly illustrated the necessity of time series measurements of currents in the upwelling zone, a zone which in the Great Lakes probably extends only 5 or 10 km offshore from the beach.

In Lake Ontario, near Oshawa, Ontario, we were able to place current meters in the nearshore zone where upwelling was thought to frequently occur. Blanton (1974) has reported on the currents and some of their complexities in this area. This paper will look in some detail at the currents accompanying upwelling or downwelling of the thermocline.

Csanady (1971b) characterized the summer regime in Lake Ontario by a nearshore thermocline frequently upwelling or downwelling. Further description followed (Csanady, 1972a) in which upwelling/downwelling was correlated with east/west flow along the north shore. This basic structure (i.e., a thermocline with an equilibrium position with the upwelling-downwelling fluctuations superimposed) was accounted for by a theory whereby geostrophic adjustment of currents and thermal structures to wind impulses were accomplished through conservation of potential vorticity.

Csanady (1972a) pointed out that during adjustment from upwelling to downwelling, or vice versa, complete mass exchange of water between inshore and offshore zones may occur. Inferences on mass exchange have been based on dye studies. The data presented in this paper offers some physical description of currents in the nearshore zone during periods when an upwelling or downwelling regime was in a state of fluctuation. Further study is required before we obtain a clear understanding of the mass exchange process, particularly as to the quantity of water exchanged offshore. As more data of these kinds become available, I believe we find ourselves in the position stated by Bang (1971) in his conclusion: the more detail we obtain on nearshore processes, "the less easy it becomes to reconcile these with any clear-cut theory or model."

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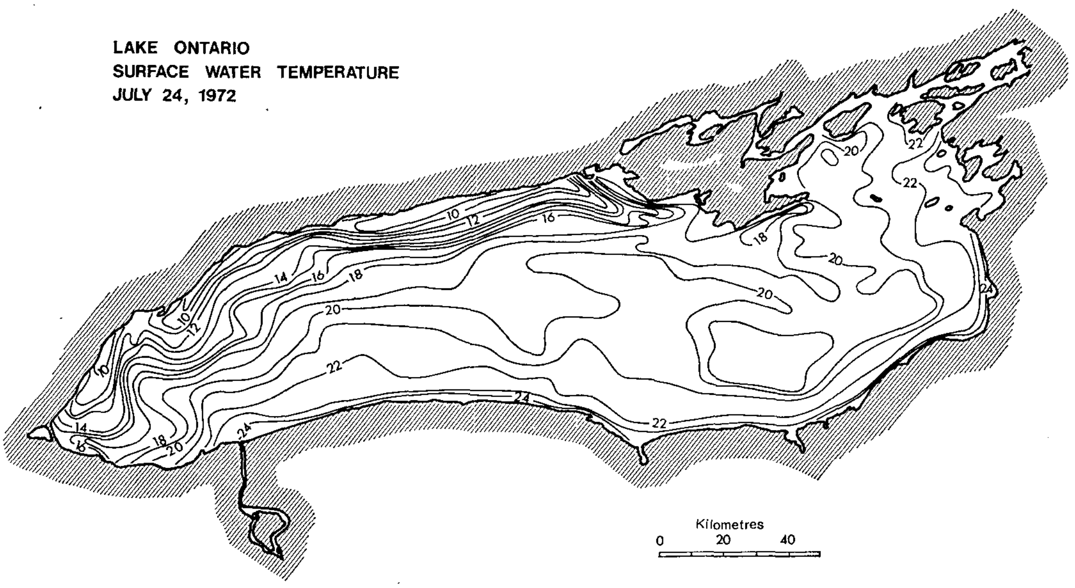

FIG. 1a. Narrow zones of cold surface temperature (°C) caused by upwelling in the coastal zones for Lake Ontario, 24 July 1972. These data were obtained through the Atmospheric Environment Service of the Canadian Department of Environment as a part of its Airbourne Radiation Thermometer Survey of the Great Lakes.

2. Data for this study

The nearshore zone near Oshawa on Lake Ontario has been monitored for four years by the Canada Center for Inland Waters (CCIW), and by the University of Waterloo under the direction of G. T. Csanady. The results described in this paper come from efforts during years 1970 and 1972 (Fig. 2). The arrays of *in situ* current meters and thermistors coincided with a chain of current meter and temperature stations occupied daily by the University of Waterloo. The coastal chain data (Csanady, 1972a) form a valuable supplement to the CCIW current meter data, and will be used in support wherever applicable.

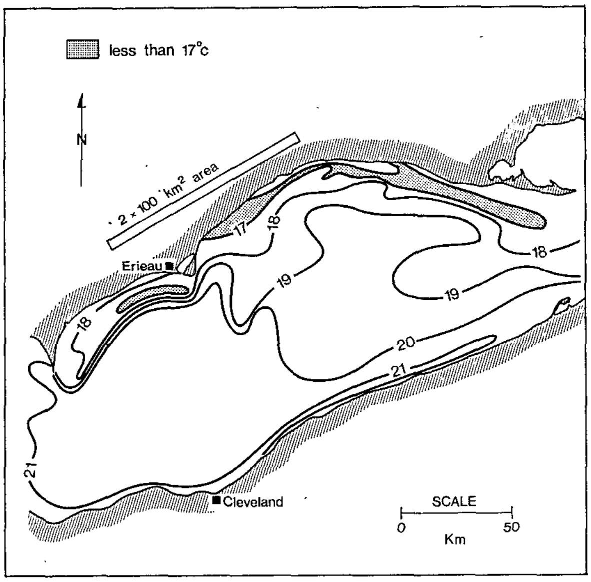

FIG. 1b. As in Fig. 1a except for central basin of Lake Erie, 21 July 1970.

Bottom profiles for the experiments (Fig. 3) were somewhat different. Contours within the 1970 and 1972 sites were generally aligned with the shoreline orientation. This orientation was along an azimuth of about 075° (Fig. 2), so all alongshore currents were resolved along that direction.

The current meter data (currents and temperatures) consist of hourly averages of 10-min readings. The sampling array in 1970 has been described by Blanton (1974). The array in 1972 was not so extensive but instrumentation was basically the same. Table 1 summarizes the data available from the two years. Consult Fig. 2 for locations.

To facilitate study and comparison of the 1970 and 1972 data, four panels were constructed of the winds, currents and temperatures measured in the arrays. Before plotting the data, the hourly values were smoothed with a cosine filter that passes more than 0.98 of fluctuations with periods > 10 h with less than ± 0.02 response for periods $\leqslant 5$ h. Occasionally, the velocity scales of the onshore-offshore components of current are different than those used for the alongshore components. Each of the four panels (Fig. 4) represent a period (Table 1) when data from the coastal chain stations and the current meter stations were collected. Along with the smoothed hourly values of temperature, currents and winds, the position of the 10 (in 1970) and the 13°C (in 1972) isotherms with respect to the shoreline has been plotted. These positions

