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Environmental Research Laboratories

Large-Scale Current Measurements in Lake Superior

PETER W. SLOSS
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BOULDER, COLO.
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LARGE-SCALE CURRENT MEASUREMENTS IN LAKE SUPERIOR

Peter W. Sloss and James H. Saylor

Analyses of current meter data collected in Lake Superior in 1967 and 1973 show a general counterclockwise circulation covering most of the lake. Currents near the shore are strong - exceeding 10 cm s^{-1} for a half-month vector average - and generally parallel to the isobaths. Open-lake currents show strong periodic motions at the local inertial frequency. An interesting periodicity is seen in the currents between Isle Royale and the northern shore. Oscillatory components observed there are driven by inertial motions when the lake becomes thermally stratified in late summer, but in spring they show periodicities related to the first and sixth free surface modes of the lake. Other persistent features of the measured flow patterns are the Keweenaw Current and a general strengthening of summertime flows as the lake becomes stratified.

1. INTRODUCTION

This report presents the results of an analysis of current meter data collected in Lake Superior during 1966 and 1967 by the Federal Water Pollution Control Administration (FWPCA). (Subsequent to collection of the data set, reorganization within the federal government placed this activity within the responsibilities of the Environmental Protection Agency.) Results of the current meter surveys have not been previously published, although several selected episodes from a few of the current meter stations have been incorporated in various studies concerning the dynamics of small areas of the lake. We attempt in this report to evaluate the usefulness of this data set and to infer from it some characteristics of the large-scale circulation patterns of Lake Superior. Additionally, comparisons of these results with those of a current study conducted by the Canada Centre for Inland Waters (CCIW) during 1973 are made to assist in verifying that the current patterns deduced are truly representative of the summertime circulation of Lake Superior.

Lake Superior is the largest of the five Great Lakes, with a length of about 650 km and a maximum width of nearly 300 km (the average width is 120 km). The average depth of the lake is 175 m, and the volume of water stored in Lake Superior exceeds the volume of water contained in all of the other Great Lakes combined. The surface area of the lake is nearly 80,000 km^2, and this large water surface exerts much influence on the climate of the surrounding land masses.

Concommitant with the current studies conducted in 1966 and 1967, water temperatures were measured at the same levels in the water column as the current meters on each mooring. The water temperatures were recorded in analog form on a waxed paper chart. Unfortunately, the usefulness of the temperature data was limited by many mechanical failures of the recording devices and uncertainties in the timing of many records. The data were not systematically reduced and edited, but some features of the temperature structure observed in Lake Superior were reported in Federal Water Quality Administration (FWQA, 1968) reports. Millar (1952) discussed the annual cycle of water temperature distribution in Lake Superior, and the 1966-67 data agree fairly well with Millar's results.

Lake Superior is nearly isothermal from December through early June of each year. The fall turnover occurs as the water at the lake's surface is cooled to 4°C. After attaining a nearly isothermal condition at this temperature, further cooling and intense wind stirring during winter result in an essentially isothermal lake water mass at a temperature of 0° to 2°C. Heating of the lake water in spring occurs first in the shallow water near the lake coasts; this heated water spreads gradually during the course of early summer toward the deeper areas near the center of the lake basin. Because of the deep mean depth of Lake Superior, the quantity of water which warms and forms the summer and early fall epilimnion is only a small fraction (estimated in FWQA as 15 percent) of the lake's total water volume. An important feature of epilimnion formation and distribution during the course of summer heating is its unequal thickness over the lake basin, with a deeper epilimnion near the coasts of the lake and a thinner layer over the deep lake center. This characteristic is common to other lakes as well, and is typical, for example, of the summer temperature distribution in Lake Huron. This pattern is perturbed by intervals of wind stress which generate upwellings and downwellings. Since wind stress and the distribution of water density are the two most important forces driving the currents in the Great Lakes during the season of density stratification, the temperature distributions are indicative of current patterns. Whether the density distribution drives the currents, or the currents establish and help maintain the density distribution is an unanswerable question at this time. The important point is that they are interrelated, and that the observed temperature distributions fit the pattern, inferred from the current meter recordings, of a general counterclockwise circulation of Lake Superior during summer.

2. DATA COLLECTION AND TRANSLATION

A network of current meter moorings was deployed in Lake Superior from the fall of 1966 through the summer of 1967 by the FWPCA. Seven moorings were placed for the winter observations, and 16 for the summer; locations of the summer moorings are shown in figure 1. A 17th summer mooring was lost.

Each mooring comprised a string of Geodyne current meters at FWPCA standard depths of 10, 15, 22, 30, 60, 90, 120, and 150 meters, with the number of meters on each mooring determined by water depth. Surface winds were recorded at nine summer moorings. Current speed and direction were recorded optically every 30 min as Gray-binary coded numbers represented by dot images on 16 mm film. Data films were decoded by an automatic flying-spot scanner at Geodyne with the data transferred to BCD magnetic tape for computer analysis.

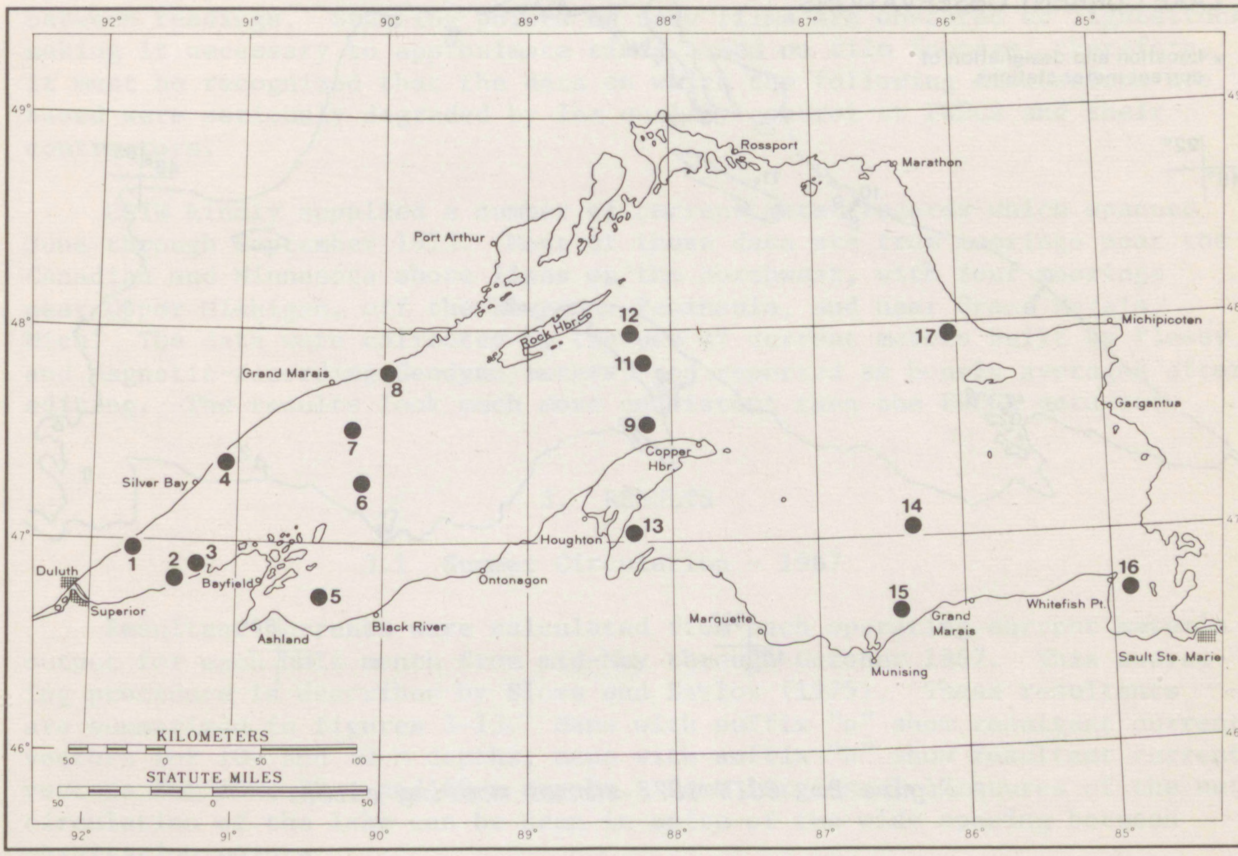

Figure 1. FWPCA 1967 summer mooring sites.

Additional data were supplied to the Great Lakes Environmental Research Laboratory (GLERL) by the CCIW from their 1973 summer field season. Data were returned from 12 moorings at 1 or more depths. Locations of CCIW moorings are shown in figure 2.

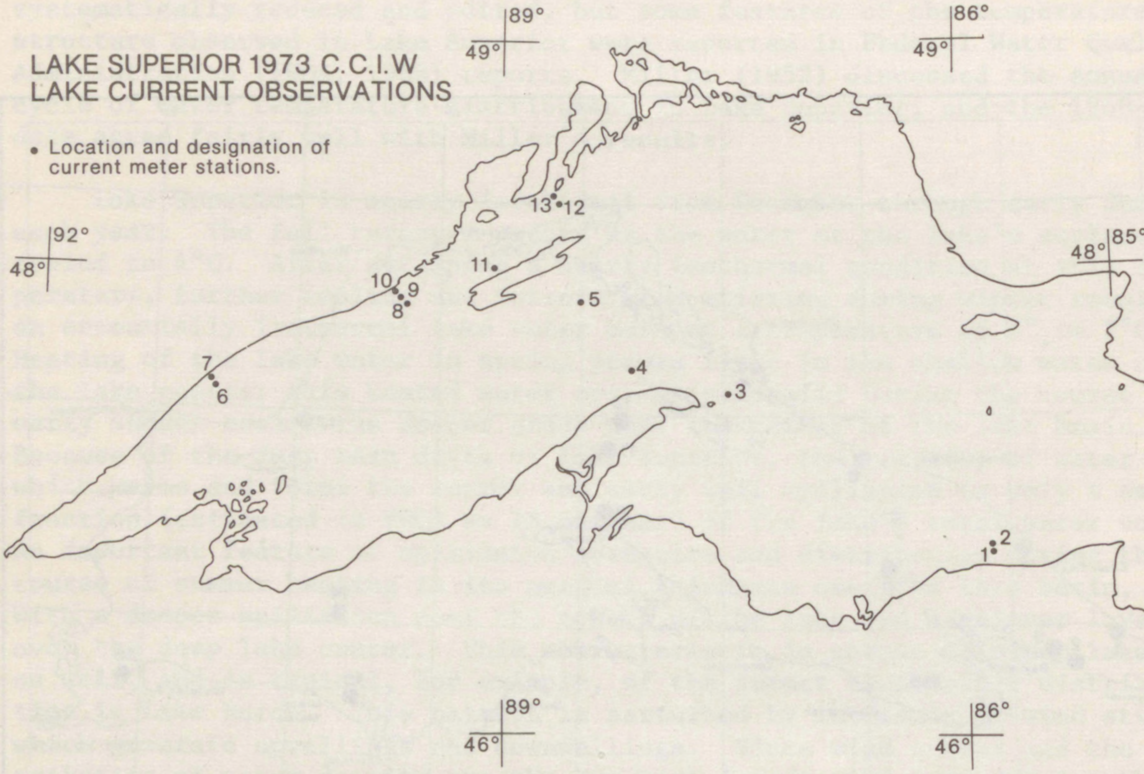

Figure 2. CCIW 1973 summer mooring sites.

Of 145 current meter and 9 wind data films collected by FWPCA, only some 61 were usable; the rest showed some obvious malfunction of the current meter clock, film system, or sensors and were not scanned. After automatic scanning, several additional bad films became evident. There was a problem in the scanner that caused it to lose track of the rotor-impulse channels on the film, resulting in spurious zero-speed reports. All data analyzed by the flying-spot scanner at Geodyne showed this defect with varying degrees of severity. In addition to the spurious zero speeds, many data readings on most films were flagged by the scanner as unreadable either for speed or direction or both. Typical film translations resulted in some 10 percent of the data points being flagged as unreadable or zero-speed. The net return of data is thus some 40 percent of the expected sample, not including several current meters which operated for only part of the intended season. Only three wind films ran all summer, and some were as short as 3 to 10 days. Normalizing the sample size to expected record lengths would further decrease the percentage of return.

Absolute timing of readable data is uncertain in some records since there is evidence that some meters sometimes failed to advance the film between readings. Starting points on many films are obscured or lightstruck, making it necessary to approximate times based on film footage; therefore, it must be recognized that the data on which the following discussions are based were seriously degraded by lax quality control at FWPCA and their contractors.

CCIW kindly supplied a number of current meter records which spanned June through September 1973. Most of these data are from moorings near the Canadian and Minnesota shore lines on the northwest, with four moorings near Upper Michigan, off the Keweenaw Peninsula, and near Grand Marais, Mich. The data were collected by the use of current meters built by Plessy and magnetic-recording Geodyne meters, and reported as hourly averages after editing. The results look much more consistent than the FWPCA data set.

3. RESULTS

3.1 Summer Circulation - 1967

Resultant currents were calculated from each operating current meter's output for each half month from mid-May through October 1967. This averaging procedure is described by Sloss and Saylor (1975). These resultants are summarized in figures 3-13. Maps with suffix "a" show resultant current vectors for 10- and 30-m depths; maps with suffix "b" show resultant current vectors for 15-, 22-, and 60-m depths. Some large-scale features of the net circulation of the lake can be seen in spite of the wide spacing between observation points.

Thermal stratification begins in Lake Superior in early June and continues into September, but the thermocline is unlikely to pass for any long duration below 30 m. The average maximum epilimnion thickness is about 22 m (FWQA, 1968). As a result, most current vectors presented here represent flow in the hypolimnion. It is highly probable that current speeds reported here are lower than the actual values due to the frequent incidence in the data of zero speed readings which continuity would seem to contradict. Canadian data from 1973 (discussed later) show considerably higher speeds at nearly the same locations studied during 1967 and under similar conditions.

Usable data started with the second half of May 1967 (fig. 3a, b) for stations west of 88°W longitude. Winds for this period averaged from the northerly quadrant, but recorded currents at 10 and 30 m show no organized pattern. Flow at 10 m is offshore at moorings 2 and 3. This pattern suggests that upwelling along the southern shore may have occurred in the western part of the lake because the 30-m flow is onshore at station 2.

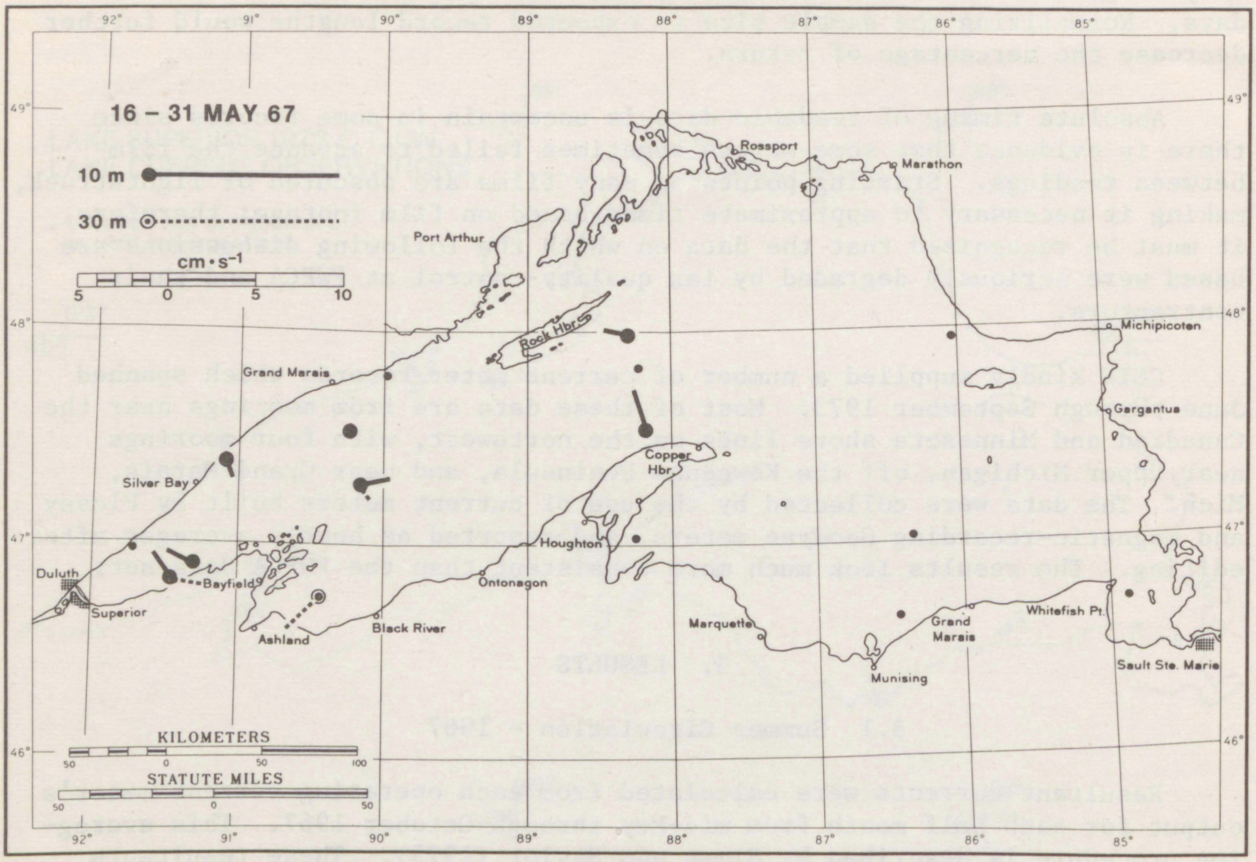

Figure 3a. (FWPCA) half-month average current vectors, 16-31 May 1967, 10 and 30 m.

The first half of June saw mean winds at approximately 3 m s^{-1} from the northeast. Currents at 10 m flowed southwestward along the shore at station 4 and continued offshore at 2 and 3 (fig. 4a). Strong offshore flow at station 1 at 15 m indicated the flow turned to follow the shore in a counterclockwise pattern (fig. 4b). At station 9, the Keweenaw Current was beginning to appear in the data. Smith (1972) reported that this current reached 80 cm s^{-1} and averaged 26 cm s^{-1}, although no such magnitudes were seen in the FWPCA data. This is assumed to be related to measurement hardware, not nature. Smith's data were confirmed by CCIW measurements at their mooring 4. No other organized flow was evident for this period in the FWPCA data.

