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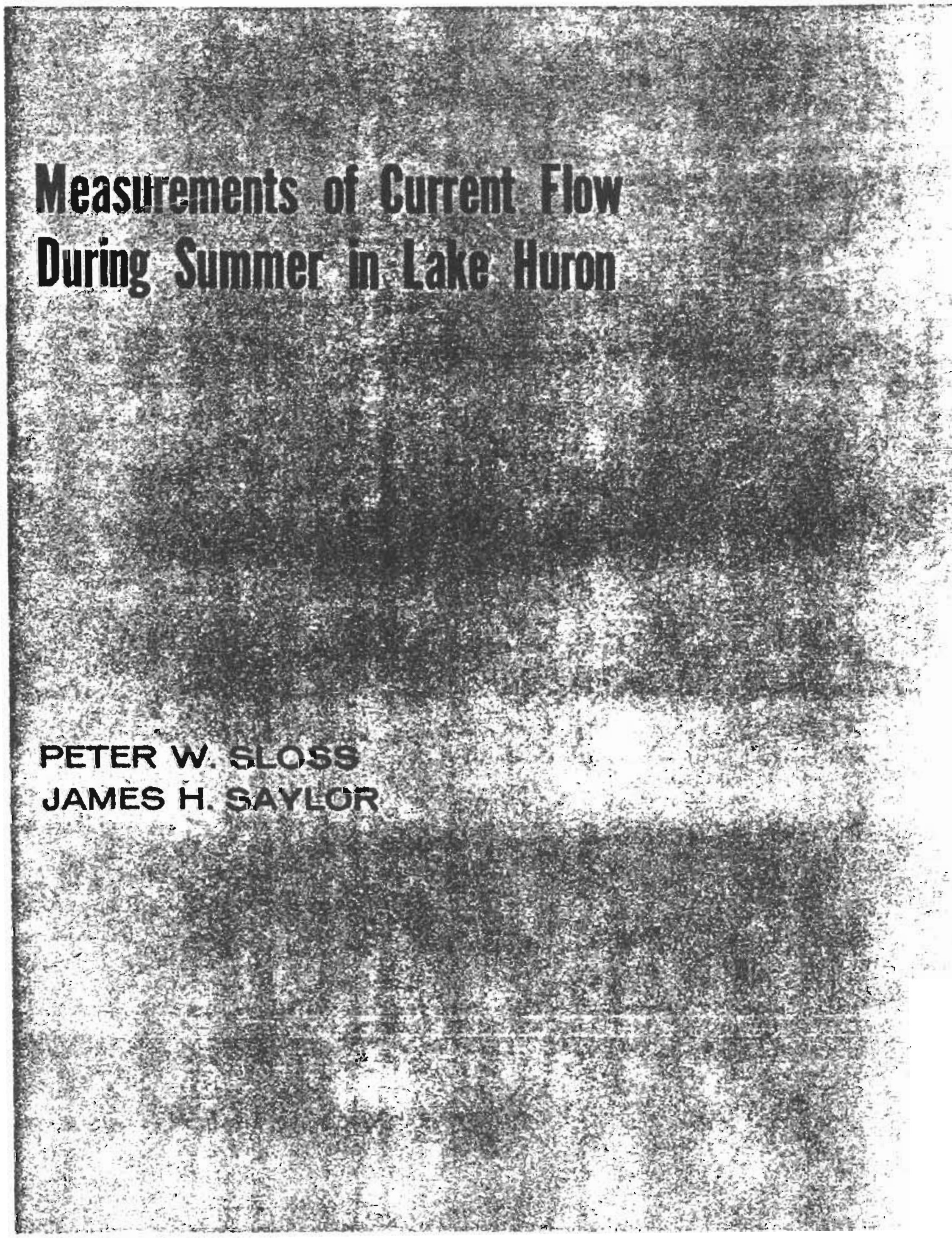

Measurements of Current Flow During Summer in Lake Huron

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Foreword

This report presents the results of an analysis of water current recordings collected in Lake Huron during 1966 by the Federal Water Pollution Control Administration. Most of the current data were collected during the interval of May through September 1966 and are therefore representative of the summer heating and density stratified season of Lake Huron. This is a contribution to the International Joint Commission Upper Lakes Reference Study and was supported through an Interagency Agreement by the Environmental Protection Agency, Region V.

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MEASUREMENTS OF CURRENT FLOW DURING SUMMER IN LAKE HURON

Peter W. Sloss and James H. Saylor

Reanalyses of the data from the 1966 Great Lakes-Illinois River Basin Project (GLIRBP) of the (then) Federal Water Pollution Control Administration (FWPCA) reveal some of the large-scale, persistent summertime circulation patterns in Lake Huron. The greatest density of data from the original 45 current meter moorings covers June through August 1966, when some 21 stations returned synoptically-significant data from meters at depths of 10 and 15 m. From this somewhat sparse sample, it is deduced that at 10-m depth a counter-clockwise circulation dominates the northern 2/3 of the lake. The shallower southern portion shows a more complex pattern, with generally southward flow along the shorelines on both sides and a return flow northward near the centerline of the southern basin. This latter pattern may decay later in the summer, but the data become too patchy for definite analysis. The data set from 15-m depth indicates similar circulations. Spectral analysis of currents at individual stations reveals a strong inertial rotation of the current vector at open-lake sites. Only the data from the Straits of Mackinac lack the inertial components and are dominated by the lunar semidiurnal tide and the seiches of Lake Michigan.

1. INTRODUCTION

Currents in Lake Huron were described in an early study by Harrington (1895) in which drift bottles were the measuring devices. More recently, Ayers et al. (1956) combined drift bottle paths with temperatures and the resulting dynamic height data to determine large-scale flow patterns at three times during the summer of 1954. Neither study used continuous current measurements to determine the degree of persistence or the variability of the reported currents.

In 1966, under the auspices of the Federal Water Pollution Control Administration (FWPCA) and its Great Lakes-Illinois River Basin project (GLIRBP), some 40 current-meter moorings were placed in Lake Huron for varying intervals of time from April through September. Seven moorings also were deployed through the previous winter at locations near the Michigan shore. Usable data were returned from stations 1, 4, and 9, but were too sparse for any interpretation of winter currents. Details of typical moorings and meters can be found in the report entitled "Lake Michigan Currents" (FWPCA, 1967). The Lake Huron station network is shown in fig. 1.

Of the summer moorings, a maximum of 25 produced simultaneous, usable data representing flow at the same depth (10 m) for the interval mid-June through July 1966. By the middle of August, the number of functioning instruments at

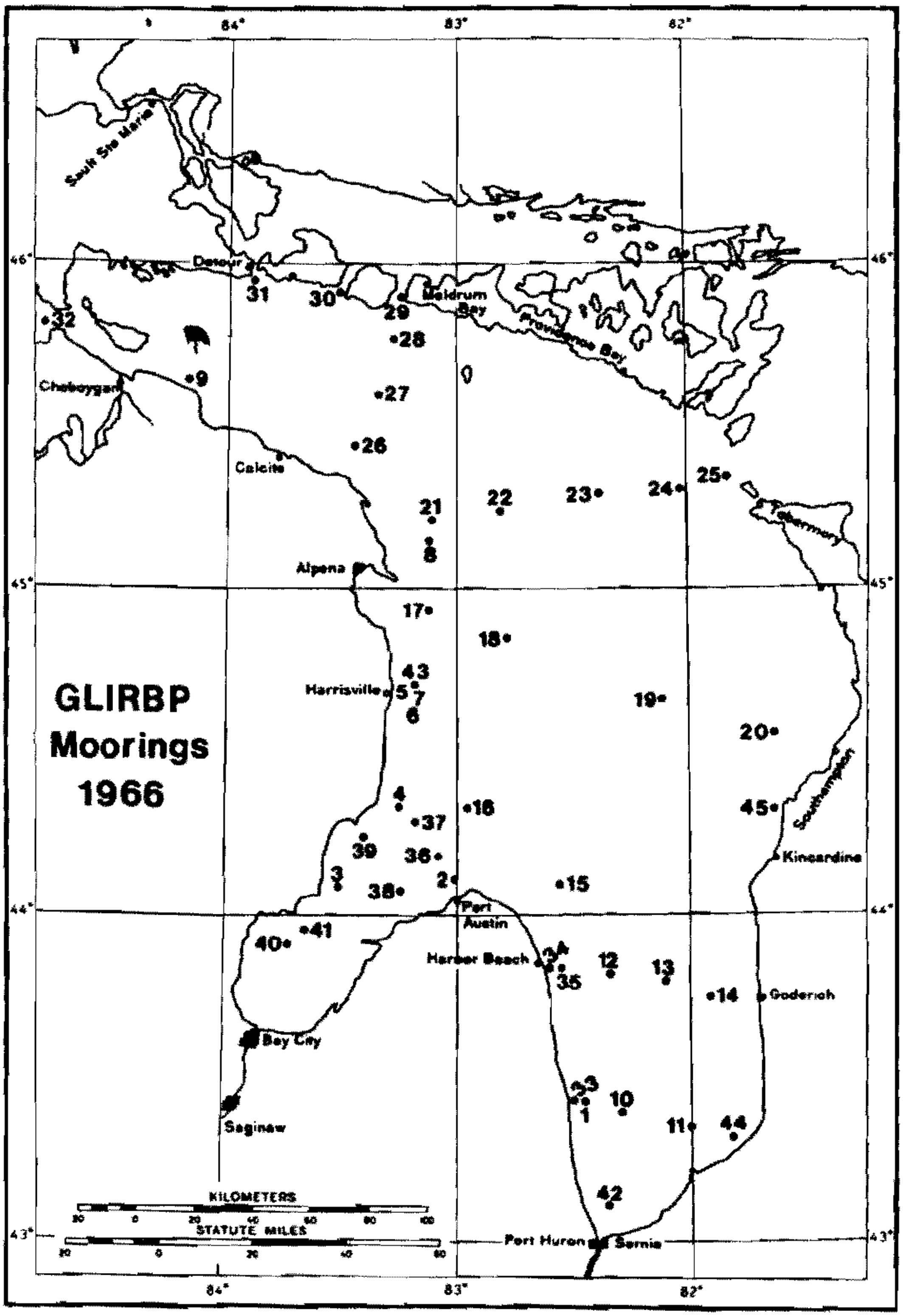

Figure 1. Location map for 1966 FWPCA current-meter moorings in Lake Huron. Stations 1 and 4-9 were deployed for winter 1965-66; the remainder were set late April through September 1966.

10-m depth was down to 13. At other depths, the maximum number of simultaneous usable records was 12 at 30-m depth during the second half of June. The entire available data set from all moorings consists of 187 data files on magnetic tape. There are, however, timing and data-quality problems evident on many of the files. The exact percentage of "good" data returned depends on the user's quality criteria and patience--some 30 of the original data films from the current meters were recently reprocessed by Geodyne, Inc., to correct serious timing discrepancies in cases where the number of observations was not in agreement with the indicated start and stop dates and the interval between observations. Absolute timing, for purposes of correlation between different meters, remains a serious problem with much of the data the authors have seen from Geodyne "Type G" meters.

The majority of the current data was recorded at 30-min intervals, although some records were timed at 20-, 10-, or 5-min spacing, and data from station 16 include several periods of about a week's duration each, during which data were taken at 1-min spacing. The purpose of these intensive observations is not known.

2. DATA ANALYSIS

The velocity time series generated by the current meters were analyzed in two ways: block averages over various time periods, and spectrum analysis. Spectrum analysis of lake current data (Verber, 1966; Malone, 1968) has shown a strong component of rotary motion at the local inertial frequency in open-lake areas during the season of stratification. The GLIRBP Lake Huron data show this behavior at stations as close as 5 km from the shore.

The presence of a strong inertial component in the current fluctuations suggests that short-term net flows can best be computed on the basis of vector-averaged currents from an integral number of inertial periods. Inertial periods in Lake Huron range from 17.6 hours at the south end of the lake (latitude 43°N) to 16.7 hours at the north end (latitude 46°N). For data taken every 30 min, this north-south variation represents a difference of two data points per inertial period; thus, the same averaging interval does not apply to every station.

For convenience, the averaging interval could be chosen to be one inertial period rounded back to the nearest data point. For data spaced at 30-min intervals, application of this averaging scheme results in a maximum deviation from a complete inertial cycle of about 10° of rotation. Closer data spacing reduces the deviation at some stations to less than 1 percent of a cycle. For example, spectra of currents at station 13 in the southern arm of Lake Huron indicate that in July more than 1/3 of the total kinetic energy in long-period motions was contained in a band of frequencies spanning 1/16 to 1/18 cycles per hour. More details of spectrum computations are presented later in this paper.

Longer-term averages of vector velocities are not as sensitive to inertial currents. The above example of station 13 had a mean flow at 10-m depth of about 1 cm s^{-1} over a 16-day period, while the standard deviations of the current components were on the order of 8 cm s^{-1}. At the latitude of station 13 the local inertial period is 17.3 hours, so the 16-day averaging period represents 22.15 inertial cycles. The weight of the "extra" 0.15 cycle, spread over the whole interval, does not affect the long-term mean current significantly as it represents less than 1 percent of the total time.

3. CIRCULATION PATTERNS

The greatest density of data was obtained from the 10-m level, with more than 20 stations operating from mid-June through July. The surface-layer circulation is assumed to follow a pattern similar to the 10-m currents in summer. The thermocline was below 10 m after early July. Fig. 2-10 depict the surface-layer circulation measured over 14-16-day intervals from 1 May through 14 September. Larger circles represent operating current meters; the average current vectors are represented by line segments originating at the mooring locations and extending in the direction of flow with a length proportional to the speed of flow. Map fig. (2, 3, 4, 5, 6, 7, 8, 9, and 10) marked a show 10- and 30-m currents; figures marked b show 15- and 22-m currents.

The first group of data for 10-m currents represents 1-14 May 1966, shown in fig. 2a. Data were returned only from meters in the southern end of the lake and show evidence of a possible counterclockwise circulation. Strong shears are evident between 10 and 30 m. Currents at intermediate levels (fig. 2b) show similar patterns. The lake was thermally homogeneous for the period of these maps.

A slightly larger data sample was returned for the second half of May (fig. 3a), but the measured flow looks extremely disorganized, in spite of several frontal passages early in the period. Data from the northern part of the lake show another possible small counterclockwise gyre west of stations 26-28, visible also in fig. 3b.

Fig. 4a-b show flows for 1-14 June. The flow northward from station 26 toward station 28 continued at all depths. There is evidence of the reestablishment of the gyre in the southern lake, but data are sparse. The lake was still homogeneous through this period.

Fig. 5a-b, representing the second half of June, show a somewhat disorganized pattern of flow. There is an apparent counterclockwise circulation occupying the middle 1/3 of the lake, flowing southward past Harrisville and returning northward on the Ontario side. Local weather patterns for this period were dominated by high-pressure or westerly to southwesterly winds. Net current speeds averaged around 2 to 3 cm s^{-1} over the lake, being stronger in coastal areas than in the open lake.

During the period 1-14 July there were some four frontal passages over Lake Huron. Meteorological conditions were determined from summary maps for each day (American Meteorological Society, 1966), and wind recorders at moorings 11, 16, 28, 29, and 32. Stronger and more frequent winds from the

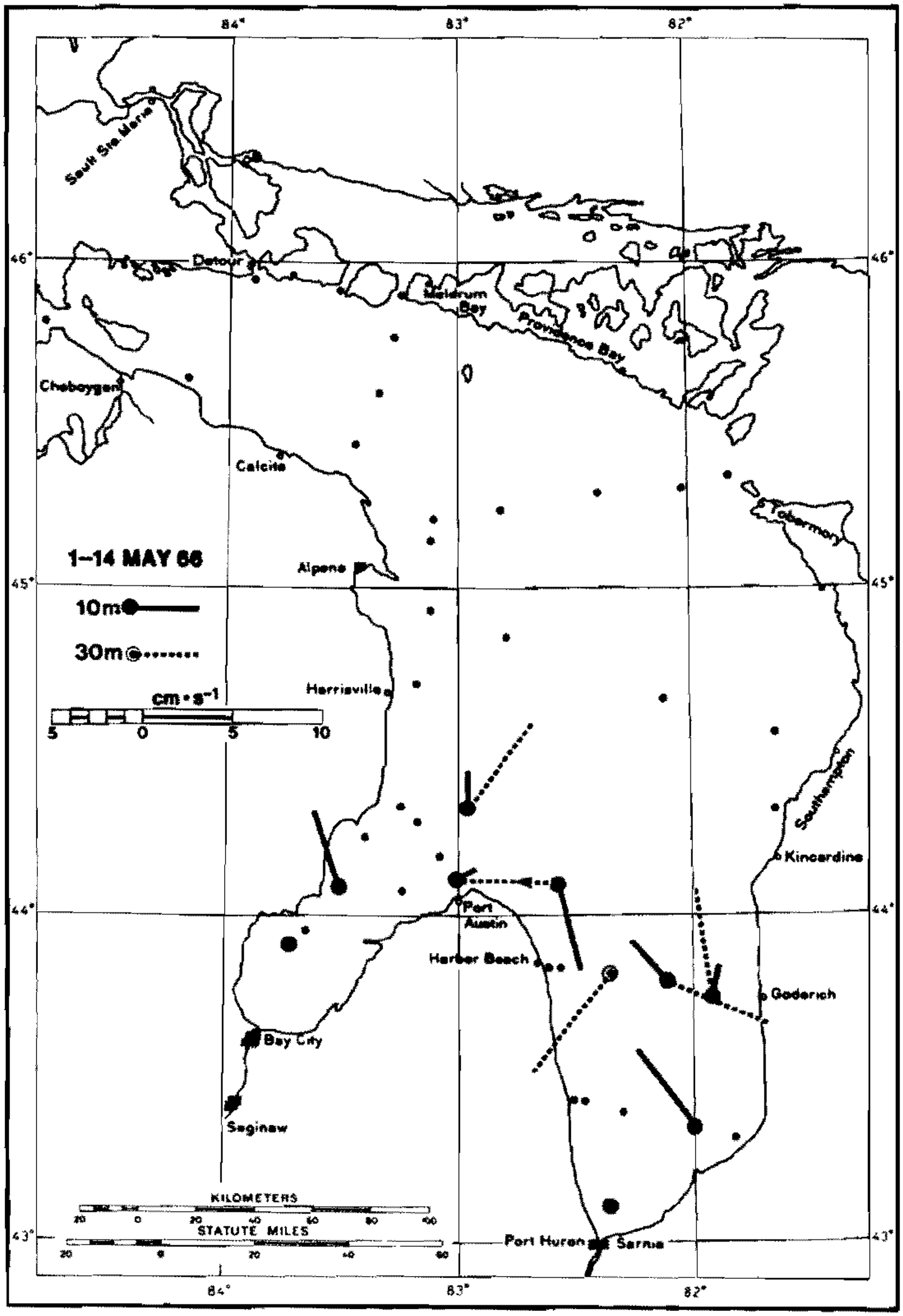

Figure 2a. Half-month average current vectors at 10 m and 30 m for 1-14 May 1966.