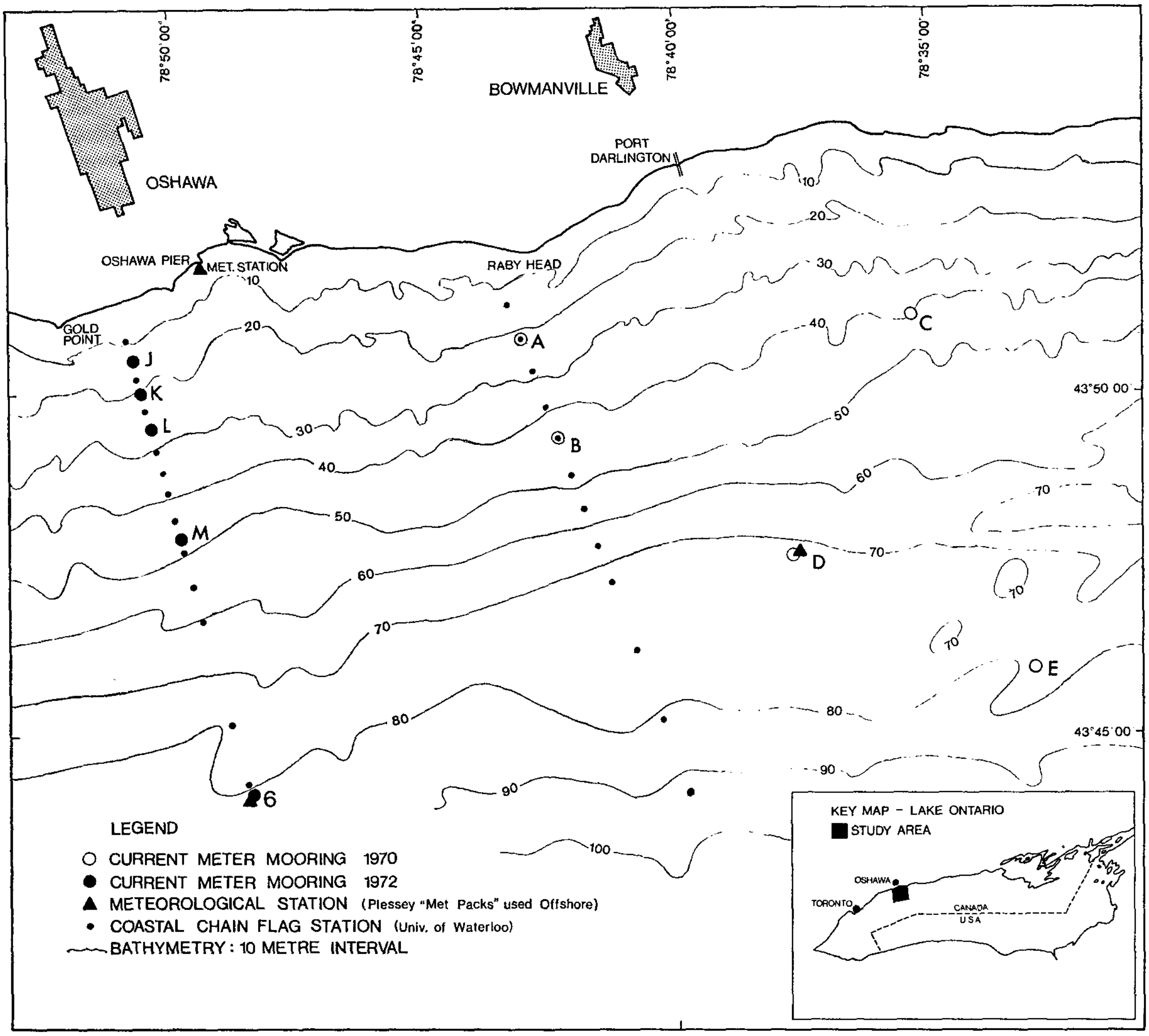

FIG. 2. The study area along the north shore of Lake Ontario. Moorings A through E were set in 1970; moorings J through M and No. 6 in 1972 as a part of the International Field Year for the Great Lakes. Depths are in meters.

are determined from daily plots of isotherms in the nearshore zone furnished by G. T. Csanady and B. Pade (University of Waterloo). Distances are positive when the indicator isotherm is upwelled and located at the lake surface. When downwelling occurs, the isotherms are bent downward along the lake bottom, and these distances offshore are negative. Periods of upwelling are easily determined from the plot. The 10°C isotherm appeared to be consistently in the thermocline in 1970 (Fig. 5) while the 13°C isotherm was the best indicator of the thermocline in 1972 (Fig. 6).

3. Upwelling and Downwelling episodes

The position of the 10 or 13°C isotherms is used here to define the occurrence of each upwelling and downwelling cycle. Each of the four sets of data (Fig. 4) has one definite cycle, extending over periods of 12 to 16 days. Most of the kinetic energy nearshore (hereafter, meaning less than 8 km offshore) is associated with motions having periods $\geqslant 3$ days (Blanton, 1974). Farther offshore, motion in the stratified lake has high amounts of energy concentrated near or slightly below the theoretical inertial period.

No detailed discussion of each episode will be attempted here. Some basic phenomena appear consistent. For example, during the changeover between upwelling and downwelling and *vice versa*, the currents farther offshore usually reverse several hours up to a couple of days later [see Blanton (1974) for a discussion of these reversals in the 1970 data]. No consistent pattern appears in the sense of the onshore-offshore components when one compares all upwelling cycles with one another as well as all downwelling cycles with one another.

Cross correlation of the components of adjacent current records by other scientists at CCIW revealed

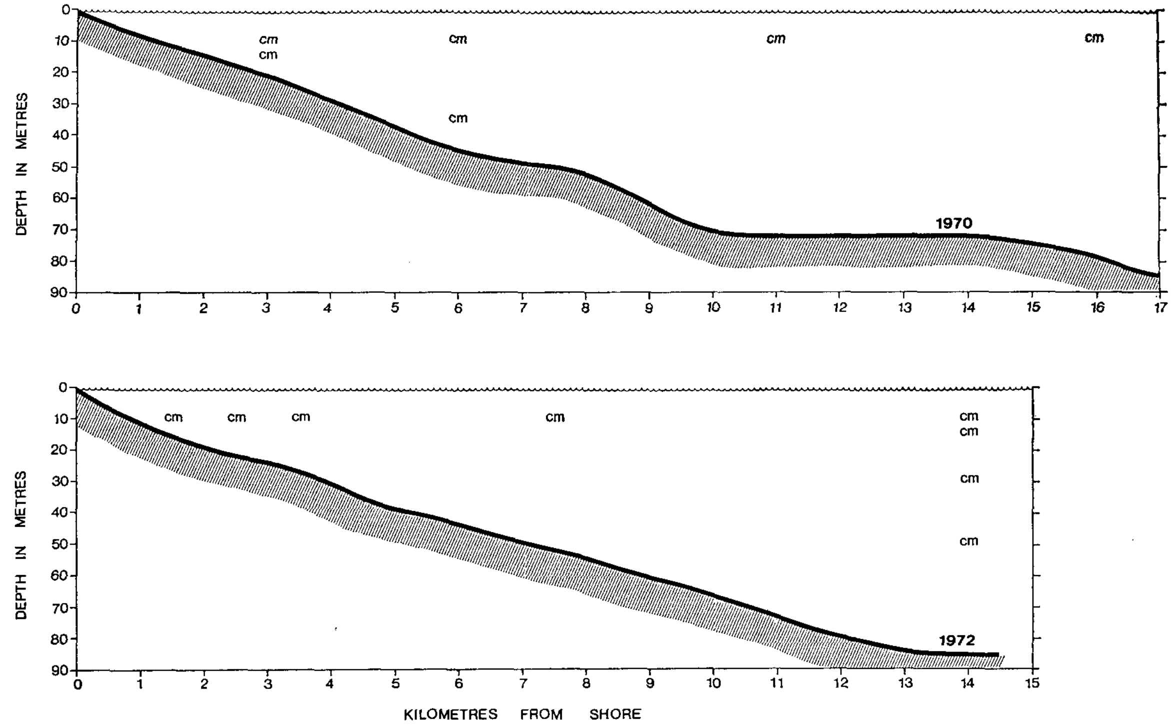

FIG. 3. Bottom profiles at the 1970 and 1972 experimental locations near Oshawa, Lake Ontario. Current meter locations are marked "cm".

that long-period (>1 day) oscillations were approximately in phase and well-correlated. The more important fact of the differing reversal times can be masked in this type of statistical analysis. The 14–17 h oscillations were not consistently in phase when comparing one cycle with another; occasionally, lags of 1 or 2 h can be observed for a day or so then becoming essentially in phase. While these oscillations appeared reasonably well-correlated between adjacent records, it is important to note that the kinetic energy of the oscillations can vary by a factor of 2 or more, and I feel that a "good" correlation of 0.7 or higher may detract from the more important fact that these energy levels diminish rapidly as distance to shore decreases.