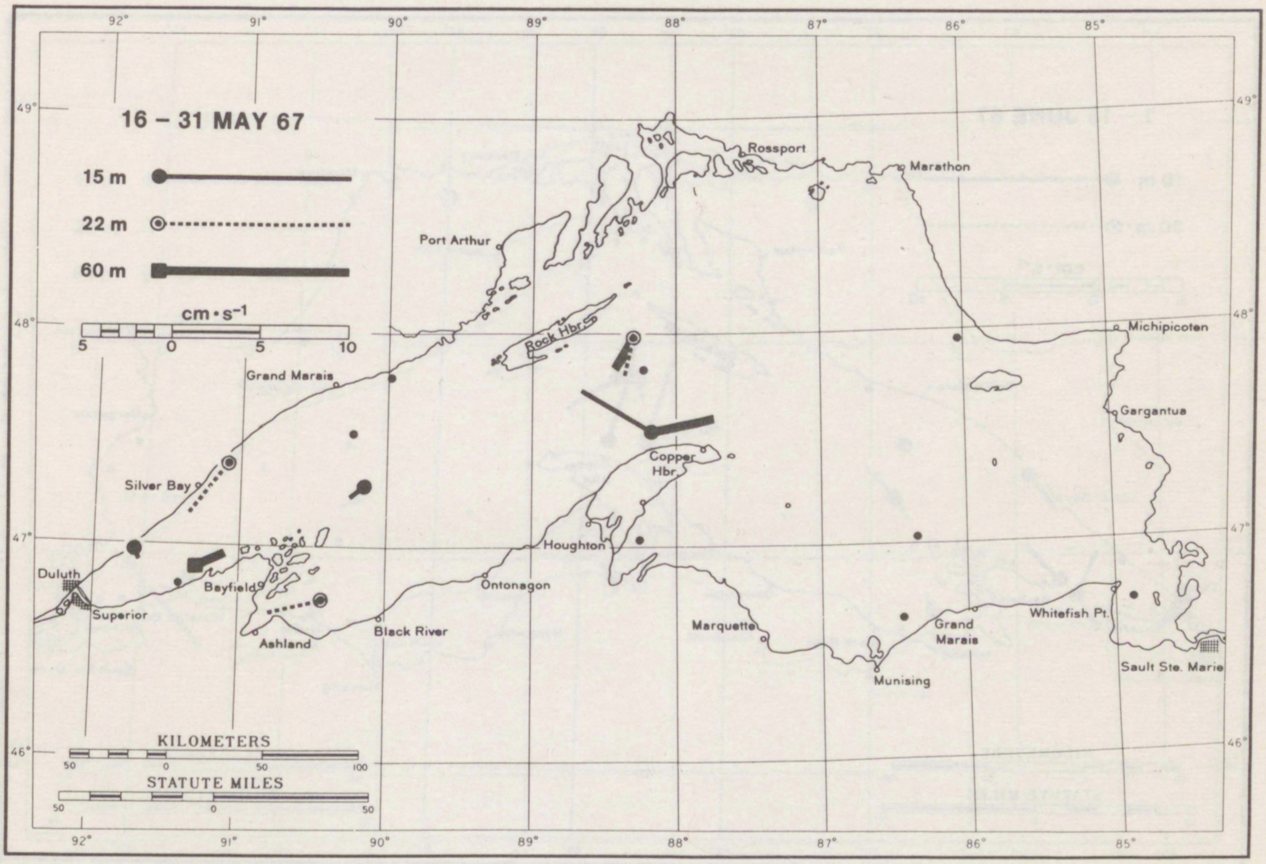

Figure 3b. (FWPCA) half-month average current vectors, 16-31 May 1967, 15, 22, and 60 m.

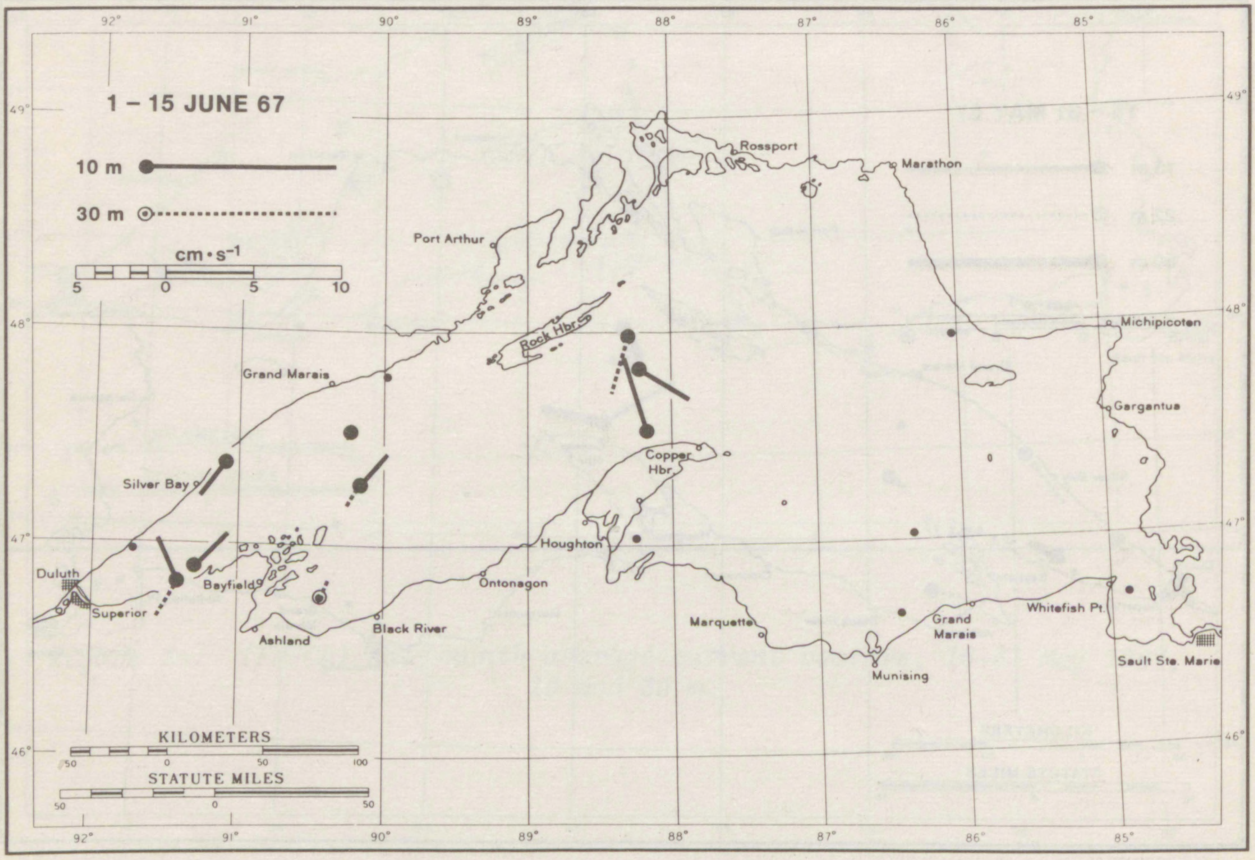

Figure 4a. (FWPCA) half-month average current vectors, 1-15 June 1967, 10 and 30 m.

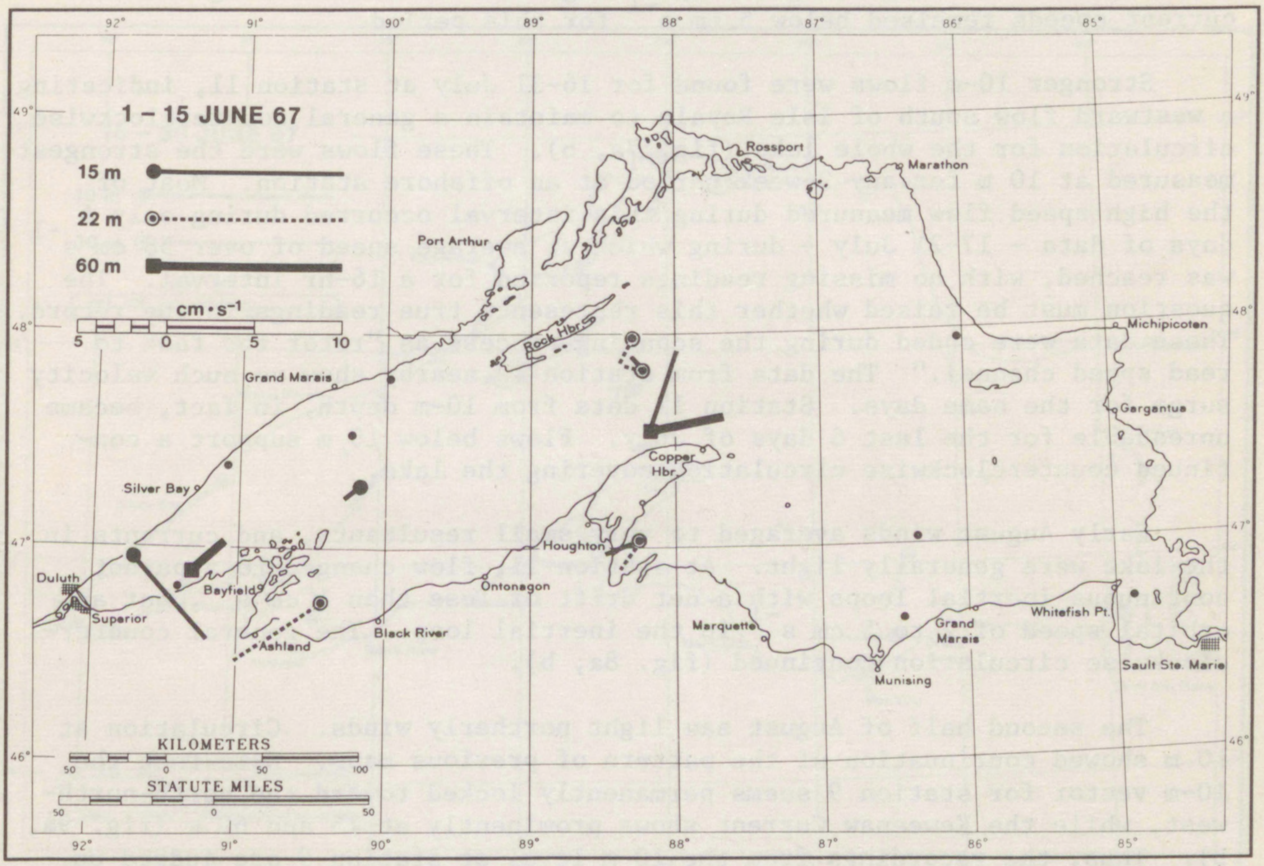

Figure 4b. (FWPCA) half-month average current vectors, 1-15 June 1967, 15, 22, and 60 m.

Data for 16-30 June (fig. 5a, b) began to show a general counterclockwise flow encompassing the whole lake in the 10- and 15-meter layers. Flows at 30 m opposed shallower flows at many stations. Mean winds were light and had switched to the south quadrant.

Southerly winds in early July triggered possible upwelling along much of the south shore of Lake Superior (fig. 6a, b). While 10-m flows were offshore or parallel to shore at most southern lake stations, 30-m flows were strongly onshore. Surface layer (10-m) flow at stations 11 and 12 was to the south, as were all deeper flows at station 12, suggesting a return flow there supporting the upwelling. All measured average 10-m current speeds remained below 5 cm s^{-1} for this period.

Stronger 10-m flows were found for 16-31 July at station 11, indicating a westward flow south of Isle Royale to maintain a general counterclockwise circulation for the whole lake (fig. 7a, b). These flows were the strongest measured at 10 m for any 2-week period at an offshore station. Most of the high speed flow measured during this interval occurred during only 4 days of data - 17-21 July - during which an average speed of over 58 cm s^{-1} was reached, with no missing readings reported for a 16-hr interval. The question must be raised whether this represents true readings in the record. These data were coded during the scanning process as "rotor too fast to read speed channel." The data from station 12 nearby show no such velocity surge for the same days. Station 11 data from 10-m depth, in fact, became unreadable for the last 6 days of July. Flows below 10 m support a continued counterclockwise circulation covering the lake.

Early August winds averaged to very small resultants, and currents in the lake were generally light. At station 11, flow changed to apparent continuous inertial loops with a net drift of less than 1 cm s^{-1}, but an orbital speed of 2 to 5 cm s^{-1} in the inertial loop. The general counterclockwise circulation continued (fig. 8a, b).

The second half of August saw light northerly winds. Circulation at 10 m showed continuation of the pattern of previous maps. Note that the 10-m vector for station 9 seems permanently locked toward the north-northwest, while the Keweenaw Current shows prominently at 15 and 60 m (fig. 9a, b). Thus, the recordings from the 10-m level at station 9 are judged unreliable.

The maps for 1-15 September (fig. 10a, b) are similar to the August set. The counterclockwise lakewide circulation persisted and the Keweenaw Current averaged some 13 cm s^{-1} at 15 m. At station 15 at 30 m, the current exceeded 15 cm s^{-1} parallel to bathymetry. Flow at station 16 at both 10 and 15 m pointed into the lake rather than toward Sault Ste. Marie, Mich. This station was located west of the deepest water in the region, and indicated a circulation pattern in Whitefish Bay which may be usually clockwise in summer, with St. Marys River water originating in a southward flow along the Canadian shore of the bay. Flows at stations 2 and 3 were parallel to shore, following the prevailing circulation.

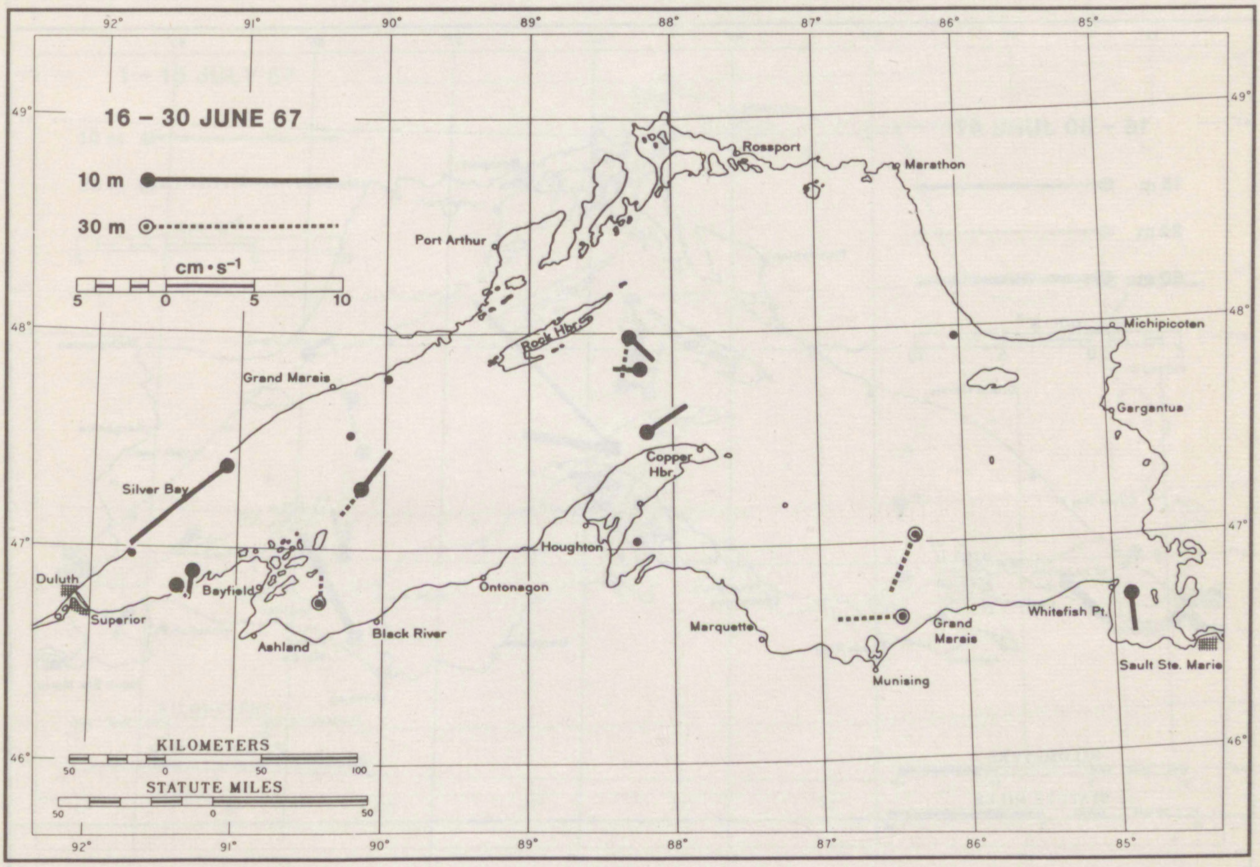

Figure 5a. (FWPCA) half-month average current vectors, 16-30 June 1967, 10 and 30 m.

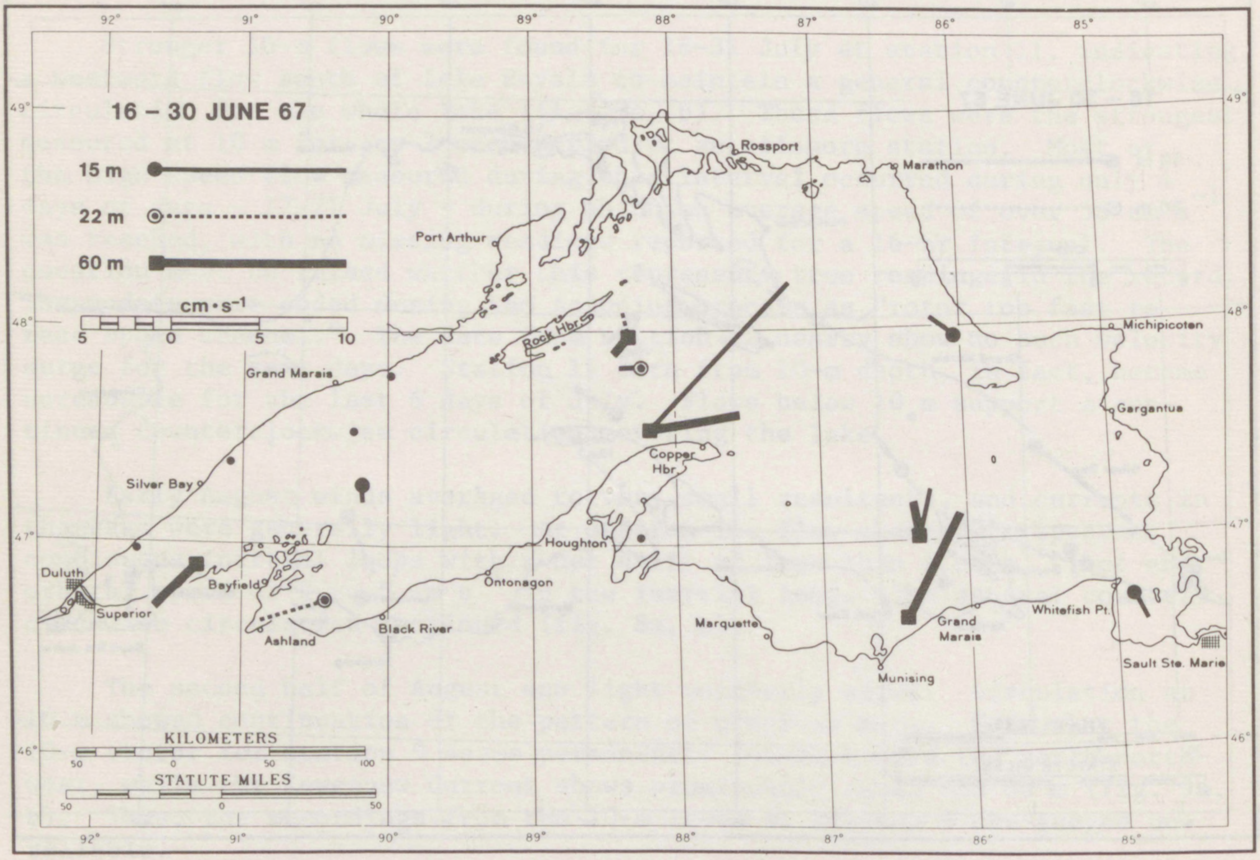

Figure 5b. (FWPCA) half-month average current vectors, 16-30 June 1967, 15, 22, and 60 m.