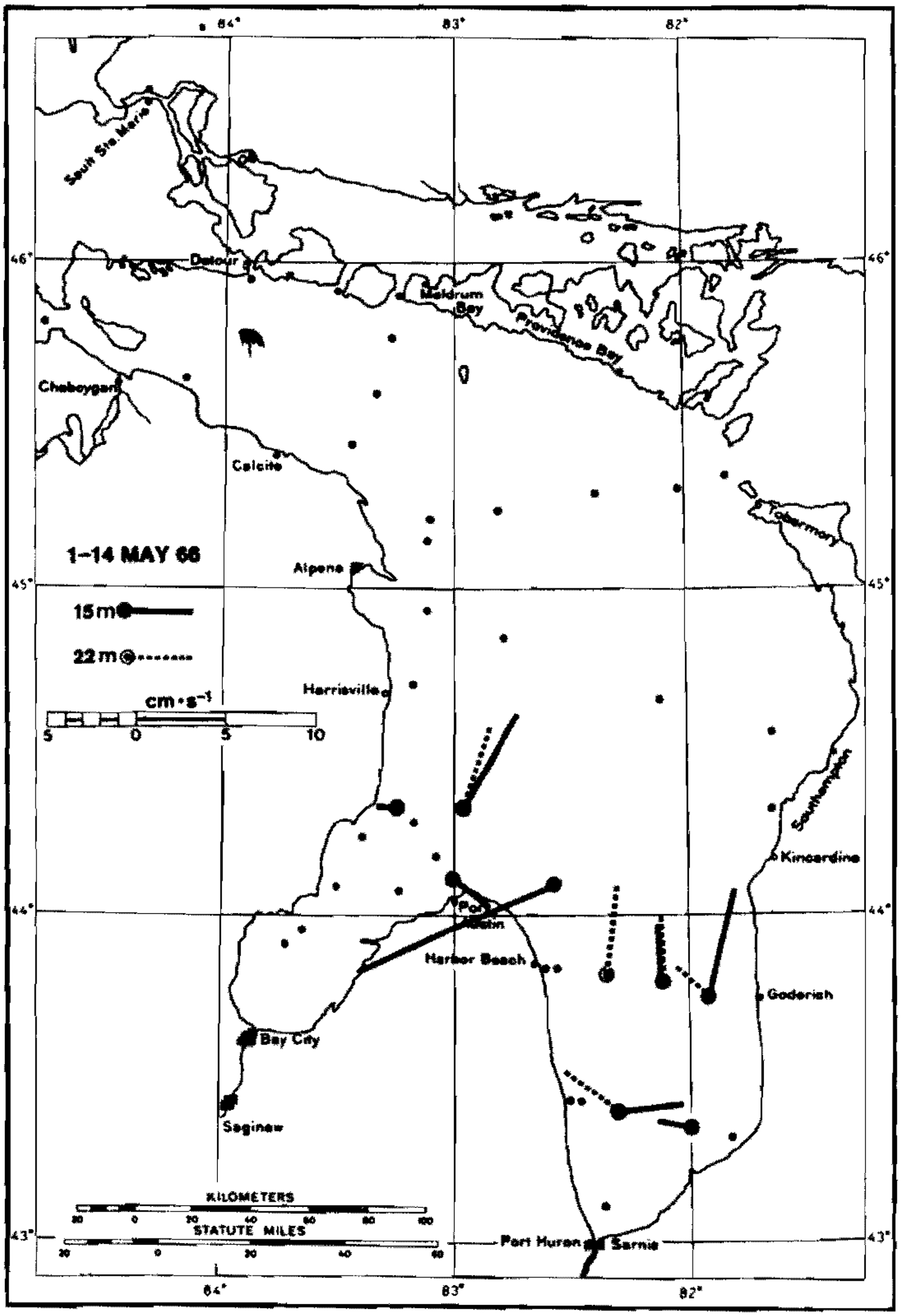

Figure 2b. Half-month average current vectors at 15 m and 22 m for 1-14 May 1966.

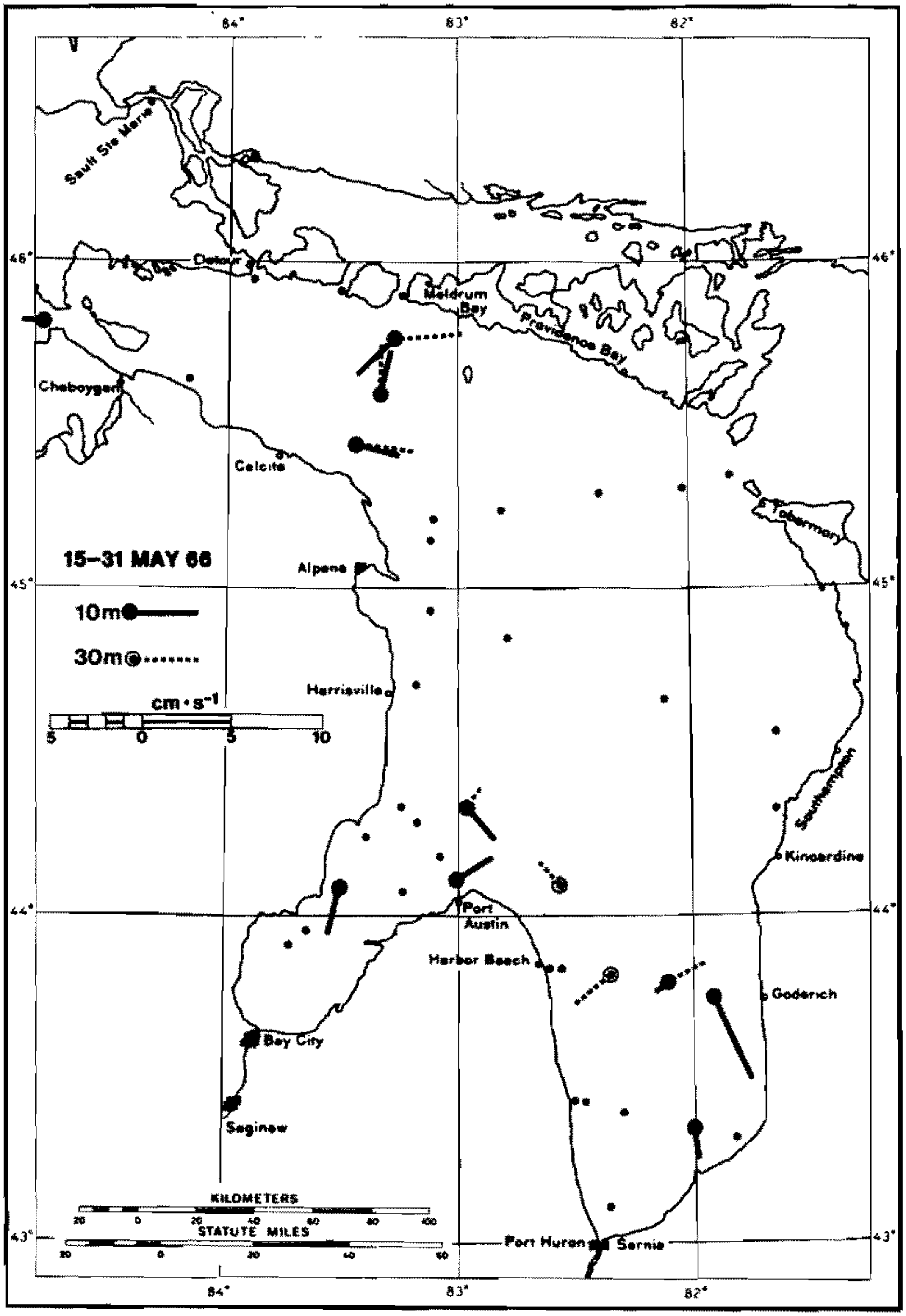

Figure 3a. Half-month average current vectors at 10 m and 30 m for 15–31 May 1966.

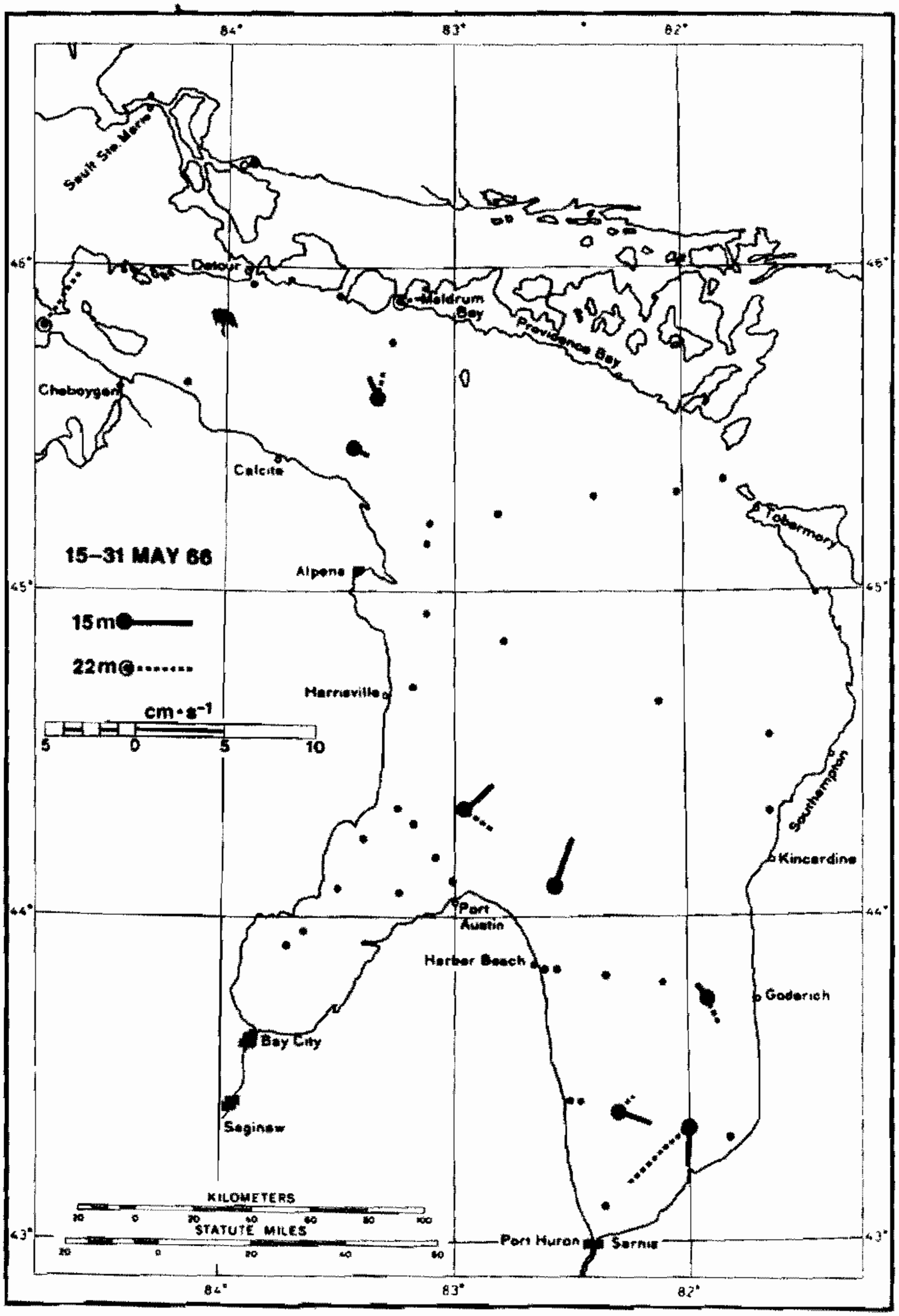

Figure 3b. Half-month average current vectors at 15 m and 22 m for 15-31 May 1966.

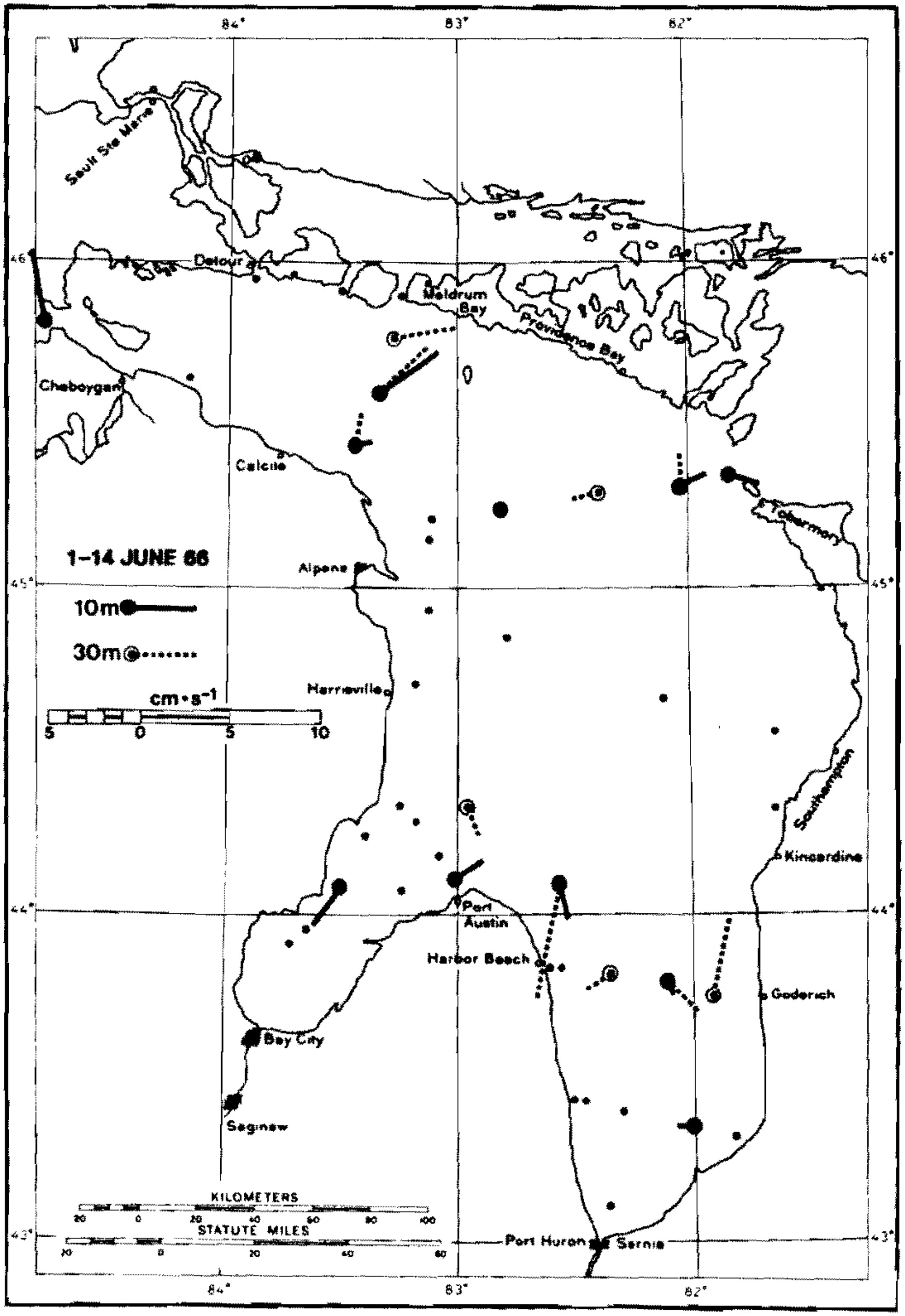

Figure 4a. Half-month average current vectors at 10 m and 30 m for 1-14 June 1966.

