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STUDIES OF LARGE-SCALE CURRENTS IN LAKE ERIE, 1979-80[1]

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ABSTRACT. Currents and water temperatures were recorded at a large-scale grid of fixed moorings in Lake Erie from May 1979 through June 1980. Currents measured in the lower half of the central basin water column were mostly return flows (beneath the surface wind drift) driven by the surface pressure gradient. Often observed was a complex system of Lake Erie circulation gyres as predicted by models. Another common occurrence was for one of the central basin gyres to become dominant and envelop the whole basin in either uniform clockwise or anticlockwise flow. It is not fully certain why one of the circulation cells grows as opposed to the others, but the curl of the wind stress had influence. The currents were more barotropic than predicted by full Ekman layer current models. Tidal-like currents driven by the longitudinal seiches of Lake Erie dominate the island-filled passages between the western and central Lake Erie basins, with currents across the whole island chain very closely in phase. Processes of hypolimnion volume entrainment are suggested from the central basin temperature recordings. Large volume water exchanges between the central and eastern basins occurred after the water mass in the vicinity of the shallow ridge that separates them had become unstratified. These and other topics are discussed as the large data set generated from the experiment is explored.
ADDITIONAL INDEX WORDS: Water temperature, water circulation, water exchange.

INTRODUCTION

We measured currents and water temperature distributions in Lake Erie from May 1979 through June 1980. The measurements were undertaken as a contribution to the Lake Erie Surveillance Program performed for the International Joint Commission (IJC) by the Environmental Protection Agency (EPA), and the EPA provided partial funding for this work. Because of research interest in the large-scale lake circulation processes, our measurements were made on a lake-wide grid of stations as shown in Figure 1. Inserted into this lake-wide grid were several area-specific concentrated water temperature and current measuring programs performed by Canada's National Water Research Institute (NWRI). Their studies were locally intensive and process-oriented (e.g., diffusion of oxygen across the thermocline in the central basin). Data collection schedules and station configurations were generally coordinated prior to the experiment. Following completion of the field experiments, F. M. Boyce of NWRI organized regular workshops where discussions of progress and goals in data analyses were held.

Early estimates of current speed and direction in Lake Erie, largely based on studies of drifting objects, were reviewed in Hamblin (1971) and listed in the historical paper by Mortimer in this issue. The first extensive studies of lake currents using direct methods were made by the U.S. Public Health Service in 1964 and 1965 (FWPCA 1968). They moored current meters and water temperature recorders on a lake-scale grid and reported some general patterns of mid-depth and near-bottom current flows deduced from their observations. The measurements were made with early versions of self-contained Savonious rotor current meters that recorded on photographic film. The data were difficult to transcribe from the film in a timely and accurate fashion, even with the automated light dot scanner developed by the instrument manufacturer. Thus, long time series of reli-

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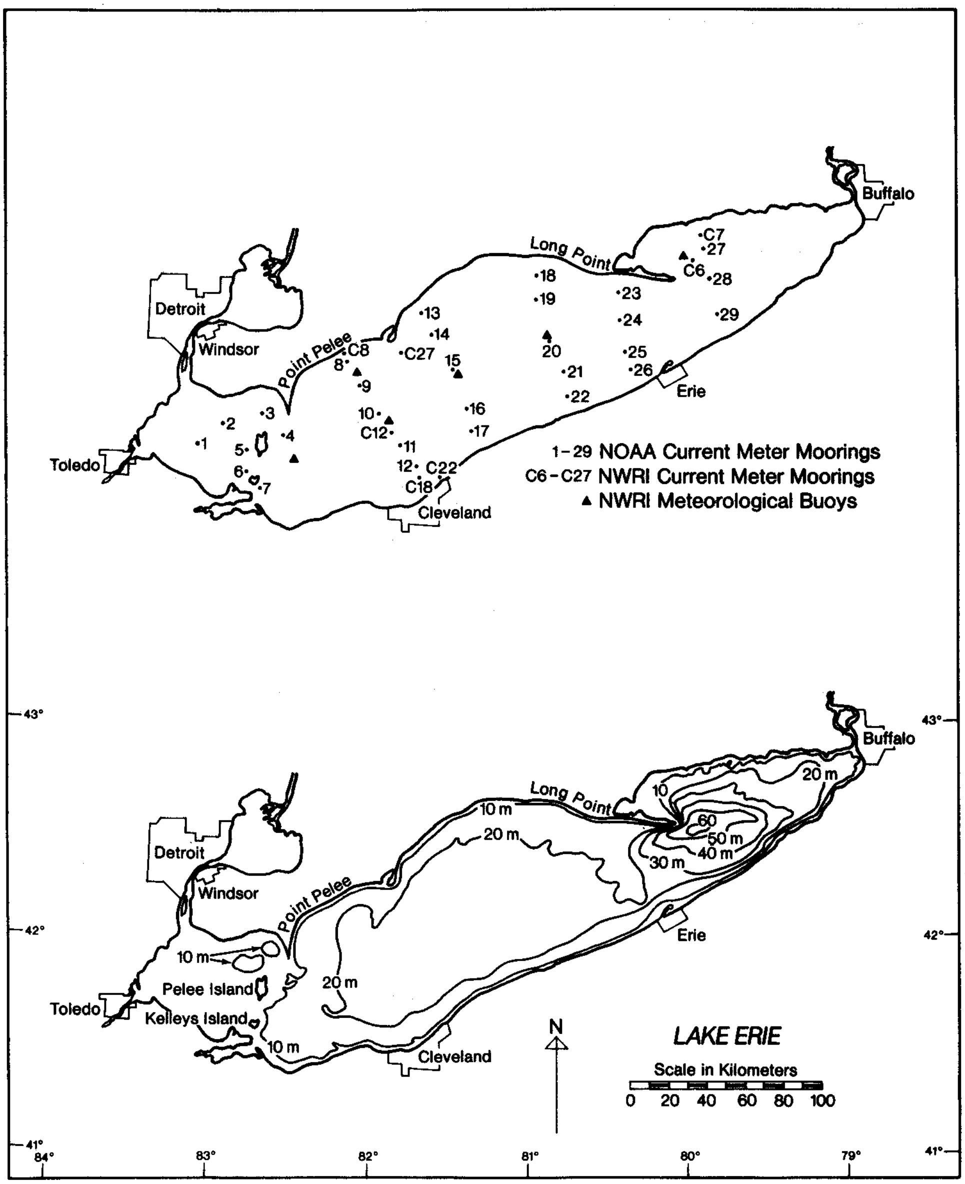

FIG. 1. Lake Erie bathymetry and instrument mooring locations.

able current velocity recordings at numerous open lake stations recorded simultaneously have generally been unavailable for model comparison.

Near-bottom currents in the central basin were measured during Project Hypo in 1970 (Blanton and Winklhofer 1971, 1972). With an array of moorings in place during July and August of that year, the same current recording instruments used in the FWPCA studies referred to above were used to measure movements of the hypolimnion water mass. These investigations revealed a dynamic thermocline interface separating the surface and bottom layers, pushed generally deeper along the southern shore of the lake in response to prevailing southwesterly winds and with upwelling of the hypolimnetic layer along the northern shore. The tilt of the thermocline during those 2 months was associated with northwesterly flow of bottom water across the basin, conforming to bottom current patterns suggested by movements of seabed drifters released in the central basin during 1965 by Hartley (1968).

One process of bottom water renewal suggested by the results of Project Hypo was a deep inflow of hypolimnion water from the eastern basin to the central basin through the deep channel south of the Pennsylvania Ridge. Comprehensive current velocity, water temperature, and dissolved oxygen profiles across this ridge and extending into both the eastern and central basins were measured by NWRI in 1977 and 1978 and reported by Boyce *et al.* (1980) and Chiocchio (1981). A review of this work and more recent findings is to be found in this paper.

The objectives of this report are to present the characteristic flow patterns and their persistence as derived from analyses of our new measurements in Lake Erie and to relate the patterns to the driving forces. We will describe how these new data fit into the existing circulation knowledge base and how they relate to what is known of the water volume exchange processes between the three basins. We will also compare our results with several earlier numerical simulations of currents in Lake Erie and discuss some of their similarities and differences.

DESCRIPTION OF MEASUREMENTS

Currents and water temperatures were measured with an array of EG&G vector averaging current meters, which accumulate in electronic storage registers the east and north components of the current flow past the meter for a preselected fixed interval of time: 15 min in Lake Erie. Computation of the direction vector was triggered eight times for each revolution of the Savonious rotor current speed sensor, the characteristics of which have been described by Gaul *et al.* (1963). For example, in a 50 cm s^{-1} current, 10,400 current vector computations are completed in a 15-min sampling period. The threshold speed was about 2.5 cm s^{-1}. The averaged current vector, together with a reading of the ambient water temperature from a thermistor in the meter housing and accurate to $\pm 0.1°C$, was then read onto a magnetic tape cassette at the end of the interval.

In May 1979, we deployed 29 current metering stations in Lake Erie at the locations shown in Figure 1. All of the stations consisted of a series of current meters stretched in a taut line and suspended in the water column beneath a subsurface float (Fig. 2). This mooring arrangement minimizes the vertical movements of the current meters, since it is well known that the Savonious rotors tend to overspeed with vertical accelerations of the meters. The subsurface buoys were placed deep enough to be beneath significant wind wave orbital velocities for all but the most intense Lake Erie storms. In the shallow western basin of the lake, only one current meter per mooring was placed at stations 1 through 7. With the intention that these moorings would be recovered in fall 1979, a surface float was attached to the anchor at the end of the ground line. The other 22 moorings had more than one current meter and were also equipped with EG&G acoustic releases placed in the current meter strings just above the railcar wheel anchors. No surface markers were attached to these moorings.

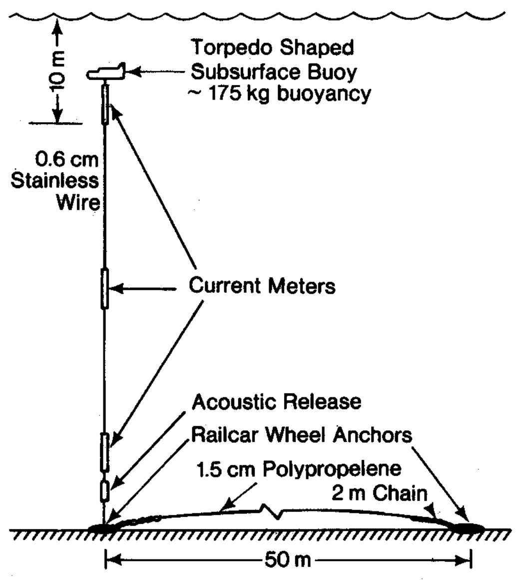

FIG. 2. Typical configuration of a Lake Erie current meter mooring.

Outside the western basin, a current meter was deployed 10 m below the water surface at each station. Each of these stations also had a current meter as close to the bottom as the fastening hardware and acoustic release length would permit, with the current sensor itself thus placed at 2.3 m above the bottom. (This was the design depth; actually the anchor settles into the bottom some unknown distance and the measurements are somewhat closer to the lake floor.) Several stations in water deeper than 20 m in the central basin had a third current meter between the 10-m depth and the bottom meter. In the eastern basin, the third current meter was placed near mid-depth.

Thermistor chains were moored separately, close to the current meters at stations 9, 11, 19, and 21. These moorings had a configuration similar to those for current meters, with the string of thermistors stretched between a subsurface float and an anchor and with a surface float attached to the end of the groundline. The thermistor chain itself consisted of 11 thermistors spaced at 2-m intervals. The recording package was attached to the subsurface float and the 20-m-long chain was tied to the mooring cable and then wrapped back again on itself. Thus near the bottom of the string, the measuring interval was somewhat less than 2 m. Water temperature was recorded once each hour, with the accuracy of the measurement again being $\pm$ 0.1°C.

We exchanged data with NWRI, and current meter records from several of their 1979 stations have been used to fill holes in our own data set. These locations are shown in Figure 1. Although the instruments vary somewhat from those described earlier, the mooring techniques are similar and the data are compatible.

It was planned that the moorings outside the shallow western end of Lake Erie would be deployed for about 1 year. The acoustic releases used to retrieve the moorings had proven themselves very reliable in past overwinter deployments, but in Lake Erie this was not to be the case. A batch of defective acoustic release batteries were received from the instrument manufacturer. On the recovery trip in June 1980, only a few more than one-half of the stations released on command of the shipboard acoustic control. Several other of the acoustic devices released randomly some time after the initial command for interrogation and release; these surfaced a week or two later and were found by passing small boats or lake freighters.

Faced with many remaining stations with defective acoustic releases, we spent the latter half of summer 1980 looking for the moorings by both searching with a side-scanning sonar device and grappling for the ground lines. This search was only partially successful and five stations, with a total of nine current meters, were ultimately lost to the lake. The search was difficult for two reasons. Several moorings on the Canadian side of the lake were apparently moved by fishing vessels that trawl very intensively for smelt. Two moorings were actually recovered by these fishermen, one recovery in summer 1981 was of a mooring (station 9) that had been dragged off station in either 1979 or 1980. The second complication was that, in the eastern half of the lake, several of the moorings in the relatively shallow water of the central basin apparently walked along the bottom in response to intense fall and winter storms. Without very precise positions, backup recovery methods were essentially useless. Had the acoustic releases worked, these would not have been insurmountable problems because their range for interrogation and position finding has generally exceeded 5 miles. But their failure ensured equipment losses and, together with malfunctioning current meters, accounts for the holes in the data collections.

NWRI deployed six meteorological buoys dispersed throughout Lake Erie in 1979 (Fig. 1). Wind speed and direction and air and water surface temperature were measured continuously from early May through late October. Schwab (1982) used these observations to compute hourly wind stresses that he then compared with the stress determined inversely from the recorded Lake Erie wind tides. His computed wind stresses from the meteorological data were shown in figures in Schertzer *et al.* (1987) to give the reader a ready reference to the seasonal, monthly, or episodic forcing. Wind stress during the period late October 1979 through June 1980 was computed by the methods of Resio and Vincent (1977) and Schwab (1978). We used the wind observations from Toledo and Cleveland, Ohio; Erie, Pennsylvania; Buffalo, New York; and London, Ontario, to determine these values.