TABLE 1. Summary of currents and temperature time-series records off Oshawa, Lake Ontario, for 1970 and 1972. See Fig. 2 for station locations. The Geodyne Model 920 gives the average of 13 "instantaneous" speeds and directions at 10-min intervals. The Plessey Model M021 gives an integrated speed (total length travelled) over a 10-min interval and gives the direction as an arithmetic average of three "instantaneous" determinations each 10 min. Instrument code: G = Geodyne; P = Plessey.

Period	Station/Depth (m)	Water depth (m)	Instrument
7–16 July 1970	A/15	23	G
	B/9, 36	44	P, P
	C/8	37	P
	D/7	73	P
	E/6	80	P
1–13 October 1970	A/6, 14	23	G, G
	B/7	44	G
	D/8	73	G
16 July–15 August 1972	J/10	13	P
	K/10	20	P
	L/10	27	P
	M/10 (stopped 30 July)	49	P
	6/10, 30, 50	83	P, G, G
15 September–6 October 1972	L/10	27	P
	M/10	49	P
	6/10, 15, 30, 50	83	P, P, G, G

a. *Long-period (>1 day) phenomena*

The data in Fig. 4 were broken into upwelling and downwelling events (Table 2). Examples of the thermal structure associated with the events are shown in Figs. 5 and 6. For each event, the long-period velocity data were calculated by drawing a smoothed curve that averages out the oscillations and by calculating the average value for this curve. Five-day averages were used in the calculations except for the two upwelling events in 1970. Examples of this smoothing are shown for the alongshore component of one nearshore current record and the alongshore component of wind (Fig. 7).

The average alongshore component of the upwelling episodes is in all cases eastward (Table 2), thus supporting qualitatively past theoretical and experimental work in oceans and lakes. During downwelling, along-

Table 2. Amplitudes of current oscillations with periods of 11, 14 or 17 h during upwelling and downwelling episodes off Oshawa, Lake Ontario. $U \gtrless 0$ is the mean speed (cm s^{-1}) of the onshore-offshore component; $V \gtrless 0$ is the mean speed of the east-west component. A_u and A_v are the average amplitudes (cm s^{-1}) of the oscillations for the U and V components, respectively. D stands for dominant period.

Episode/Date	Station/ Depth (m)	U	A_u	$\lvert A_u/U \rvert$	V	A_v	$\lvert A_v/V \rvert$	D (h)
Upwelling 5–8 July 1970 (2.5 days)	A/15	+0.6	5.9	9.8	+7.2	4.8	0.67	14
	B/9	+0.9	3.9	4.3	+2.3	2.4	1.0	14
	B/36	−0.7	1.6	2.3	+5.0	1.0	0.2	14
	C/8	−0.6	1.3	2.2	+1.9	2.4	1.3	14
	D/7	−0.8	6.5	8.1	+2.9	7.8	2.7	17
	E/6	+1.6	6.9	4.3	+5.6	7.0	1.3	17
Downwelling 9–13 July 1970 (5.0 days)	A/15	+2.5	3.7	1.5	−12.1	2.5	0.21	17
	B/9	+0.8	2.9	3.6	−10.4	3.2	0.31	17
	B/36	−1.4	1.9	1.4	−7.7	1.5	0.19	17
	C/8	+1.8	3.3	1.8	−14.1	4.0	0.28	14
	D/7	+2.2	10.6	4.8	−4.4	11.5	2.6	17
	E/6	+3.0	10.6	3.5	−4.2	11.1	2.6	17
Upwelling 2–7 October 1970 (4.4 days)	A/6	−3.9	5.1	1.3	+10.2	7.0	0.69	17 (11?)
	A/14	+3.3	2.4	0.74	+4.6	2.0	0.43	11
	B/7	−4.0	9.7	2.4	+10.9	8.1	0.75	17
	D/8	−4.0	9.3	2.3	+6.9	7.1	1.0	17
Downwelling 10–14 October 1970 (5.0 days)	A/6	−2.9	0.9	0.31	−12.8	1.5	0.12	?
	A/14	+6.8	0	0	−15.8	1.0	0.06	?
	B/7	+2.5	2.0	0.80	−29.0	2.4	0.08	?
	D/8	+6.6	3.6	0.55	−13.3	4.8	0.36	?
Upwelling 23–27 July 1972 (5.0 days)	J/10	+0.2	3.7	18	+2.0	1.2	0.60	17
	K/10	+2.4	4.1	1.7	+3.4	1.8	0.53	?
	M/10	+1.2	6.6	5.5	+1.8	2.7	1.5	17
	6/10	+1.2	6.3	5.3	+5.2	5.8	1.1	17
	6/30	−0.8	3.9	4.9	+2.2	4.0	1.8	17
Downwelling 3–9 August 1972 (5.0 days)	J/10	<+0.1	0.6	>6	−7.2	1.6	0.22	?
	K/10	−2.0	2.6	1.3	−14.5	2.4	0.17	17
	6/10	−0.8	12	15	+9.7	14.3	1.5	17
	6/30	+0.3	3.9	13	+7.5	5.9	0.79	17
Upwelling 16–19 September 1972 (5.0 days)	L/10	−1.2	1.6	1.3	+6.3	4.2	0.67	14
	M/10	−1.7	5.6	3.3	+7.1	5.8	0.82	14
	6/10	−5.1	17	3.3	+13.5	20	1.5	17
	6/15	−4.0	6.6	1.7	+7.0	8.2	1.2	17
	6/30	−4.1	3.6	0.88	+8.6	5.6	0.65	17
Downwelling 21–26 September 1972 (5.0 days)	L/10	+2.0	1.8	0.9	−8.7	1.9	0.22	14
	M/10	−0.2	8.1	40	−20.5	6.7	0.33	17
	6/10	−1.2	29	24	+2.1	29	14	17
	6/15	−1.1	24	22	+5.8	25	4.3	17
	6/30	+2.2	7.5	3.4	+0.28	5.0	18	?

shore components nearshore are westward. Beyond the nearshore zone, two of the four downwelling events had eastward mean alongshore velocities. The onshore-offshore sense of the currents is undoubtedly partially, if not wholly, dependent upon the vertical position of the observation relative to the position of the thermocline. For example, the offshore flow at J and K during downwelling (Fig. 4c) is probably compensated by onshore flow at shallower depths.

No coastal jet emerges from this analysis. The means observed during upwelling farther offshore are sometimes as great if not greater than those closer to shore. During downwelling, maximum alongshore velocities were westward and occurred in the nearshore zone; while beyond, magnitudes diminished and even changed to eastward flow on two of the four downwelling events. Our spatial resolution is undoubtedly too coarse to reveal any jet-like structure in the currents since that structure probably shifts greatly in space.