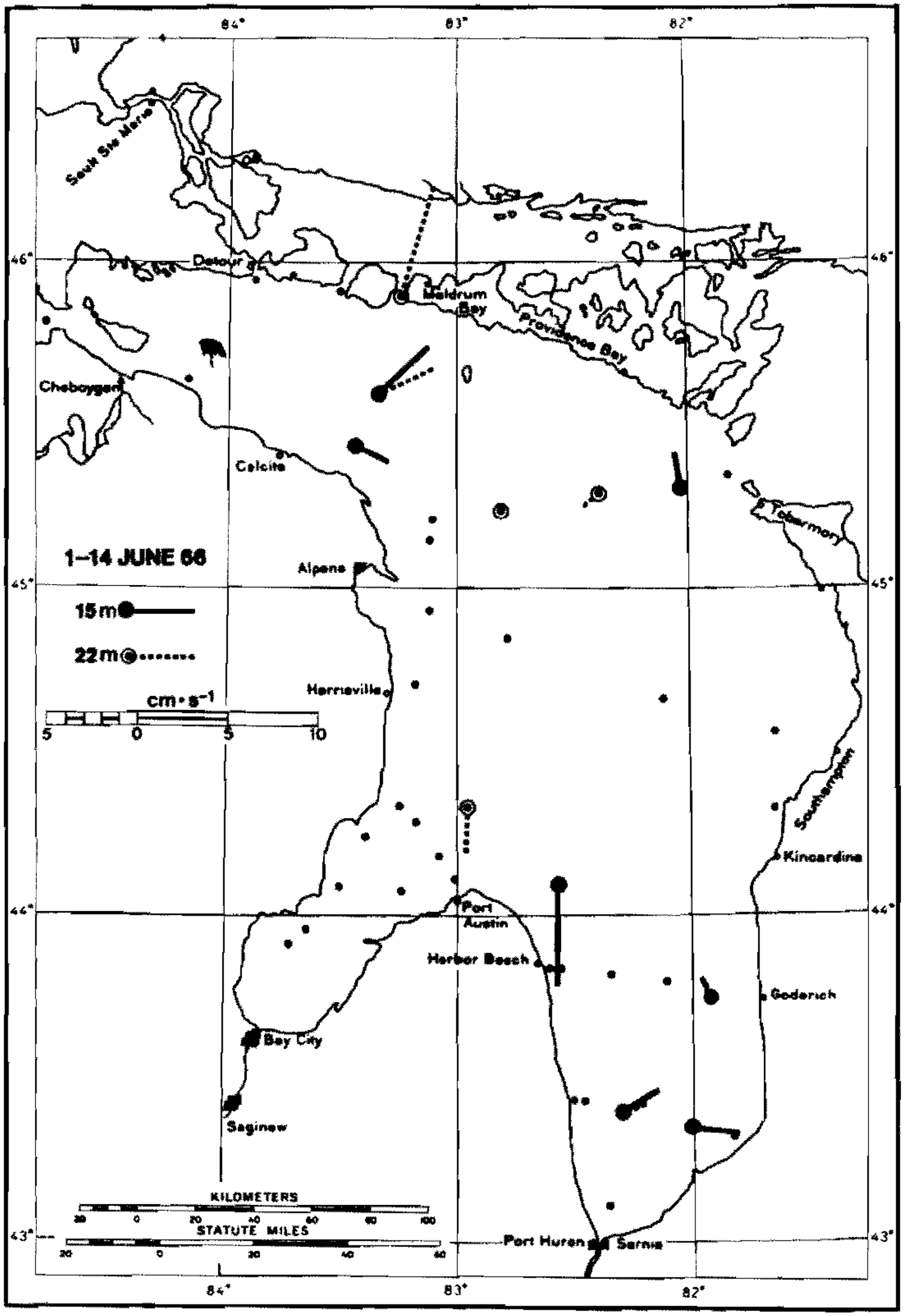

Figure 4b. Half-month average current vectors at 15 m and 22 m for 1-14 June 1966.

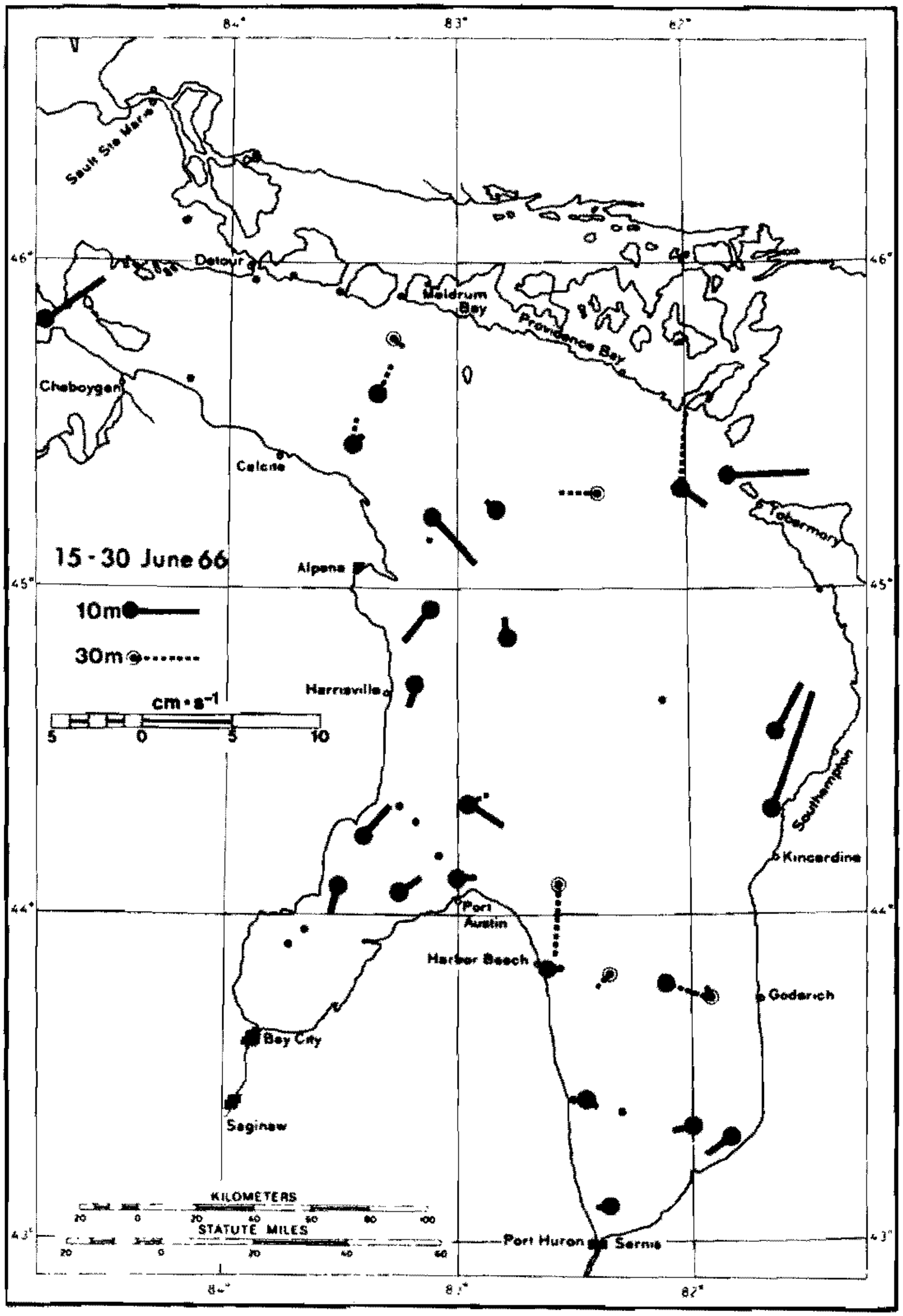

Figure 5a. Half-month average current vectors at 10 m and 30 m for 15-30 June 1966.

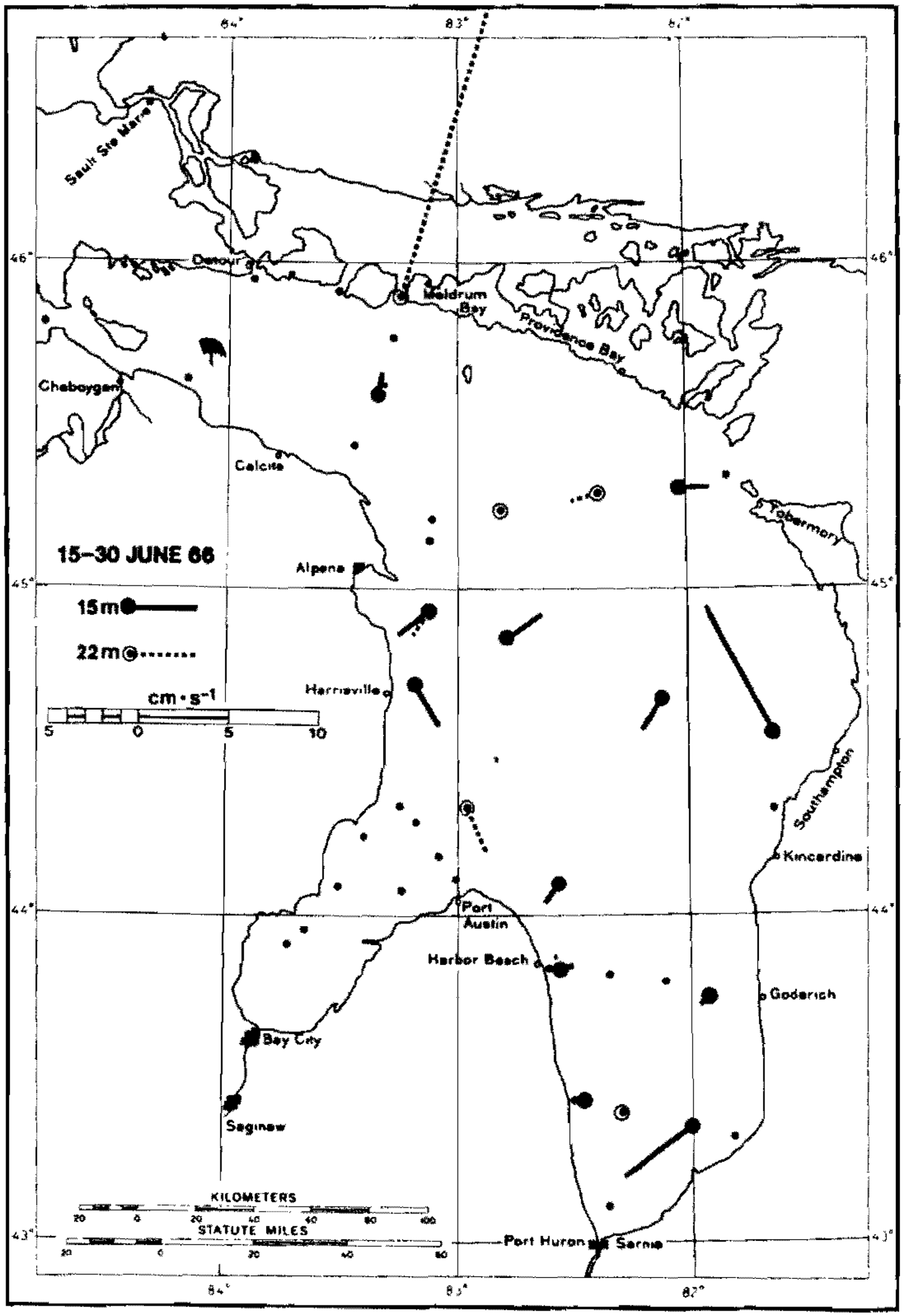

Figure 5b. Half-month average current vectors at 15 m and 22 m for 15-30 June 1966.

northwest quadrant apparently strengthened the southward flow along the western shore as shown in fig. 6a-b. The gyre in the central part of the lake, between latitudes 44° and 45°, was less well defined than in the previous half month. There was a net inflow of some 10 cm s^{-1} from Lake Michigan and an outflow of 8 cm s^{-1} into Georgian Bay; both of these appear to be responses to the prevailing winds. It should be noted, however, that the direction of surface flow in both the Straits of Mackinac and the channel into Georgian Bay does not prevail to the bottoms of the channels and, in fact, may be nearly balanced by opposing currents at great depth (E. B. Bennett, personnel communication, 1975).

The second half of July saw three major frontal passages which continued the pattern of prevailing westerly to northwesterly winds. Wind records from the moorings equipped with functioning anemometers showed evidence of the frontal activity. The average winds at stations 16 and 32 tended to be westerly, but the winds recorded at stations 11 and 29 had a more north-south bias. It should be noted that for the interval 15-31 July some 30 percent of the expected wind data points from station 11 were missing or of unusable quality. Station 29 winds were dominantly from the northwest.

Currents at 10 m for 15-31 July (fig. 7a) reflected the dominance of northwesterly flow, with a strengthening of the southward flow along the Michigan shore, with mean speeds up to 8 cm s^{-1}. The gyre in the central region of the lake retained its identity, but flows in the Saginaw Bay mouth and the southern basin of the lake remained complex. Flow in the Straits of Mackinac appeared to angle across the channel, but long-term averaging of flows which oscillated with amplitudes up to 100 cm s^{-1}, alternately eastward and westward, confused the picture. The meter at mooring 32 (Straits of Mackinac) at 22-m depth (fig. 7b) gave mostly north-south readings, although no equipment malfunction or data processing errors were reported; compass failure or misalignment is assumed to be the cause of these anomalous direction readings at 22 m. In the southern basin, flow at 15 m shows a strong gyre.

The weather maps for 2, 8, and 14 August show low-pressure centers crossing the Lake Huron region. Wind records at station 29 show wind directions rotating through two complete circles during the first half of the month. Unfortunately, the current meters at stations 26 and 27 had ceased functioning. Winds at station 16 prevailed westerly and southwesterly, while winds at station 11 were largely from the south until a deepening storm over Quebec pulled winds around to the north on 12 August. The lack of northerly wind components at station 16 gives cause for suspicion that the data from that meter are not entirely reliable.

Current patterns determined from the 13 meters still operating during the first half of August show the effects of the more southerly wind flow (fig. 8a-b). In the southern basin, flow was northward along both shores, as was the flow out of Saginaw Bay. Evidence of the gyre in mid-lake remained, indicated principally by vectors at stations 17, 20, and 21.

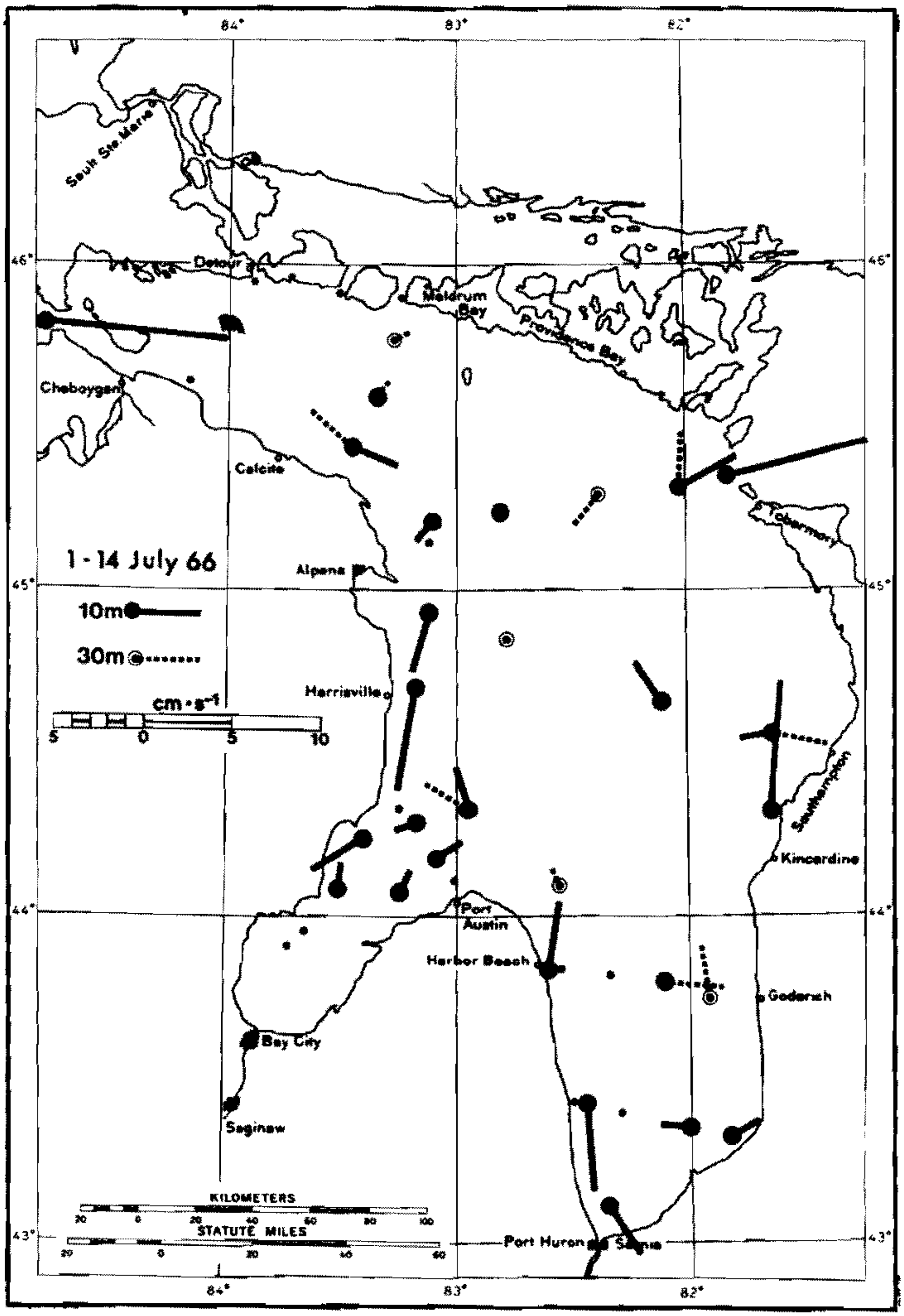

Figure 6a. Half-month average current vectors at 10 m and 30 m for 1-14 July 1966. Note reversal between 10 m and 30 m levels at station 26.