CURRENTS IN LAKE ERIE

Efforts to measure water currents and to derive resulting circulation patterns in Lake Erie are at best frustrating. As noted in Mortimer (1987), past efforts have been split into distinct groups, either the drift bottle, drift card, or other type of surface water drift measurement on the one hand, or measurements with fixed current meter (with the highest instrument usually 5 m or more below the surface) on the other. In shallow Lake Erie, the two techniques are measuring different fields of flow and few attempts have yet been made to measure the two together.

The lake is divided into three distinct and very different basins and these differences complicate the observer's dilemma. The shallow western basin has an average depth of about 8 m, all but ruling out useful deployments of fixed current meters. (Most state-of-the-art current meters just do not perform close to the surface where wind waves are large.) Moreover, it is separated from the rest of the lake by a string of islands that limit basin interactions through the restricted passages. The central basin accounts for almost two-thirds of Lake Erie's surface area, but it, too, is relatively shallow and very flat, with a mean depth slightly less than 20 m. The oxygen depletion problem has made the region a productive area for hydrodynamic research, and current meter studies are certainly feasible in the lower half of the water column. The upper half, however, gives the same problems as encountered in the western basin, with the added complication that large ships in commercial trade are free to travel almost anywhere without fear of grounding. (The navigation routes in the western basin are clearly restricted by water depths.) We experienced major problems with ships in our studies. One mooring was retrieved after being caught by a ship's rudder and dragged 15 km; another had the subsurface buoy pierced by a ship's propeller.

The eastern basin has an average depth of nearly 24 m and is a bowl-shaped depression with maximum depth in the center of about 64 m (Fig. 1). It is separated from the central basin by the Pennsylvania Ridge, which trends southerly from the north shore west of Long Point. The deepest communication between the basins occurs through the narrow channel in the southerly reaches. The eastern basin is also isolated in its dynamical characteristics as we will show later, although water volume exchange processes across the sill are of great interest in the study of central basin stratification.

In this report, we were constrained for whole-lake currents to use surface currents suggested by historical drift object studies or inferred from numerical simulation. Results of our own launching of Woodhead surface drifters in the central and eastern basins of Lake Erie during current meter deployments are shown in Figure 3. The courses of drift resemble earlier results closely; the surface drift is eastward with the prevailing wind stress. Hamblin (1971) summarized many of the earlier drift studies pictorially, and the reader is referred to his report for comparative results.

Currents During Central Basin Stratification

The bulk of our current measuring program was directed toward dynamics of the central basin, which (as discussed in Schertzer, *et al.* 1987) is stratified for just a short part of the year. In 1979 stratification lasted no longer than the last half of June, July, August, and the first two-thirds of September, having no doubt been shortened by the wind-driven whole-basin mixing episode of late May, illustrated in Figure 4 as an example of the current response of strong winds blowing transversely to the lake's major axis. A return flow at 10-m depths and deeper was against the wind stress but with and driven by the surface pressure gradient.

Vector resultant currents were computed on a monthly-averaged basis for May 1979 through June 1980 (Saylor and Miller 1983). The number of working current meters steadily decreased from the time of deployment, very few were giving useful data in the last several months. The current charts were separated into two parts, one showing near-surface currents (mostly at 10 m) and the other near-bottom flows. Monthly-averaged currents yielded a complicated set of charts on which concise and strong flow patterns did not persist for lengthy intervals of time stretching into many months, but they did sort into several frequently observed modes.

During July, August, and September (Figs. 5, 6, and 7), a consistent pattern of near-bottom flow developed in the central basin. It consisted of a west-southwestward flow of bottom water that flowed parallel to the south coast of the lake. Developing in the eastern half of the basin in July, the pattern intensified and dominated the flows of August and September. The same pattern appeared at the 10-m level also, with August revealing a whole-basin clockwise flow that strengthened and even enveloped most of the eastern basin circulation in September. The shear between midlevel and bottom level currents was small. The flows bore close resemblance to those reported during the same part of the stratification cycle by Blanton and Winklhofer (1972). Their measurements were also near the bottom and were concentrated in the center of the lake, where the currents are more northwesterly (in the cross-lake flow, central part of our whole-basin pattern). Our measurements have delineated westward flow along the entire southern shore and have closed the circulation in a clockwise fashion with eastward currents observed along much of the northern shore. The bottom waters are transported northward across the lake in the western part of the basin and southward in the eastern part. The circulation is similar to one given by FWPCA (1968) for bottom flow (labeled "prevailing annual bottom flow" . . . Fig. 35).

August and September currents were unusual when compared with the other months, for the only other month in which clockwise circulation

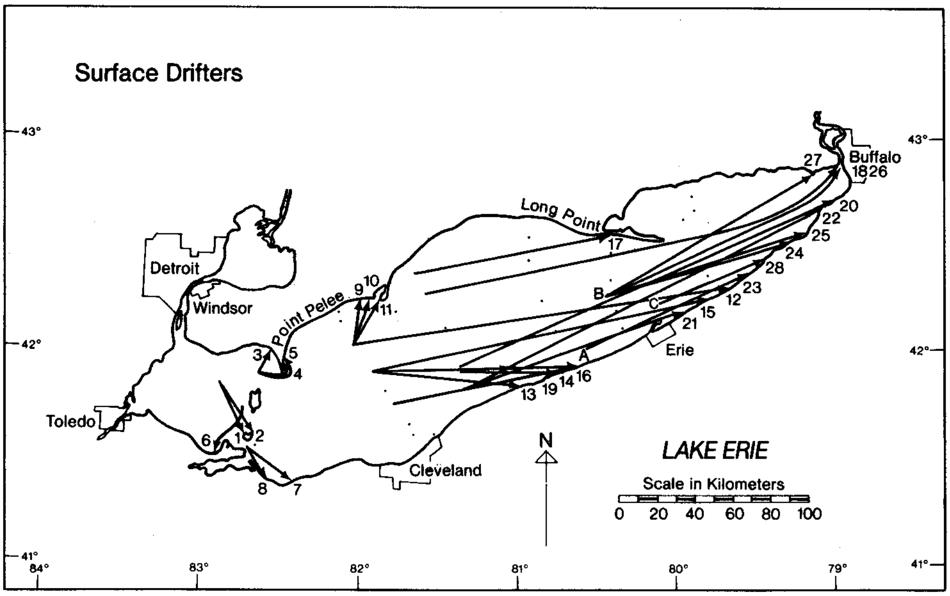

FIG. 3. Movements of Woodhead sea surface drifters released and recovered in Lake Erie in 1979.

filled the central basin was February 1980. The epilimnion circulation at 10 m did not differ substantially from the near-bottom flow even during the most intensely stratified months, although there are a few obvious exceptions, such as at stations 18 and 19 in July.

In the eastern basin, the monthly-averaged currents were cyclonic from the time of current meter deployment in May through August. The basin appeared quite isolated from the currents of the central basin, and this was the case also in daily-averaged current charts that were computed for the entire date collection interval. Cyclonic flow during the stratified season in the eastern basin was suggested by Hamblin (1971) because of a constantly shallower thermocline in the basin's center and geostrophy, and our measurements confirm this distribution. It was not until September that this pattern broke down and clockwise flow from the central basin spilled over and surrounded the eastern basin as well.

It was of interest to integrate the circulation for the entire season of intense central basin stratification, i.e., from say 1 July through the first two-thirds of September. Results of this integration are shown in Figure 8. The current pattern that emerged was one of a general clockwise flow encircling the central basin and represented in both the mid-depth epilimnion currents and the near-bottom flow. The part of the lake basin that deviated from this description was the northeastern section, where the deep flow at station 19 was northwesterly (the average was greatly influenced by the strong northwesterly flow observed here in July) and where currents at station 18 were bimodal, with no strong component parallel to the lake's major axis over the averaging interval. Bottom currents of a few centimeters per second on average may appear to be rather small, but steady flow of a 2 cm s^{-1} equals about 50 km $month^{-1}$ of water transport past a current meter.

Currents During the Unstratified Season

After central basin stratification ended, the three nearly isothermal months of October, November, and December exhibited a similarity in current flows. Averaged together, the resultant vectors are shown in Figure 9. Near-bottom current flows with directions comparable to and magnitudes slightly greater than those of the summer season continued. Different in the pattern of bottom currents is the contraction of the clockwise central basin cell to the northeastern two-thirds of the basin, while in the southwestern third an anticlockwise pattern prevails. The same circulation controls the mid-depth level measurements with little shear at most

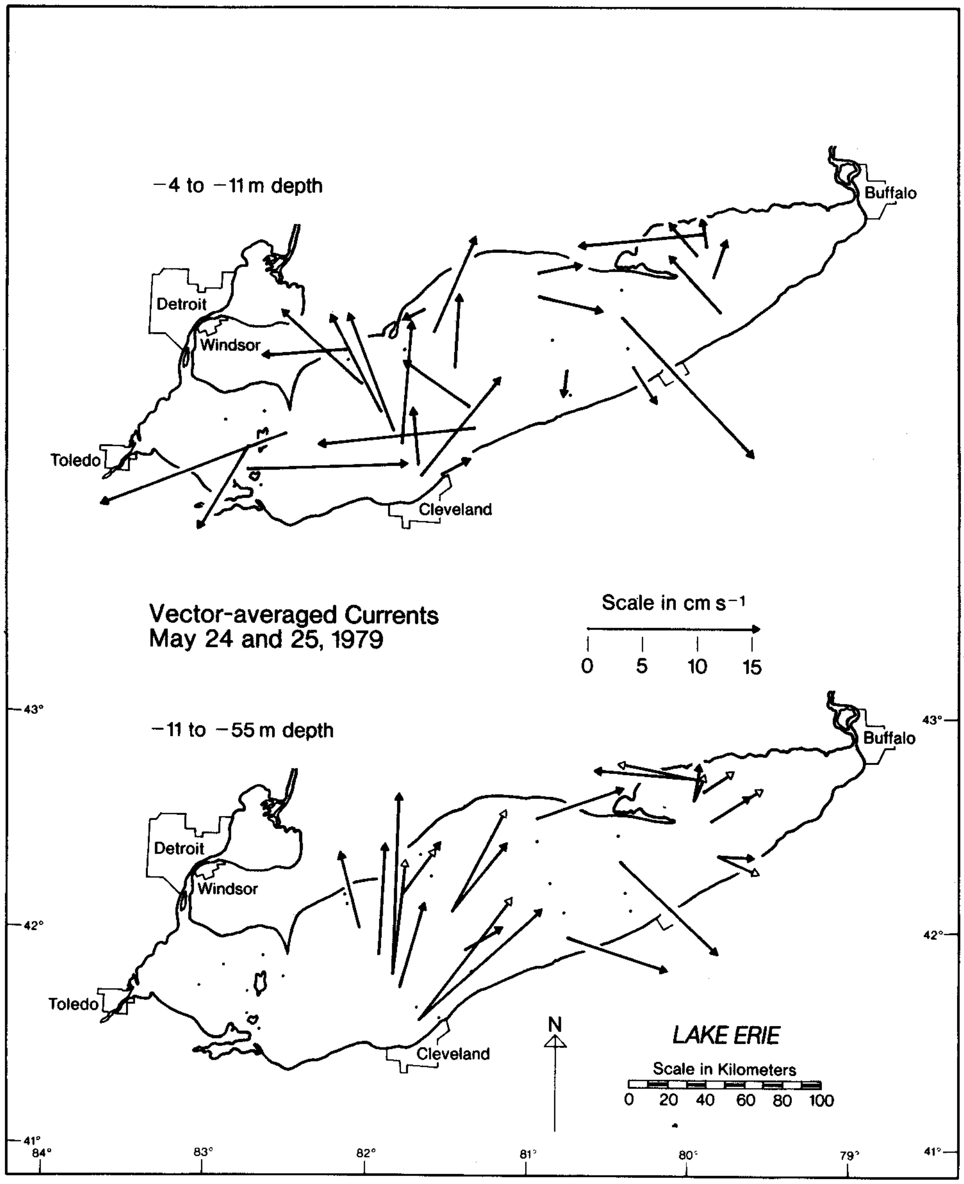

FIG. 4. Vector-averaged lake currents observed on 24–25 May 1979, during a storm with winds from the north-northeast. The arrowhead indicating direction of flow is not included as a part of the current speed scale. Open arrowheads show currents closest to the bottom on the moorings that had three current meters.

stations between the two levels. The same patterns dominated the monthly-averaged data, together with a cyclonic gyre in the south half of the eastern basin. Fall experienced larger wind stresses than observed during summer, but the velocity of the bottom currents were only slightly larger.