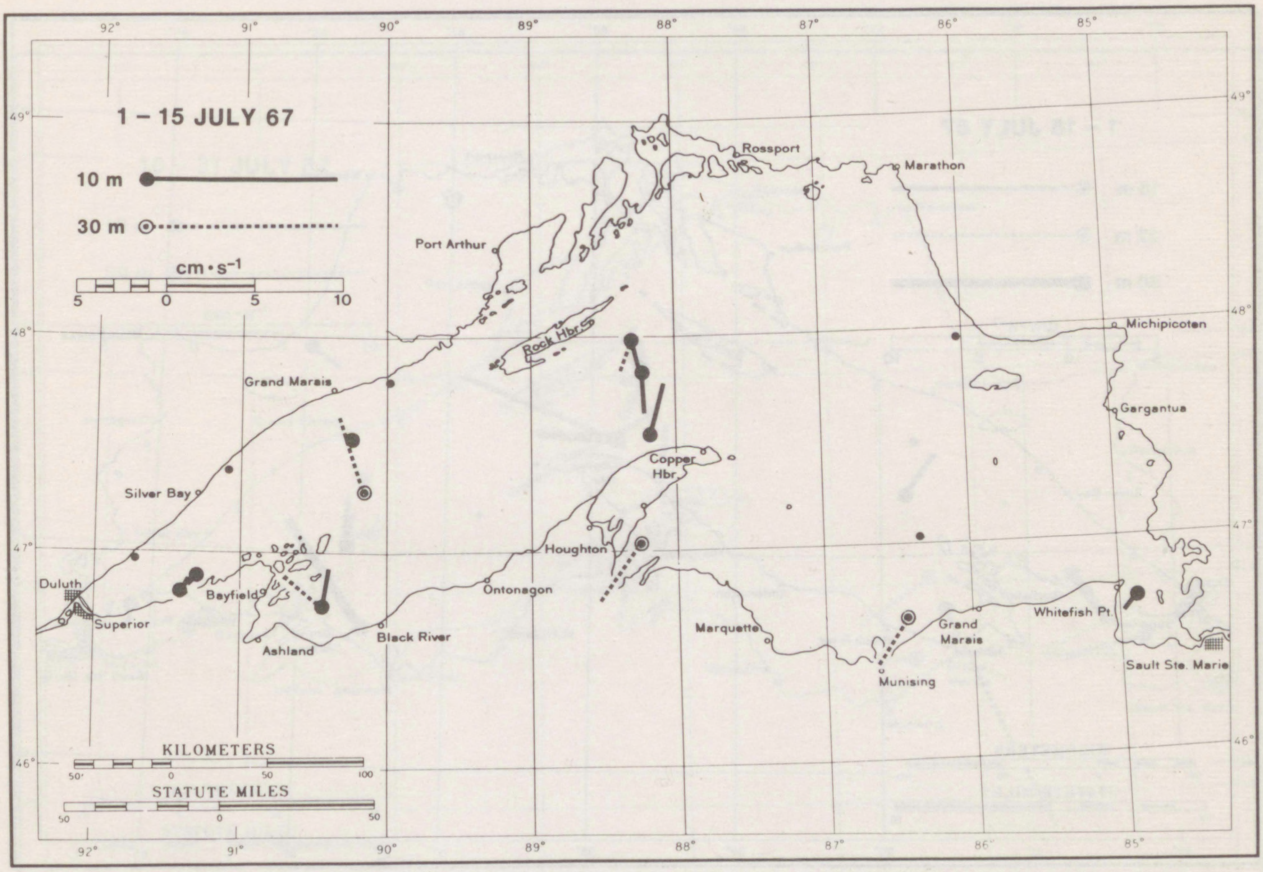

Figure 6a. (FWPCA) half-month average current vectors, 1-15 July 1967, 10 and 30 m.

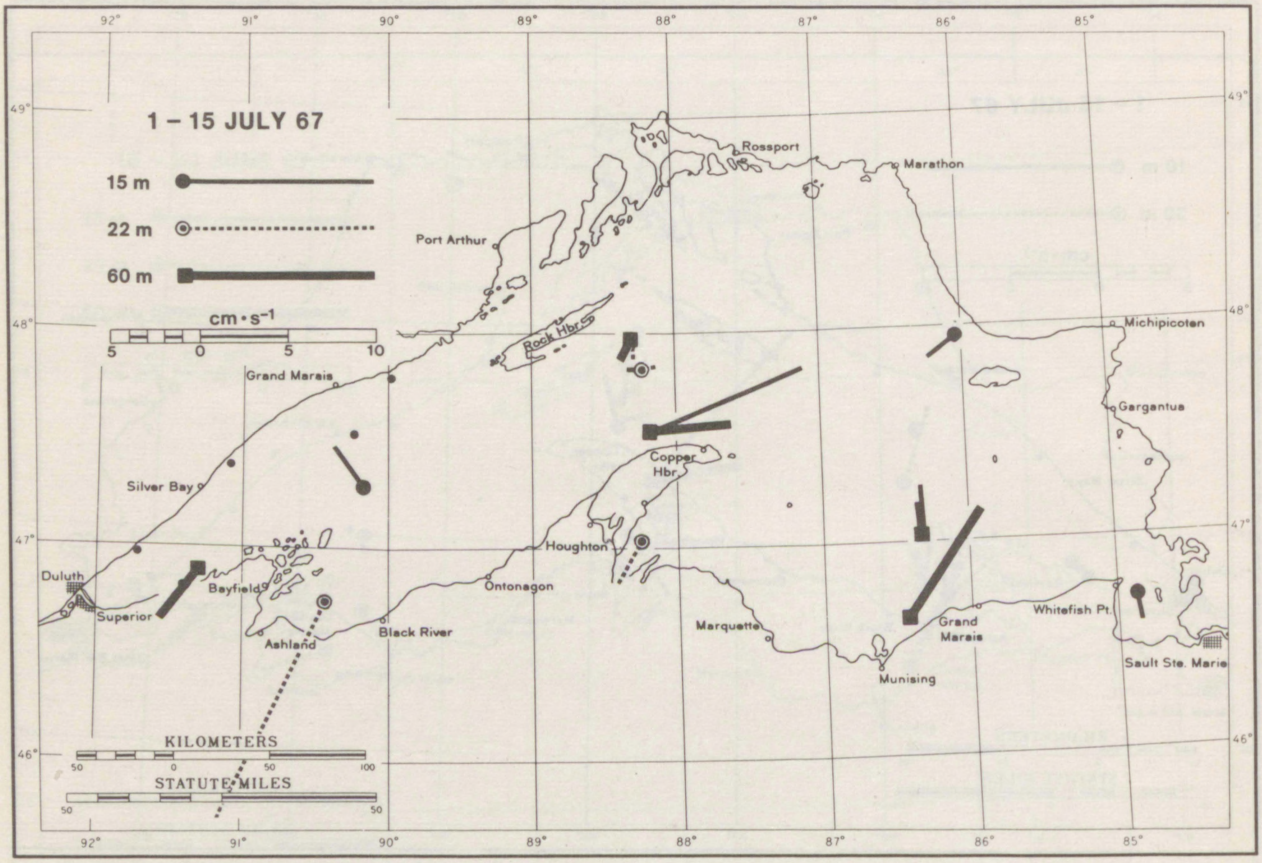

Figure 6b. (FWPCA) half-month average current vectors, 1-15 July 1967, 15, 22, and 60m.

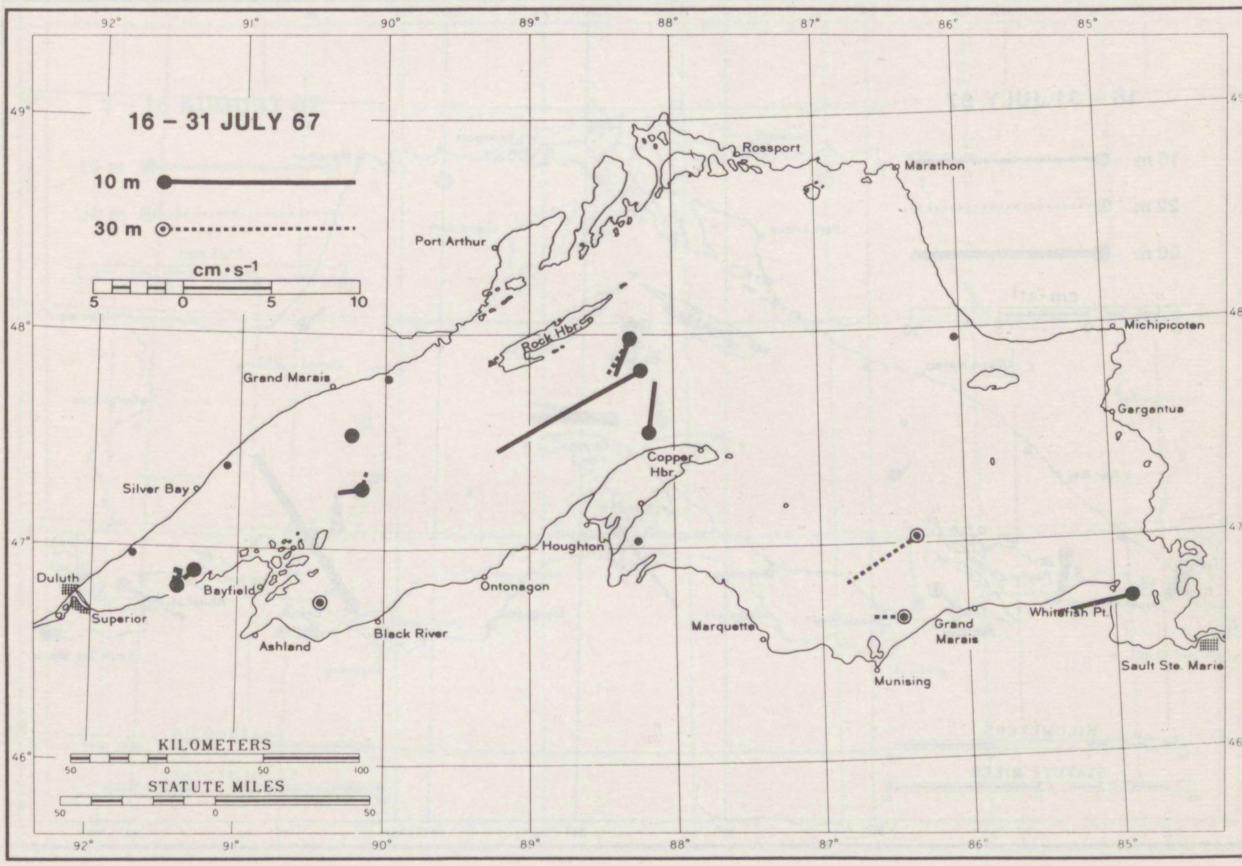

Figure 7a. (FWPCA) half-month average current vectors, 16-31 July 1967, 10 and 30 m.

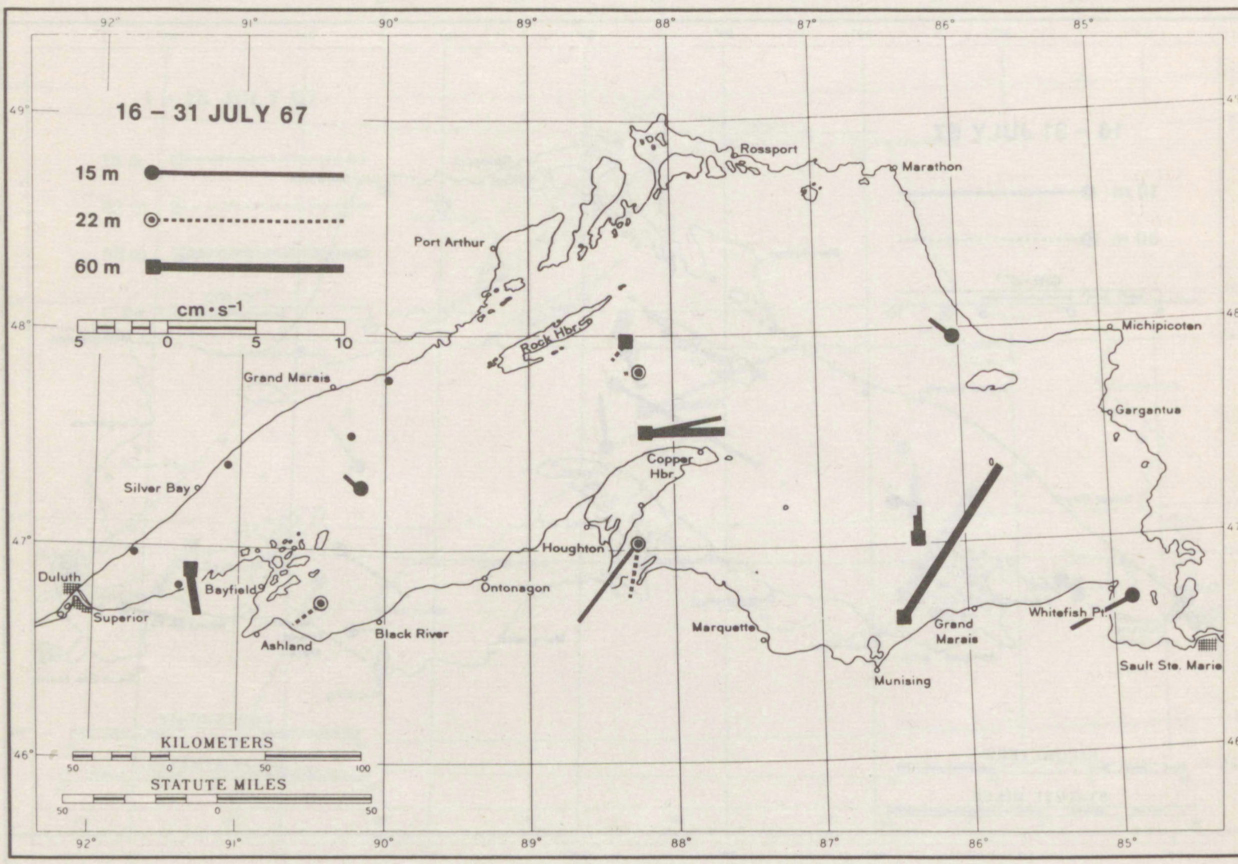

Figure 7b. (FWPCA) half-month average current vectors, 16-31 July 1967, 15, 22, and 60 m.

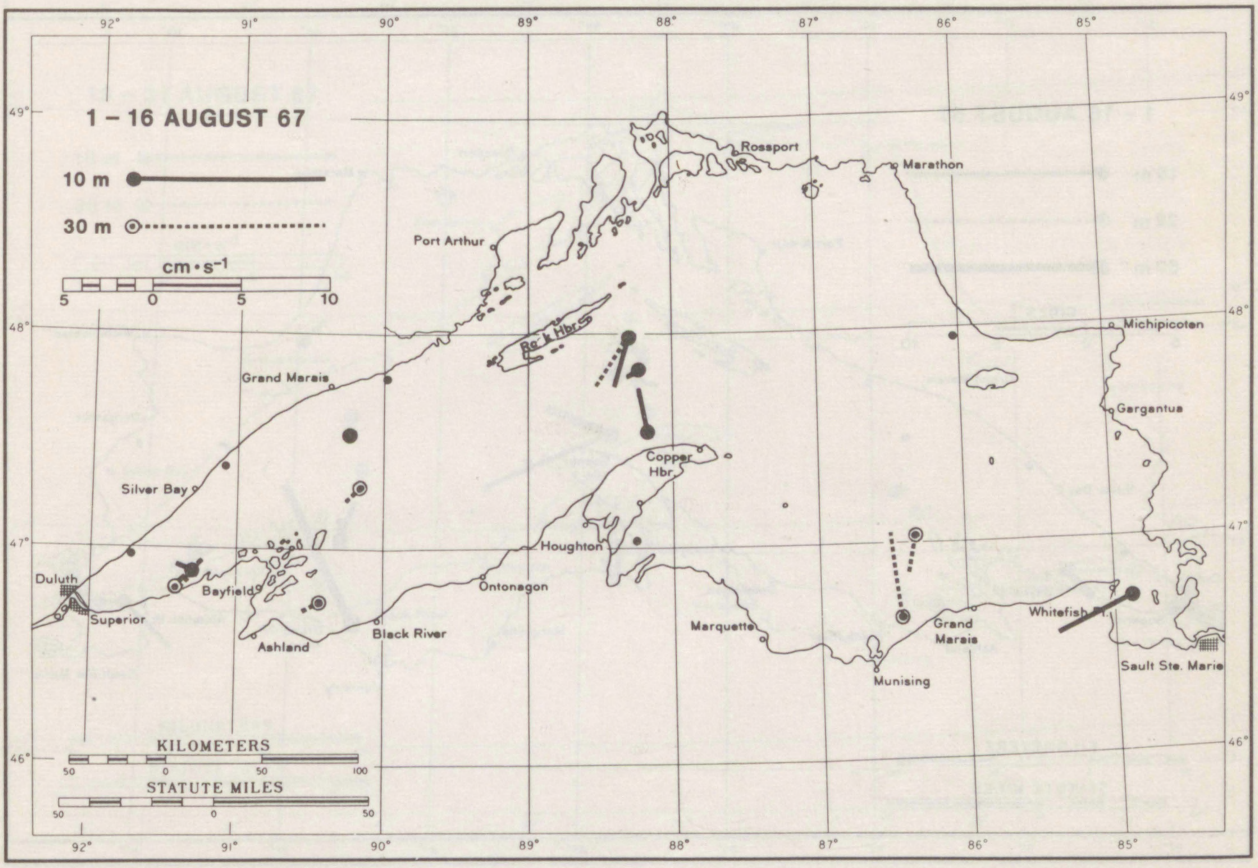

Figure 8a. (FWPCA) half-month average current vectors, 1-16 August 1967, 10 and 30 m.