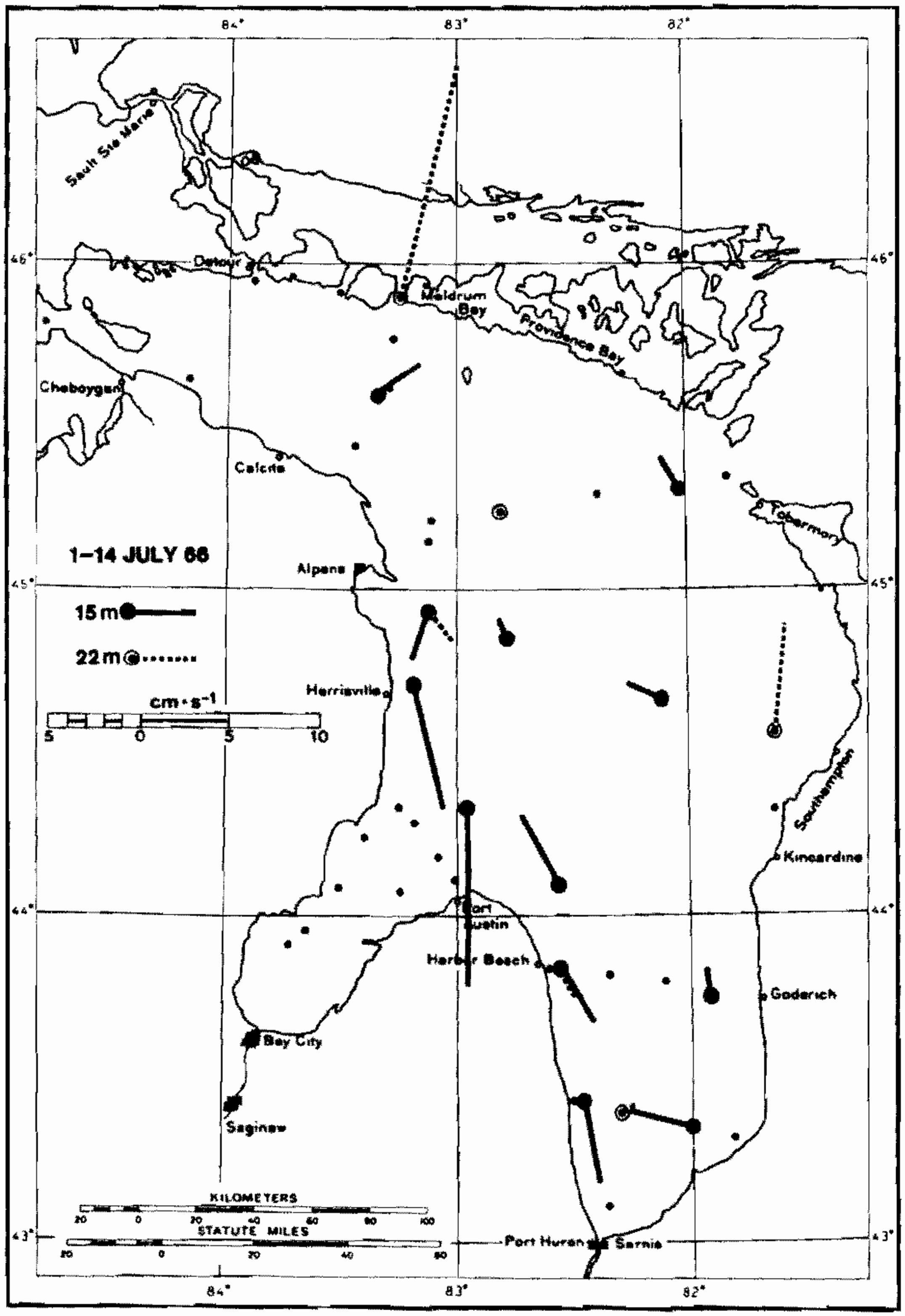

Figure 6b. Half-month average current vectors at 15 m and 22 m for 1-14 July 1966.

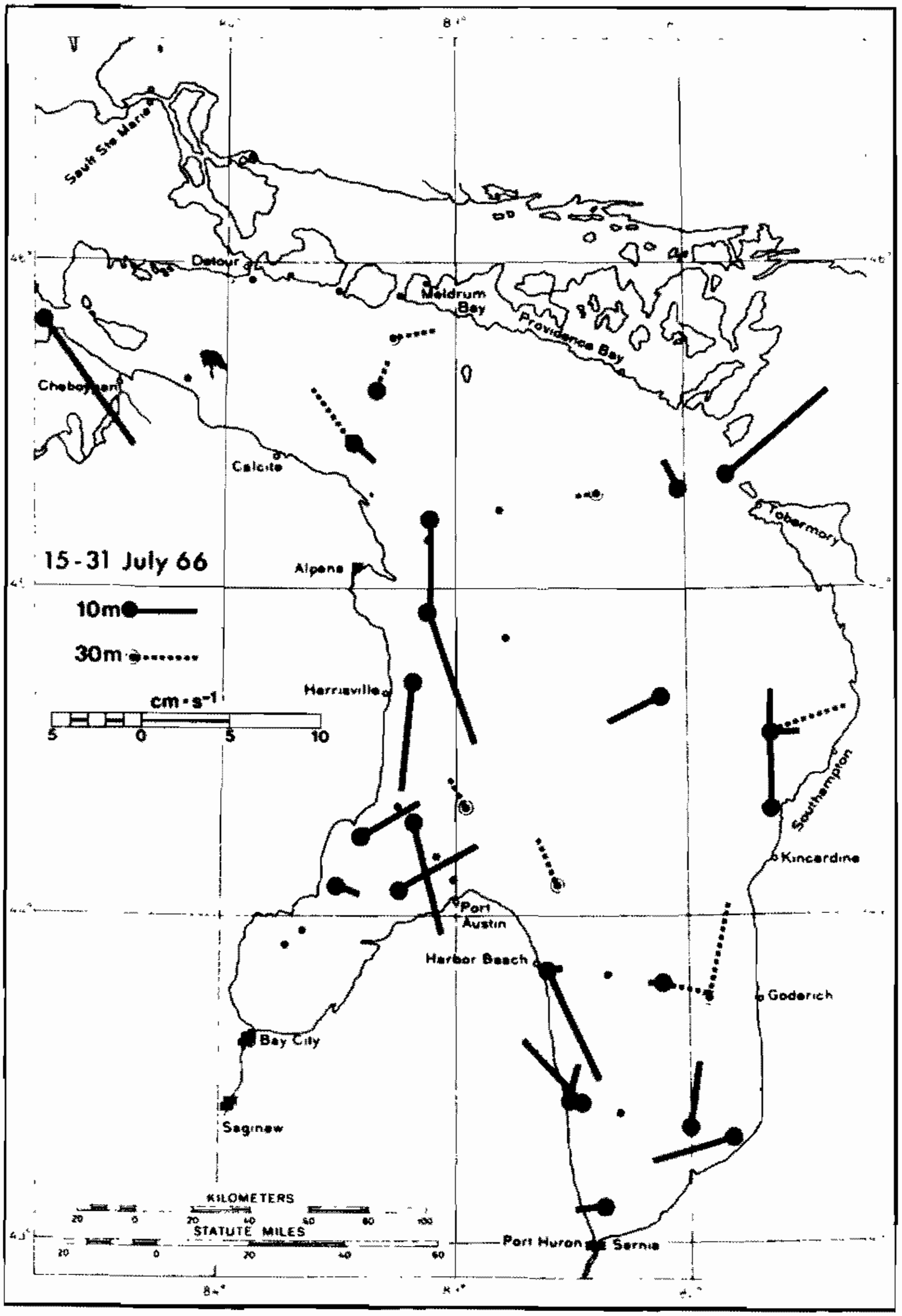

Figure 7a. Half-month average current vectors at 10 m and 30 m for 15-31 July 1966. Note that 30 m flow at stations 15 and 16 runs opposite apparent 10 m flow.

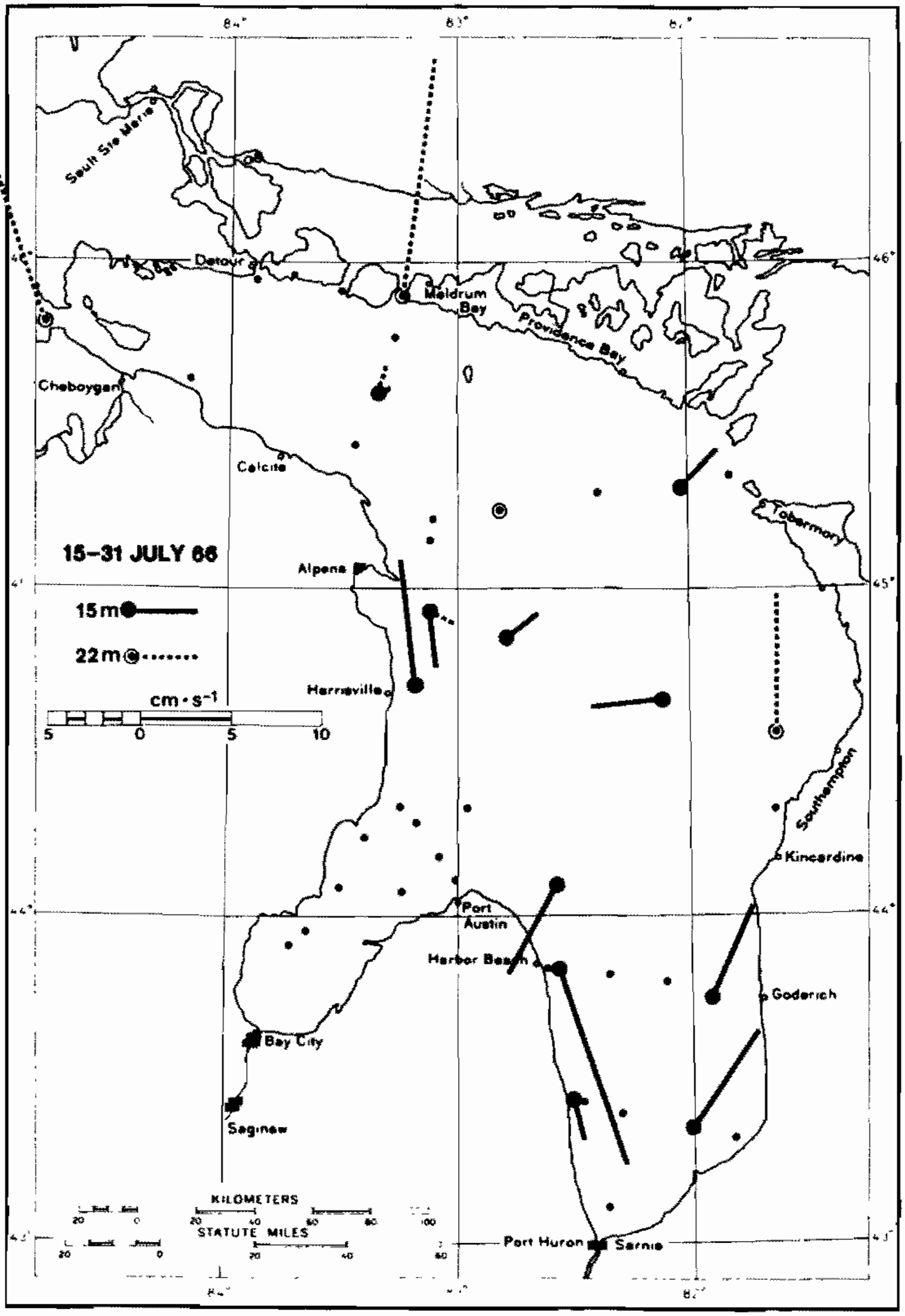

Figure 7b. Half-month average current vectors at 15 m and 22 m for 15-31 July 1966.

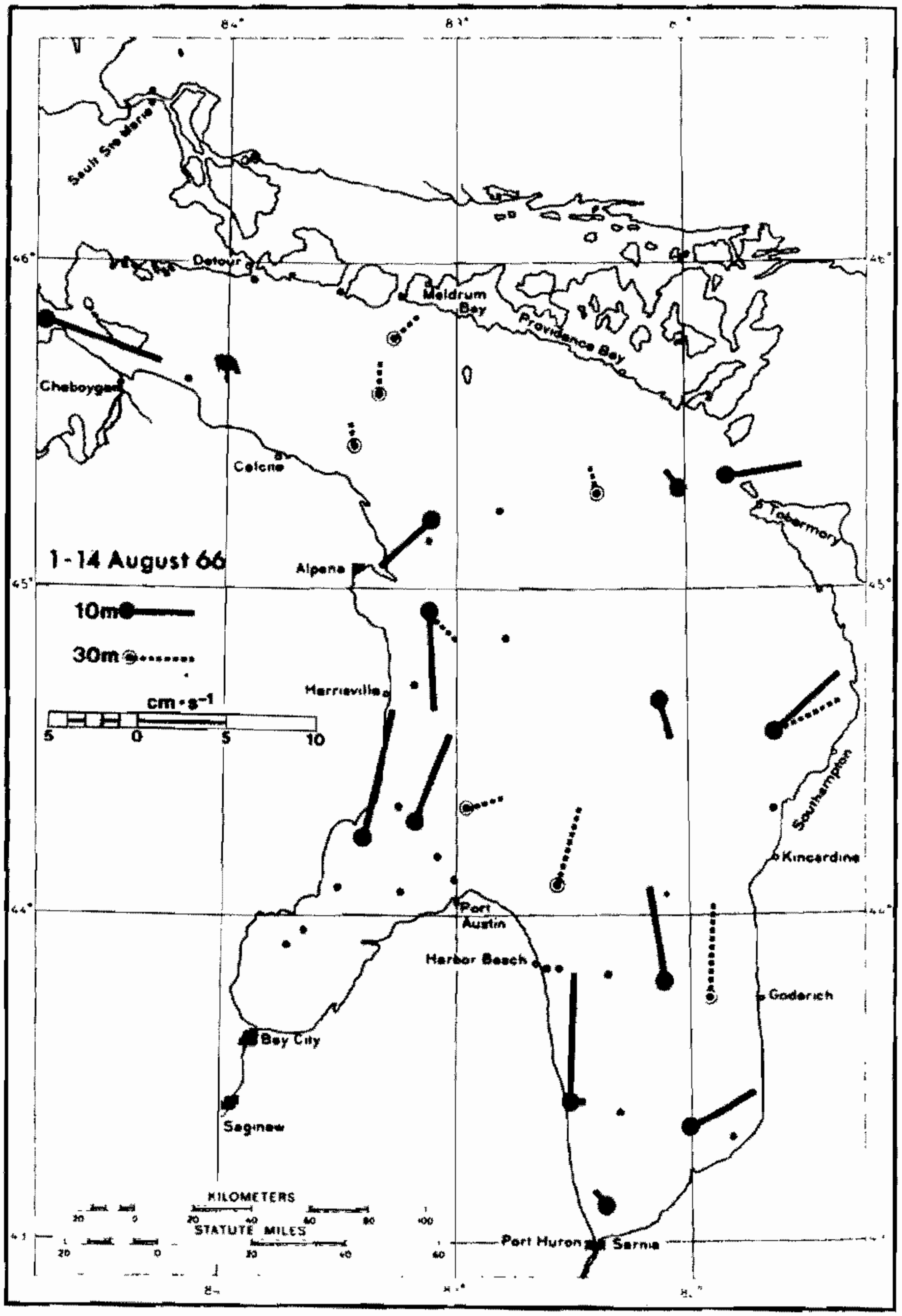

Figure 8a. Half-month average current vectors at 10 m and 30 m for 1-14 August 1966.