We released some Woodhead seabed drifters (Fig. 10) during instrument deployments, repeating on a lesser scale the experiments of Hartley (1968). Arrows showing the drifter movements are presented in Figure 11. The results were similar to those reported by Hartley, verifying that the measured currents do indeed represent the dominant bottom flow regime. Northwestward flow across the basin from the vicinity of Cleveland was obvious, as was an eastward drift close to

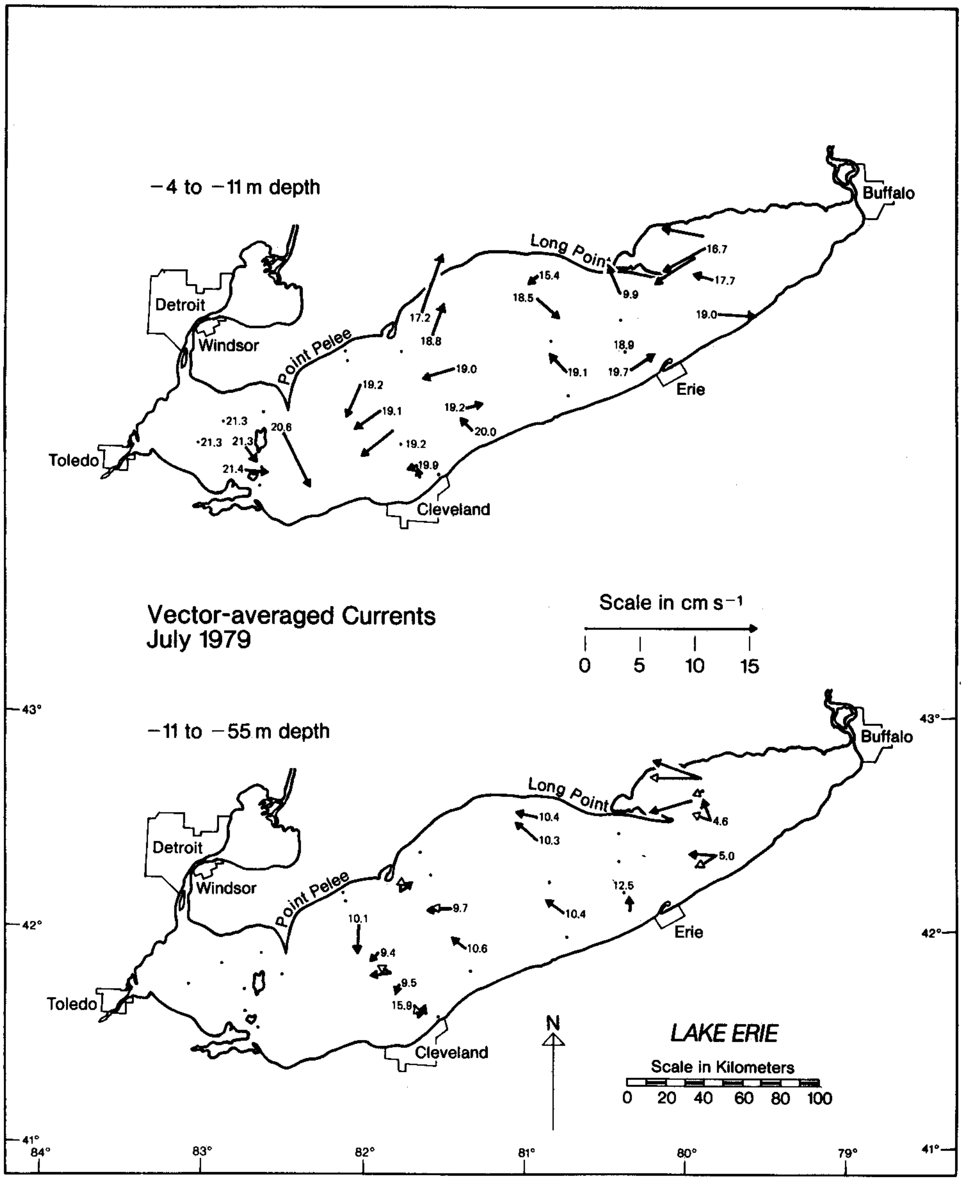

FIG. 5. Lake Erie resultant current vectors for July 1979.

both the northern and southern shores in the eastern parts of the lake. Westward movements from stations 24 and 25 indicated a westward or northwestward flow of bottom water across the Pennsylvania Ridge and into the central basin as reported by Boyce *et al.* (1980). The course of flow of this water during summer was shown by the station 19 deep current measurement in Figure 5. Westward movements from station 28 were indicative of the same bottom water movement and of the cyclonic gyre in the southern half of the eastern basin driven by eastward-directed wind stress impulses.

The monthly or longer period averaged currents we have discussed were composites of numerous wind-driven episodes. Spectra of the wind stress presented in the following section show energy accumulations in the 4- to 6-day range, which represent some average values for the major weather system passages. The response of lake currents to these impulses of wind stress was indeed complex as we will describe.

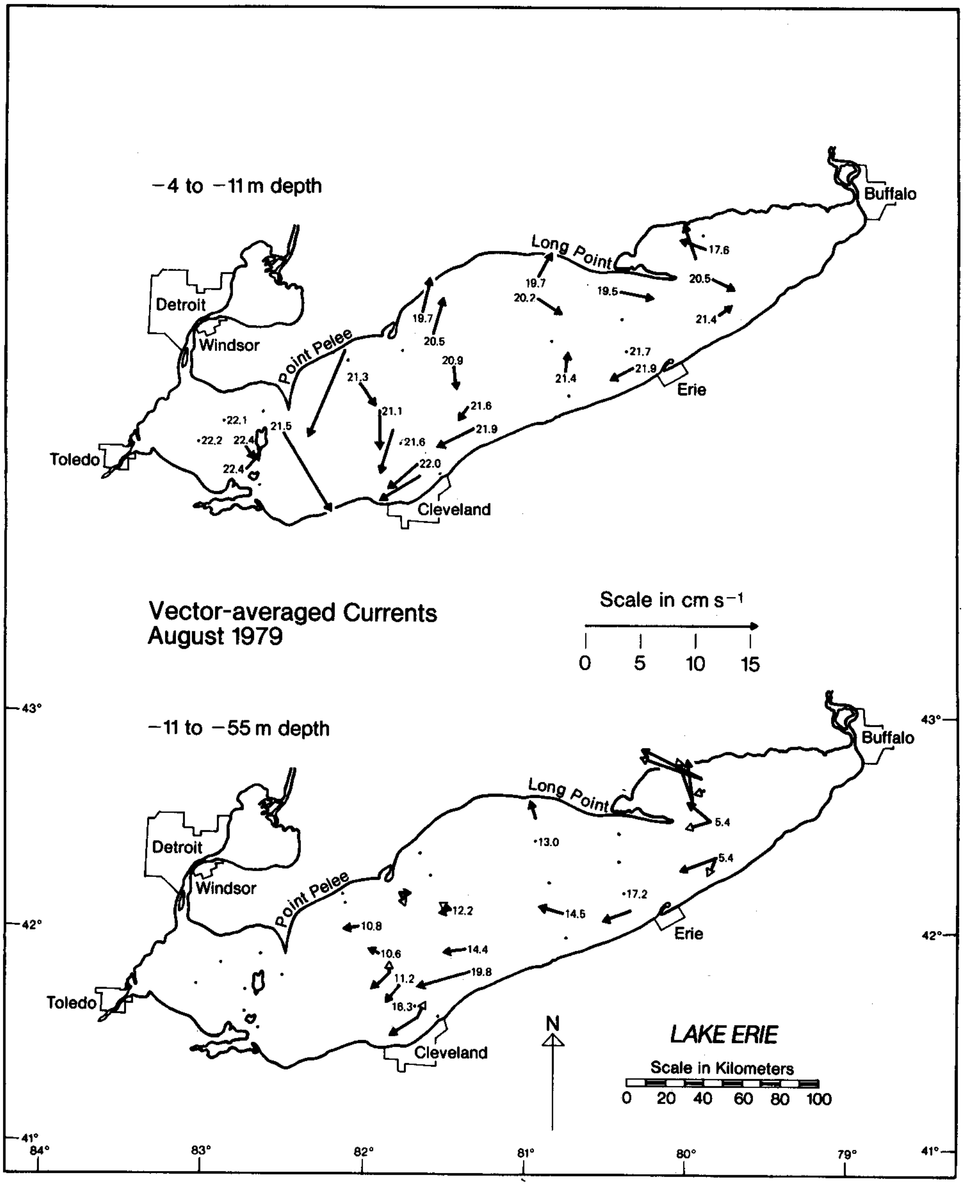

FIG. 6. Lake Erie resultant current vectors for August 1979.

Coinciding with the last vestiges of central basin stratification, two strong frontal passages over the lake occurred during 17 through 22 September 1979. There were common sequences of events in the wind field both times. With the first front there were about 1.5 days of southwesterly wind, turning clockwise to northwest and then to north on the 19th. With the second front, the wind turned clockwise from southwest on the 21st to northeast on the 22nd. Early in the episode, the lake spun up into an intense clockwise circulation encompassing the entire central and eastern basins; it remained fixed in that state for the episode's duration (Fig. 12). This pattern was common and many such episodes of whole central basin, or in this case central and eastern basin, clockwise flow at both 10-m and near-bottom depths, were evident in charting the daily current vectors. In September, wind stresses from the 10th through the 12th and from the 27th through the 30th also provided essentially the same pattern of clockwise circulation. The first of the episodes clearly was the result

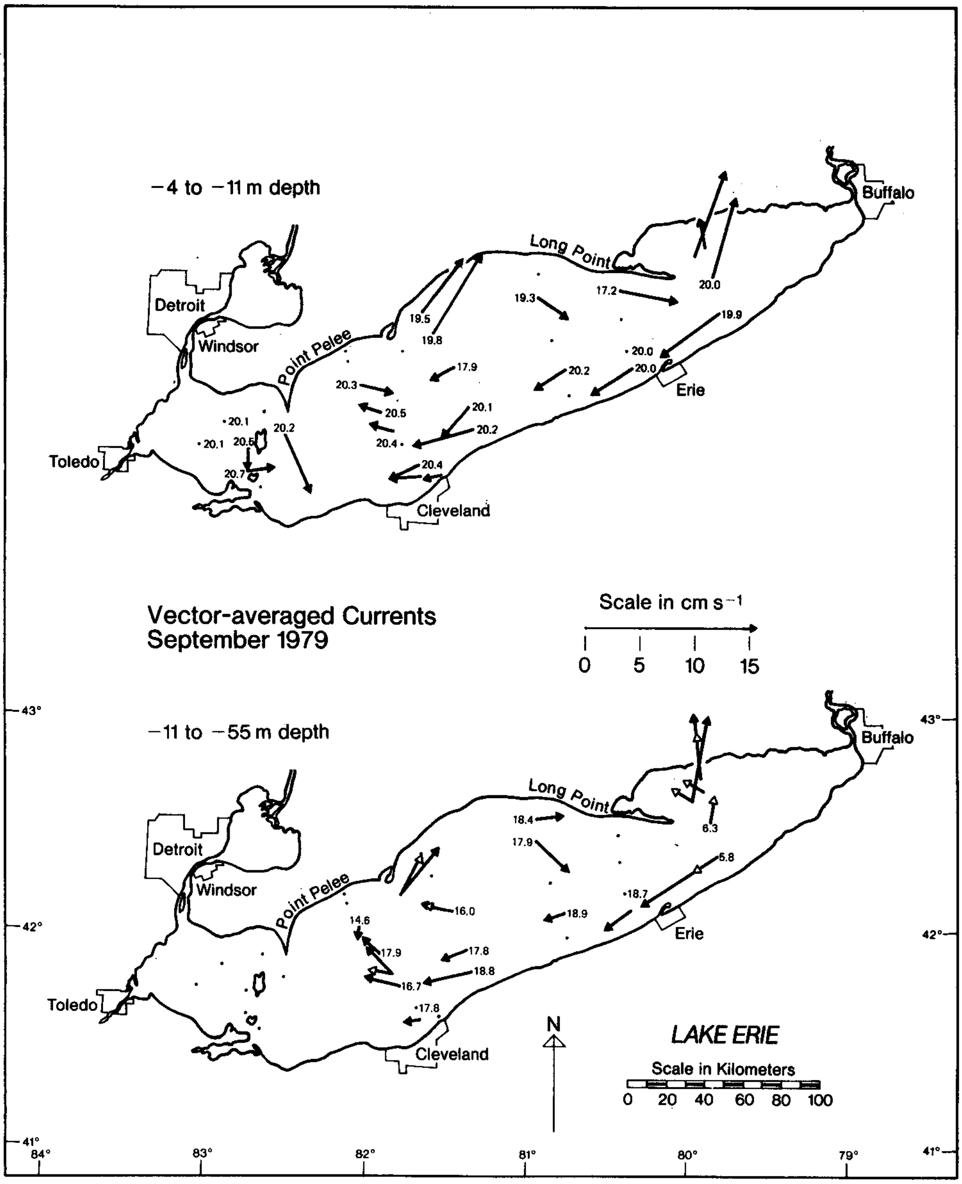

FIG. 7. Lake Erie resultant current vectors for September 1979.

of a strong southwesterly wind field lasting nearly 1 day and turning clockwise to northeasterly. The second accompanied a relatively light wind from the south. Because no other organized wind-driven current patterns were evident that month, September, as the monthly chart illustrates, was characterized by dominant clockwise circulation.