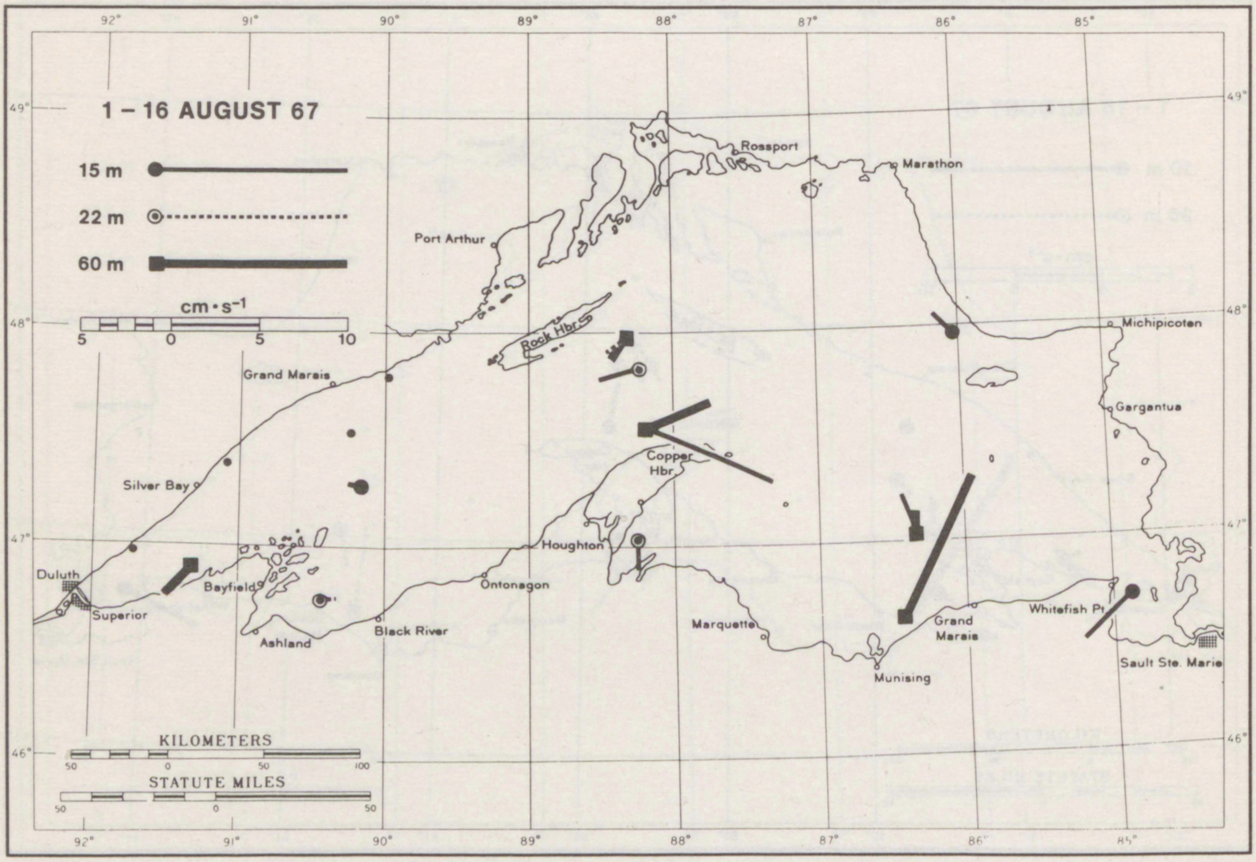

Figure 8b. (FWPCA) half-month average current vectors, 1-16 August 1967, 15, 22, and 60 m.

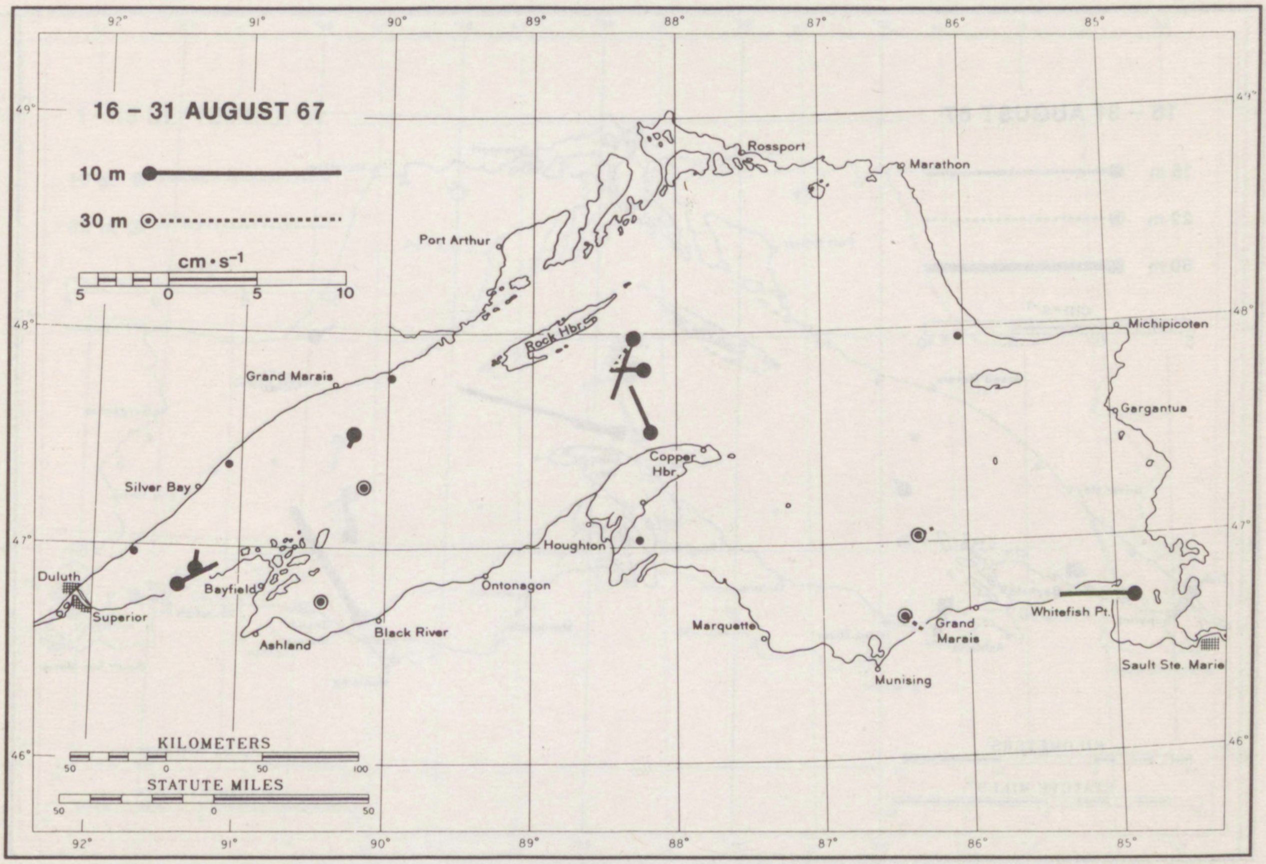

Figure 9a. (FWPCA) half-month average current vectors, 16-31 August 1967, 10 and 30 m.

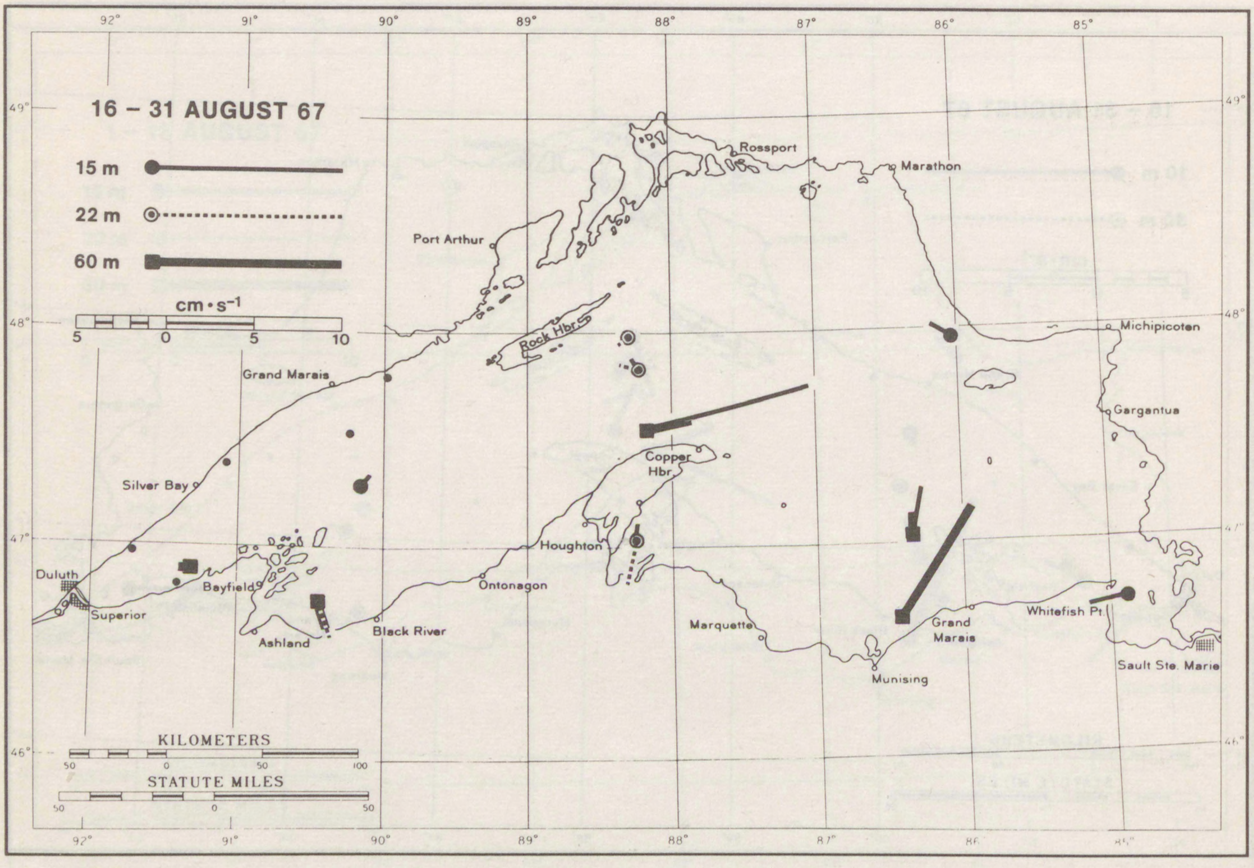

Figure 9b. (FWPCA) half-month average current vectors, 16-31 August 1967, 15, 22, and 60 m.

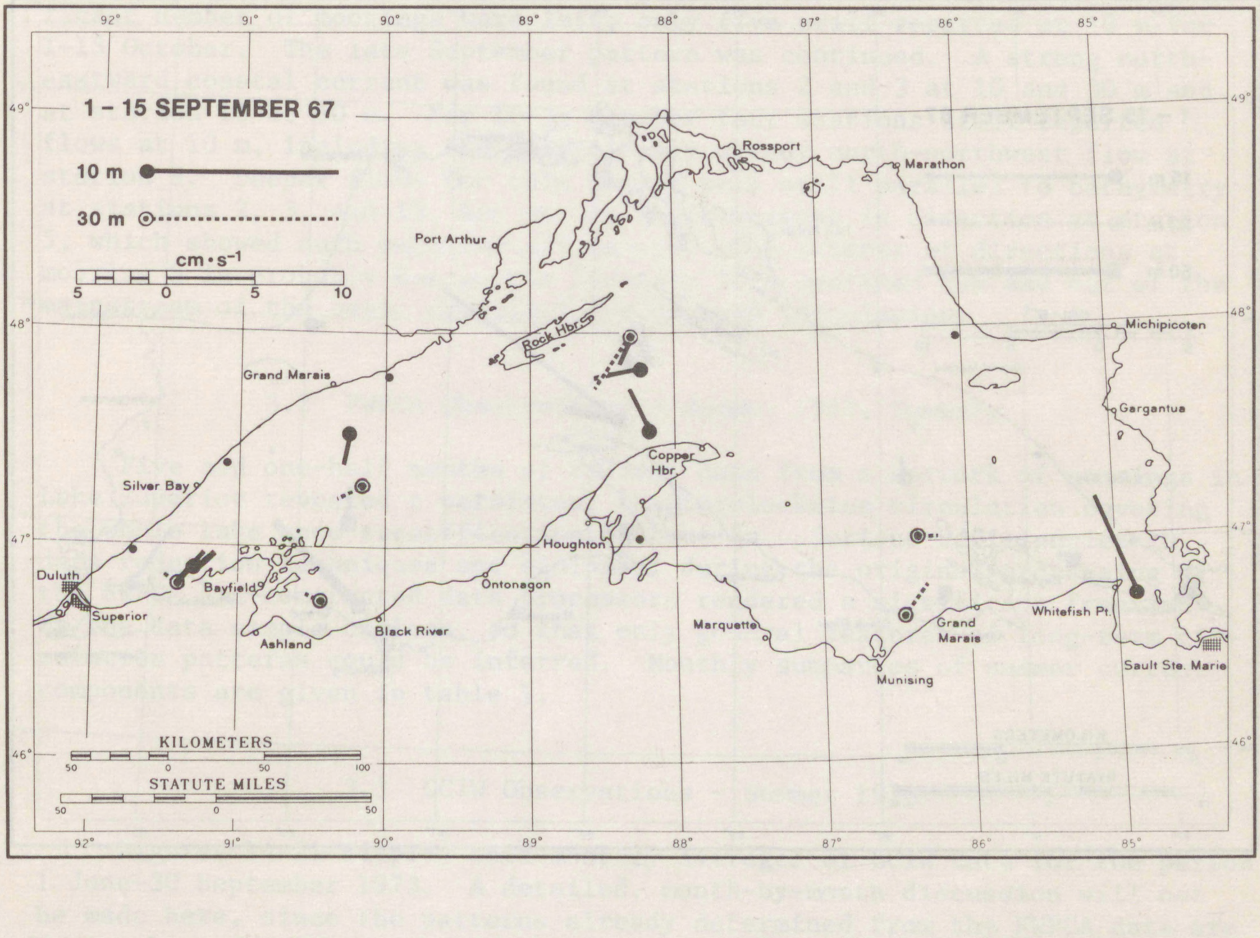

Figure 10a. (FWPCA) half-month average current vectors, 1-15 September 1967, 10 and 30 m.

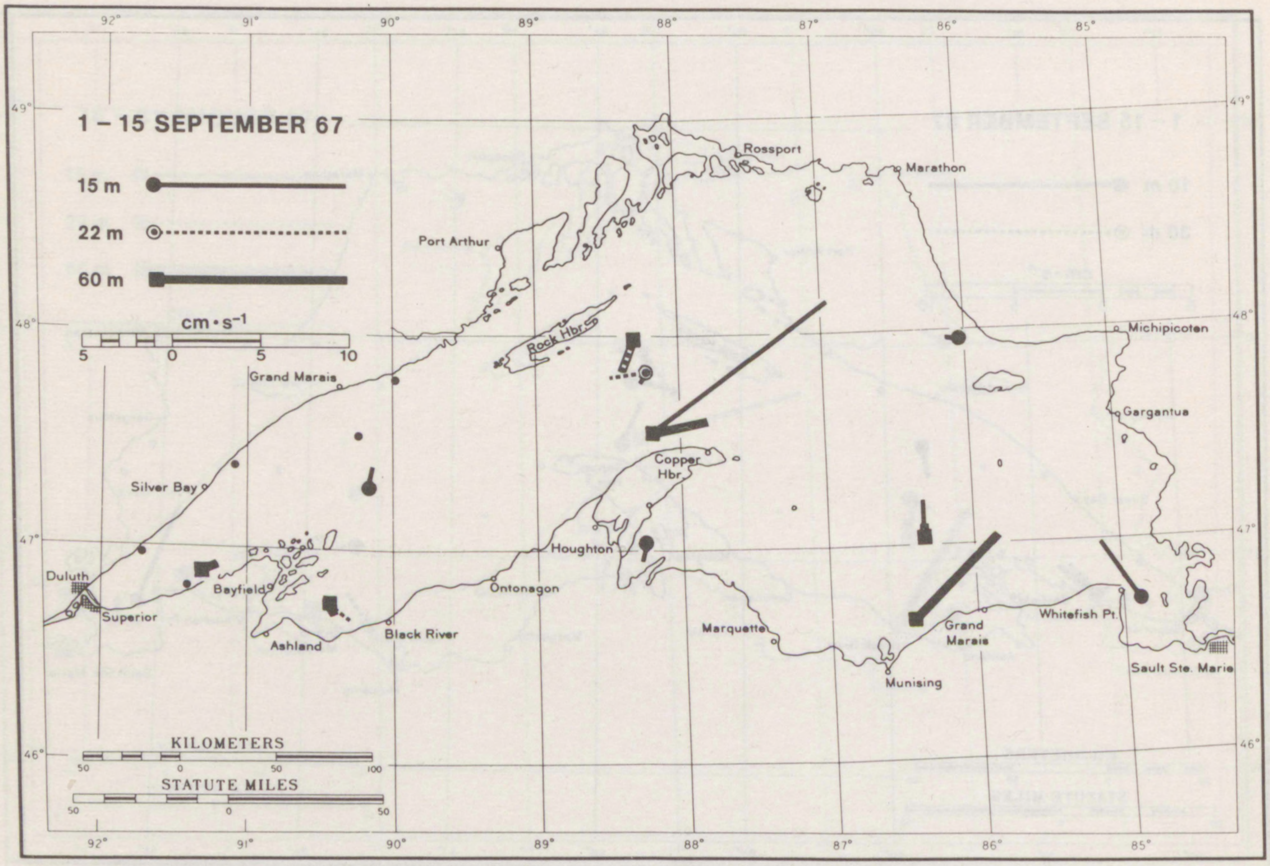

Figure 10b. (FWPCA) half-month average current vectors, 1-15 September 1967, 15, 22, and 60 m.

The second half of September (fig. 11a, b) seemed to contain a change in the flow pattern as a current flowed from the Keweenaw Peninsula toward Isle Royale at 15 m at station 9, and at 10 and 15 m at station 11. Winds were predominantly from the north. There was still evidence of a strong counterclockwise circulation west of 88°W to the tip of the lake and of another cell occupying the eastern half. The cross-lake current from station 9 may have been an artifact of the hardware used in data collection or reduction. Thus, the suggestion of two counterclockwise cells in the lake can be inferred from the data, but certainly not proved conclusively.

October (fig. 12a, b and 13a, b) was the last month in which a significant number of moorings were left; only five still reported at 10 m for 1-15 October. The late September pattern was continued. A strong northeastward coastal current was found at stations 2 and 3 at 10 and 30 m and at station 15 at 60 m. For 16-31 October four stations still reported flows at 10 m, including the suspiciously steady north-northwest flow at station 9. Deeper flows for this period were still parallel to bathymetry at stations 2, 3, and 15, but strong and divergent in direction at station 5, which showed such behavior all season. The scatter of directions at mooring 5 is probably due to its location in a confined bay and out of the mainstream of the basic counterclockwise lake circulation.

3.2 FWPCA Observations - Summer 1967, Summary

Five and one-half months of current data from a network of moorings in Lake Superior revealed a persistent counterclockwise circulation covering the whole lake once stratification had set in. Serious deficiencies in data reduction techniques and equipment during the original processing by the FWPCA and contracted data processors rendered a significant fraction of the data sample useless, so that only general features of long-term circulation patterns could be inferred. Monthly summaries of summer current components are given in table 1.