At some time during each of the upwelling periods, strong winds to the east occurred; a similar statement applies for winds to the west during downwelling. However, the duration of each of the four upwelling events was shorter than for the corresponding downwelling event (Fig. 7). The alongshore currents nearshore take on a time distribution resembling a skewed "wave." Note that the smoothed alongshore components displayed in Fig. 7 correlate generally well with the offshore position of the indicator isotherm in Fig. 4. The half-periods of these waves are around 6 to 8 days as measured from the time of maximum east velocities to maximum west velocities. While perturbations on

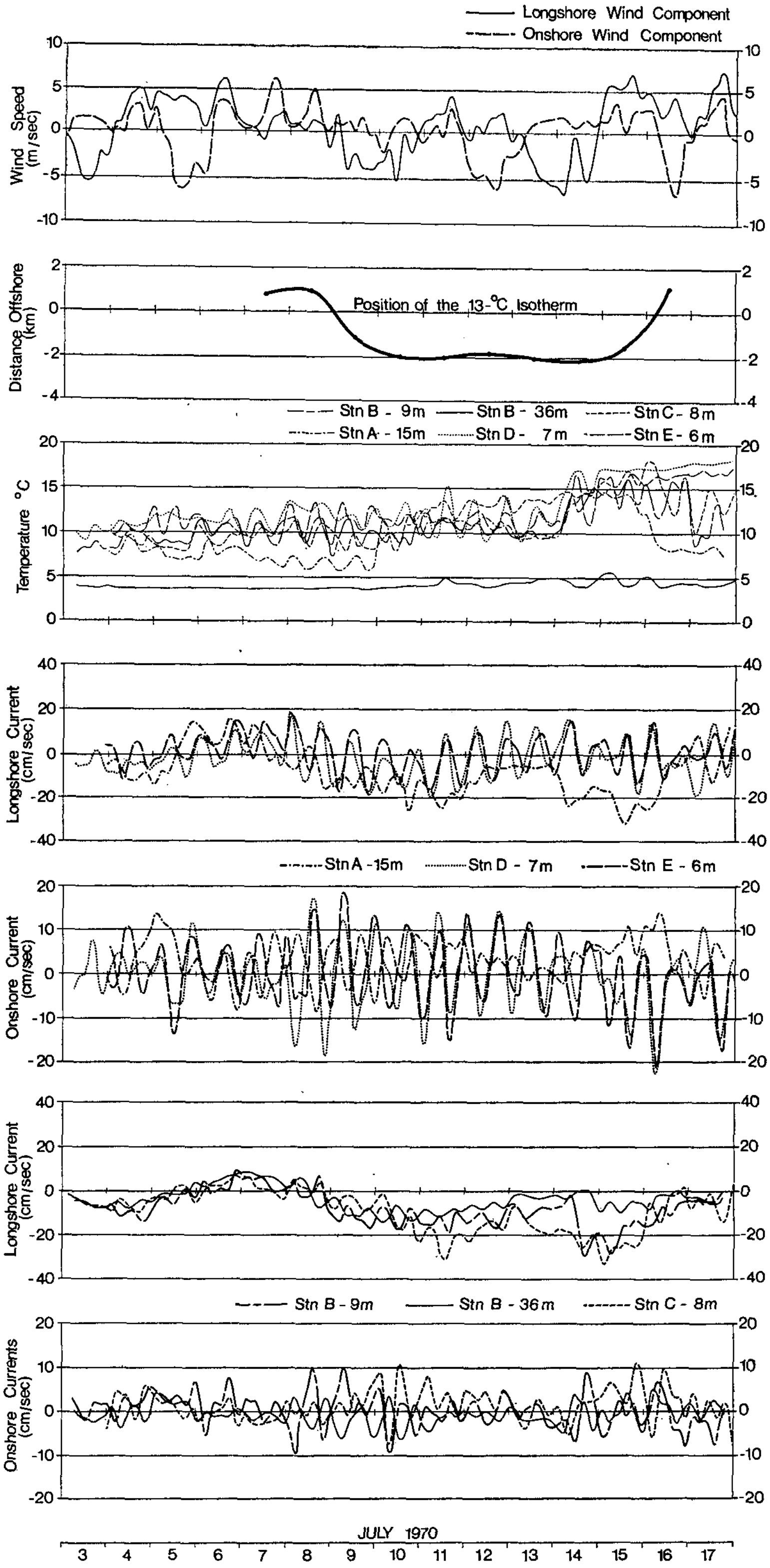

FIG. 4a. Simultaneous measurements of wind velocity, thermocline position, temperature and current components. Wind velocity was measured at the pier. Positive alongshore components flow almost eastward. Negative onshore components flow offshore. Hourly values were filtered so that only fluctuations with a period >10 h were preserved. July 1970. The insert in parts a and b identifying the position of the 13°C isotherm should be corrected to read the 10°C isotherm.