Equally certain in whole central basin dominance was the anticlockwise circulation pattern that characterized the episode from the 3rd through the 7th of October 1979 (Fig. 13). In this case, we found that a light southwesterly wind on the 3rd and 4th rotated clockwise to northwesterly on the 5th, and was followed by stronger southwesterly winds on the 6th, rotating clockwise to northwesterly on the 7th. The wind history was therefore similar to that observed from 17 through 23 September, but the circulation was exactly reversed. The exception occurred at station 26, where outflow from the eastern basin through the deep channel in the Pennsylvania Ridge continued, especially at the deepest level. Thus, the central

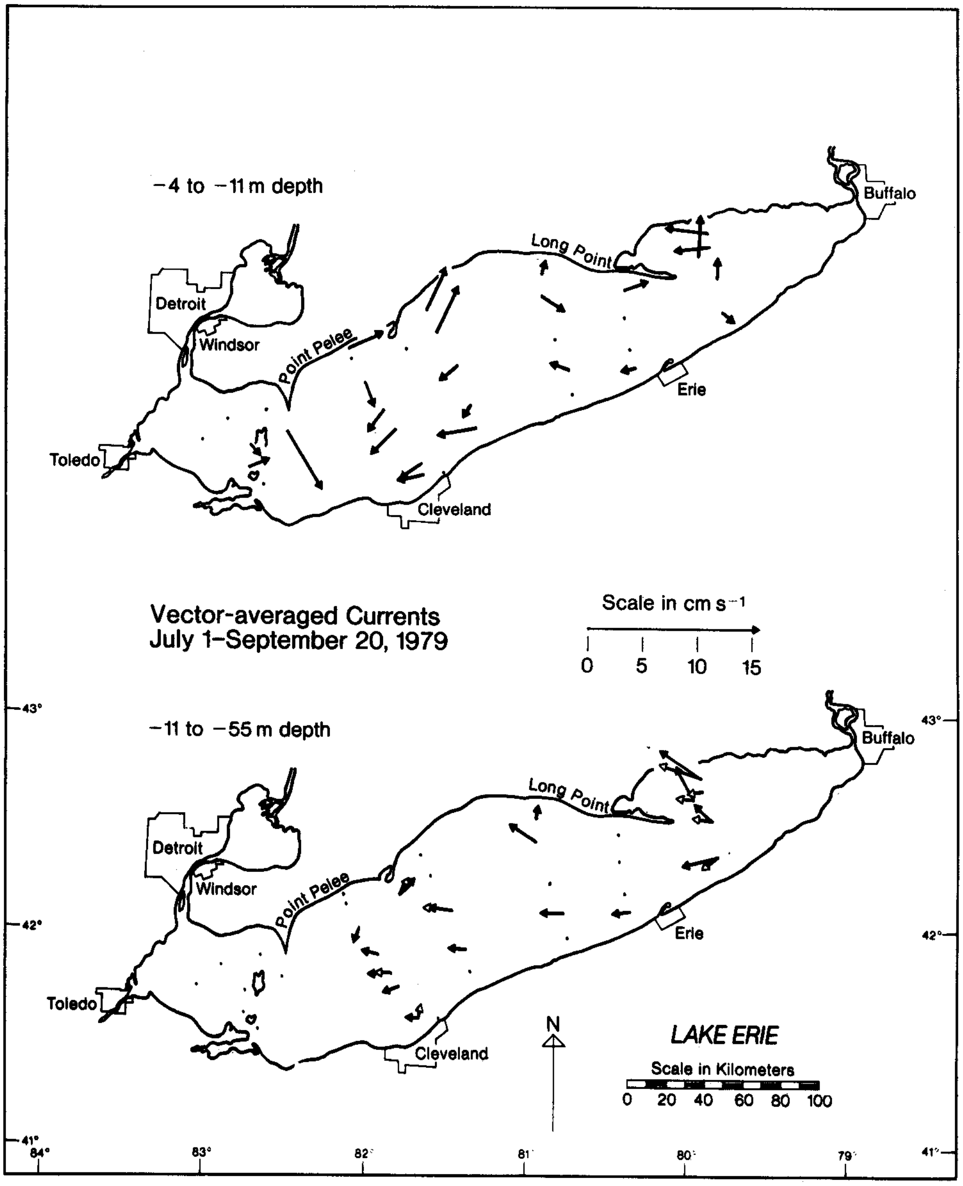

FIG. 8. Lake Erie resultant current vectors for the period 1 July through 20 September 1979.

basin circulation was very sensitive to subtle changes in the nature of the driving wind stresses and to the initial momentum of the currents as the impulse was applied.

The eastern basin was separate from the anticlockwise circulation of the central basin in Figure 13, as it was in most charts of monthly-averaged currents and in many dominant pattern episodes of a few days' duration. After the cyclonic flows related to geostrophy during stratification ended, the eastern basin exhibited a characteristic two-cell circulation. Because of the prevailing westerly winds, currents along both the northern and southern shores tend to flow easterly with the wind stress. Return flow occurs westward along the axis of the basin much like the lake basin simulations described by Bennett (1974). Because Long Point projects southward, interrupting full development of the pattern along the northern shore, we found the southern half of the pattern (the anticlockwise

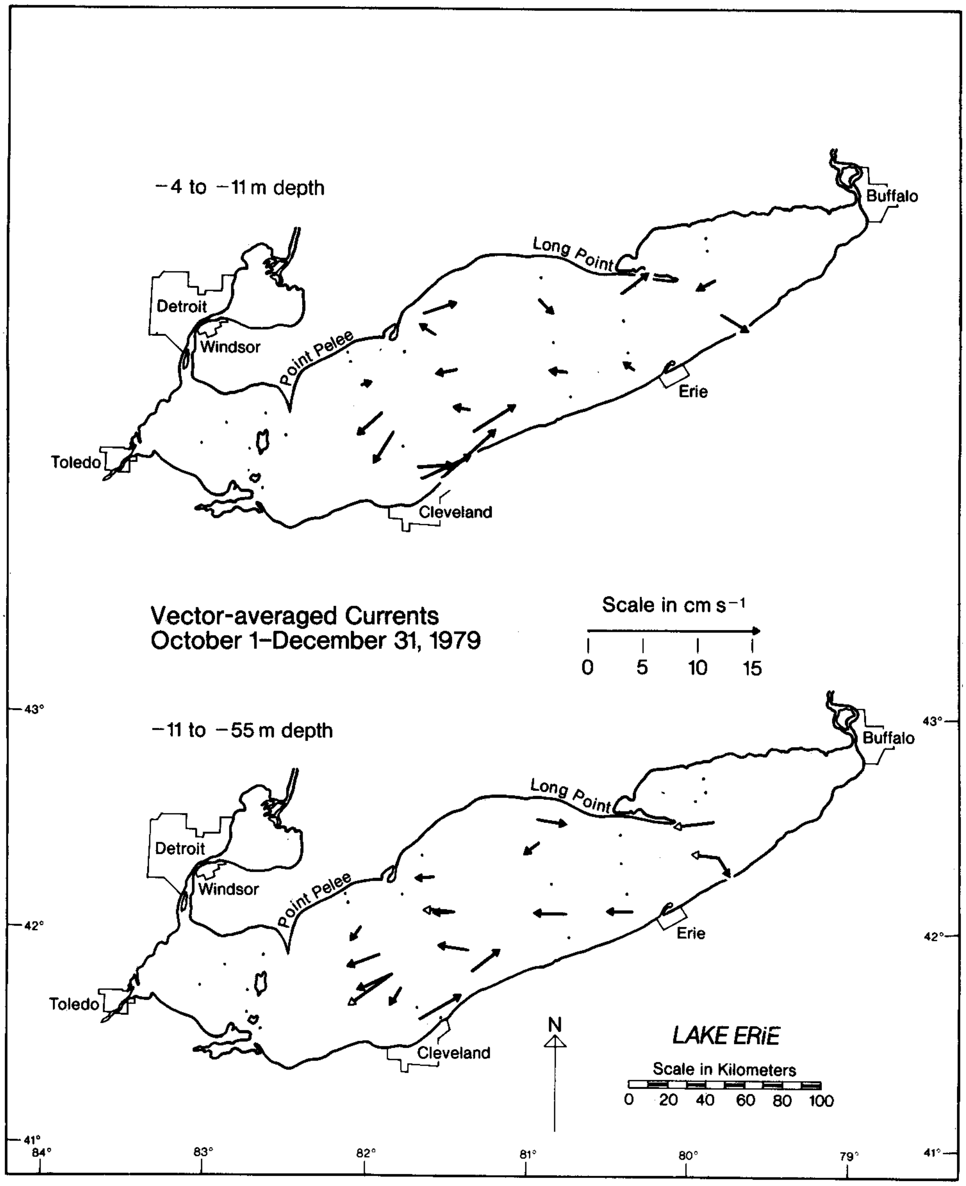

FIG. 9. Lake Erie resultant current vectors for the period 1 October through 31 December 1979.

cell) was stronger and larger than the northern half. We will describe later how this pattern can rotate as a topographic wave, but yet retain its whole-basin two-cell features. The eastern basin alone responded in the two-cell pattern whether the stress impulse was easterly or westerly, although of course the currents along the coasts were just reversed for the two directions.

One month revealed domination by anticlockwise currents: April 1980. Two episodes of intense cyclonic flow occurred, one from the 1st through the 7th and the other from the 23rd through the 26th. Alternate wind stresses easterly and westerly along the lake's major axis were experienced 1-7 April while winds were lighter and more variable during the second episode. These two periods dominated the monthly-averaged currents and determined the basin-wide circulation. April was a

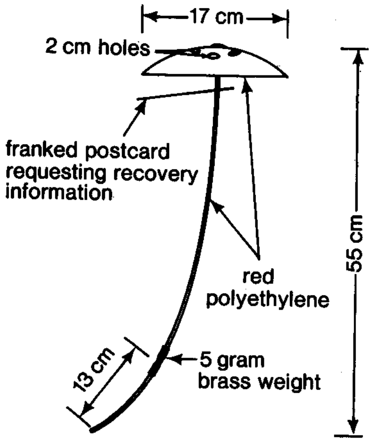

FIG. 10. A drawing of the Woodhead seabed drifter. It is weighted at the tail so that it stands upright on the Lake bottom; bottom currents fill the umbrella-shaped head and drag the drifter along. The surface version floats head downward.

month when lake water was warming (first in the shallow water along the coasts and augmented by river inflows) and establishing thermal gradients supportive of cyclonic flow around the basin's perimeter (cf. Huang 1972). Intense thermal bar gradients were not recorded by our offshore instruments, however, and the slight warmth we recorded in inshore waters compared to those offshore was not sufficient to support the magnitudes of currents observed. Simulations of currents in Lake Erie during the year of Project Hypo by Simons (1976) hindcasted a nearly month-long (25 October through 29 November 1970) interval of strong cyclonic currents filling the central and eastern basins. He attributed the pattern to unusual wind stress distributions. Clockwise patterns, such as those in September 1979, were not revealed clearly in his hindcast intervals however.

A third pattern of circulation we observed regularly is shown schematically in Figure 14. It consisted of a large clockwise flowing gyre in the northeastern part of the central basin and an anticlockwise gyre in the southwestern part. Usually the eastern basin circulation was separate and is shown as such in the figure. The pattern was not static, but evolved in a complex manner from episode to episode and from month to month in longer period averages. The northeast clockwise cell often expanded westward to envelop the whole northern shore east of Point Pelee and also eastward and southward to encompass the whole eastern two-thirds of the central basin and part of the eastern basin as well. It did this at the expense of the anticlockwise gyre, which retreated to a small cell in the southern half of the lake mostly west of

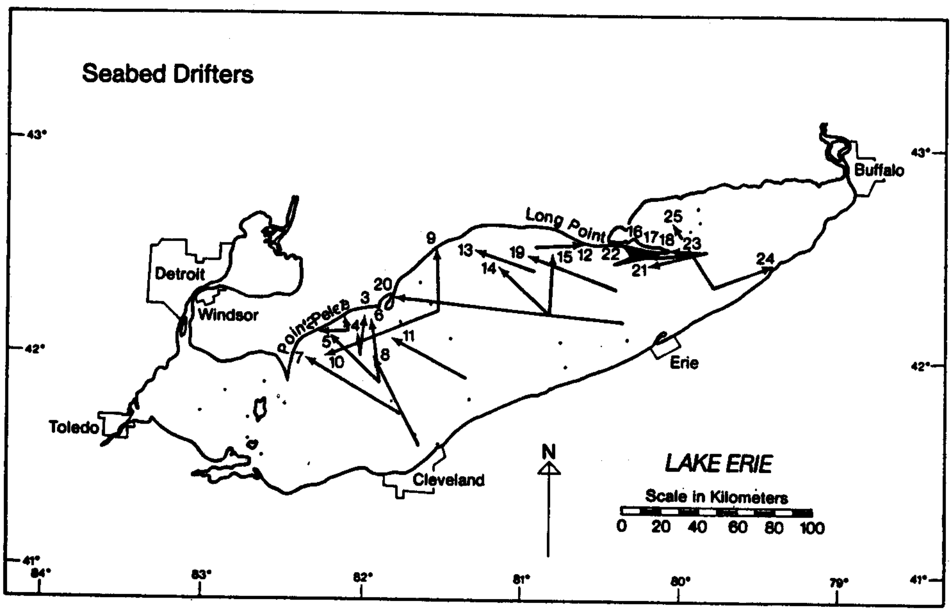

FIG. 11. Movements of Woodhead seabed drifters released in Lake Erie in 1979 and subsequently recovered.