3.3 CCIW Observations - Summer 1973

Figures 14-21 display half-monthly averages of CCIW data for the period 1 June-30 September 1973. A detailed, month-by-month discussion will not be made here, since the patterns already determined from the FWPCA data are again present. There are, however, some significant differences. CCIW mooring 4 reported a consistent, strong east-northeast Keweenaw Current at speeds exceeding 30 cm s^{-1} from a location near FWPCA site 9, which showed north-northwest currents at 10 m with lower speeds for a similar season. Currents at CCIW site 3 showed an extension of the Keweenaw Current as it swept around with the bathymetry although some of the data from FWPCA site 13 showed this flow continuing to the south-southwest.

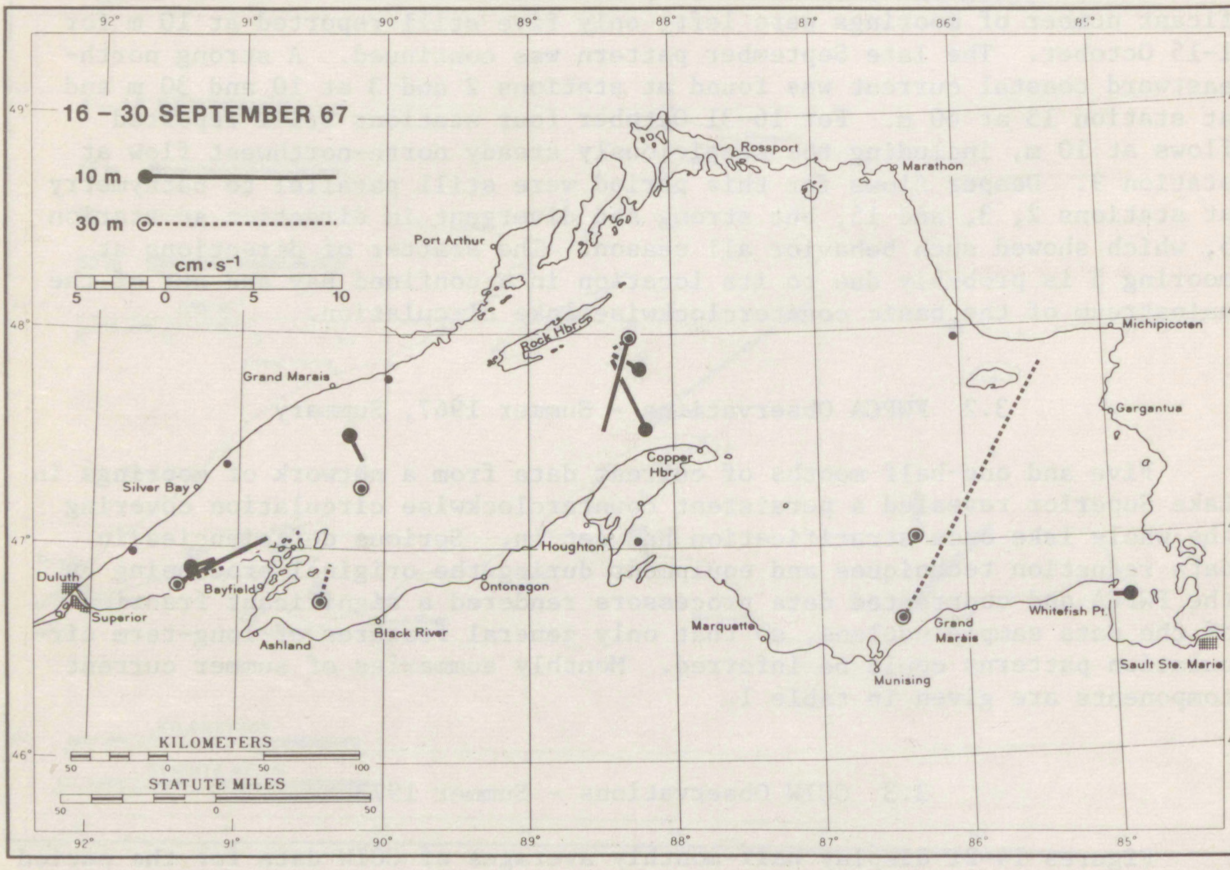

Figure 11a. (FWPCA) half-month average current vectors, 16-30 September 1967, 10 and 30 m.

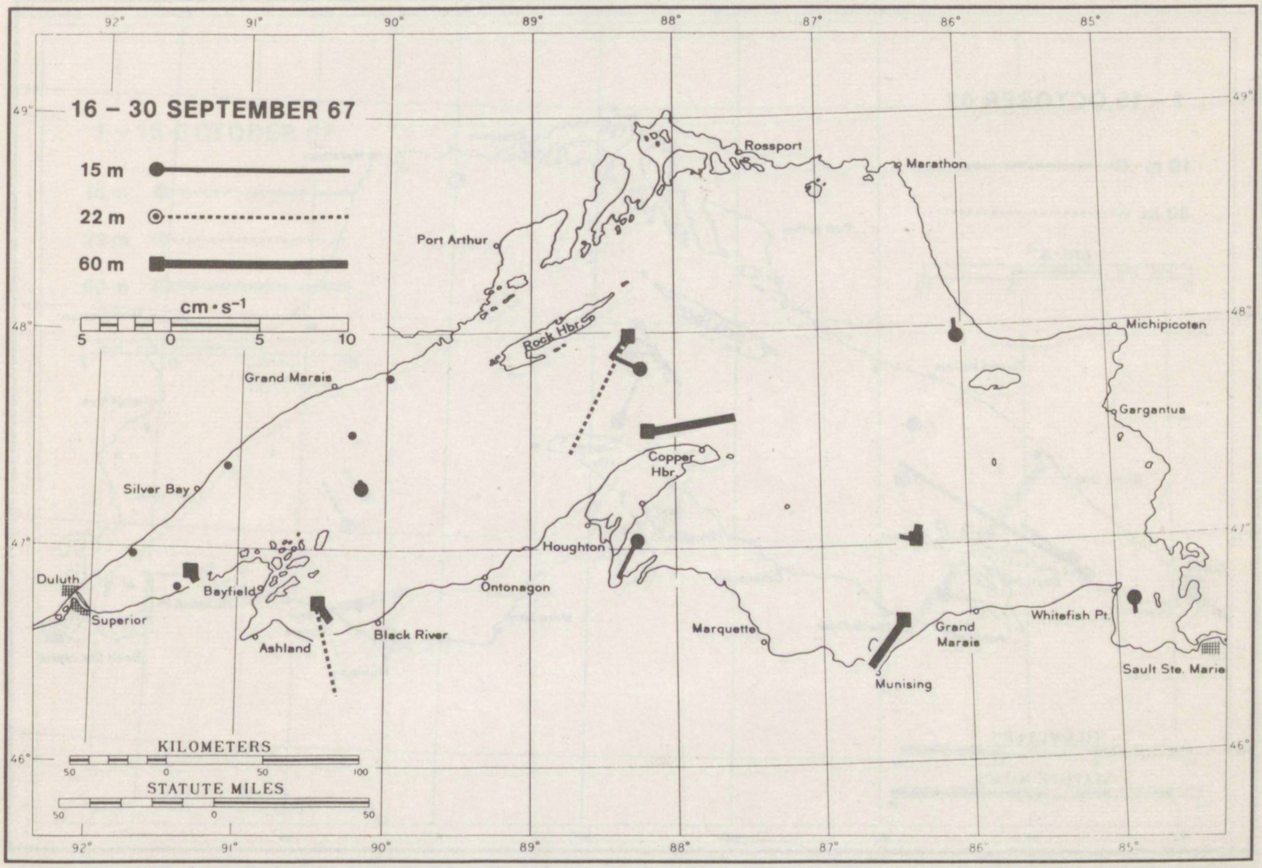

Figure 11b. (FWPCA) half-month average current vectors, 16-30 September 1967, 15, 22, and 60 m.

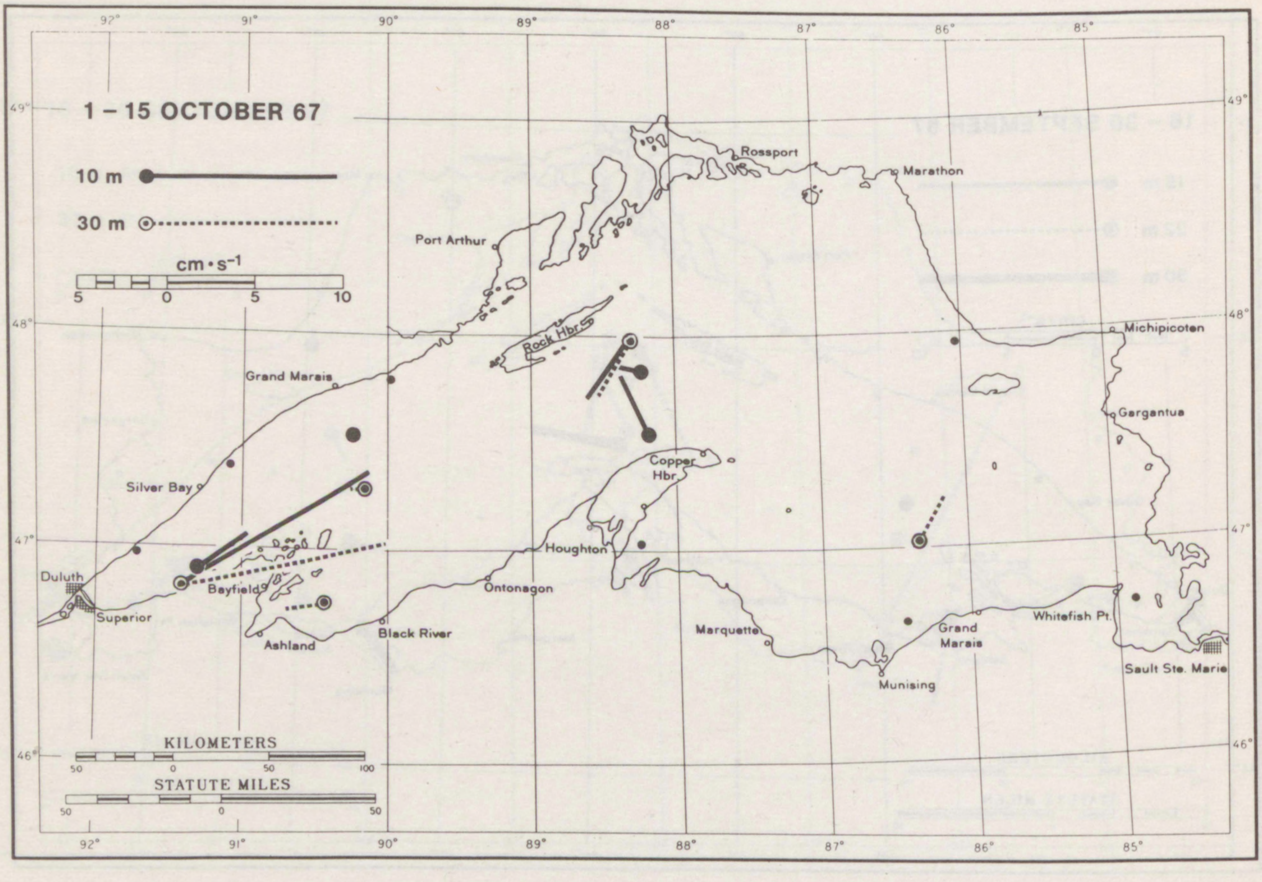

Figure 12a. (FWPCA) half-month average current vectors, 1-15 October 1967, 10 and 30 m.

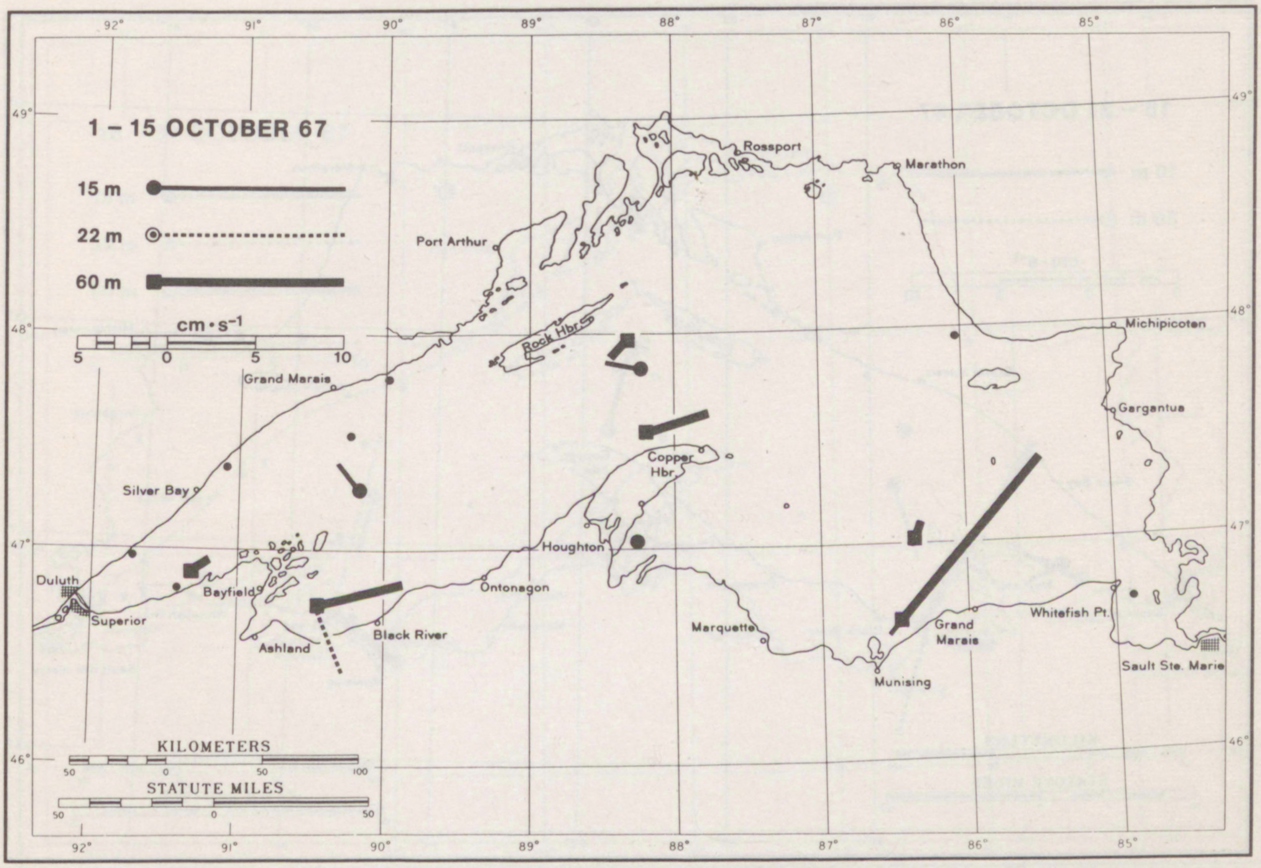

Figure 12b. (FWPCA) half-month average current vectors, 1-15 October 1967, 15, 22, and 60 m.

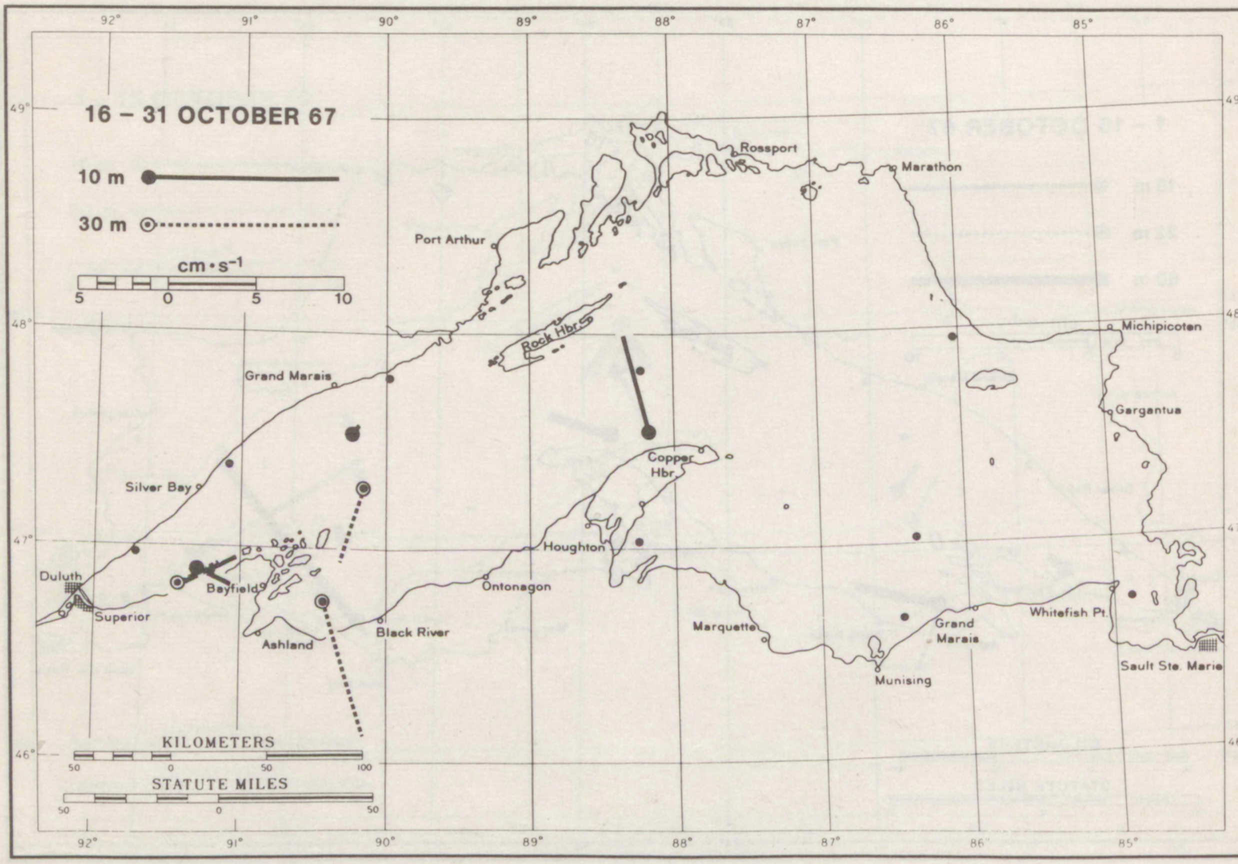

Figure 13a. (FWPCA) half-month average current vectors, 16-31 October 1967, 10 and 30 m.