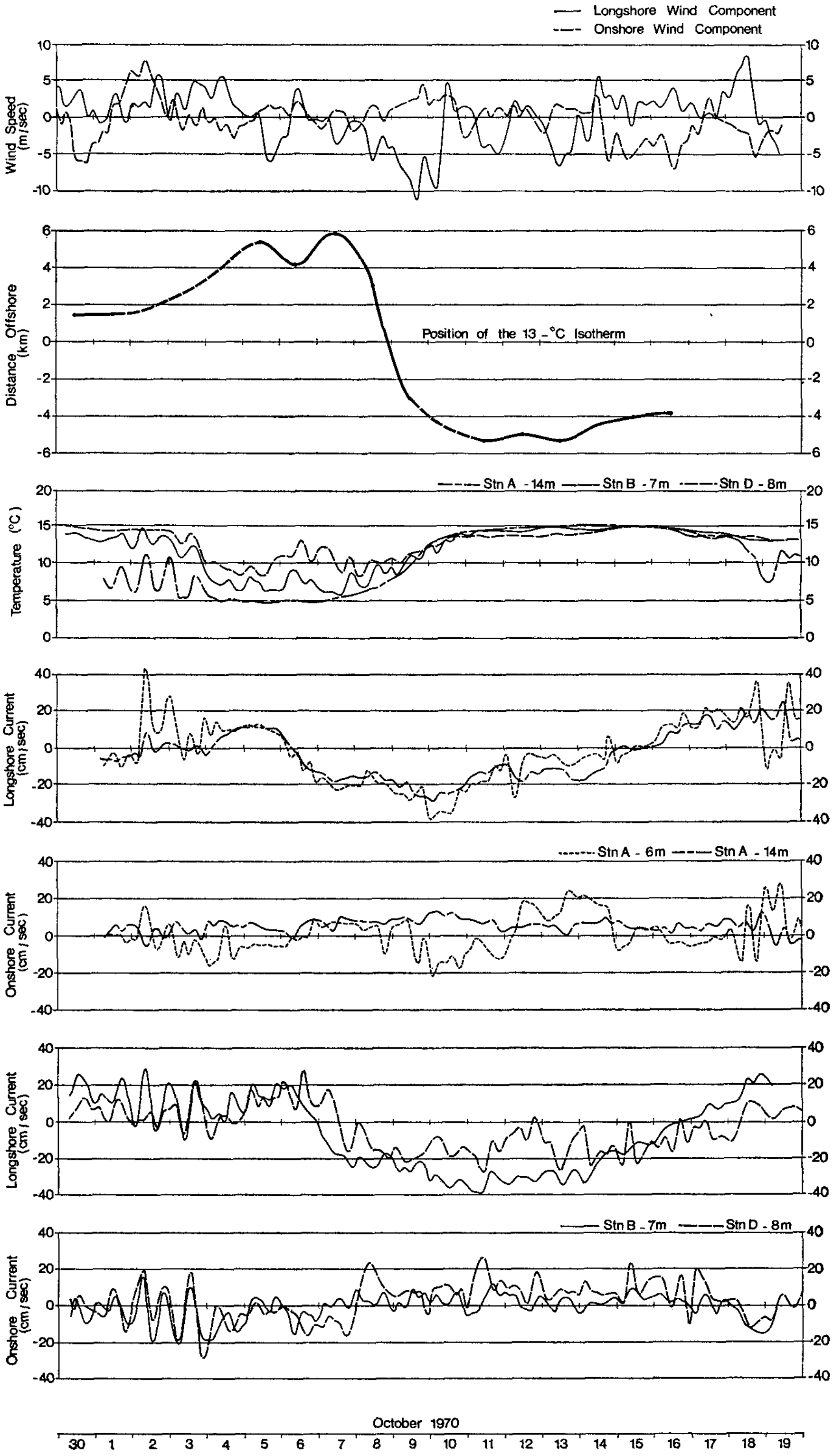

FIG. 4b. As in Fig. 4a except for October 1970.

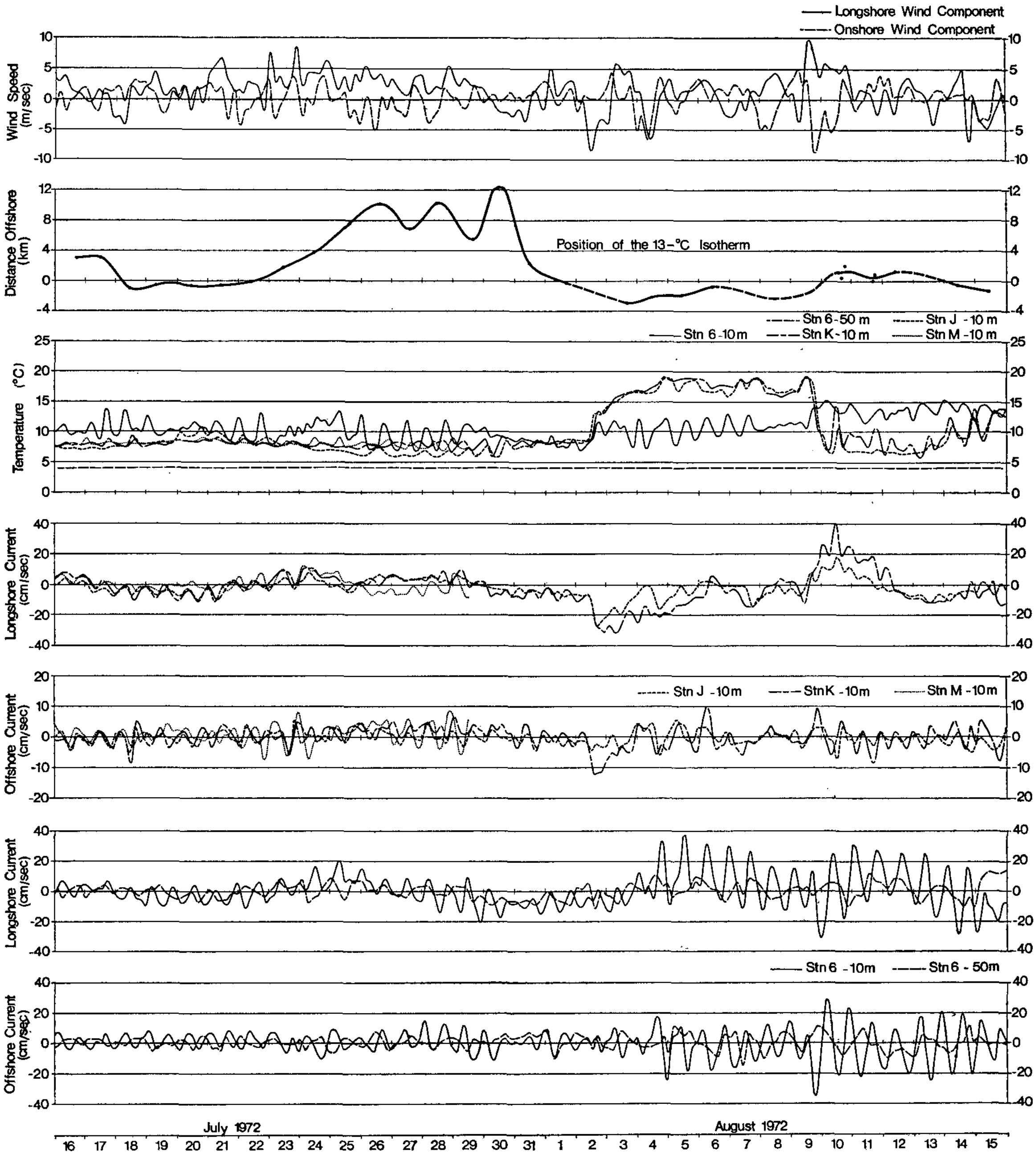

FIG. 4c. As in Fig. 4a except for July–August 1972.

these waves appear to be related to the local winds, the wave itself appears more consistent in form. The periods associated with these measurements (12–16 days) exceed the periods of cyclonic activity expected for the Great Lakes, between 2 and 7 days (Oort and Taylor, 1969).

Csanady (1972b) has theoretically concluded that the Great Lakes, when stratified, have a predominantly baroclinic response in the form of rotating Kelvin waves. Characteristics of these waves are large alongshore velocities and a period of the order of 10 days. Thus the upwelling and downwelling events observed here could be associated with a form of Kelvin wave. Mortimer (1971) has also commented on this possibility from observations in Lake Michigan, and his conceptual model of the nearshore Kelvin wave interacting with rotational Poincaré waves offshore is especially intriguing in light of the direct measurements reported here. Nevertheless, the evidence here is inconclusive mainly because there is only one wave in each data set.