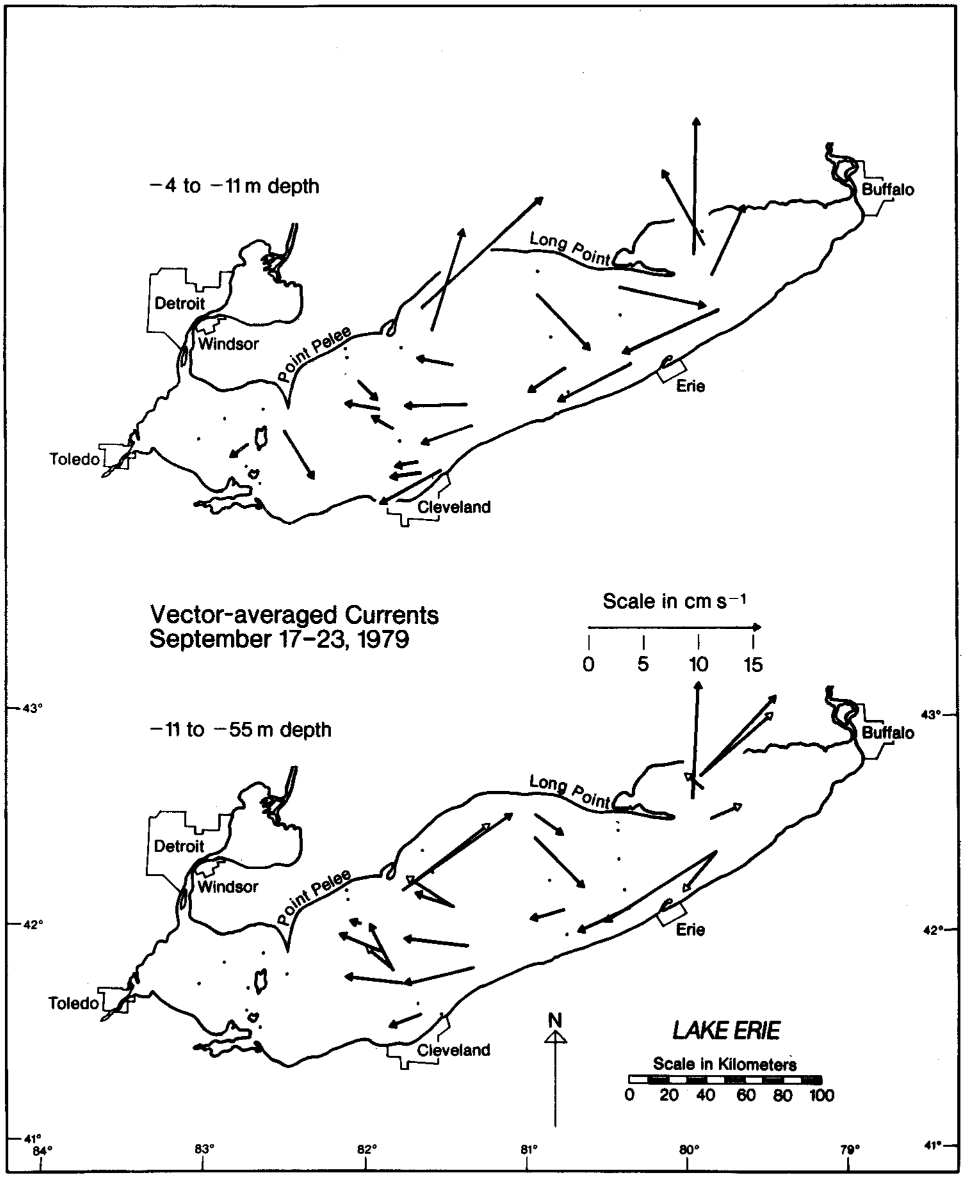

FIG. 12. Lake Erie resultant current vectors for 17-23 September 1979. Clockwise circulation prevails in both the central and eastern basins.

Cleveland. At other times the anticlockwise gyre expanded to fill the western half of the central basin, while the anticlockwise gyre in the southern half of the eastern basin expanded westward to envelop the region to the west of the ridge. We have also noticed how one or the other of the two central cells became dominant basin wide.

The proportion of the month or season that experienced one pattern or another controlled the long period-averaged circulation. For example, from the time when current meter deployments were completed in mid-May 1979 through September, charts of daily current vectors revealed 27 days of clearly clockwise circulation and 8 days of clearly anticlockwise in the central basin. October through December 1979 splits 25 clockwise and 22 anticlockwise, while January 1980 through March is 11 even. February had 5 days clockwise and none anticlockwise. April had 12 days anticlockwise and none clockwise. Thus we see how the monthly or

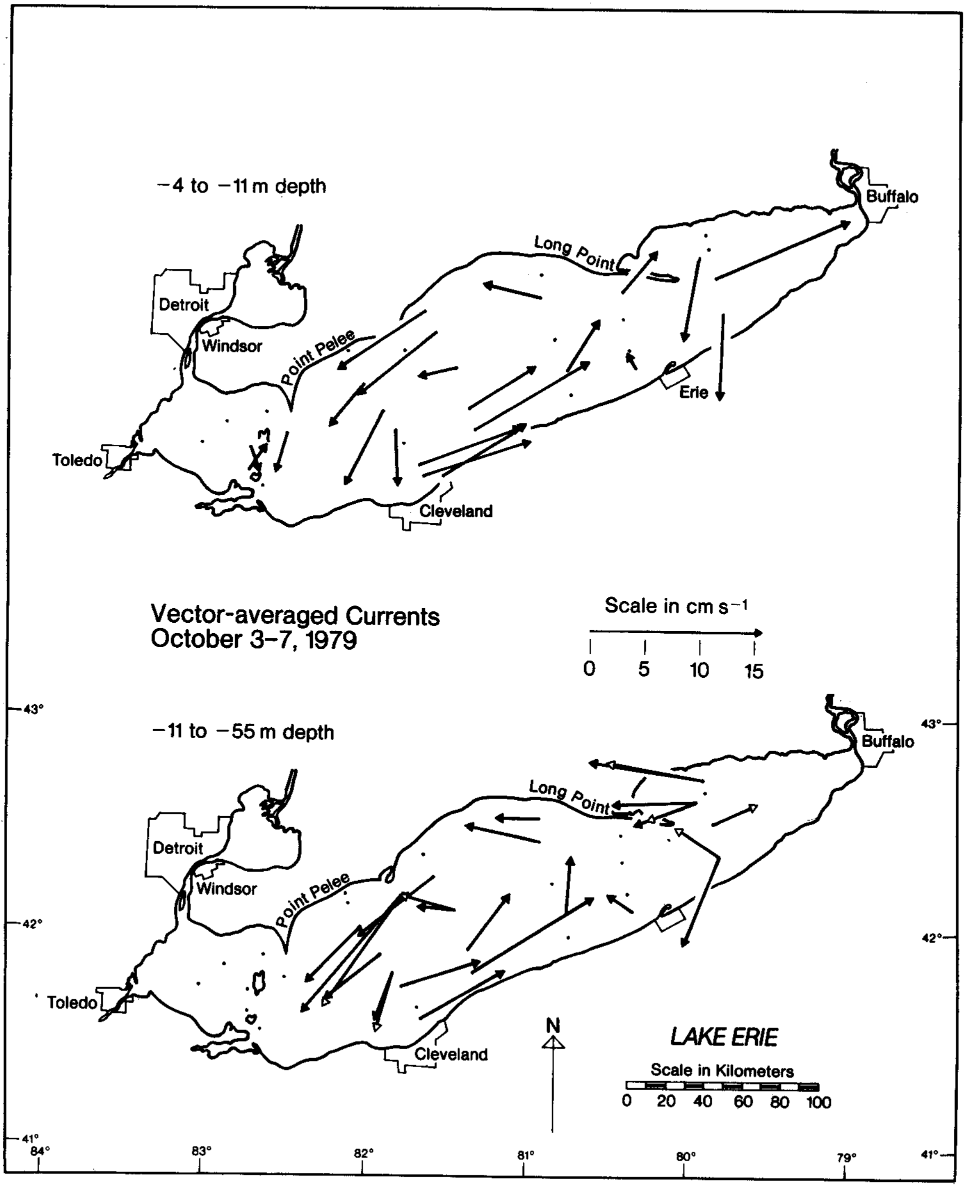

FIG. 13. Lake Erie resultant current vectors for 3–7 October 1979. Anticlockwise circulation prevails throughout the central basin and the northern half of the eastern basin.

seasonal averages evolved from the dominance of episodal patterns in the interval. When there was relative balance between the simple whole-basin rotations, our third and most common pattern of several central basin gyres prevailed.

Oscillatory Components

Several periodic components contribute substantially to measured current velocities. Spectra presenting the distribution of kinetic energy as a function of frequency are useful in picking out some of the more energetic oscillatory components in the velocity records. Spectra were computed by use of the fast Fourier transform method. All were computed from multiple, overlapping, unfiltered data subsets of 256 values of either hourly or 4-hourly averaged data, which were first transformed and then ensemble-averaged and smoothed by Han-

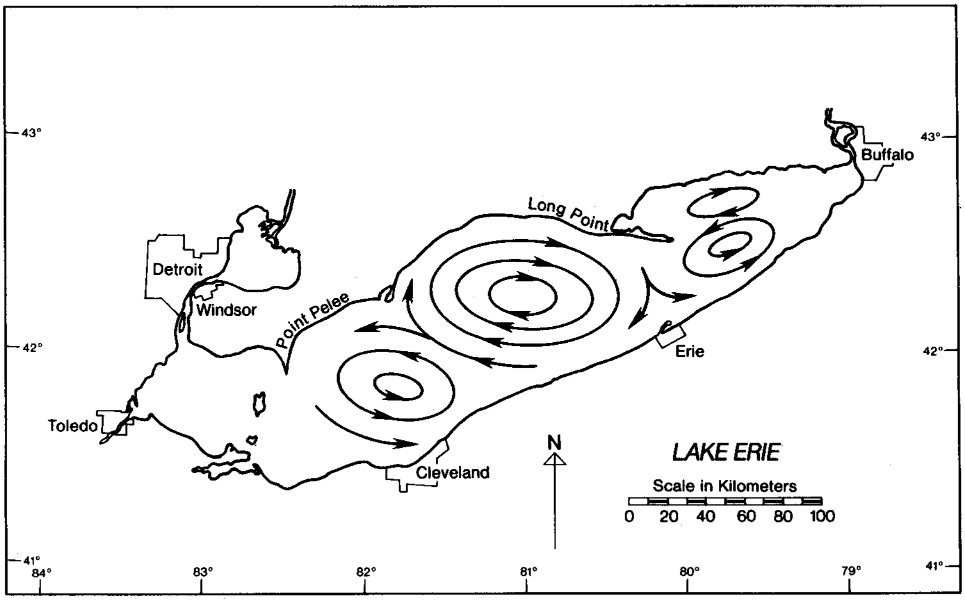

FIG. 14. Generalization of the third dominant circulation pattern observed in the Lake Erie current charts.

ning. Figure 15 shows spectra computed using hourly data from a current meter placed on mooring 17, 10 km offshore from Fairport Harbor, Ohio. The clockwise rotary spectrum shows a strong peak at nearly 18 h. This is known from numerous Great Lakes studies to be the near-

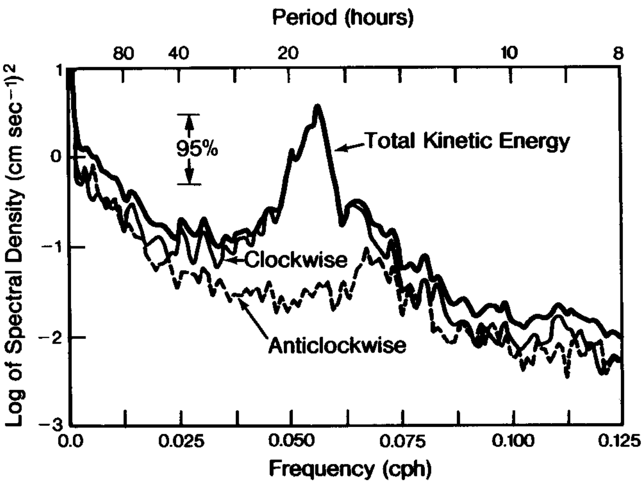

FIG. 15. Kinetic energy spectra computed from hourly averaged current velocity recordings at station 17 during May through October 1979. Both the rotary components and the total kinetic energy are presented.

inertial period for oscillations of thermocline and currents that dominate this range of the kinetic energy distributions when the lake water is density stratified. It was so stratified during parts of this May through October 1979 computation [cf. FWPCA (1968) and Mortimer (1971)].

Close to the near-inertial period peak in the clockwise component was a second peak at just a slightly shorter period, i.e., at 14.2 h for the resolution possible here. The peak was even clearer in the anticlockwise component though, for where the two rotary components of this oscillation were close in amplitude, the inertial component was suppressed. This oscillation was the fundamental (longest period) longitudinal seiche of the lake; the period was computed theoretically by Platzman and Rao (1963) at 14.08 h in a dynamical study of Lake Erie. Revealed also in the spectra were two additional oscillations at periods centered around 9.5 and 5.7 h; they were the second and third longitudinal seiches of the lake. Most of the energy was in the clockwise rotating component of the spectra for all of the three seiches noted, as expected from dynamical considerations. Figure 15 shows considerable energy at longer periods, but the resolution was too poor to suggest oscillatory components important at low frequencies.

Inertial responses were best developed in the deep water of the eastern basin during the stratified season, with currents just out of phase in the top and bottom layers. The meters moored there revealed spectra similar to those in Figure 15, with sharp and strong kinetic energy peaks for clockwise rotating currents. The seiche currents were unimportant and not easily identified there. Although present in the central basin, at most stations the inertial response was not as well defined as that in Figure 15 because the energy distributions were spread over a broader frequency range, the central frequency was harder to differentiate, and the energy levels were lower. This occurs because of the thinness of the lower layer and the nonlinearities associated with wave propagations on the thermocline in this situation. The longest period seiche was easily recognized as a significant contributor to current flows throughout the entire central basin; the second and third modes appeared less regularly. The location off Fairport Harbor was close to a nodal line of all three modes and was probably atypical in its clarity of seiche currents activity.

The frequencies of the seiches were not directly related to important wind forcing constituents, but it was interesting to inquire as to what the spectrum of this forcing looks like and whether obvious periodicities in it show up in the current responses. We computed a rotary spectrum of the Lake Erie wind stresses determined from the NWRI buoy measurements by Schwab (1982); Figure 16 gives the result for 4-h averaged stresses. The forcing was mainly from stresses that exhibited clockwise rotations of the wind vector, with a broad and energetic peak centered about the 85- to 100-h period range. Also noticeable were energy accumulations at the inertial and diurnal periods. Inertial period current responses are not highly dependent on that period in the wind stress forcing for generation, and the diurnal period except in special cases was not found to be significant in the kinetic energy of currents.