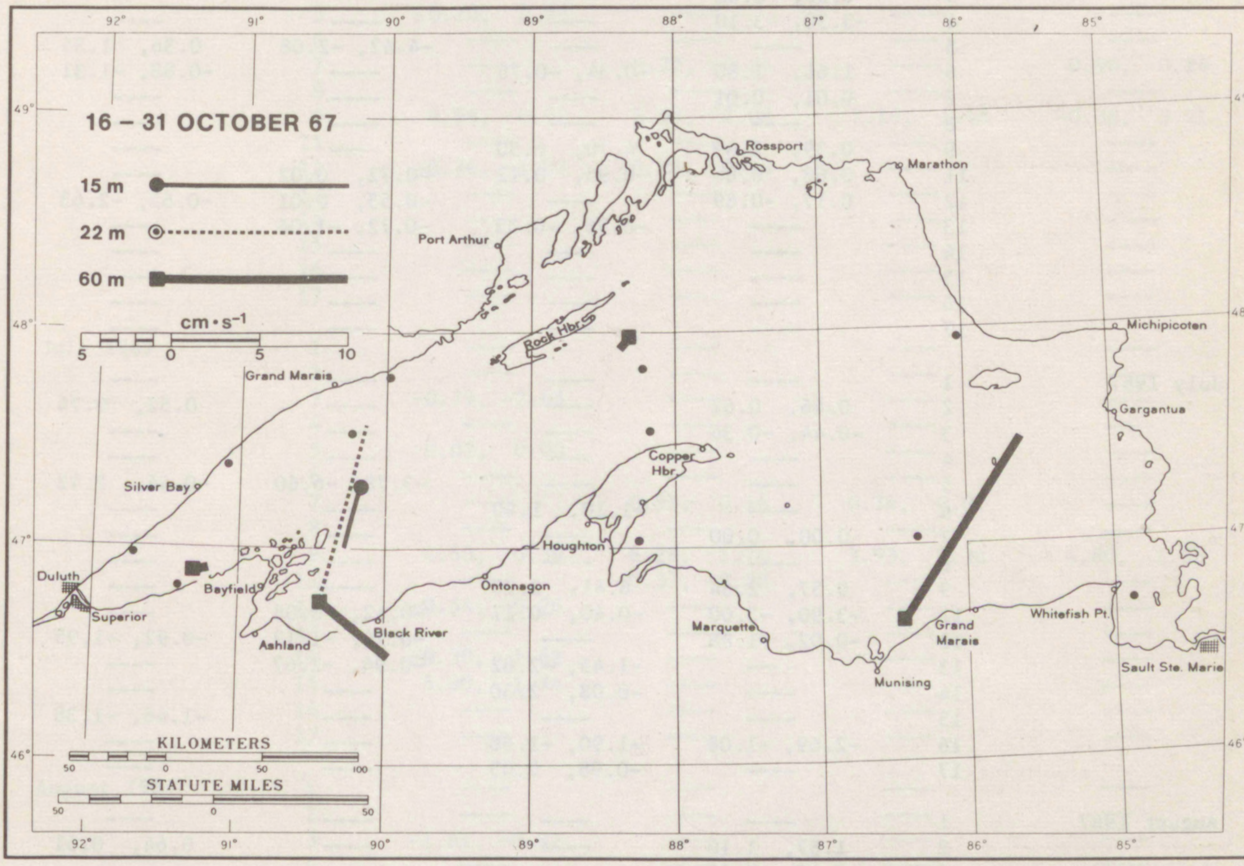

Figure 13b. (FWPCA) half-month average current vectors, 16-31 October 1967, 15, 22, and 60 m.

Table 1. (FWPCA) Current Components (East Component Followed by North Component; Both in cm/s^{-1})

Date	Station	Depth 10 m	Depth 15 m	Depth 22 m	Depth 30 m
June 1967	1	----	----	----	----
	2	-0.33, 1.15	----	----	-0.20, -1.35
	3	0.80, 0.08	----	----	----
	4	-3.30, -3.10	----	----	----
	5	----	----	-4.42, -2.08	0.36, 1.35
	6	1.66, 1.80	-0.34, -0.76	----	-0.88, -1.31
	7	0.01, 0.01	----	----	----
	8	----	----	----	----
	9	0.39, 2.69	4.70, 6.50	----	----
	11	0.68, 0.86	-0.95, 0.12	-0.72, 0.02	----
	12	0.17, -0.89	----	-0.55, 0.01	-0.65, -2.63
	13	----	-0.96, -0.33	-0.72, -1.06	----
	14	----	----	----	----
	15	----	----	----	----
	16	----	----	----	----
	17	----	----	----	----
July 1967	1	----	----	----	----
	2	0.46, 0.62	----	----	0.52, 0.74
	3	-0.44, -0.36	----	----	----
	4	----	----	----	----
	5	----	----	-3.78, -6.60	-0.44, 2.42
	6	----	-1.10, 1.40	----	----
	7	0.00, 0.00	----	----	----
	8	----	----	----	----
	9	0.57, 2.64	6.41, 2.20	----	----
	11	-3.90, -3.00	-0.40, -0.17	-0.62, -0.08	----
	12	-0.02, -1.88	----	-0.24, -1.12	-0.92, -1.95
	13	----	-1.45, -2.82	-0.94, -2.67	----
	14	----	-0.08, 2.30	----	----
	15	----	----	----	-1.46, -1.38
	16	-2.69, -1.08	-1.90, -1.66	----	----
	17	----	-0.98, 0.05	----	----
August 1967	1	----	----	----	----
	2	1.87, 1.10	----	----	0.64, 0.61
	3	-0.30, 0.47	----	----	----
	4	----	----	----	----
	5	----	----	1.02, -0.91	-0.35, 0.03
	6	----	0.10, 0.30	----	-0.30, 0.00
	7	-0.17, -0.44	----	----	----
	8	----	----	----	----
	9	-0.94, 2.47	8.36, -0.24	----	----
	11	-1.12, -0.20	-1.30, -0.24	-0.87, 0.06	----
	12	-0.92, -2.91	----	-0.64, -0.70	-1.54, -2.46
	13	----	0.12, -0.54	-0.17, -1.32	----
	14	----	-0.32, 2.59	----	0.05, -0.66
	15	----	----	----	0.16, 2.80
	16	-4.06, -1.20	-2.72, -1.56	----	----
	17	----	-1.19, 0.88	----	----

Table 1. (FWPCA) Current Components (East Component Followed by North Component; Both in cm/s^{-1}) (continued)

Date	Station	Depth 60 m	90 m	120 m	150 m
June 1967	1	----	----	----	----
	2	----	----	----	----
	3	-0.25, -0.12	----	----	----
	4	----	----	----	----
	5	-0.20, 0.28	----	----	----
	6	----	----	----	----
	7	----	-0.22, -0.24	----	0.96, 0.24
	8	----	----	----	----
	9	4.56, 0.92	6.95, 2.08	7.16, 1.46	-0.38, 3.21
	11	----	----	----	----
	12	-0.76, -1.07	-0.89, 0.16	----	----
	13	----	----	----	----
	14	----	----	----	----
	15	----	----	----	----
	16	----	----	----	----
	17	----	----	----	----
July 1967	1	----	----	----	----
	2	----	----	----	----
	3	-0.79, -2.65	----	----	----
	4	----	----	----	----
	5	0.02, 0.00	----	----	----
	6	----	----	----	----
	7	----	0.92, 0.16	0.74, 0.07	----
	8	----	----	----	----
	9	4.50, 0.39	6.28, 1.74	3.93, 2.36	4.80, 1.25
	11	----	-0.37, -0.08	----	----
	12	-0.54, -0.76	----	----	----
	13	----	----	----	----
	14	-0.30, 1.62	----	----	----
	15	5.00, 1.74	----	----	----
	16	----	----	----	----
	17	----	----	----	----
August 1967	1	----	----	----	----
	2	----	----	----	----
	3	-1.61, -0.92	----	----	----
	4	----	----	----	----
	5	0.38, -0.54	----	----	----
	6	----	----	----	----
	7	----	0.23, 0.09	----	0.02, 0.19
	8	----	----	----	----
	9	3.10, 1.08	4.08, 2.26	2.65, 0.80	-1.08, 0.90
	11	----	-0.41, -0.07	----	----
	12	----	----	----	----
	13	----	----	----	----
	14	-0.16, 1.54	----	----	----
	15	3.98, 7.34	----	----	----
	16	----	----	----	----
	17	----	----	----	----

Table 1. (FWPCA) Current Components (East Component Followed by North Component; Both in cm/s^{-1}) (continued)

		Depth			
Date	Station	10 m	15 m	22 m	30 m
September 1967	1	----	----	----	----
	2	3.61, 2.07	----	----	1.32, 0.66
	3	1.36, 0.76	----	----	----
	4	----	----	----	----
	5	----	----	1.16, -2.96	0.02, 1.28
	6	----	0.14, 0.77	----	-0.34, -0.30
	7	0.24, -1.62	----	----	----
	8	----	----	----	----
	9	-1.50, 2.90	----	----	----
	11	-1.94, -0.01	-0.68, 0.11	----	----
	12	-1.04, -3.78	----	-1.70, -3.73	-1.24, -1.76
	13	----	-0.59, -1.60	----	----
	14	----	-0.67, 1.14	----	-0.30, -0.09
	15	----	----	----	4.47, 8.20
	16	-1.72, 2.72	-1.14, 1.20	----	----
	17	----	-0.36, 0.42	----	----
October 1967	1	----	----	----	----
	2	7.12, 4.02	----	----	7.17, 1.98
	3	2.42, 0.68	----	----	----
	4	----	----	----	----
	5	----	----	2.28, 3.14	0.08, -3.84
	6	----	-0.90, -0.96	----	-0.82, -1.94
	7	0.11, 0.22	----	----	----
	8	----	----	----	----
	9	-1.54, 4.18	----	----	----
	11	----	----	----	----
	12	----	----	----	----
	13	----	----	----	----
	14	----	----	----	----
	15	----	----	----	----
	16	----	----	----	----
	17	----	----	----	----

Table 1. (FWPCA) Current Components (East Component Followed by North Component; Both in cm/s^{-1}) (continued)

		Depth			
Date	Station	60 m	90 m	120 m	150 m
September 1967	1	----	----	----	----
	2	----	----	----	----
	3	0.67, -0.15	----	----	----
	4	----	----	----	----
	5	0.52, -0.74	----	----	----
	6	----	----	----	----
	7	----	0.84, -0.11	----	-0.29, -0.04
	8	----	----	----	----
	9	4.18, 0.92	4.33, 1.76	4.28, 0.60	-1.16, 0.48
	11	----	-0.70, -0.02	----	----
	12	-0.72, -1.56	----	----	----
	13	----	----	----	----
	14	-0.03, 1.10	----	----	----
	15	1.50, 1.29	----	----	----
	16	----	----	----	----
	17	----	----	----	----
October 1967	1	----	----	----	----
	2	----	----	----	----
	3	1.12, 0.51	----	----	----
	4	----	----	----	----
	5	4.36, -0.79	----	----	----
	6	----	----	----	----
	7	----	0.94, 0.60	----	0.76, 0.28
	8	----	----	----	----
	9	----	----	----	----
	11	----	----	----	----
	12	-0.54, -0.69	----	----	----
	13	----	----	----	----
	14	----	----	----	----
	15	7.20, 10.14	----	----	----
	16	----	----	----	----
	17	----	----	----	----

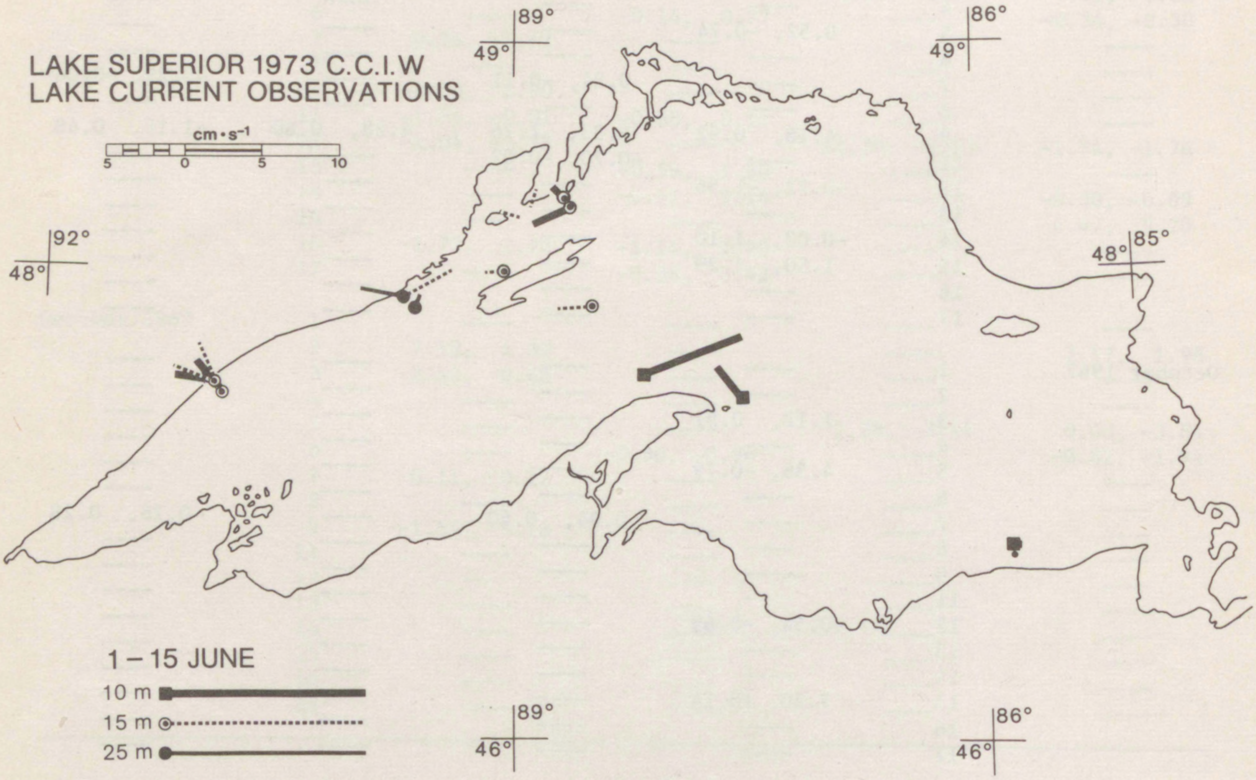

Figure 14. (CCIW) half-month average current vectors at 10, 15, and 22 m, 1-15 June 1973.

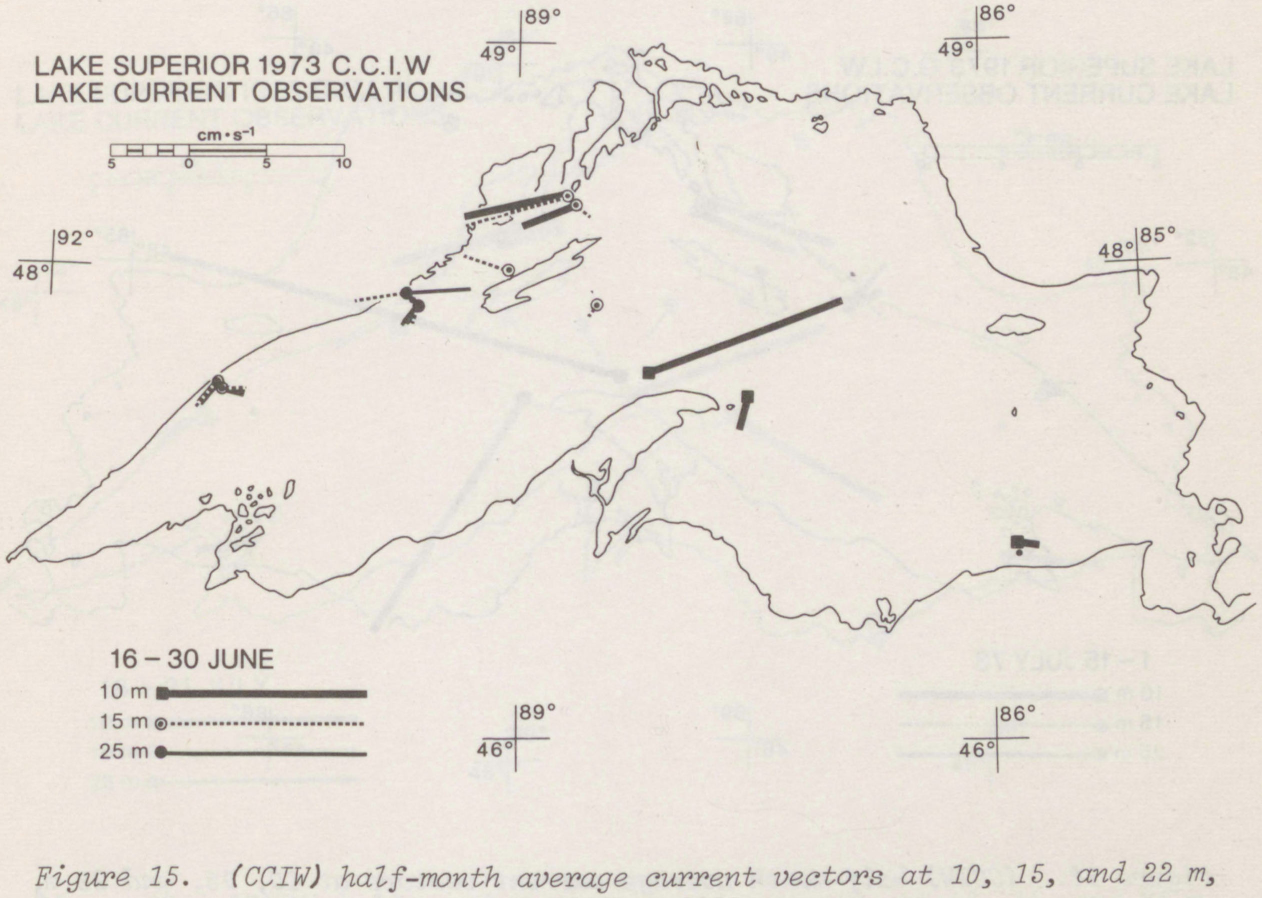

Figure 15. (CCIW) half-month average current vectors at 10, 15, and 22 m, 16-30 June 1973.