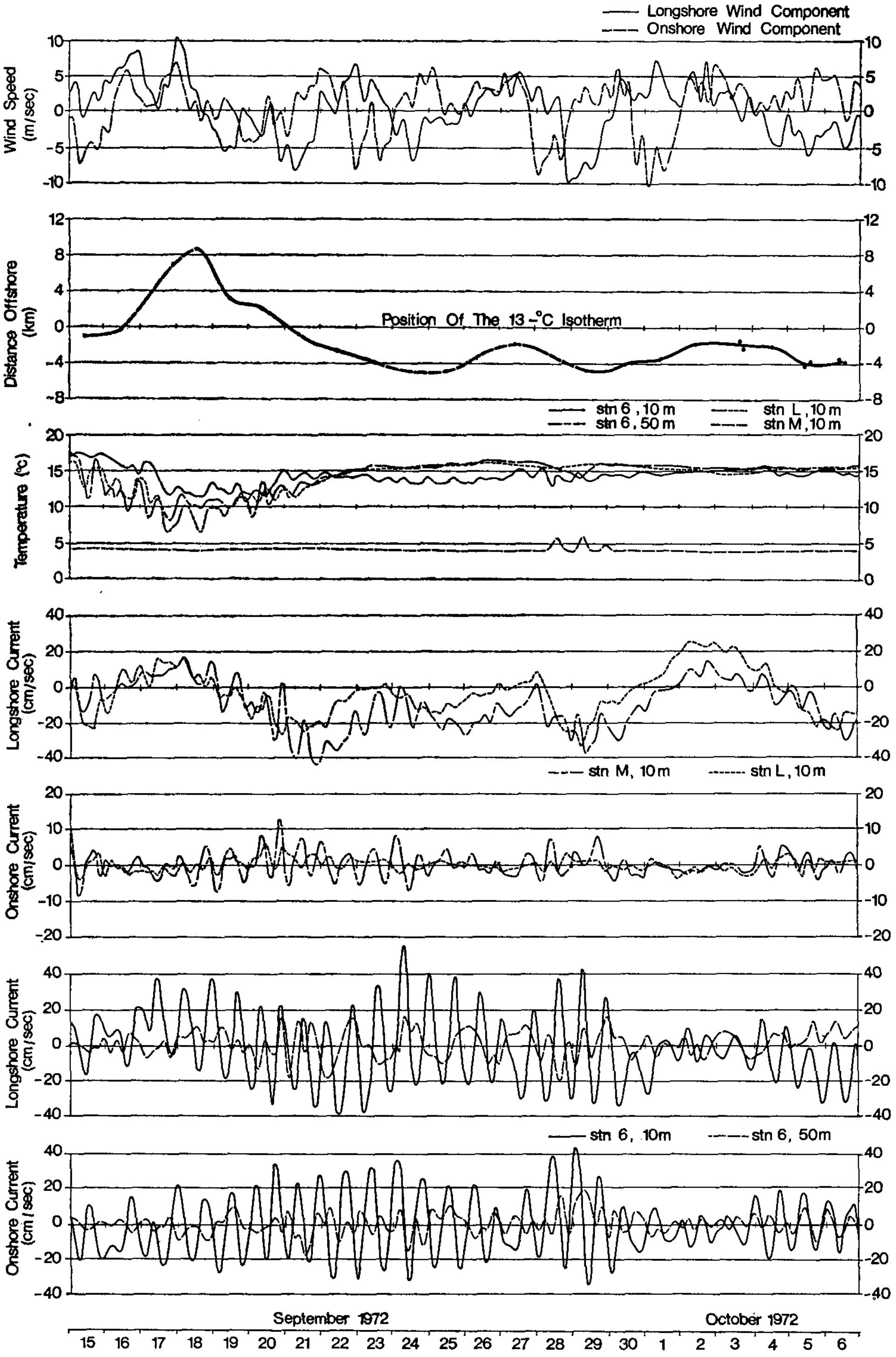

FIG. 4d. As in Fig. 4a except for September–October 1972.

Moreover, the hypothetical Kelvin waves and the upwelling/downwelling cycles reported here are responses to lakewide wind events, so that the most that may be said of the data here is that upwelling and associated east velocities are not highly correlated with local winds, but seem to be in response to a much larger-scale phenomena. The model proposed by Csanady (1972b) concludes that the sloping bottom in the nearshore zone reduces the wave frequency by a factor of 3 over that of the constant-depth model (periods ~10 days). Thus

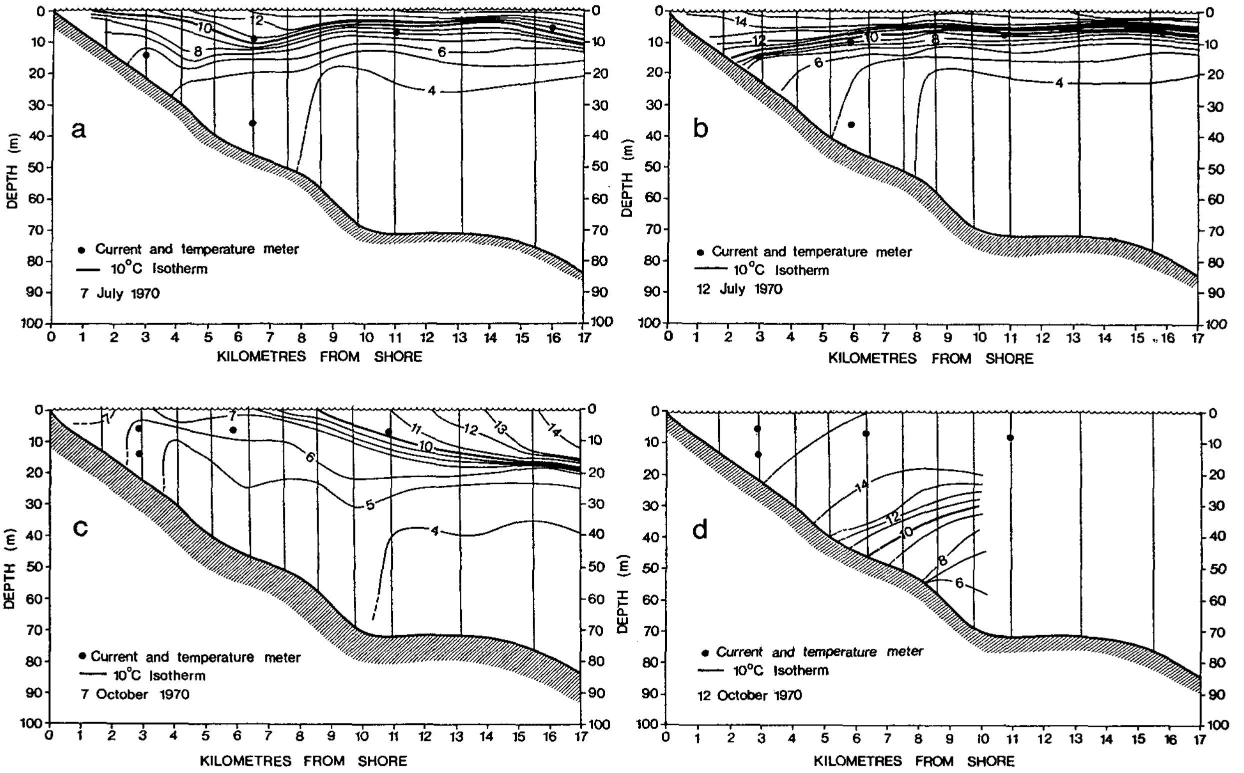

FIG. 5. Representative profiles of temperature off Oshawa, Lake Ontario, from 1970 data obtained from surveys by the University of Waterloo: (a) upwelling, 7 July; (b) downwelling, 12 July; (c) upwelling, 7 October; (d) downwelling, 12 October.

the flow pattern might appear almost stationary. A preliminary examination of nearshore temperature data along the north shore of Lake Ontario has failed to indicate that the observed upwelling/downwelling cycles rotate around the lake.

Related to this is the fact that westward currents off Oshawa are more frequent and stronger than east currents, a fact noted in 1970 data by Blanton (1974). As indicated in Table 3, winds to the east are usually locally prevalent during the times of study which would lead one to expect at least an equal distribution of east flow (west flow) upwelling (downwelling) regimes if not a prevailing east flow near the surface. Evidence based on the thermocline topography and current measurements indicates, contrary to the above reasoning, a net westward flow nearshore (Blanton, 1974). The additional data support previous findings. A conceptual model that incorporates the evidence discussed here begins when a new strong episode of winds to the east initially produces upwelling and east currents in the nearshore zone, but they are soon replaced by west currents and downwelling in response to a return flow along the north shore. Wind stress to the east may still continue.