Wind energy in the longer time scale of 4 to 5 days has been recognized for many years as important in shaping current responses in the Great Lakes. A thorough summary of the dynamical processes was provided by Csanady (1982) who discussed how, in addition to setting up the quasi-steady circulation gyres and forced current flows, the energy propagated about the basins in the form of bathymetry sensitive rotational waves. The simplest form of these waves, revealed with very distinctive characteristics from analytical studies of

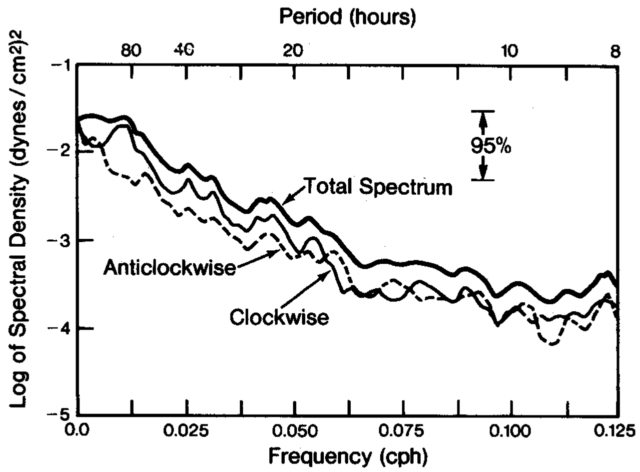

FIG. 16. Rotary spectra of the hourly wind stress vectors computed by Schwab (1982) from National Water Research Institute buoy wind measurements during May through October 1979.

regularly configured nonuniform depth (with greatest depth in the central regions) circular or elliptical basins, is the gravest (lowest azimuthal wave number) vortex mode. Saylor *et al.* (1980) reported its existence in southern Lake Michigan and now the results of this field study suggest a time varying flow with similar properties in the eastern basin of Lake Erie.

Figure 17 shows streamlines for the gravest vortex mode in a basin configured as an elliptical paraboloid and their rotation with the wave form over one-quarter wave period. The two-cell current pattern, originated by impulsive wind stress, fills the basin and rotates cyclonically just opposite to the clockwise torque observed in the wind stresses. For the first radial modes, the gravest azimuthal mode is unique because the current velocity does not vanish at the center of the basin as it does for higher ordered modes. In the center of the basin, there is an area of anticlockwise rotating currents. Closer to shore, the currents rotate in a clockwise fashion. These features are important in detecting the wave form.

Figure 18 shows rotary spectra of currents measured at three moorings in Lake Erie, each computed from 4-hourly averaged data recorded from May through September 1979. The spectrum from mooring 28 at the center of the eastern basin reveals features similar to those seen in Lake Michigan: a large accumulation of kinetic energy associated with anti-clockwise rotations of the current

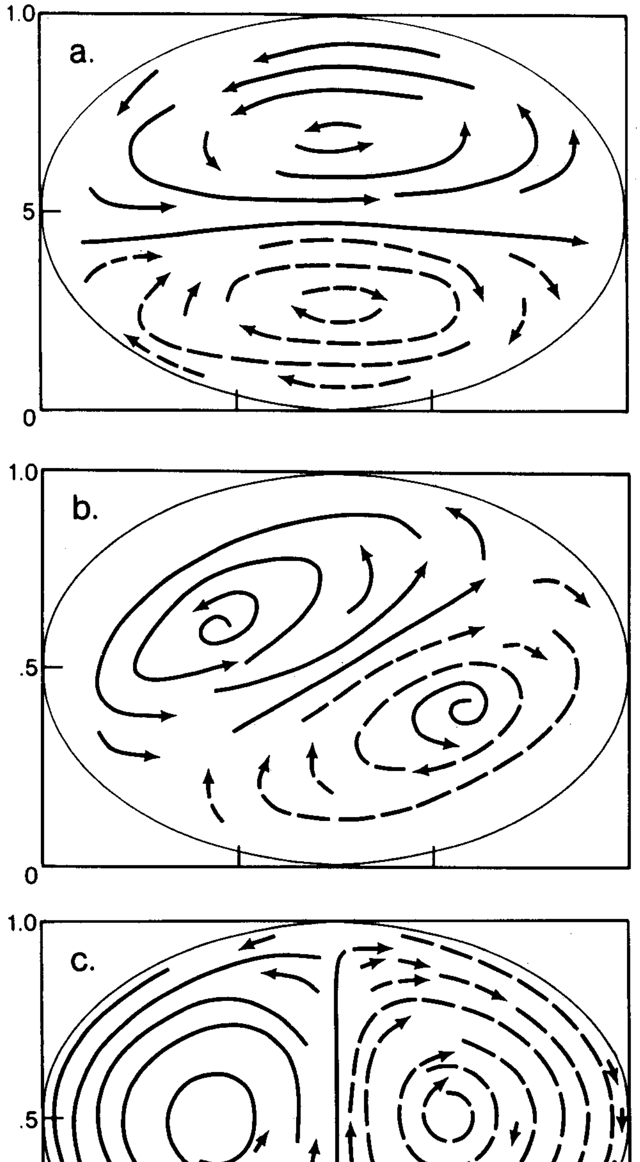

FIG. 17. Transport streamline pattern of the gravest mode vorticity wave in an elliptic paraboloid. From Saylor et al. *(1980).*

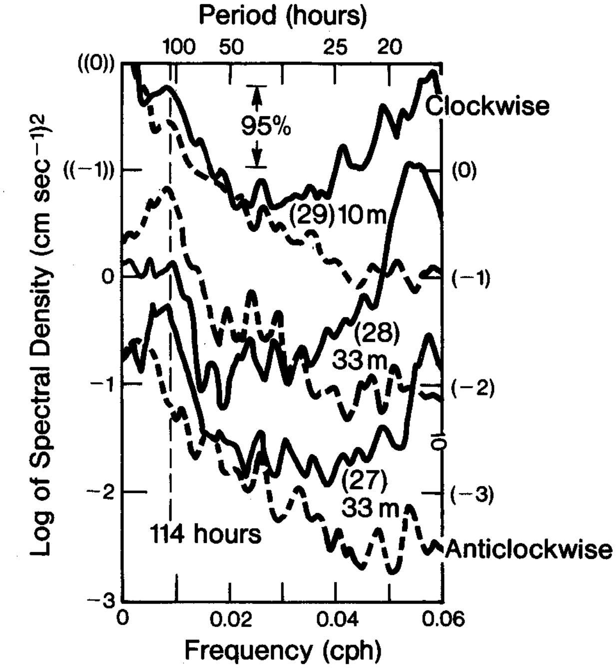

FIG. 18. The rotary components of kinetic energy spectra computed from 4-h-averaged current velocity recordings during May through November 1979 at three moorings situated on a cross section of the eastern basin of Lake Erie.

vector. Here the peak was rather broad, although it did exhibit decay about a central period near 114 h. Closer to the north and south coasts of the eastern basin, moorings 27 and 29, respectively, energy in the period band was shifted to the clockwise rotating component. The peak at mooring 29 was submerged deeper into the more energetic low frequency lake currents occurring at the site.

A current hodograph almost circular in form from a current meter moored near the center of the southern basin of Lake Michigan provided graphic evidence of the persistence of the anticlockwise rotations in Saylor *et al.* (1980). Presented in a slightly different fashion, Figure 19 shows low-pass filtered wind vectors and current vectors drawn at intervals of 2 h from the center of the eastern basin (mooring 28) for August 1979. The currents were low-pass filtered to remove the inertial and shorter period oscillations. Anticlockwise rotations dominate the current structure, with the major axis of the current ellipses oriented nearly east-west and parallel to the axis of the basin.

Figure 20 shows a rotary spectrum of kinetic energy computed from currents recorded during the same time interval in the middle of Lake Erie's central basin (mooring 15). It reveals no indication of oscillations in the period range of interest at the low frequency end of the wind spectrum and no unequal partitioning of energy in the two rotary

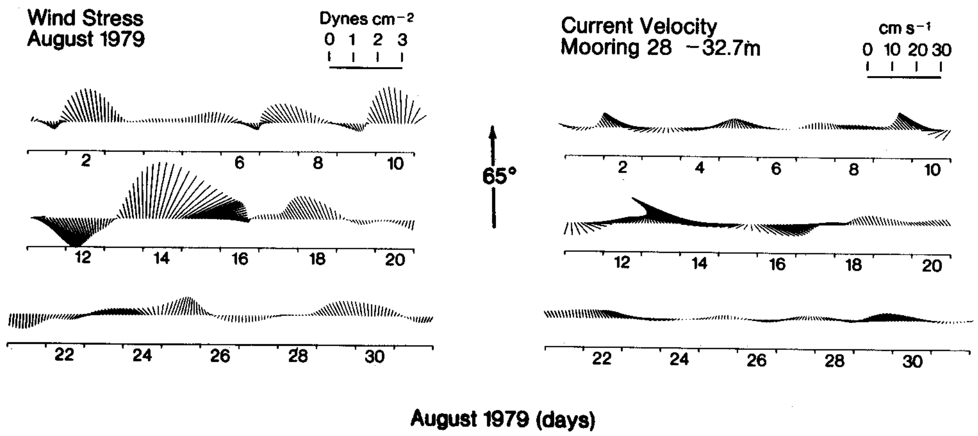

FIG. 19. Low-pass filtered wind stress vectors and hourly-averaged current velocity vectors (drawn at 2-h intervals) from a middle of the eastern basin (mooring 28) current meter at 33 m depth for the month of August 1979.

components. Topographic waves were not generated in the flat-bottomed central basin.

To end our discussion of oscillatory flows, Figure 21 shows kinetic energy spectra computed from observations of current flow at station 6 between Kelleys Island and Pelee Island and at the juncture of the west and central basins. Computed from hourly averaged currents, the first three longitudinal modes of the lakes seiches were revealed in detail. The spectra resemble those obtained through analysis of water level records, and record inconsequential, but recognizable, inertial and diurnal components (and perhaps some higher order seiche modes at periods of 3 to 4 h). This inter-island passage was truly dominated by the tidal-like seiche-driven current flow, with clockwise rotating ebb and flow reversals. Though not reproduced here, spectra from mooring 4 in the Pelee Passage presented a virtual image of Figure 21.

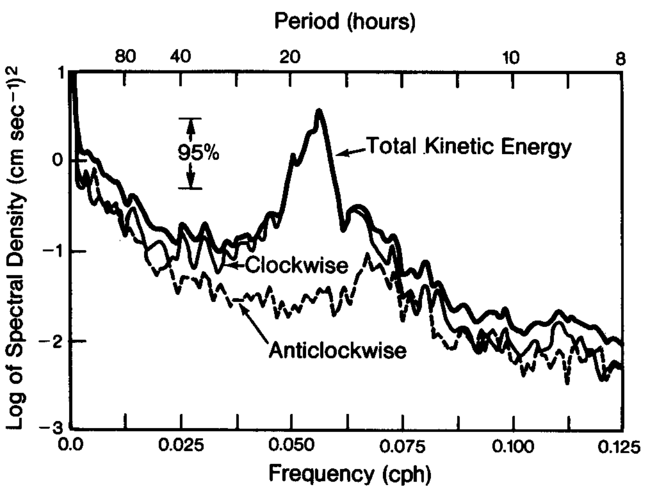

FIG. 20. Kinetic energy spectra computed from 4-h-averaged current velocity recordings at mooring 15 (middle of the central basin) during May through December 1979.

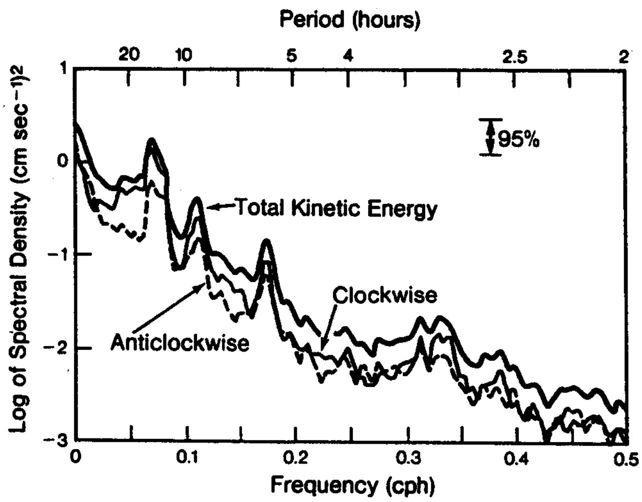

FIG. 21. Kinetic energy spectra computed from hourly-averaged current velocity recordings at mooring 6 (juncture of the western and central basins) during May through October 1979.

Inflow From the Western to the Central Basin

The lack of current meter data in the western basin and inter-island passages attests to the difficulty of maintaining moored instruments and recording quality data in this shallow water environment. The 1979 program was not immune; meters on moorings 1, 2, and 7 experienced electronics failures in the velocity component-resolving circuitry and mooring 3 was not recovered. This left moorings 4, 5, and 6 (Fig. 1), all located in the island passages. So although nothing definitive can be advanced concerning circulation in the western basin, the long continuous data from the passages afforded a look at the flow between basins.

Before presenting the 1979 data, it would be useful to review results from previous investigative efforts in this region. Flow from the western to the central basin depends on the inflow to western Lake Erie. The basin receives about 80 percent of its water supply via the Detroit River; the Maumee River is the only other significant tributary in the basin and during summer its flow is minimal.

The majority of western basin studies, as referenced in Mortimer (1981), relied solely on drift objects to qualitatively describe circulation. The investigators have found that Detroit River water first sweeps southeastward and then clockwise through the basin, with the major portion entering the central basin through Pelee Passage. A clockwise rotational gyre around Pelee Island was alluded to in all reports, while the southern channel's flow was considered variable by Olson (1950) and Hamblin (1971) and dominantly westward and part of the clockwise gyre by Verber (1955).

FWPCA (1968) moored one current meter in Pelee Passage and another off Catawba Island at a depth of 9 m during 1964–65. FWPCA interpreted the limited data return as surface currents rotating in a clockwise gyre through the island region with anticlockwise bottom currents. Hamblin (1971) reviewed these data (together with all previous work) and concluded that, although there is randomness in currents in the inter-island area, the clockwise gyre is a prominent feature and it extends to the bottom.

The 1979 inter-island current measurements displayed a variety of processes. The short-period seiche-driven currents, illustrated spectrally in Figure 21, contributed markedly to turbulent mixing and diffusion. Figure 22 shows the persistence and magnitudes of these current responses to wind setups and seiching. Current components from moorings 4 and 5 have been rotated to orient with the bathymetry; mooring 6 did not require rotation. The currents between islands were in phase and in concert with water-level fluctuations.