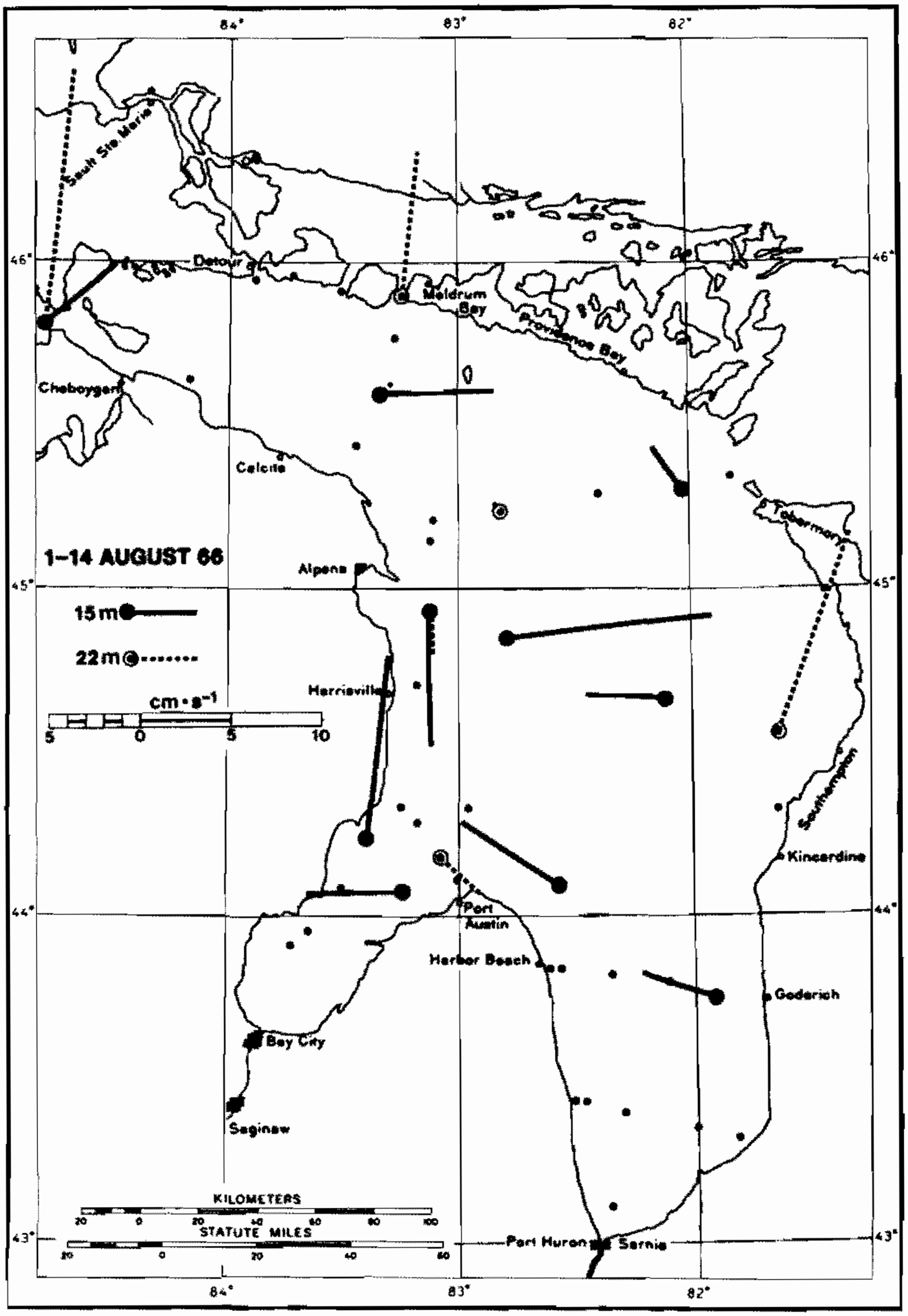

Figure 8b. Half-month average current vectors at 15 m and 22 m for 1-14 August 1966.

Flows for 15-31 August remained similar to those for the first half of the month. Fig. 9a-b show the same large mid-lake gyre and persistent northward flow at stations 26-28 appearing in fig. 10a-b for 1-14 September. These flow patterns seem to define the circulation throughout the stratified season.

Thus, the general summertime circulation of surface water in Lake Huron appears to consist of a large counterclockwise gyre, which occupies most of the lake north of latitude 44°N, and more complex and transient flows in the southern arm and around Saginaw Bay. Circulation patterns determined from the GLIRBP data have some of the characteristics described in the study by Ayers et al. (1956), and although the lake's response to meteorological inputs created significant differences, such features as the persistent southward current along the Michigan shore at latitude 45°N and a southward (along shore) flow at the south end of the lake are common to both sets of observations.

Also confirming the May through August current patterns revealed by the moored current meters are numerous dynamic height computations made for this interval from Lake Huron temperature data collected since 1960 by the Great Lakes Institute of the University of Toronto and by the Canada Centre for Inland Waters. These data invariably show a pool of colder water centered over the deep basin in the northeastern part of Lake Huron with warmer, less dense water along both the United States and Canadian coasts. Dynamic height computations therefore indicate a large counterclockwise circulation about the colder core, essentially of the same dimensions as the current meters reveal. Current speeds determined by the two methods are of the same order of magnitude. Therefore, bathymetry of the lake basin plays an important role in shaping the circulation pattern during the summer heating interval we have examined.

4. FLOWS AT DEPTHS BELOW 10 m

Flows at 15-m depth [map fig. (2, 3, 4, 5, 6, 7, 8, 9, and 10) marked b] generally seemed to follow the shallower layer, but the density of observations was not great enough to define circulations. Particularly problematical was a lack of simultaneous, reliable data for more than one depth at any mooring. Phase relationships between inertial oscillations above and below the thermocline, as reported by Malone (1968), are difficult to determine from the GLIRBP Lake Huron data. Only 6 moorings provided data at both 10- and 15-m depths in July, and only 11 moorings gave any usable 15-m data at all. Missing data are attributable to instrument failures and possible inadequacies in the automated data-reduction hardware and processing methods (Mehr, 1965 and 1970). Data were also taken at 22-, 30-, 60-, 90-, and 120-m depths, where applicable, but the sample sizes from these levels were smaller than even the 15-m set. Half-monthly flows could be computed at a maximum of 12 moorings for 30-m depth, and only for the second half of June were that many available.

Existing 30-m data showed flows similar to surface currents in the southern basin and a persistent current northeastward and anticyclonically curved from station 26 toward station 28. There were insufficient data to determine the continuations up or downstream of this region, but the prevailing winds

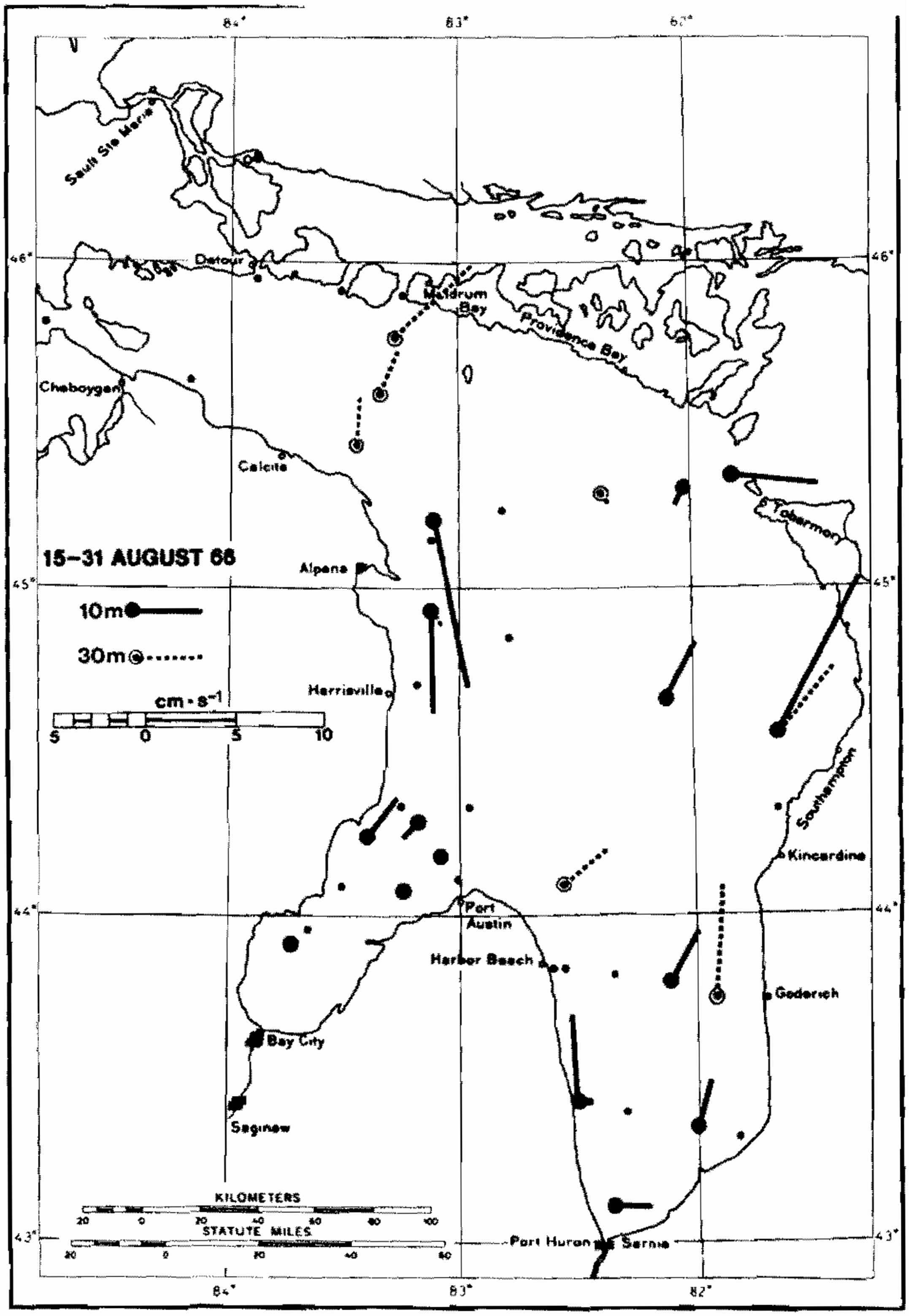

Figure 9a. Half-month average current vectors at 10 m and 30 m for 15-31 August 1966.

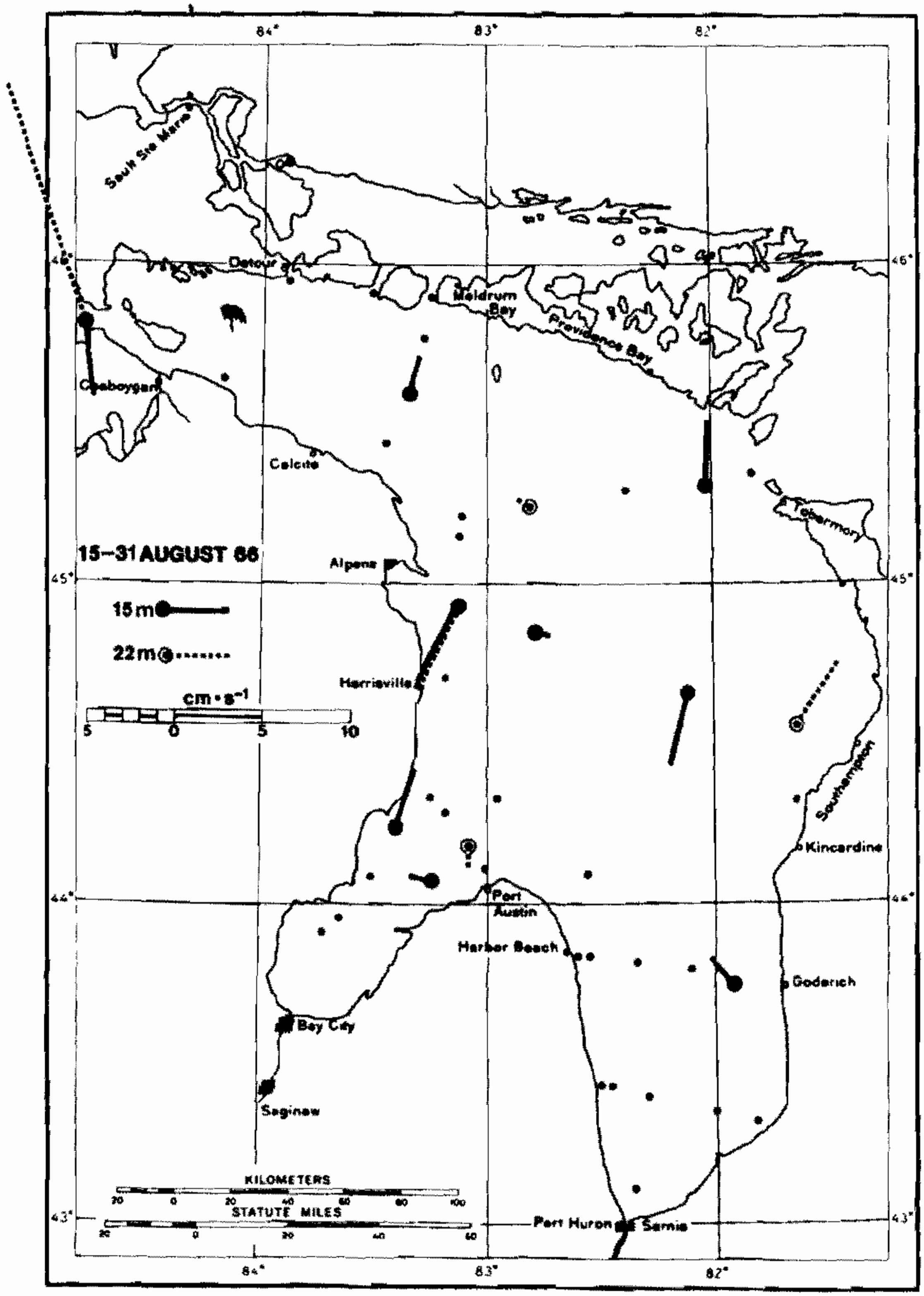

Figure 9b. Half-month average current vectors at 15 m and 22 m for 15–31 August 1966.

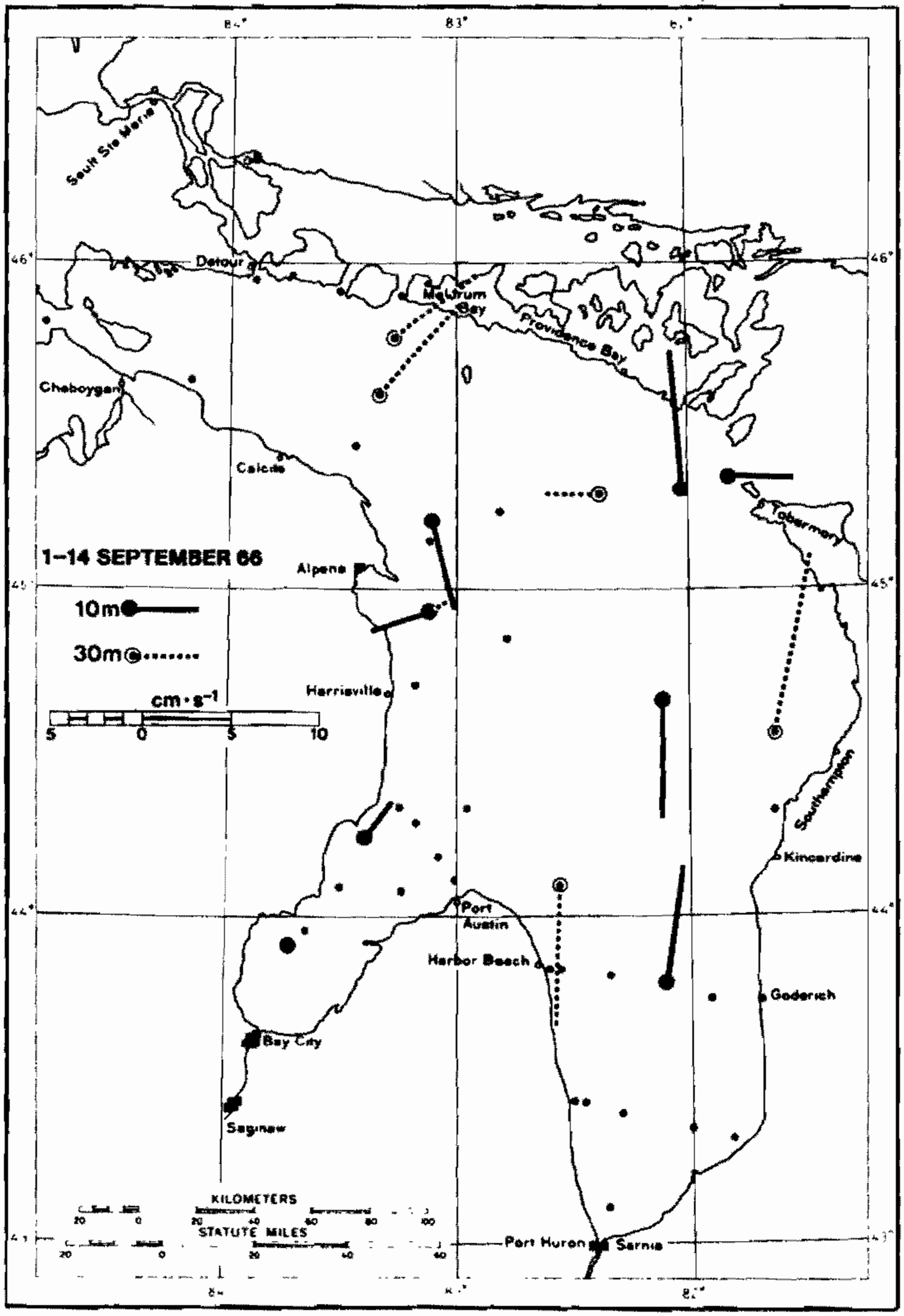

Figure 10a. Half-month average current vectors at 10 m and 30 m for 1-14 September 1966.