TABLE 3. Number of days of east and west winds >2.5 m s^{-1}. Record totals are from the data in Figs. 4 and 6.

	July 1970	October 1970	July–August 1972	September–October 1972
East	4.2	4.4	10.4	6.4
West	1.2	4.7	3.3	5.6
Record total	15	19	31	23

I have investigated the vertical shear in the alongshore currents at B/9 m and B/36 m (Fig. 4a) and compared the values with those calculated by a thermal wind equation applied to the University of Waterloo data for the dates 7 through 16 July inclusive. Figs. 5a and 5b show the positions of the current data with respect to the thermal structure. The shears calculated from 17 temperature sections were compared with the smoothed velocity shear corresponding to the average time at which each section was completed. The sign of the shear was correct in 15 of the 17 determinations. However, the magnitude of the computed shear was, in all cases but two, greater by a factor of 2 to 10 over that measured by the current meters. Thus any conclusions based on the geostrophic nature of the alongshore current nearshore are supported only qualitatively. The consistent overestimate of shear by the thermal wind equation is a puzzling yet perhaps significant result. I suspect that the two instruments are well above a benthic boundary layer and that at least the deeper instrument is well below the wind-mixed

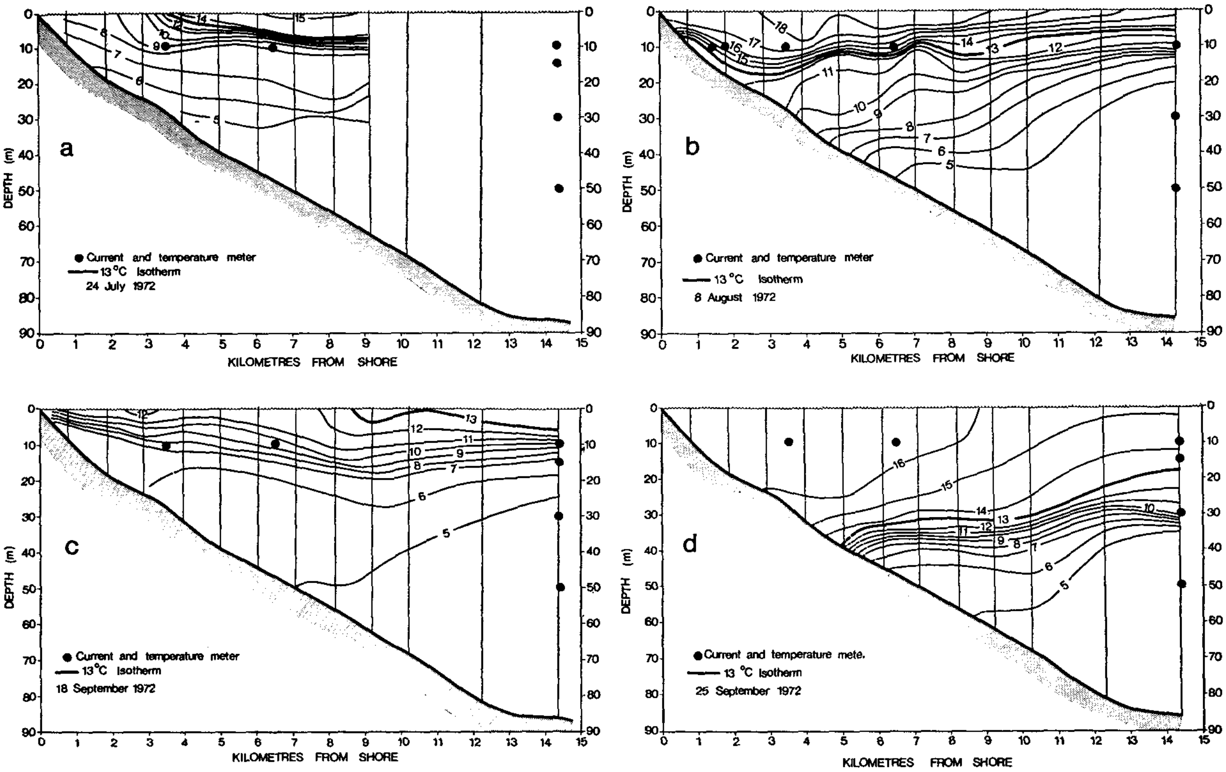

FIG. 6. As in Fig. 5 except for 1972: (a) upwelling, 24 July; (b) downwelling, 8 August; (c) upwelling, 18 September; (d) downwelling, 25 September.

layer. The thermocline passed through or below B/9 m. Until detailed vertical velocity profiles become available for this nearshore area, it will be impossible to properly interpret the apparently low vertical shear in terms of boundary layers.

The above comparison between thermal wind calculations and the measured vertical shear is at variance with oceanic comparisons off the Oregon coast (Collins and Pattullo, 1970; Smith, 1974). The sloping pycnocline off Oshawa suggest qualitatively a quasi-geostrophic adjustment of the nearshore currents, but the thermal wind balance only agrees in sign. Thus the oceanic studies cited above appear to confirm the geostrophic nature of the alongshore flow as predicted by theory (Charney, 1955; Csanady, 1971a; among others). The low observed shears in the upwelling zone of Lake Ontario make a similar conclusion premature for the Lake.

b. Short-period ($\leqslant 17$ h) phenomena

The smoothed low-passed curves used in the previous discussion of long-period phenomena were substracted from the curves in Fig. 4. For each of the episodes in Table 2, the period of the oscillation was determined by a best fit of an 11, 14 or 17 h template that was laid over the data for the onshore component of current. This result is called the dominant period (D in Table 2). There is theoretical justification for selecting the 11, 14 or 17 h templates because these periods represent the transverse baroclinic seiches in Lake Ontario with 5, 3 and 1 nodes, respectively (Mortimer, 1971). The rms amplitudes of the dominant periods are denoted A_v and A_u for the alongshore and onshore components, respectively. The ratio A_v/V or A_u/U denotes a "wave intensity" (anologous to the turbulent intensity based on the rms of velocity fluctuations over the mean).

The amplitudes of the short-period oscillations are generally higher in the offshore records as was clearly manifested in the statistical analysis by Blanton (1974) of nearshore and offshore currents. Table 2 indicates that A_v/V is usually less than 1 nearshore, but greater than 1 offshore. Most observations indicate that A_u/U is greater than 1 for all locations with a tendency for increasing values with distance offshore. The dominant periods during upwelling were 14 or 17 h with the 14 h periods occurring only in the nearshore observations. Dominant periods of 14 h in the nearshore were less frequent during downwelling.