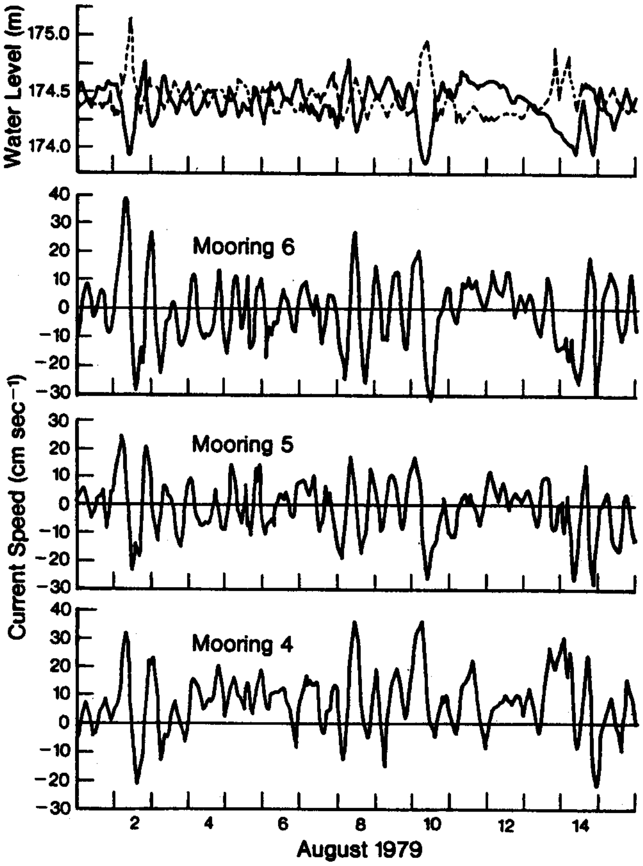

FIG. 22. Hourly water levels at Toledo (solid line) and Buffalo and the current velocity component parallel to the channel axis at moorings 4, 5, and 6, 1–15 August 1979.

Although seiche-driven currents were persistent throughout the year, the net transport by seiche action only was near zero for each cycle and the current run during each half cycle was generally less than 5 km. Outflow from the western basin can be better illustrated by looking at longer periods.

There is no question that the major outflow from the western basin was through Pelee Passage. The resultant current at mooring 4, which offset to the east of the navigation channel to avoid ship traffic, was 4.4 cm s^{-1} directed into the central basin during the 6-month period; the scalar mean speed was 9.2 cm s^{-1}. Using a rough estimate of the

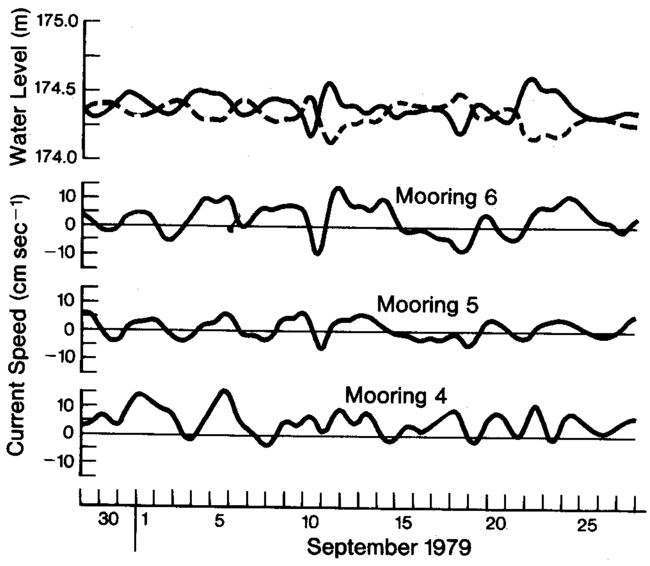

FIG. 23. Low-pass filtered water levels at Toledo (solid line) and Buffalo and the current velocity component parallel to the channel axis at moorings 4, 5,and 6, 29 August-27 September 1979.

cross-sectional area of the channel, we found that the net flow into the central basin was only slightly less than the Detroit River inflow.

The dominance of a clockwise Pelee Island gyre around the islands was not reflected in our data. The Kelleys Island region was certainly not a low-velocity area, as is illustrated in Figure 22, but rather an area dominated by seiche-driven currents and storm surges. The resultant current was eastward at 2.4 cm s^{-1} (7.8 cm s^{-1} mean scalar speed) during the 6 months. To illustrate further, assuming that an eastward direction of the Pelee Passage currents is a necessary condition for the existence of the gyre, we found that 77 percent of the hourly values was directed toward the central basin. Of this 77 percent, mooring 6 north of Kelleys Island had concurrent eastward flow 69 percent of that time; mooring 5, 70 percent; and all three, 60 percent of that time. Although the Pelee Island gyre was not a dominant feature, examples of this gyre could be seen in the data set, particularly during strong southwest winds. Interestingly, our resultant currents were nearly identical to the flow pattern of tracers observed in a rotating model of Lake Erie (Rumer and Robson 1968).

Figure 23 shows Toledo and Buffalo water levels and longitudinal currents from the three moorings during September 1979. Data were low-pass filtered to eliminate the seiche components, the currents remaining were those resulting from long-period water level variations caused by mesoscale winds. Schwab (1978) discussed the wind and water level relationships that occur in Lake Erie. Our concern here was the response of currents to water level changes and their role in water volume exchange between basins. Mooring 6 currents followed the trends in water level; mooring 5 currents were similar but with reduced amplitude. Large amplitude current variations in Pelee Passage superposed on the net eastward current compared similarly during the first 12 days, but then took on their own oscillating character. This was common during the measurement season. The variations may be related to the position of the Detroit River plume or to the central basin's current regime, although the short-interval resultants were similar during oppositely rotating central basin flows (Figs. 12 and 13). Figure 4 does give evidence of a different pattern of island-passage currents during very strong wind from the north-northeast, however, that would fit a storm surge increase in water level on the south shore of the western basin. Our data did not indicate any seasonal variability other than an increase in magnitude of the driving forces and current responses as winter approached. Unfortunately, November and December storm surges and setups were greatest, but the moorings were retrieved before then.

Water Volume Exchange Processes Between the Eastern and the Central Basins

Our data recovery from the current meter moorings placed on the Pennsylvania Ridge (which separates the eastern and the central basins of Lake Erie) was very meager. At the north end of the cross section (station 23), only the top current meter at 10-m depth provided velocity recordings. At the south end (station 26), both the 10- and 17.5-m deep meters provided current measurements from June through November 1979, but the deeper instrument's temperature circuitry failed. Little useful current information was collected from the center two moorings, although water temperature records from station 25 were recorded during summer and fall 1979. Currents, water temperature, and dissolved oxygen concentrations were measured extensively about the ridge structure by NWRI in 1977 (Boyce *et al.* 1980) and 1978 (Chiocchio 1981), however, and much is known of the exchange characteristics. It is within this framework of knowledge that we can interpret our sparse data return.

The transport of cold, oxygenated mesolimnion and hypolimnion water from the eastern to the central basin has been considered for some time to be a possible oxygen renewal mechanism for the central basin bottom water (Burns and Ross 1972). Boyce *et al.* (1980) found that deep layer flows across the ridge were basically just counter to the wind component along the lake's major axis, and that most of the cold water driven westward into the central basin flowed through the deep channel at the southern end of the ridge. During periods of sustained easterly-directed wind stresses, substantial quantities of water were found to flow westward in the lower layers. In July and August, when oxygen is rapidly consumed in the central basin hypolimnion, the transport of water into this layer from the eastern basin was found to add significant oxygen to the easternmost bottom water. Chiocchio (1981) determined that nearly 80 percent of the replenishment entered through the deeper channel south of the ridge, and that the flow turned northwestward after passing through the channel, moved clockwise, and affected mainly the northeastern part of the central basin. He also found close correlation with the along-the-lake component of the wind stress, although the channel flow was more variable in 1978 than in 1977 and long intervals of persistent, large volume flow were not as distinctly defined.

In 1977 and 1978 a semi-permanent tilt of the thermocline across the ridge was observed during the stratified season, with the thermocline depressed in the south and upwelled closer to the northern boundary. Figure 24 provides evidence of this phenomenon in the 1979 data, as well, where we note that the thermocline passed for good through the 10-m level at stations 25 and 26 about 10 June, while at station 23 this occurred in early August. Currents across the ridge and the wind stress (redrawn so that the vertical axis is parallel to the major axis of Lake Erie) for the stratified month of July 1979 are shown in Figure 25. The figure first reveals great similarity between station 26 currents at 10 and 17.5 m, i.e., above and below the thermocline. (Chiocchio reported like currents through the channel from 7 m to the bottom). It also reveals station 26 currents basically out of phase and lagging the wind stress component along the lake, although there are important exceptions related to the whole-basin currents. For example, during 1 through 3 July, the currents flowed with the wind and were related to a strong cyclonic flow pattern set up in the central basin during the episode. The strongest pulse of channel flow occurred during the first week of the month and was directed into the eastern basin. Bottom water flow to the central basin through the channel was significant only during July 20–25.

Perhaps a closer fit with the wind stress impulses is demonstrated in Figure 26, which shows the related currents across the ridge observed in September 1979. Through the channel, flow was again nearly out of phase and lagged the wind stress. The strong monthly-averaged currents that yielded westward channel velocities received part of this bias from the clockwise circulation that dominated the lake in September, as station 23 at the north side of the ridge cross section revealed eastward currents almost uninterrupted for the entire month. If the stratification had persisted long into September this year, the deep flows would have contributed oxygenated eastern water to the central basin's hypolimnion. As it was, the September flows occurred after the hypolimnion had retreated from the easternmost parts of the central basin. In August 1979 the slightly less intense westward currents through the channel contributed to bottom water renewal in the central basin.

Eid (1981) modeled exchange flow mechanisms between these two Lake Erie basins and found good correlation between the wind stress impulses along the lake and the channel transport. During the most strongly stratified season, the thermocline is deeper in the eastern basin than it is in the central basin, leading one to believe that the internal pressure gradients would not be too important. Eid's results substantiated that conclusion and showed that the principal driving force was surface wind drift and bottom return flow based on the surface pressure gradients. As noted in numerous other studies (e.g., in Saginaw Bay, see Danek and Saylor 1977), return flow is steered into the deepest return route. We also have noticed how the lake-scale circulation can influence the channel return flow intensity, but this factor was not part of the model considerations.

Observed Currents in Relation to Modeling Results

Solutions of the steady-state circulation problem in a homogeneous Lake Erie were computed by Gedney (1971) and Gedney and Lick (1972) using Welander's (1957) shallow water formulation of

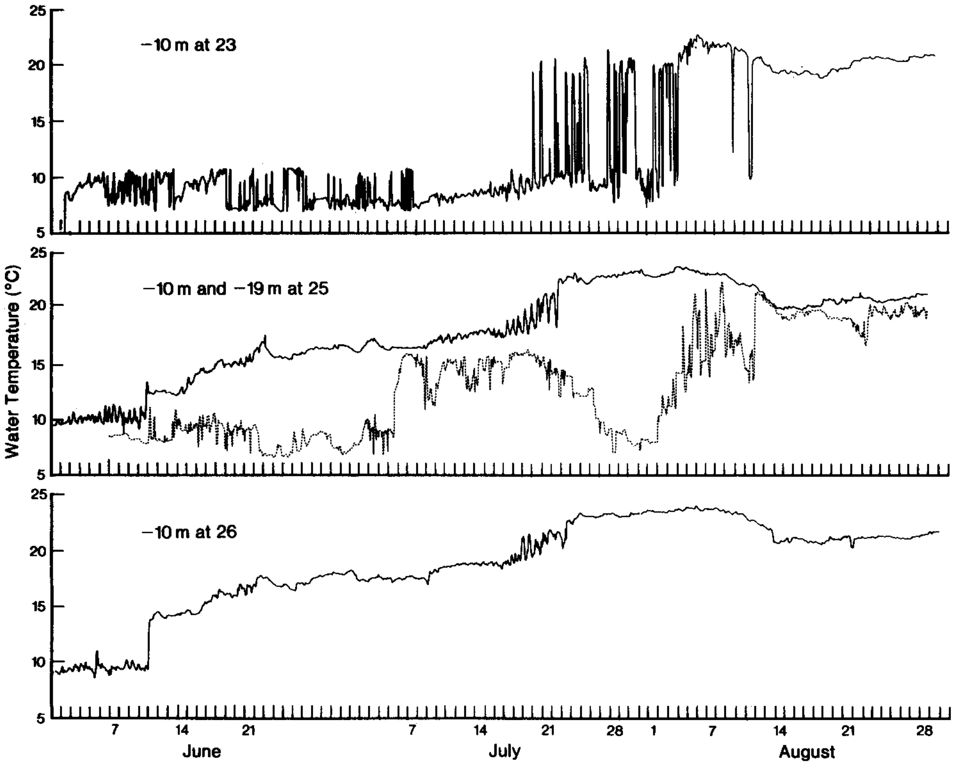

FIG. 24. Water temperature recordings at moorings 23, 25, and 26 on a cross section of Lake Erie at the Pennsylvania Ridge.

Ekman dynamics. In these computations, the stream function is first obtained to determine the pressure gradients and then the three-dimensional velocity field can be mapped. Figure 27 shows the stream function computed for a steady 5.2 m s^{-1} wind from 270° and currents at near the surface, at mid-depth, and at 1.4 m off the bottom. A constant vertical eddy viscosity of 16.8 $cm^2 s^{-1}$ was used in the calculations, making the Ekman "depth of frictional resistance" equal to 18.2 m, about the mean depth of the central basin. The horizontal distributions of the currents at each depth show less distinct patterns than the vertically-averaged currents or transports. The wind drift is confined to the surface layers and deflected a little to the right because of rotation. The deeper return currents are driven by the pressure gradients of the surface slope.