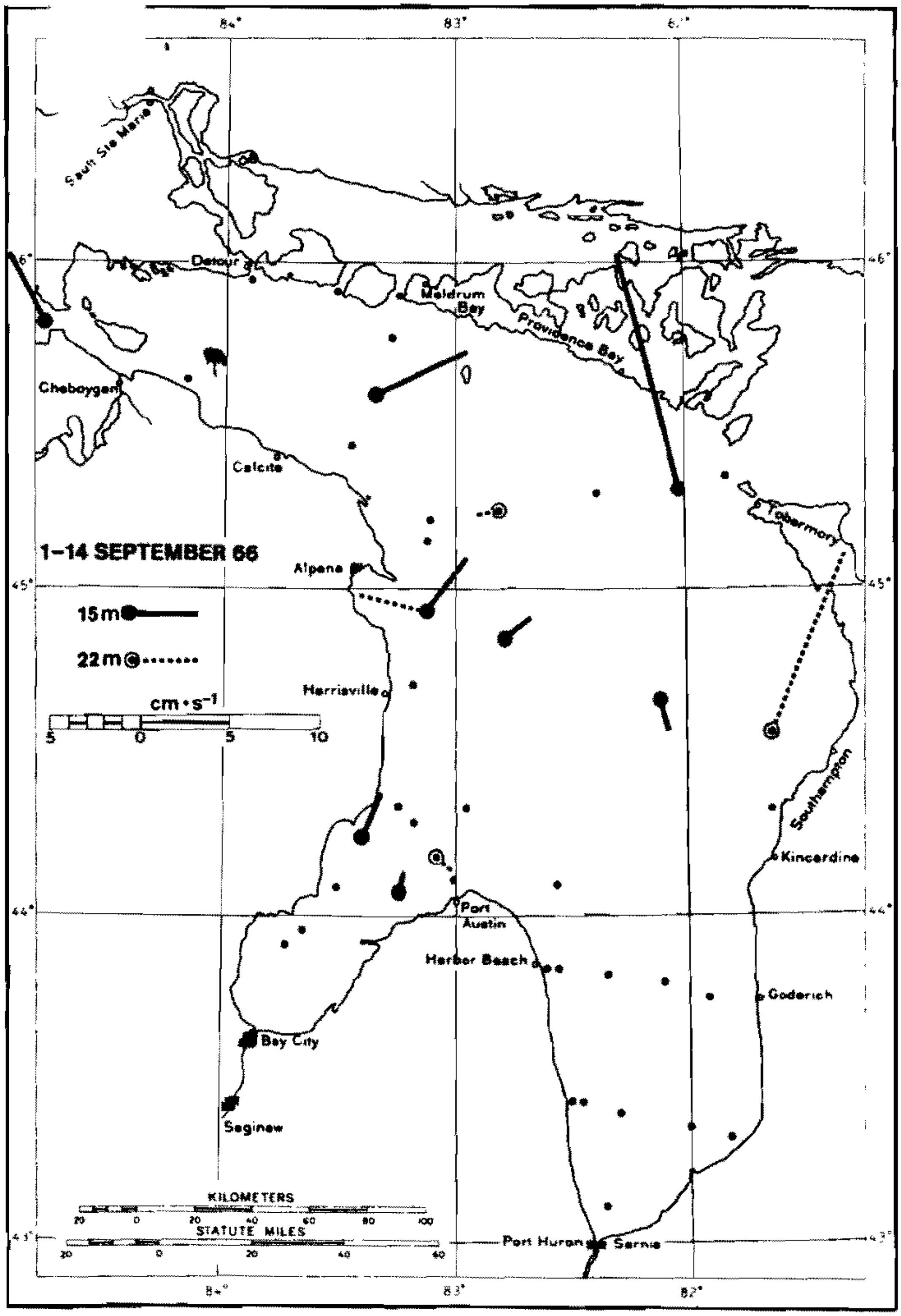

Figure 10b. Half-month average current vectors at 15 m and 22 m for 1-14 September 1966.

would have favored upwelling inshore of station 26. There are two explanations for this flow. There is a topographic ridge in the lake bottom which extends northeastward from the Michigan shore east of Calcite (at approximately 83.5°W longitude) toward, and including, the Duck Islands at longitude near 83.0°W. Also, the dynamic height computations from the Canada Centre for Inland Waters and others referred to earlier in this paper show a persistent cold core which lies west of the line of moorings 26-28 and may control the flow in that region.

5. EFFECTS OF THERMAL STRUCTURE

Fig. 11 a-d show temperature profiles taken by the U.S. Lake Survey Center's *R/V Shenehon* as part of a separate study. the profiles show stratification started in early June, with the thermocline passing 10-m depth early in July, but remaining shallower than 30 m through August. The locations at which the profiles were taken were: 11a, near mooring 27; 11b, near mooring 18; 11c, near mooring 16; and 11d, near mooring 13.

Examination of even these few, selected profiles reveals some reason for the behavior of the current vectors. Fig. 11d, from the southern basin, shows that the warm surface layer did not penetrate to the 10-m depth until after July 5. The 10-m currents at station 13 consisted mostly of inertial oscillations until mid-July, at which time a definite directional current began to develop. By early August, the surface layer was thicker than 15 m, and the mean flow at station 13 strongly directional, although the inertial component remained. (Spectrum analysis of station 13 currents is presented in the next section.) Similarly, the directional flow at stations 17 and 21 strengthened as the epilimnion deepened. Flow in the upper hypolimnion, represented by the 30-m vectors, sometimes opposed the surface flow, as at moorings 26 in all of July and at mooring 20 in the first half of July. Other thermal effects have been described earlier in this paper.

6. OSCILLATORY CURRENTS

Spectrum computations in this study were done by applying the fast Fourier transform (FFT) algorithm to time series formed from the cartesian velocity components along the east-west and north-south directions. Following the method of Gonella (1972), rotary spectra also were computed. A multispectral averaging technique was employed, rather than prefiltering and sub-sampling as was done by Malone (1968). In the present study, spectra were computed for several overlapping subsets of the total data series; then the spectra were ensemble-averaged and smoothed by Hanning to produce a single spectrum representative of the entire data series. The alignment of overlapping data is shown schematically in fig. 12. Each subset was linearly detrended and cosine-tapered at the ends before transforming.

The resulting spectrum admittedly is biased in favor of the middle portion of the data series, which is included in more than one subseries, but by varying the amount of overlap, it is possible to cover almost the entire original data series in spite of the FFT constraint which requires a number of data points equal to a power of 2. Sufficient resolution may be obtained

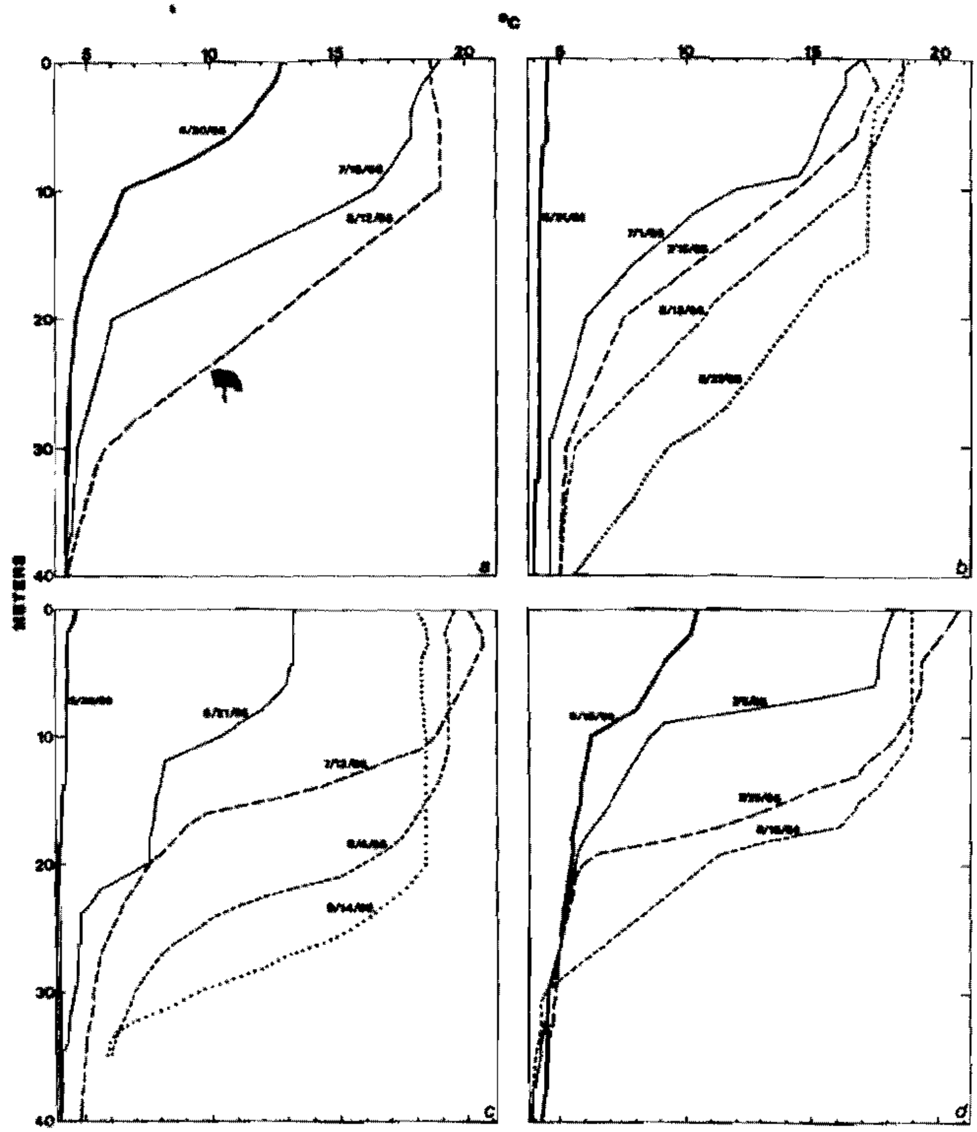

Figure 11a. Temperature profiles (bathythermograph) from R/V Shenehon *taken near mooring 27. The thermocline passed 10 m in early July 1966 and had not reached 30 m by last date shown. Maximum temperature gradient is 1.0°C m^{-1}.*

Figure 11b. Temperature profiles from near mooring 18. Thermocline touched 30-m depth first at end of analysis period. Maximum temperature gradient is 0.7°C m^{-1}.

Figure 11c. Temperature profiles from near mooring 16. Epilimnion included 10-m depth first at end of analysis period. Maximum temperature gradient is 1.6°C m^{-1}.

Figure 11d. Temperature profiles from near mooring 13. Epilimnion reached 10 m in mid-July 1966. Maximum temperature gradient is 2.8°C m^{-1}.

with a transform of length 256 points, which results in 129 spectral estimates from zero frequency to the Nyquist frequency; this is analogous to a "conventional" Fourier transform using 128 lags. For example, 32 days of hourly data give a total set of 768 observations that may be subdivided into 3 contiguous, independent subsets of length 256 and 2 more subsets of length 256 which are centered over the 2 connecting points between the other 3 sets. The overlaid sets will pick up details of the signal that may have been suppressed by the tapering at the ends of the independent sets.

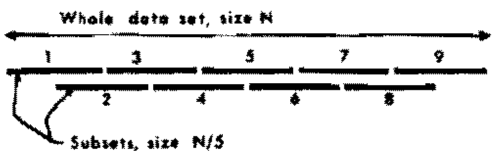

Figure 12. Schematic representation of data subsets for spectrum computation. Each subset must consist of an integer power of 2 points. For the case shown, a subset of 256 points would allow coverage of a total of 1,280 points (not an integer power of 2). Overlap shown is 50 percent.

Statistical degrees of freedom (ν) are calculated on the basis of the number of independent data points, by the formulae

$$\nu = (2N - N/4M)/(N/2M) \tag{1a}$$

or

$$\nu = 4M - 1/2, \tag{1b}$$

where N is the number of points in the total data set and M is the number of transformed subsets. Note that the degrees of freedom do not depend on the size of the transformed subsets, but only on their number. The dependence of ν on the ratio of the size of a subset to the total sample, which would be controlled by the number of lags used, is eliminated here since the FFT is analogous to a lagged-product method using all the allowable lags. The FFT yields spectral estimates at $n/2 + 1$ nonnegative frequencies for a sample of size n.

Rotary components of the velocity vector are computed following Gonella (1972), according to

$$P_{CW}(f) = [P_A(f) - Q_{XY}(f)]/2 \tag{2a}$$

$$P_{CCW}(f) = [P_A(f) + Q_{XY}(f)]/2, \tag{2b}$$

where P_{CW} and P_{CCW} are the clockwise and counterclockwise components of the phasor representation of the velocity at frequency f, P_A is the average scalar power at f, and Q_{XY} is the quadrature spectrum evaluated at f. While the rotary components P_{CW} and P_{CCW} could be computed from any pair of scalar series they obviously have physical meaning primarily for velocity components along perpendicular axes at a single site. The rotary components are conveniently invariant with respect to orientation of the coordinate axes. Alignment of the major axis is determined (Gonella, 1972) by

$$\tan 2\phi = 2S_{XY}/(S_{XX} - S_{YY}), \qquad (3)$$

where, for any frequency, the angle ϕ is clockwise from north, S_{XY} is the cospectrum between east and north motions, and S_{XX} and S_{YY} are the autospectra of the east and north components, respectively.

Fig. 13a-b and 14a-b show cartesian-component and rotary spectra for currents at 10-m depth at mooring 13 for the periods 1-16 July and 17 July-2 August. The raw data for each spectrum consist of 768 consecutive half-hour readings of current velocity. To increase low-frequency resolution, the data were first averaged in 4's to give 2-hourly velocities, lowering the Nyquist frequency from 1.0 to 0.25 cycle per hour. The resulting data set, reduced in length to 192 2-hourly values, was then transformed in 3 overlapping subsets of length 128; each subset began at the 33rd point of the previous set for 75 percent overlap. From fig. 11, it appears that the meter in this example was in the thermocline for at least part of the 1-16 July interval, during which there was a strong spectral component at the local inertial frequency with a clockwise rotation of the velocity vector at all frequencies up to 20 percent lower and 80 percent higher. The energy of motions with periods of 16 to 18 hours was almost 60 percent greater than the energy of all motions with periods longer than 50 hours. For the interval 17 July-3 August, energy in the inertial range (16-18 hours) exceeded the energy in long-period motions by 25 percent. The relative drop is attributable to thickening of the epilimnion and the consequent greater involvement of water at the 10-m level in meteorological scale motions; total energy had increased more than threefold. For the entire observation period, motions in the inertial range were nearly circular. There is no ready explanation for the additional energy peak in fig. 14a-b at 8.8 hours: Lake Huron has no free oscillations at that period and the spectral methods used here do not produce such strong side lobes. It is possible that inertial-period waves on the thermocline were large enough to place the meter alternately in the epilimnion and hypolimnion.

Fig. 15a-b show rotary spectra for station 17 for the period 9 July-13 September at depths of 10 and 30 m, respectively. While both records contained strong inertial components, attempts to correlate motions at the 2 depths were unsuccessful. In the light of other studies which showed coherence and expected phase reversals across the thermocline (Malone, 1968), it is evident that the data from station 17 were subject to the timing discrepancies which seem to pervade the GLIRBP data. These data were also averaged over 2-hour intervals, but longer data sets were used, with 5 subsets of length 256 and 50 percent overlap.