The most characteristic difference between the upwelling and downwelling events thus appears in the values of A_v/V in the observations of less than 15 m in depth (Fig. 8). Onshore of about 8 km, there is a clear tendency for downwelling ratios to be lower than those associated with upwelling. Offshore, the picture is not

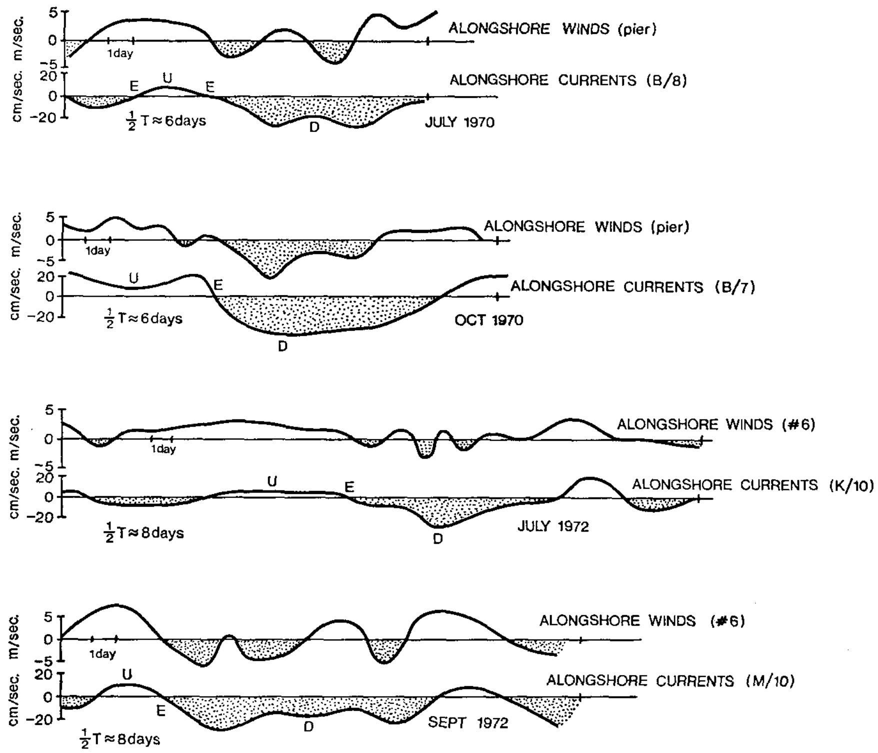

FIG. 7. Smoothed alongshore currents in the nearshore zone less than 8 km from shore plotted with the smoothed alongshore wind component. Data originate from the four time-series displayed in Fig. 4. "U" denotes the mid point in time of upwelling, "E" the approximate times of alongshore current reversal. Note asymmetry in the duration of upwelling and downwelling events. The time U–E–D has been defined as the half-period, $\frac{1}{2}T$.

so clear except that the values of A_v are quite large in this environment and tend to drive up A_v/V to values greater than 1.0 and often much greater. Since V magnitudes tend to be greater during downwelling than during upwelling, this alone might explain the lower ratio observed nearshore. However, if we look at the nearshore values of A_v and A_u for each upwelling event and compare these with the respective values in the following event, there is a tendency for A_u and A_v to diminish. In other words, given a cycle of upwelling followed by downwelling, A_u and A_v in the nearshore tend to be greater during the upwelling portion of the cycle. Furthermore, in three of the four episodes, A_u and A_v values in the offshore (8 km) tended to increase after downwelling began, thus seeming to rule out a simple energy decay of the oscillations after the time upwelling began. It would seem possible that the differing slope of the thermocline during upwelling as opposed to downwelling might be the relevant parameter in understanding these tendencies. The frontal slope may be fundamental in influencing the interaction of frontal zones with internal waves (Mooers, 1970). The nature of the interaction along the north shore of Lake Ontario requires more study.

It is puzzling why the dominant periods of 14 h seem more prevelant during upwelling and that these are all observed in the nearshore zone. Mortimer (1971) also has displayed nearshore data from the southern shore of Lake Ontario where a group of 14 h oscillations in temperature observed during upwelling were eventually replaced by 17 h oscillations as the thermocline downwelled. The possibility exists that the 14 h oscillation (three transverse nodes) receives preferential forcing during beginning upwelling episodes but rapidly damps to be subsequently replaced by 17 h waves. Alternately, our observing of the 14 h oscillation only nearshore might reflect that the nearshore is near the antinodes, assuming that the 14 h oscillation behaves as a standing 3-node Poincaré wave (Mortimer, 1971). Undoubtedly, other explanations may be equally plausible.

4. Summary and conclusions

A rather intensive study of the nearshore currents along the north shore of Lake Ontario has revealed two time scales of interest. One is associated with the upwelling-downwelling cycle that appears to last on the order of 12–16 days, and the other is near the theoretical

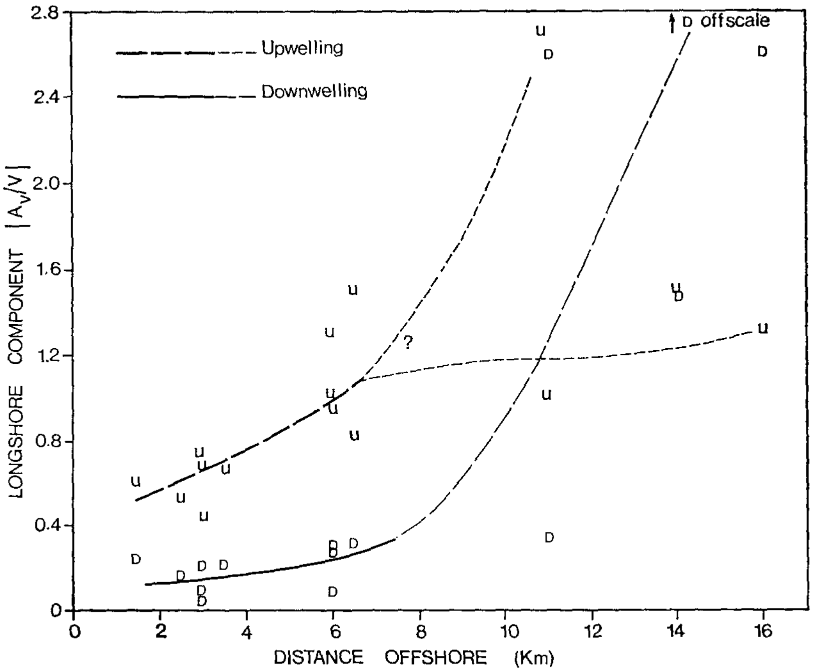

FIG. 8. A_v/V vs distance offshore for the data in Table 2: "U" represents upwelling episodes, "D" downwelling.

inertial period. This appears to support the theoretical models of Mortimer (1971) and Csanady (1972b) that predict a similar response of the nearshore zones of the Great Lakes. While the upwelling-downwelling events observed here cannot be divorced entirely from the wind forcing, it is important to note that these events appear to have longer cycles than those of major cycles of cyclone-anticyclone movement across the Great Lakes. Some quasi-periodic response is suggested.

The normally stronger westward currents may be explained by the presence of a northward boundary that confines the Ekman drift against that boundary during westward winds. Mariners have often noted that coastal currents flowing with the shore on the right are typically stronger than those flowing with the shore on the left.

The nearshore zone appears clearly delineated from the "offshore" zone (Fig. 8) by an abrupt increase in the ratio of velocities associated with the alongshore component of rotational motion to those of the mean alongshore flow. Based on Fig. 8 and statistical results reported by Blanton (1974), the nearshore zone along the north shore appears close to 8 km in width. The constant depth models of Csanady (1972b) gives this zone a width near 5 km. A sloping shore model (Csanady, 1971a) give a width near 6 km measured from the point where the equilibrium thermocline intersects the bottom. This point is located at depths between 10 and 20 m from July to October, or roughly about 1–3 km from shore, yielding a total theoretical width of about 7–9 km.

Many unanswered questions remain: What role, if any, does the upwelling and downwelling thermocline play in governing the predominance of either 14 or 17 h oscillations in the nearshore zone? What physical processes best explain the communication between the nearshore and offshore zones that are so clearly delineated during stratified conditions? Our understanding of nearshore-offshore interactions is a basic prerequisite to any successful prediction of dispersion and mass transport across the nearshore zone.

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