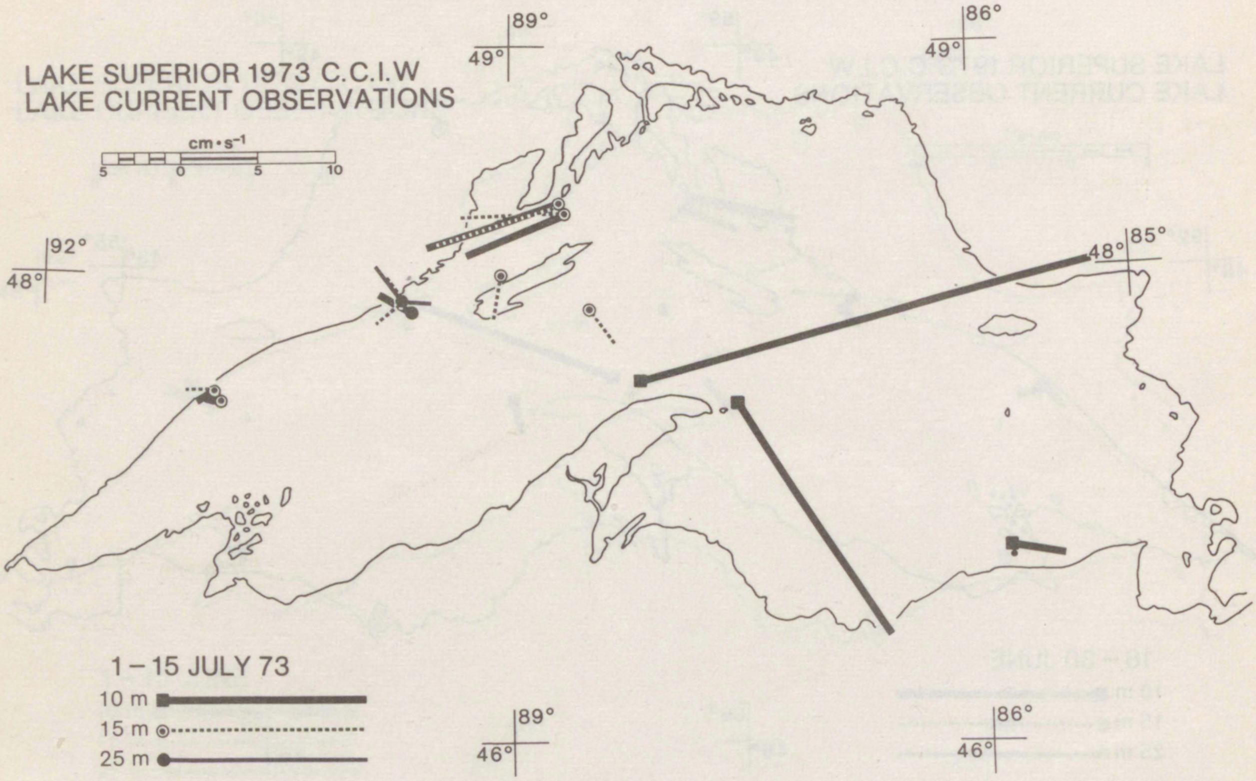

Figure 16. (CCIW) half-month average current vectors at 10, 15, and 22 m, 1-15 July 1973.

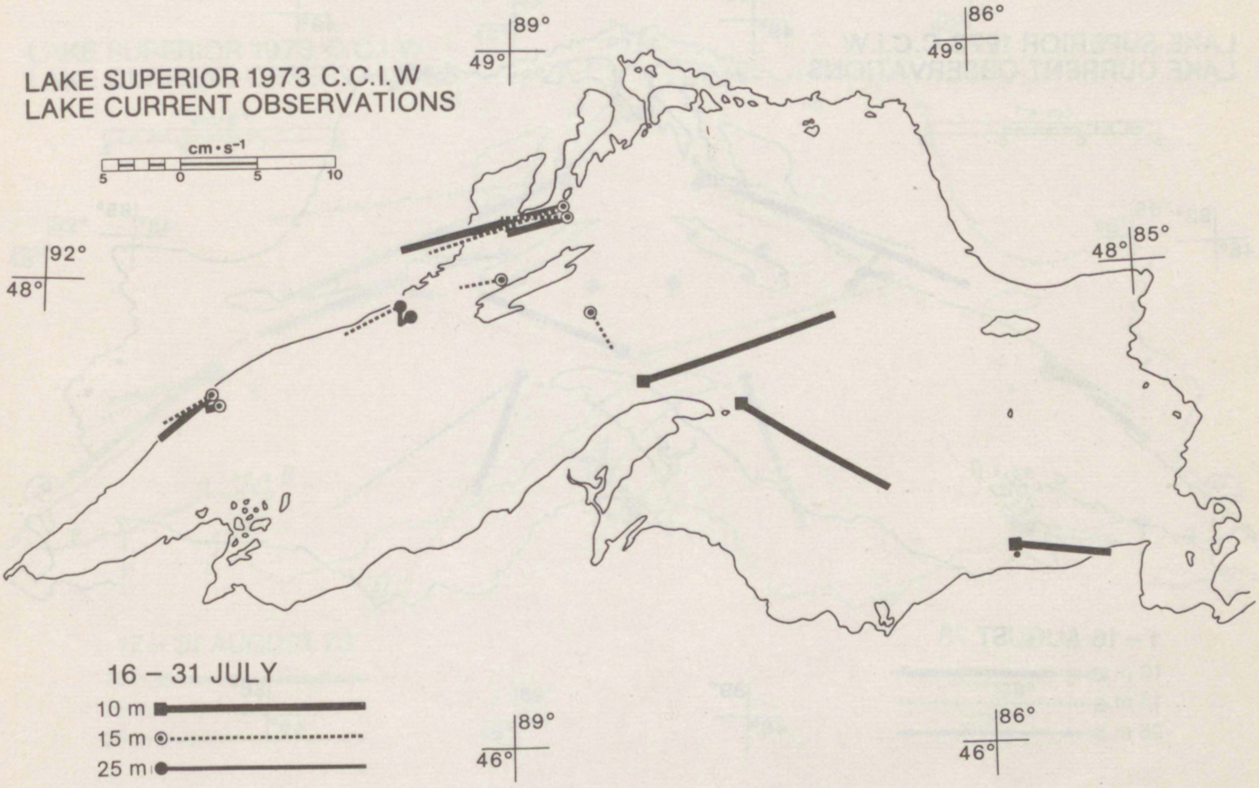

Figure 17. (CCIW) half-month average current vectors at 10, 15, and 22 m, 16-31 July 1973.

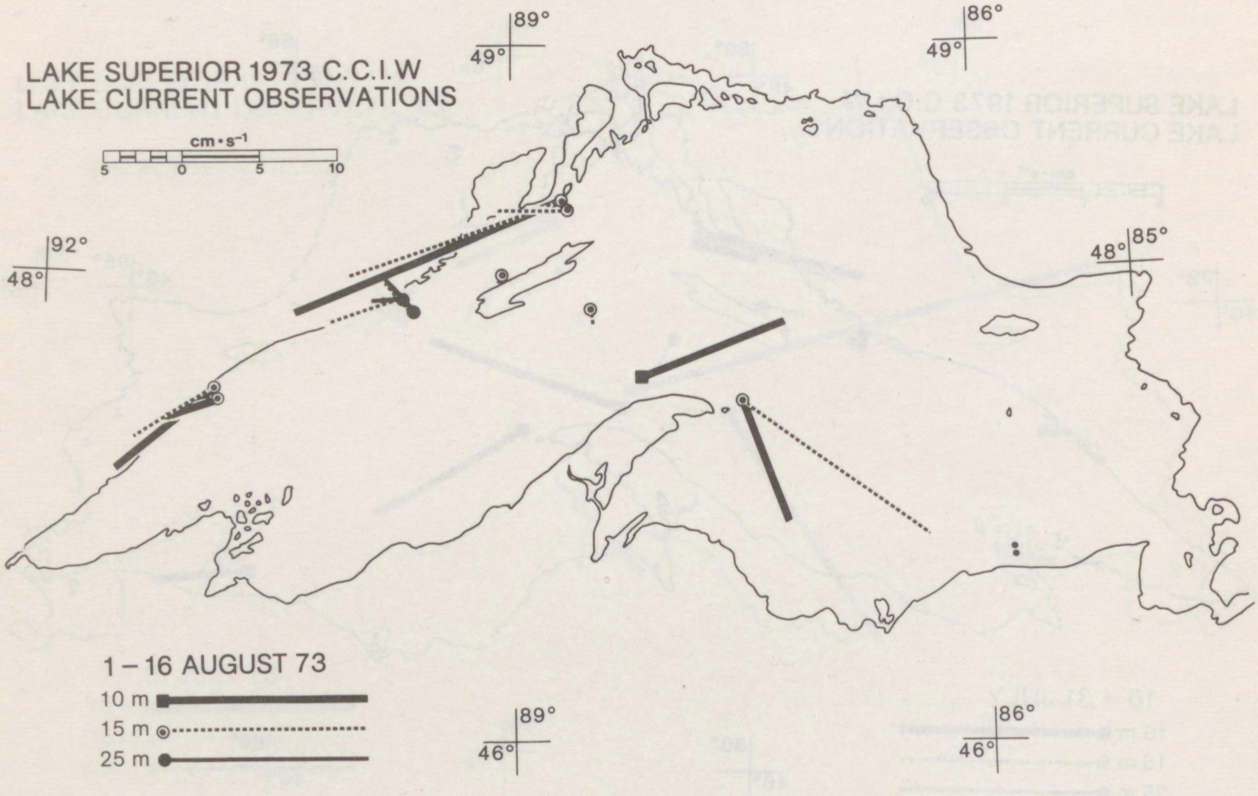

Figure 18. (CCIW) half-month average current vectors at 10, 15, and 22 m, 1-16 August 1973.

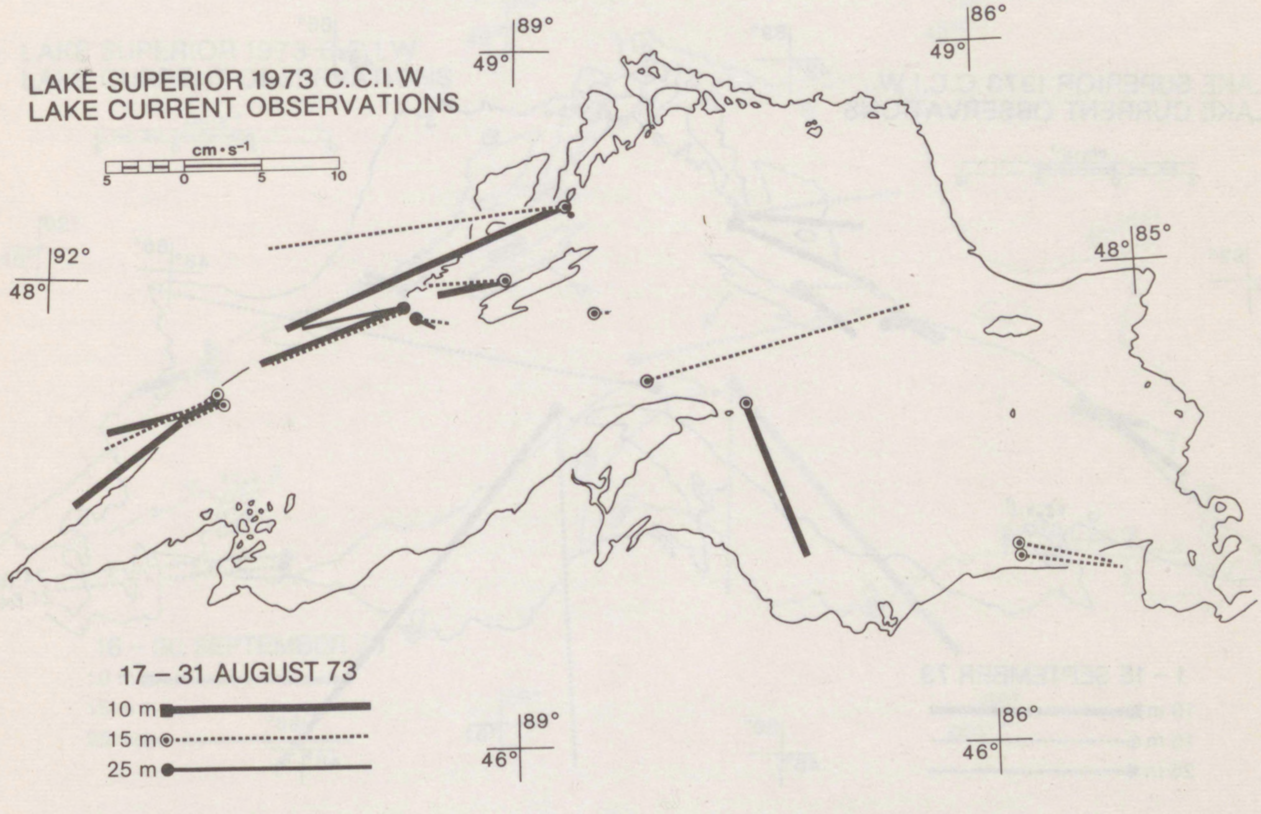

Figure 19. (CCIW) half-month average current vectors at 10, 15, and 22 m, 17-31 August 1973.

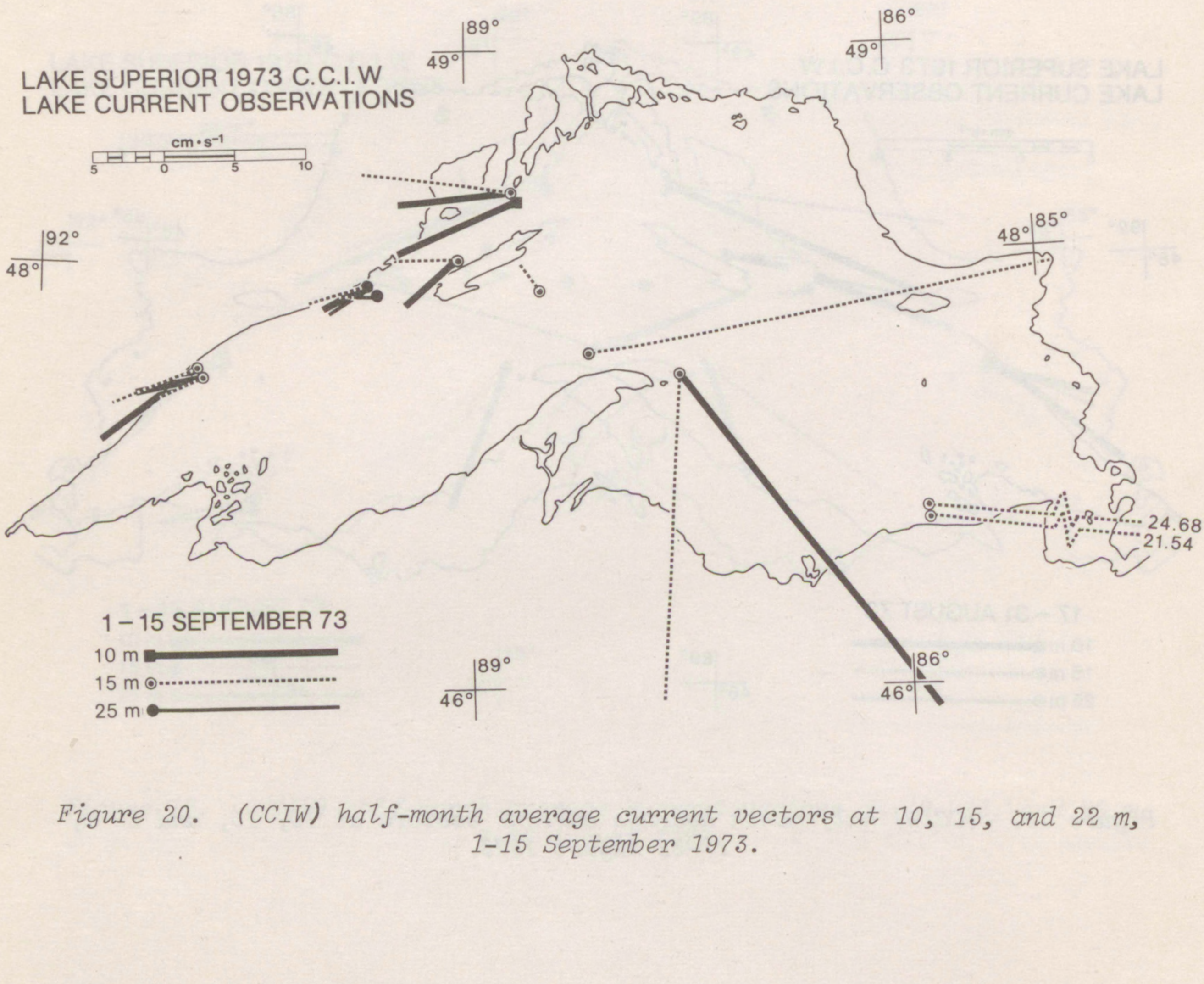

Figure 20. (CCIW) half-month average current vectors at 10, 15, and 22 m, 1-15 September 1973.

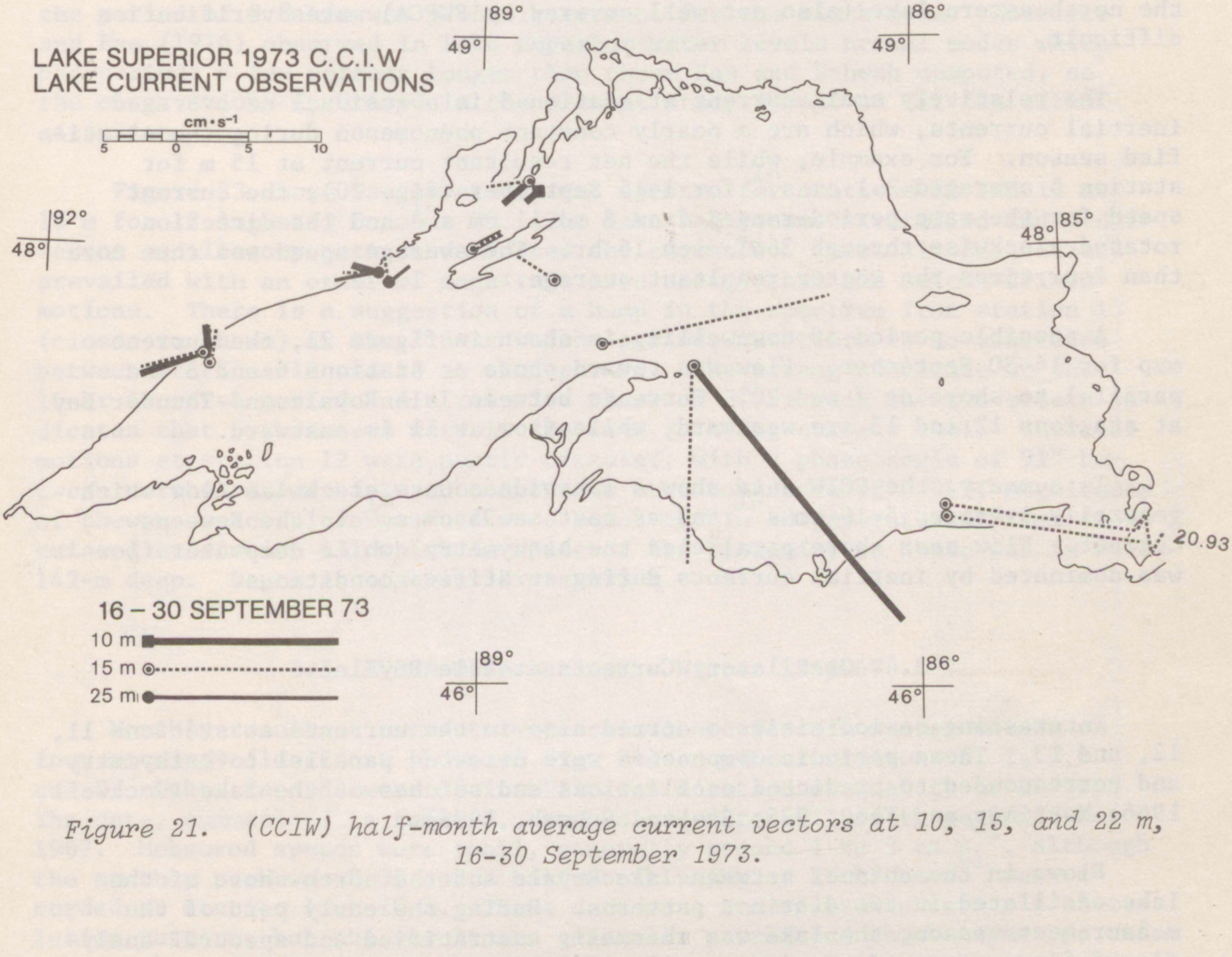

Figure 21. (CCIW) half-month average current vectors at 10, 15, and 22 m, 16-30 September 1973.