Fig. 16a-b are a component and rotary spectra for station 35 at 16-m depth, probably in the hypolimnion for the analyzed period of 16 June-20 July. Data were averaged over 1-hour intervals and transformed as 5 sets of length 256 with 50 percent overlap. The mooring was approximately 5 km from shore in a total water depth of 26 m, yet the inertial motions are quite strong,

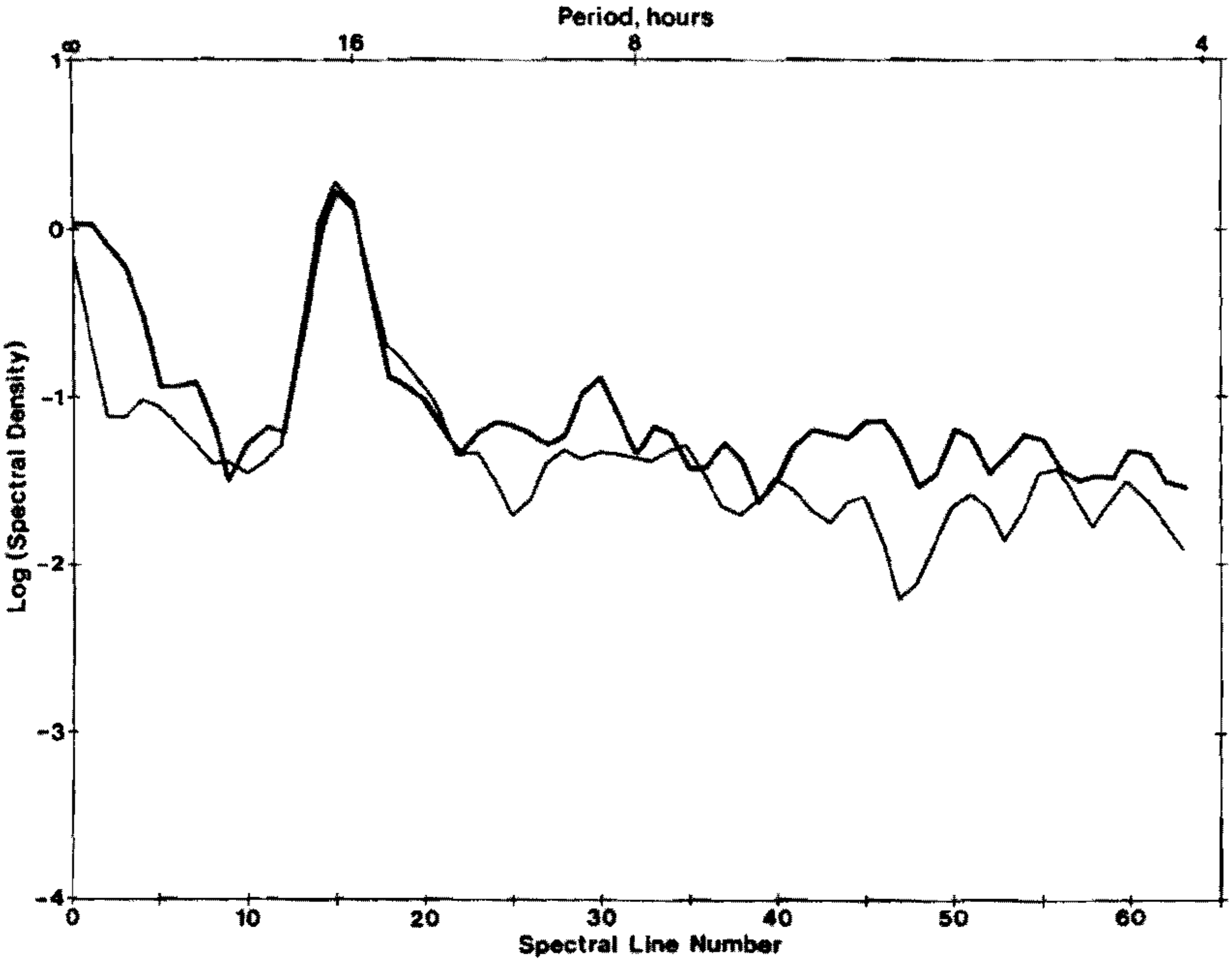

Figure 13a. Power spectra of north (heavy line) and east (light line) hourly velocity components at station 13, depth 10 m, for 1-16 July 1966. Only the first half of the computed spectrum is shown; no significant peaks appeared in lines 65-128. Note that most spectra shown in this paper are truncated in this manner; exceptions are noted. Spectral density (power) scale is logarithmic.

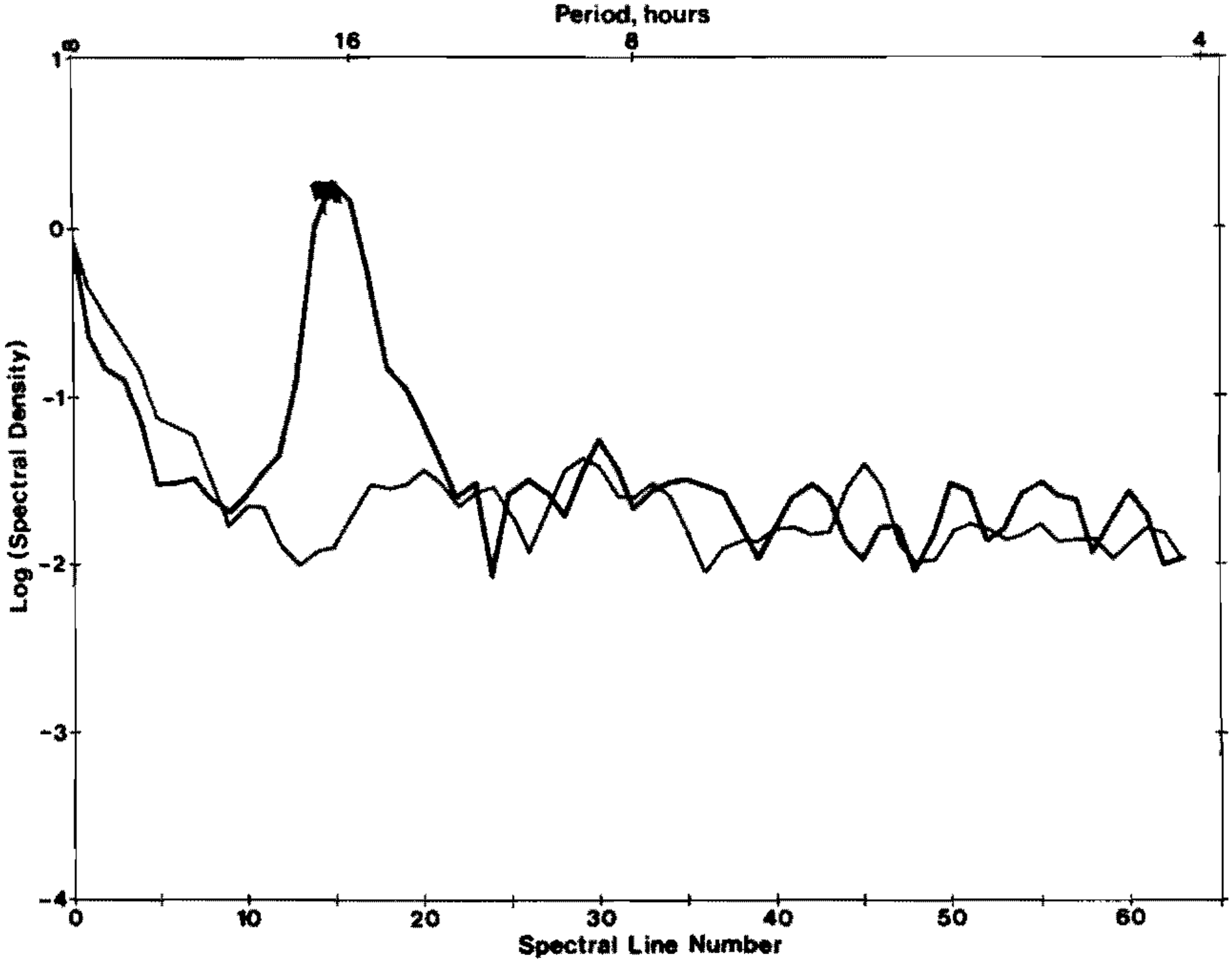

Figure 13b. Rotational spectra of clockwise (heavy line) and counterclockwise (light line) hourly velocity components at station 13, depth 10 m, for 1-16 July 1966. The inertial band contains 100 times as much energy in clockwise motions as in counterclockwise.

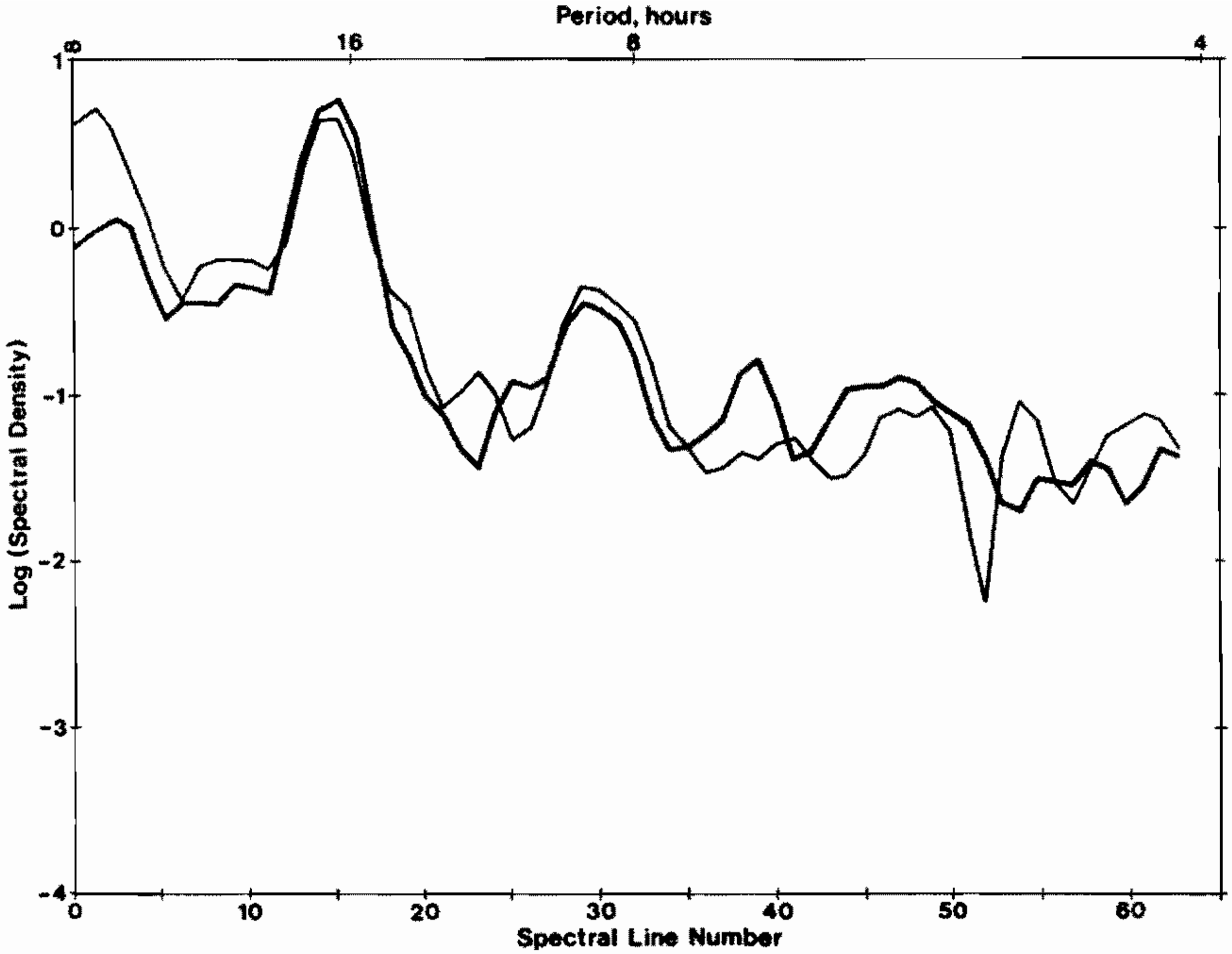

Figure 14a. Power spectra of north (heavy line) and east (light line) hourly velocity components at station 13, depth 10 m, for 17 July-3 August 1966. Power in inertial range has doubled, as has long-period power.

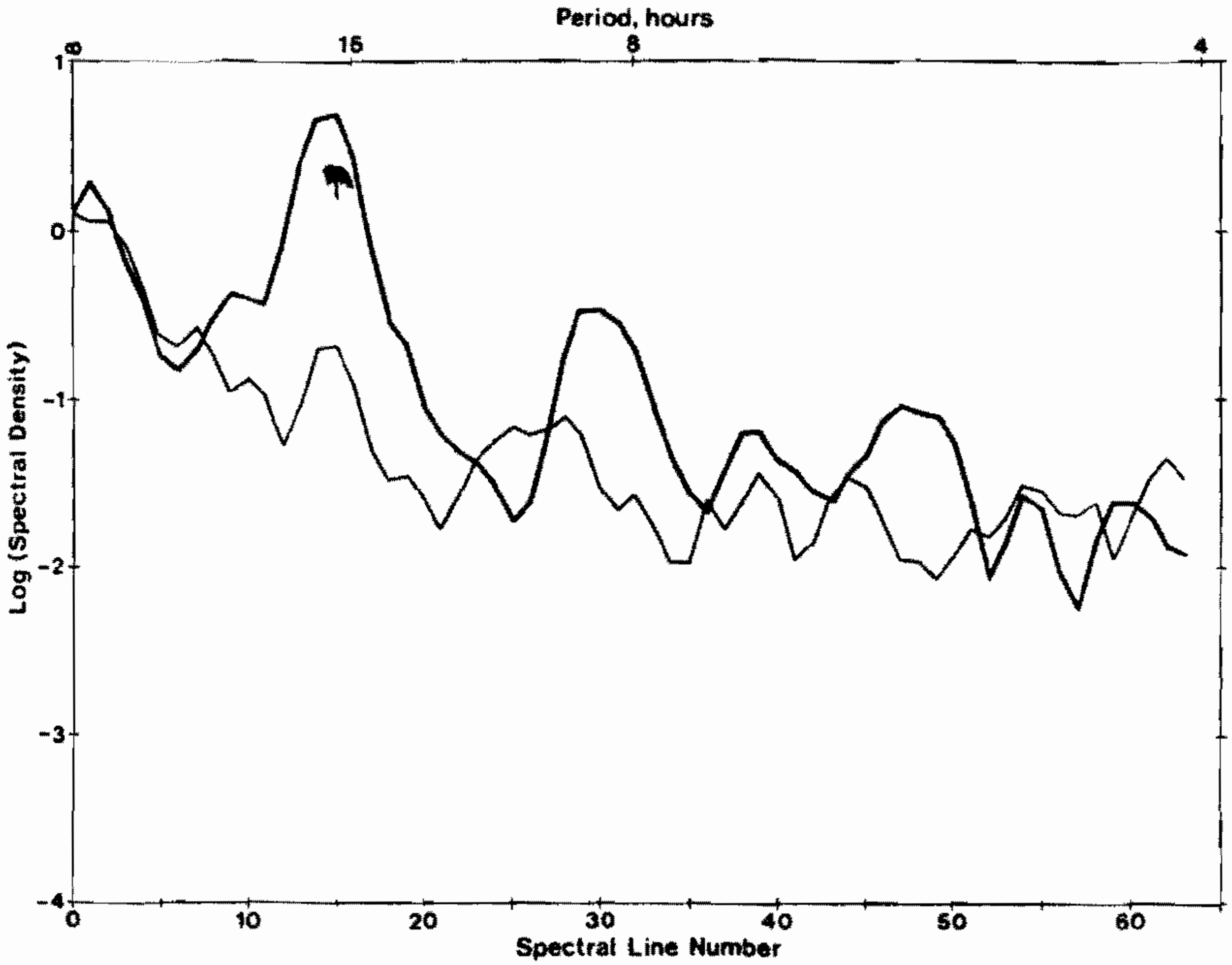

Figure 14b. Rotational spectra of clockwise (heavy line) and counterclockwise (light line) hourly velocity components at station 13, depth 10 m, for 17 July-3 August 1966. Increase in power in counterclockwise motion at inertial period may indicate development of linear motion added to rotary current.