The model results were compared to 24-hourly averaged currents measured by the FWPCA during a few episodes of relatively constant wind stress lasting several days in 1964 and 1965. That such comparisons can be meaningful was demonstrated by Haq and Lick (1975), who showed that a shallow lake like Lake Erie reaches a steady-state circulation rather quickly. Using the available current information, Gedney and Lick found reasonably good verification of their predictions in currents recorded at mid-depths and deeper mainly in the central basin. The data with which the results could be verified were sparse though, and consisted of only a few current meter recordings at each level.

The vertically-integrated currents revealed a characteristic two-cell response to wind forcing in both the central and the eastern Lake Erie basins (Fig. 27). The pattern retained this basic nature for steady winds, but varied with wind direction (Gedney 1971). Our recent measurements highlighted two interesting features: at mid-depth and near the bottom of the central basin we often observed currents that exhibited less shear than expected from the model predictions and at each level organized circulation patterns developed. Also, during significant wind stress impulses, the pattern frequently evolved to a one-cell circulation of the lower half

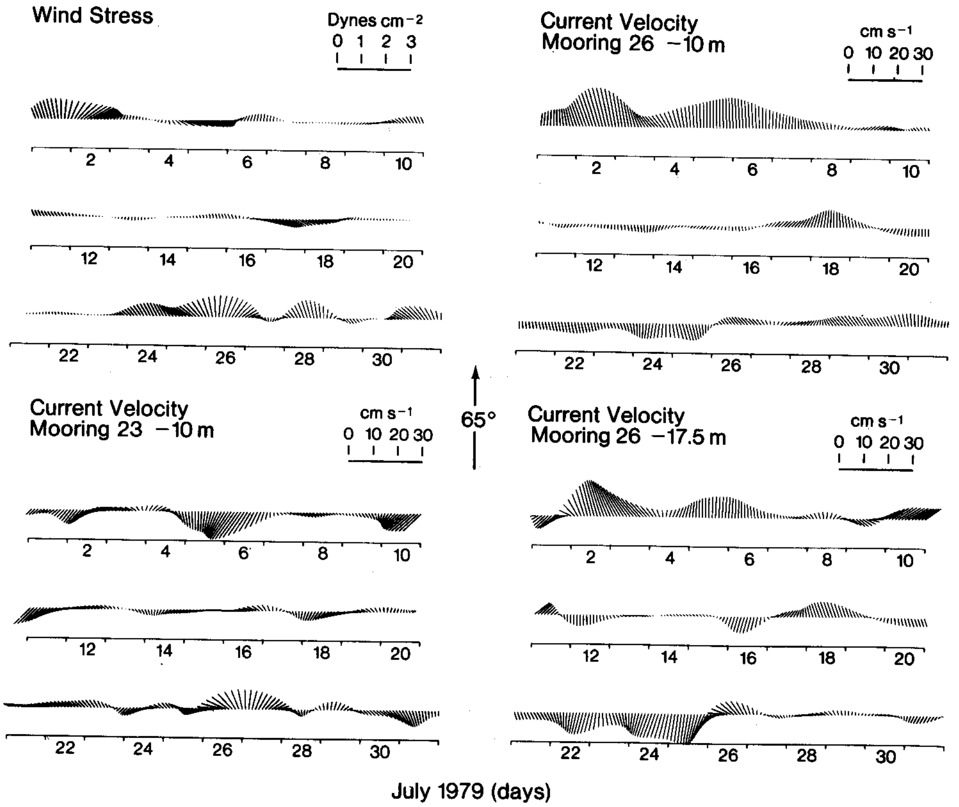

FIG. 25. Low-pass filtered wind stresses computed for Lake Erie in July 1979 (Schwab 1982) and currents (both hourly-averaged but plotted at 2-h intervals) across the Pennsylvania Ridge. Both wind stresses and currents have been rotated such that wind stress along the lake's longitudinal axis and the currents normal to the cross section are positive and eastward in the vertical axis of the graphs.

of the water mass in the central basin in either direction of flow. Further study directed toward finding why the flow is more barotropic than predicted and determining the mechanics of how one of the circulation cells expands to nearly fill the basin is needed. The rotary characteristics of the applied wind stress may be very important, since Schwab's (1982) wind stress computations for 1979 show strong dominance of the wind's clockwise rotating component. Hamblin and Elder (1972) related the direction of the wind stress rotation with the intensity of the generated surface currents.

A second numerical simulation of Lake Erie currents was performed by Simons (1976) for most of the ice-free season of 1970, the year of Project Hypo. The vertically-integrated model he developed first for Lake Ontario [Simons (1980) provides a thorough review of progress in lake circulation modeling] was used to hindcast the lake's response to measured winds for April through December. Lake surface elevations computed with the model were compared with lake level recorders for verification, while computed volume transports were used to hindcast chemical fluxes in a companion study (Lam and Simons 1976). Also considered for the months of June through September was a two-layer model designed to resolve the flow in both epilimnion and hypolimnion. Comparisons with the short interval of current velocity recordings obtained during summer stratification in Project Hypo provided verification of the currents. Because this simulation used the measured wind field to hindcast currents during 4-week-long intervals between research vessel cruises, it would be difficult to compare these results with the 1979–80 data. The results of Simons modeling effort indicated a complicated

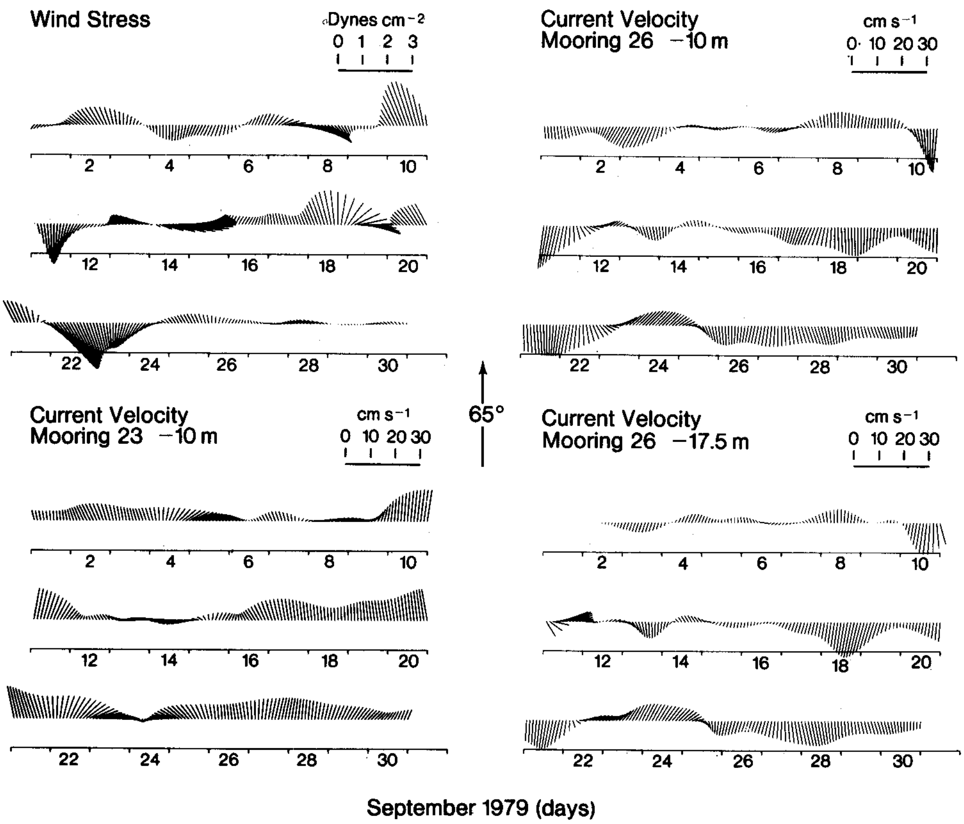

FIG. 26. Low-pass filtered Lake Erie wind stresses and currents at the Pennsylvania Ridge in September 1979.

circulation pattern of semi-independent cells or gyres that often characterize the measured currents as well.

The two-layer model provided constructive information on the nature of hypolimnion flow during summer. Results compared favorably with the Project Hypo deep current measurements and with our measurements in July and August of 1979. This model also vividly demonstrated the sensitivity of the prediction to the parameterization of bottom friction since the two-layer configuration yields a bottom friction vector that essentially reinforces or adds to the surface stress, similar to the complete Ekman formulation of Gedney and Lick (1972).

A two-layer model was developed by Gedney *et al.* (1973) and used to determine the effects of varying eddy viscosity and wind stress distributions on currents and thermocline configuration. The responses were found to vary greatly for uniform winds versus those with distinct gradients. Though not applicable directly to Lake Erie because of the nonlinearities that result from the thinness of the bottom layer and the thermocline's intersection with the bottom, their results indicated complex interactions that must be considered fully in interpreting lower layer movements.

SUMMARY AND DISCUSSION

We measured water temperatures and currents on a large-scale grid in Lake Erie from May 1979 through June 1980. Although there were operational problems during the experiment, a large volume of high-quality data extending over many months was collected. Analyses of the data have provided some valuable insights into the physics of the Lake Erie water masses, but many topics require further in-depth study.

Close to the bottom, current flows during the stratified season were generally westerly along the south shore of the central basin and northwesterly in the basin's center. The movements of seabed

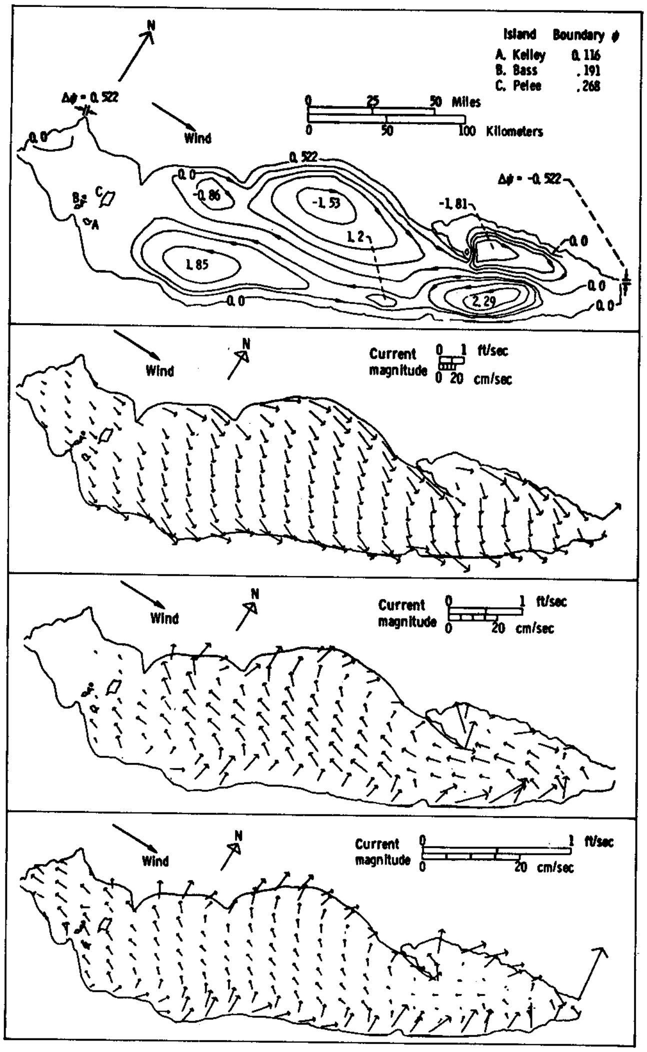

FIG. 27. Lake Erie stream function (top) for a 5.2 m s^{-1} west wind. Currents are shown for 0.4 and 9.9 m depths and for a constant elevation of 1.2 m above the lake bottom from the upper part of the figure to the lower part, respectively. (From Gedney 1971).

current drifters revealed a similar pattern. These findings confirm and expand the findings of earlier work and help explain why the last remnants of the summer hypolimnion are pushed toward the basin's western end.

Monthly-averaged resultant currents and those recorded during major wind stress impulses revealed the same prevailing current patterns. In the high current speed episodes, we often observed two-cell circulations in each of the central and eastern basins, very similar in fact to the volume transport streamlines computed theoretically for Lake Erie by Gedney (1971) and Gedney and Lick (1972). We observed the circulations in both mid-level and near-bottom currents without much shear between levels, suggesting that the currents were more barotropic than those revealed by the full Ekman layer model they used. Many episodes evolved such that one of the major central basin cells became dominant and the basin-wide currents flowed either clockwise or anticlockwise. There is no clear evidence for the cause of one pattern versus the other and either may arise from what appear to be very similar wind histories. An important consideration could be the strong tendency of the wind to veer in clockwise fashion, almost never constant over long time intervals. Effects of wind stress curl are traditional generation mechanisms for one-gyre circulations in a flat-bottomed basin and these effects are examined in Schwab and Bennett (1987). Episode dominance by one pattern or another plays a big part in determining the distribution of monthly resultant currents. Stratification does not play a major role in shaping the current responses although thermocline configuration clearly responds to the wind stress.

Periodic components, including the near-inertial period current vector rotations and the first several longitudinal seiches of Lake Erie, were identified in the current meter recordings. The seiche currents were very prominent through the inter-island passages between the west and central basins and also significant over wide areas of the central basin, adding an important component to the current velocities.

Our measurements ignored the near-surface wind drift currents and currents tight against the coasts. Previous investigators have found narrow eastward flows along both the northern and the southern shores from surface to bottom (cf. FWPCA 1968). Platzman's (1963) classic paper provided a dynamical perspective of surface currents and return flow. This and subsequent model predictions with prevailing westerly winds have confirmed both the coastal currents and the surface wind drift that has been deduced from the results of drift object experiments. These features have probably been the best known of Lake Erie circulation and nothing here contradicts those results.

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