Flows along the northwest shore follow the bathymetry and are stronger than those measured by the FWPCA. Early in the season (through mid-July) the flows at CCIW station 10 were in near opposition between 15 and 25 m, indicating probable downwelling. This is particularly clear in July (fig. 16-17) when flow at station 8 was onshore while flow at station 10 divided to flow parallel to shore, westward at 15 m, but eastward at 25 m. Note also the strength measured for the Keweenaw Current.

The entire CCIW data set supports the existence of the counterclockwise circulation of the whole lake, but wide spacing and absence of data from the northeastern lake (also not well covered by FWPCA) makes verification difficult.

The relatively small current at station 5 is a residual of averaged inertial currents, which are a nearly constant phenomenon during the stratified season. For example, while the net resultant current at 15 m for station 5 averaged 2.1 cm s^{-1} for 1-15 September (fig. 20), the current speed for the same period ranged from 8 to 11 cm s^{-1} and the direction rotated clockwise through 360° each 16 hr. The average speed was thus more than four times the vector resultant average.

A possible period of downwelling is shown in figure 21, the current map for 16-30 September. Flow was toward shore at stations 6 and 8 and parallel to shore at 7 and 10. Currents between Isle Royale and Thunder Bay at stations 12 and 13 are westward, while flow at 11 is eastward.

In summary, the CCIW data show a lakewide counterclockwise flow which generally averages 5-10 cm s^{-1} and as fast as 35 cm s^{-1} in the Keweenaw Current. Flow near shore paralleled the bathymetry, while deepwater flow was dominated by inertial currents during stratified conditions.

3.4 Oscillatory Currents at Isle Royale

Interesting periodicities occurred also in the currents at stations 11, 12, and 13. These periodic components were directed parallel to bathymetry and corresponded to predicted oscillations and seiches of the lake (Rockwell, 1966; Mortimer and Fee, 1976; Rao and Schwab, 1976).

Flows in the channel between Isle Royale and the north shore of the lake oscillated in two distinct patterns. During the early part of the measurement season, the lake was thermally unstratified and spectral analysis of flows measured at stations 12 and 13 showed strong coherence between 10- and 15-m levels at periods corresponding to the uninodal longitudinal seiche, the lunar semidiurnal tide, and all periods greater than about 20 hr. The effects of surface oscillations are not generally detectable in currents, except where amplified by some sort of constriction through which an oscillatory flow is driven. The periodic current driven by the uninodal seiche is also strongly coherent between measured east-west flows at 10 m at stations 12 and 13.

Figure 22 shows the spectra of east-west oscillations for 22 May-11 August 1973 for stations 12 and 13 at 10 m. The coherence spectrum comparing the two stations clearly shows significant correlations between the measured oscillations only at line 21 (about 12.5 hr, the lunar tidal period), line 33 (about 7.9 hr, the uninodal seiche), and line 92 (about 2.8 hr). Rao and Schwab (1976) computed a period of about 2.6 hrs for a sixth mode of Lake Superior; this mode has a significant amplitude only behind Isle Royale, and no other mode except the first strongly affects that region. Rao and Schwab (personal communication) stated that their computations provided better spatial than temporal resolution and that the period of 2.8 hrs was probably correct for the sixth mode. Mortimer and Fee (1976) observed in Lake Superior water levels normal modes which had periods a few percent longer than those Rao and Schwab computed, so the observations described in the present study appear to fit the actual situation.

Figure 23 shows east-west current spectra for stations 12 and 13 at 10 m for 12 August-3 October 73. The lake had become stratified and a different oscillatory pattern dominated the currents. Inertial oscillations prevailed with an order of magnitude more energy than the seiche-driven motions. There is a suggestion of a hump in the spectrum from station 13 (closer to shore) at the 7.8-hr seiche period, but there is no coherence between stations 12 and 13 at that period. The strong coherence at the 16-hr inertial period and a relative phase of 3° between the two meters indicates that both meters were in the same rotating current cell. Inertial motions at station 12 were nearly circular; with a phase angle of 91° between northward and eastward components at a coherence of 0.949, magnitudes of the two spectral components were equal within 10 percent. Similar flows existed at station 13, which in spite of its proximity to shore was in water 142-m deep. Depth at station 12 was 195 m.

3.5 FWPCA Observations - Winter 1966-67

Monthly resultant currents were calculated for six winter meters on four moorings (locations shown on fig. 24) at winter stations 1, 2, 7, and 8. Other records were of insufficient duration or quality to be used. The data, summarized in table 2, spanned mid-October 1966 through mid-May 1967. Measured speeds were small, generally around 1 to 3 cm s^{-1}, although the monthly peak was 8.32 and a half-month value of 11.17 cm s^{-1} was recorded at station 1 at 10 m. These data were too sparse to define a circulation pattern, but the resultants generally paralleled the bathymetry, and station 1 tended to indicate a prevailing counterclockwise pattern of general circulation. The locations of moorings 7 and 8 in particular were placed out of the expected general circulation pattern and seemed to respond to eddies shed by the main flow.

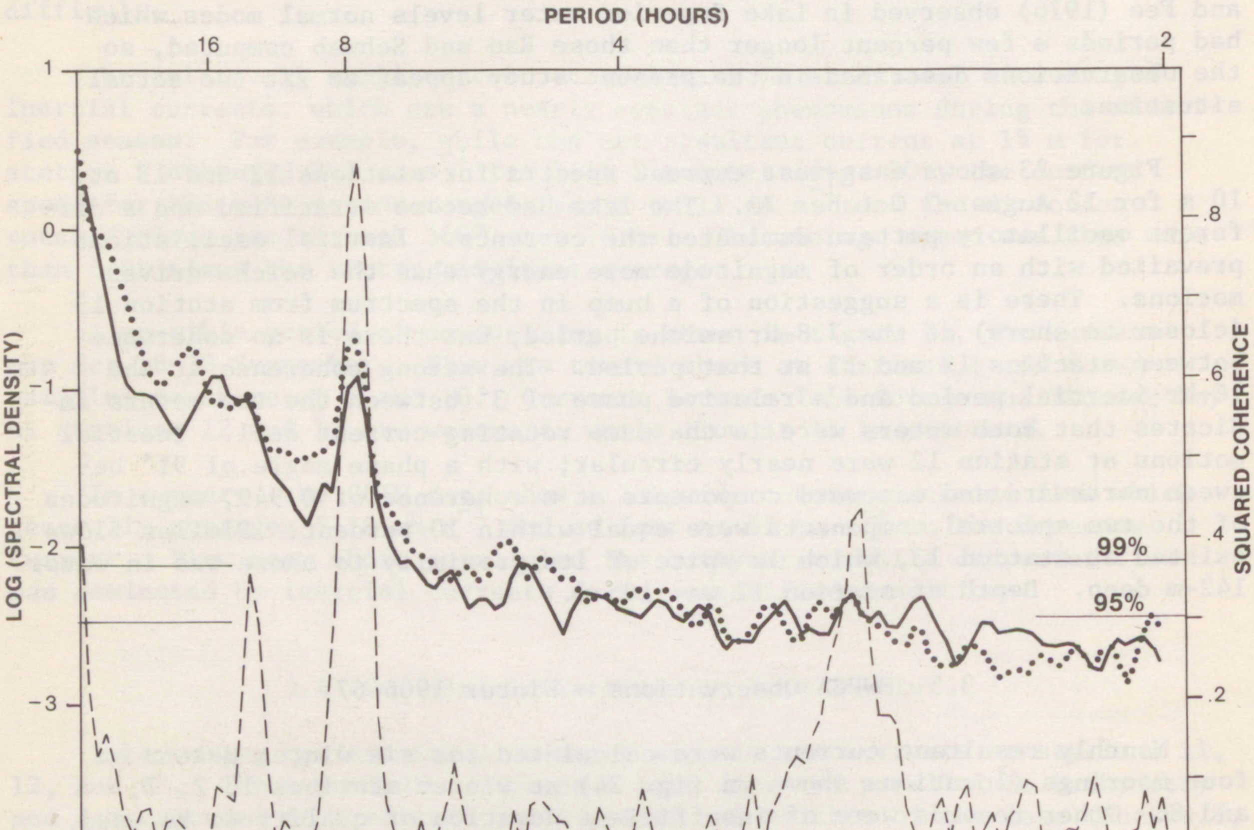

Figure 22. Spectra of the east-west current components at CCIW moorings 12 (solid line) and 13 (dotted line), depth 10 m, 22 May-11 August 1973. Broken light line is squared coherence between the two stations. Peak in coherence at 8-hr period is due to first longitudinal seiche of the lake; the peak at 2.8 hr (line 92) may be due to sixth free mode.

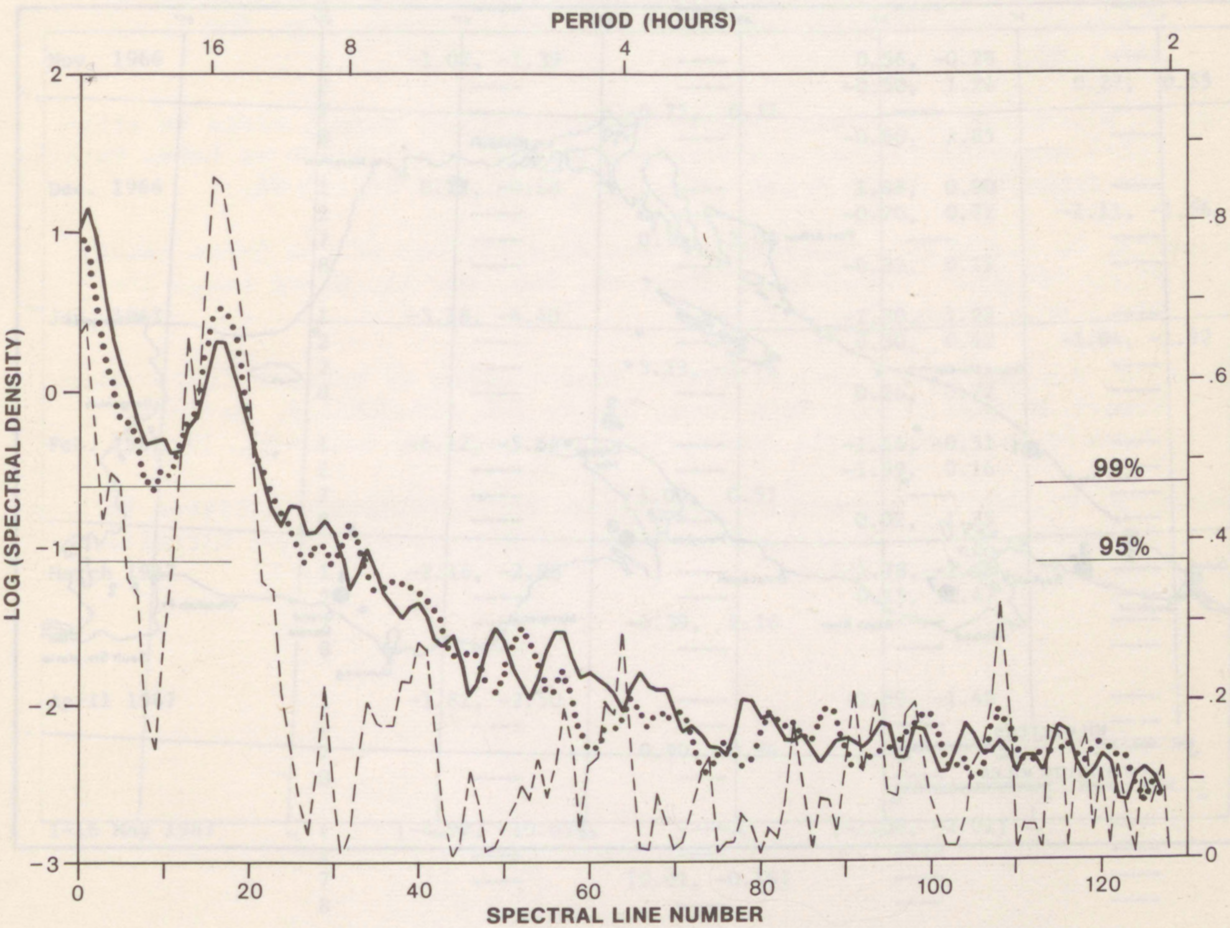

Figure 23. Same notation as figure 22, stations 12 and 13 at 10 m, east-west components, 12 August-3 October 1973. Coherence peak at 16 hr is due to inertial oscillation.

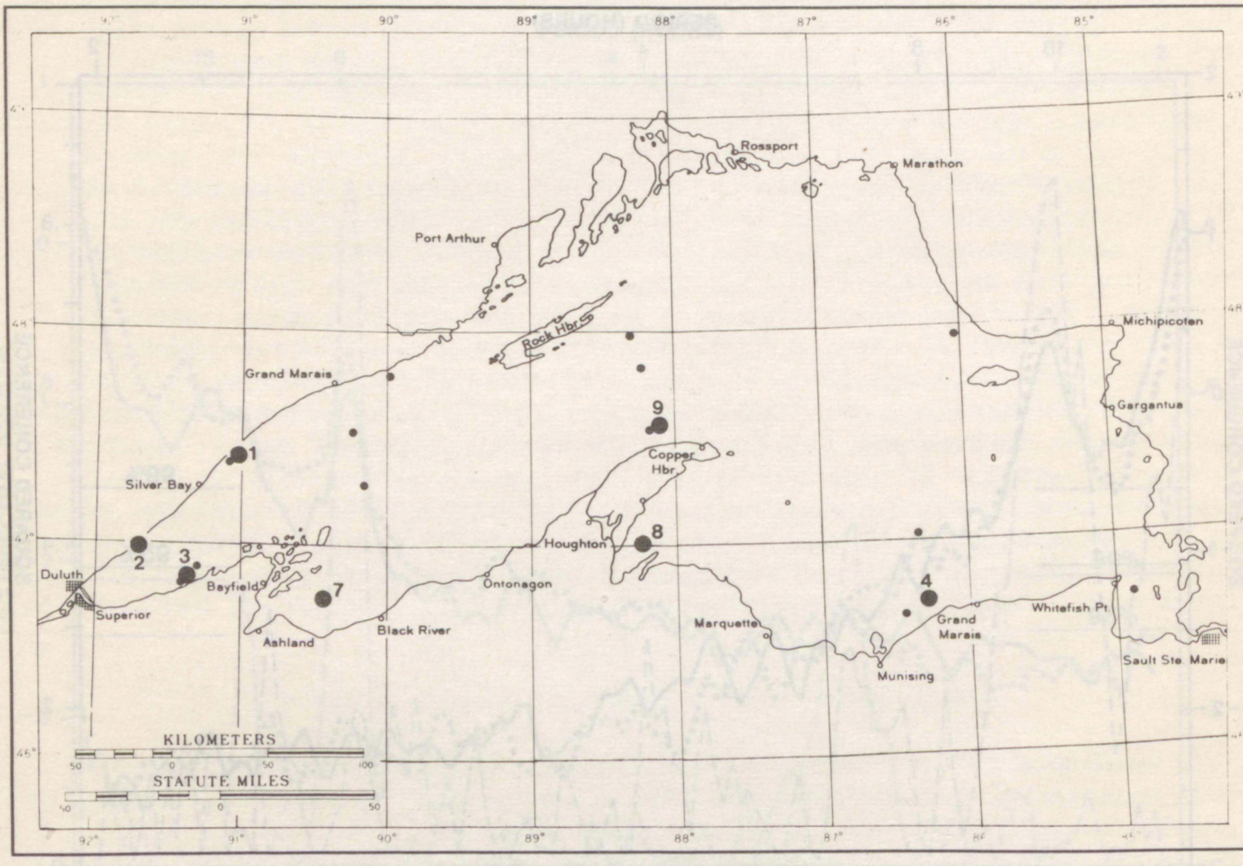

Figure 24. FWPCA winter 1966-67 mooring sites.

Table 2. (FWPCA) Current Components at Four Selected Stations (East Component Followed by North Component; Both in cm/s^{-1}; Half-Month Data in Brackets)

		Depth			
Date	Station	15 m	22 m	30 m	60 m
17-31 Oct. 1966	1	[-5.54, -6.37]	----	[-0.46, 4.96]	----
	2	----	----	[0.95, 2.55]	[-0.23, 2.32]
	7	----	----	----	----
	8	----	----	----	----
Nov. 1966	1	-1.02, -1.39	----	0.56, -0.28	----
	2	----	----	-0.50, 1.26	0.27, 0.55
	7	----	-0.72, 0.32	----	----
	8	----	----	-0.60, 2.85	----
Dec. 1966	1	0.22, -0.68	----	1.48, 0.90	----
	2	----	----	-0.70, 0.72	-1.11, -1.56
	7	----	0.91, -2.08	----	----
	8	----	----	-0.32, 0.19	----
Jan. 1967	1	-3.18, -4.40	----	-2.30, 1.28	----
	2	----	----	0.30, 0.42	-1.04, -1.92
	7	----	3.23, -1.76	----	----
	8	----	----	0.26, 0.72	----
Feb. 1967	1	-6.12, -5.64	----	-1.44, -0.51	----
	2	----	----	-1.99, 0.16	----
	7	----	1.00, 0.57	----	----
	8	----	----	0.02, 1.35	----
March 1967	1	-2.16, -2.08	----	-1.78, -1.48	----
	2	----	----	0.15, 2.47	----
	7	----	-0.39, 2.16	----	----
	8	----	----	----	----
April 1967	1	-1.82, -2.50	----	-1.69, -1.40	----
	2	----	----	----	----
	7	----	0.90, -0.96	----	----
	8	----	----	----	----
1-16 May 1967	1	[-4.92, -10.03]	----	[-1.08, -2.01]	----
	2	----	----	----	----
	7	----	[0.01, -0.16]	----	----
	8		----	----	----

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AL *Aeronomy Laboratory.* Research areas include: theoretical, laboratory, rocket, and satellite studies of the physical and chemical processes controlling the ionosphere and exosphere of the Earth and other planets, and of the dynamics of their interactions with high-altitude meteorology.

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