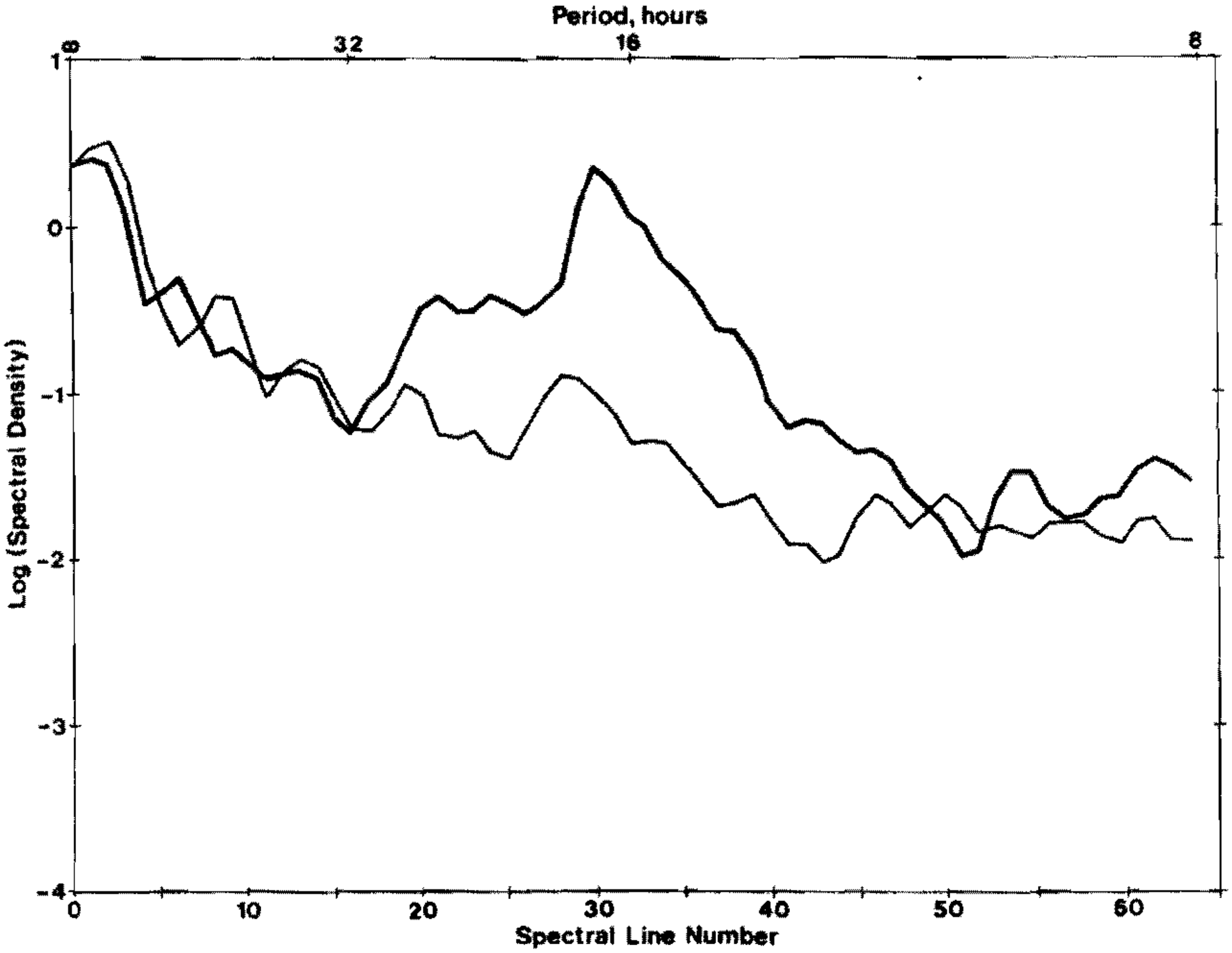

Figure 15a. Rotational spectra of clockwise (heavy line) and counterclockwise (light line) 2-hourly averaged velocity components at station 17, depth 10 m, 9 July-13 September 1966. The spectrum is again truncated at the midpoint, but the horizontal scale now covers half the interval of the previous fig. 13a-b, 14a-b.

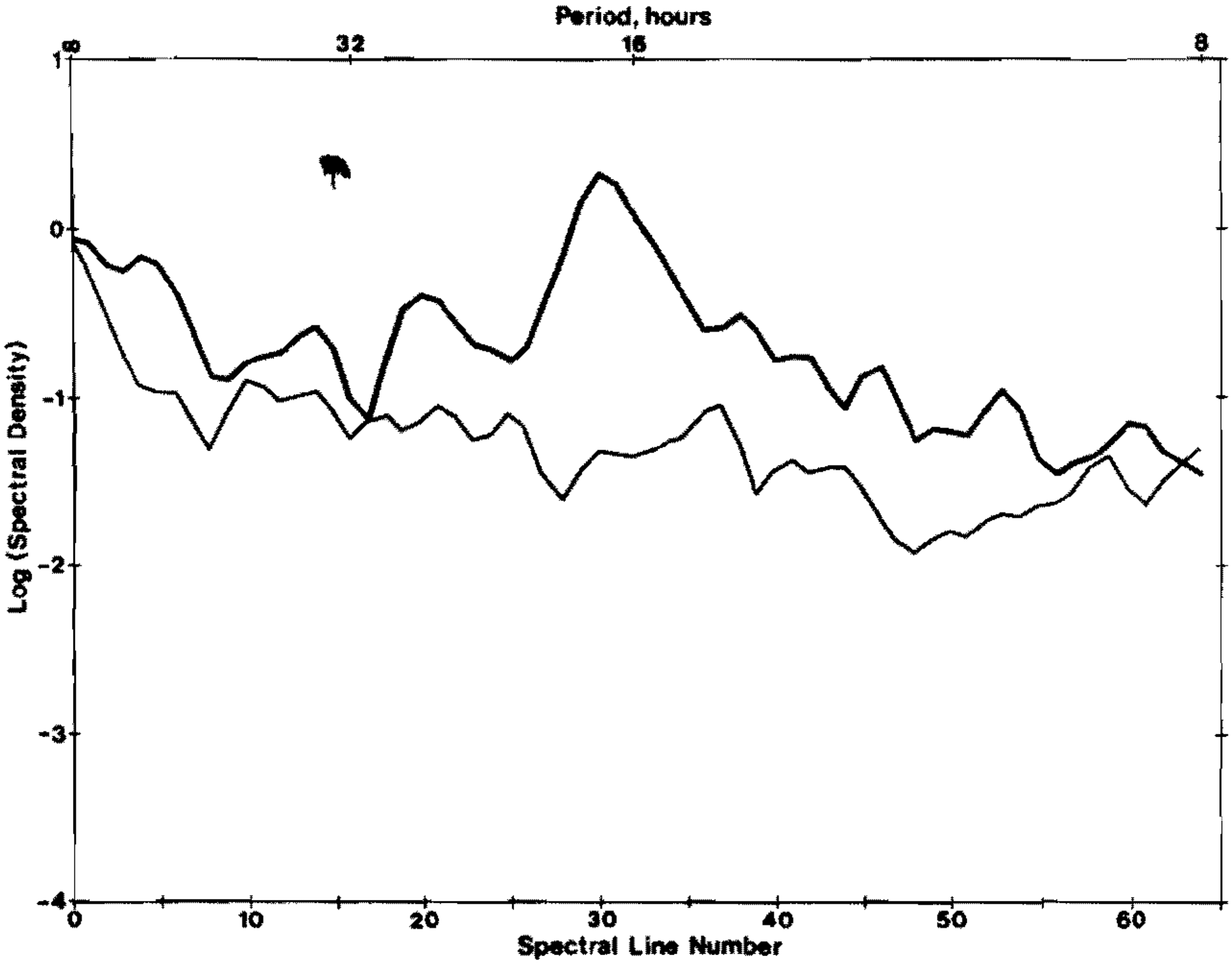

Figure 15b. Rotational spectra of clockwise (heavy line) and counterclockwise (light line) 2-hourly averaged velocity components at station 17, depth 30 m, 9 July-13 September 1966. The inertial peak is nearly the same strength as at 10 m (within 15 percent), but spread between clockwise and counterclockwise is larger.

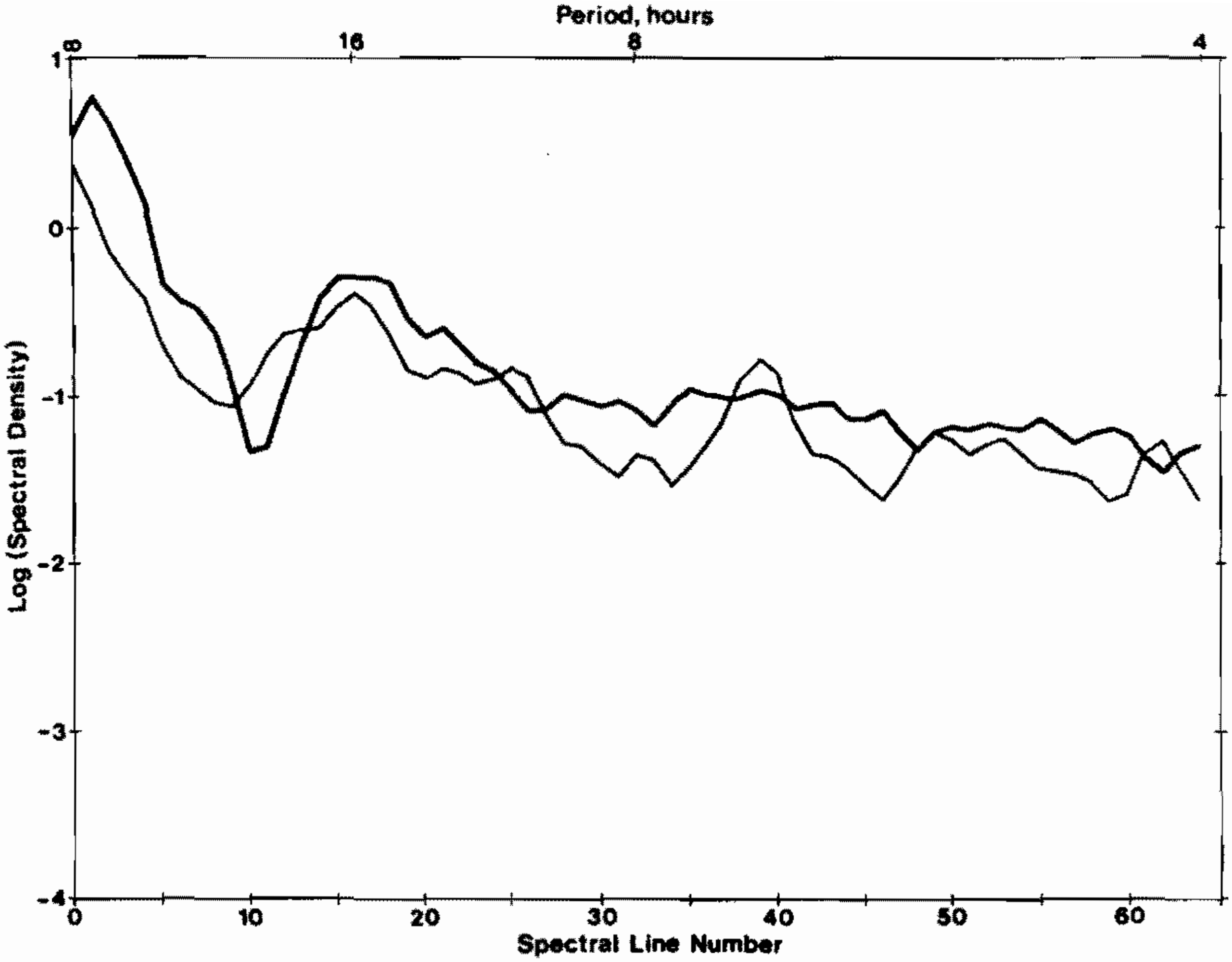

Figure 16a. Power spectra of north (heavy line) and east (light line) hourly velocity components at station 35, depth 16 m, for 16 June-20 July 1966. The east velocity peak at 6.5 hours (line 39) corresponds to the first free oscillation period for Lake Huron; the velocity vector is actually biased nearly perpendicular to shore, according to equation (3).

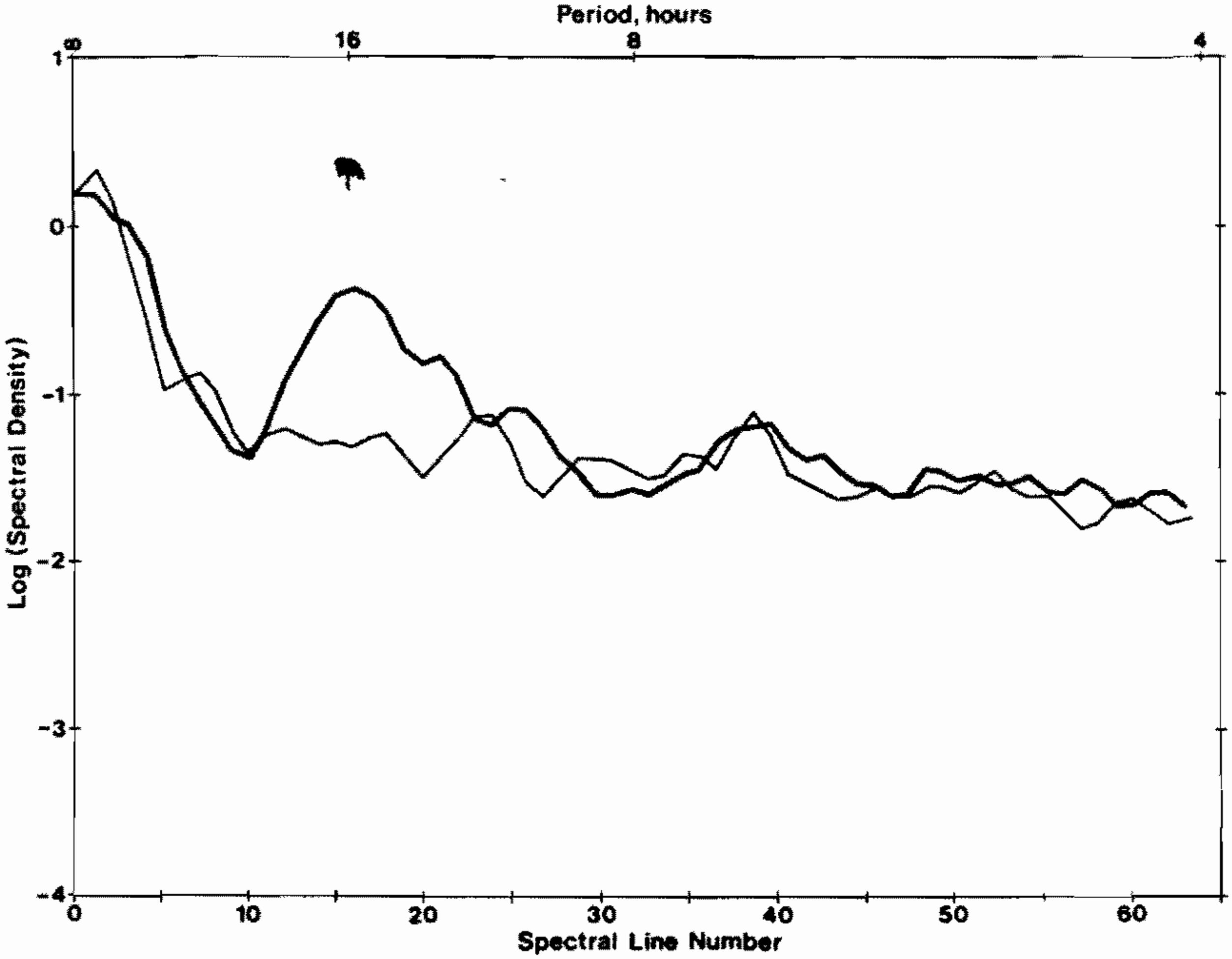

Figure 16b. Rotational spectra of clockwise (heavy line) and counterclockwise (light line) hourly velocity components at station 35, depth 16 m, for 16 June-20 July 1966. Near equality of clockwise and counterclockwise components at line 39 implies linear motion as described in the text.

describing an ellipse oriented with major axis toward 38° west of north, or parallel to shore. Also present in the east-west component (approximately 30° from perpendicular to shore) was a spectral peak at the period of the first Lake Huron seiche, 6.5 hours. Alignment of this motion was directed toward 35° east of north. Superimposed on the broad inertial peak was a motion that was coherent between the north-south and east-west components (at greater than 95 percent significance) at the lunar semidiurnal tidal frequency. The spectrum contained more energy in the north-south (30° from parallel to shore) component, and the phase between the components of about 50° (north leading east) implies an elliptical motion with major axis inclined to be nearly parallel to shore along an angle of 36° west of north.

The Straits of Mackinac are discussed in detail elsewhere (Saylor and Sloss, 1976, in press), but one spectrum from mooring 32 data is included here (fig. 17) to show a strongly directional flow dominated by meteorological scale (about 3-day) motions and a strong energy spike at the lunar semidiurnal tide. The lake seiches were poorly delineated in the record shown here, although the first seiche of Lake Michigan may be present with a period of approximately 8.9 hours (cf. Rockwell, 1966). Long-period motions had the most energy at periods ranging from 64-85 hours (cf. Powers and Ayers, 1960).

7. SUMMARY AND CONCLUSIONS

The summertime surface circulation of Lake Huron is dominated by a counterclockwise gyre which occupies most of the northern 2/3 of the lake. There is a smaller counterclockwise gyre in the northwestern end of the lake, at least partially constrained by bottom topography. The southern basin displays more complex patterns dependent on weather. A topographic ridge, separating the southern basin from the deeper main basin, is followed by the southern boundary of the main gyre. Studies of the thermal structure of Lake Huron have shown temperature patterns which suggest similar circulations. The surface circulation was not always well indicated by current meters at 10-m depth, since the thermocline remained shallower than 30 m for the entire season and appeared near 10 m until mid-July, e.g., parts of the southern lake, where upwelling prevailed along the west shore, showed hypolimnion motions at 10 m through mid-July.

Thermal stratification allowed the development of strong inertial oscillations and rotary currents in most of the lake. Inertial motions were most clearly defined where thermal stratification was sharpest and in such cases accounted for much of the total water movement. At some stations there were indications of possible tidal and seiche-driven currents, but only at the Straits of Mackinac were such motions clearly detectable. Correlations of oscillatory currents at various locations were apparently not possible due to inherent uncertainties in absolute timing of the GLIRBP data.

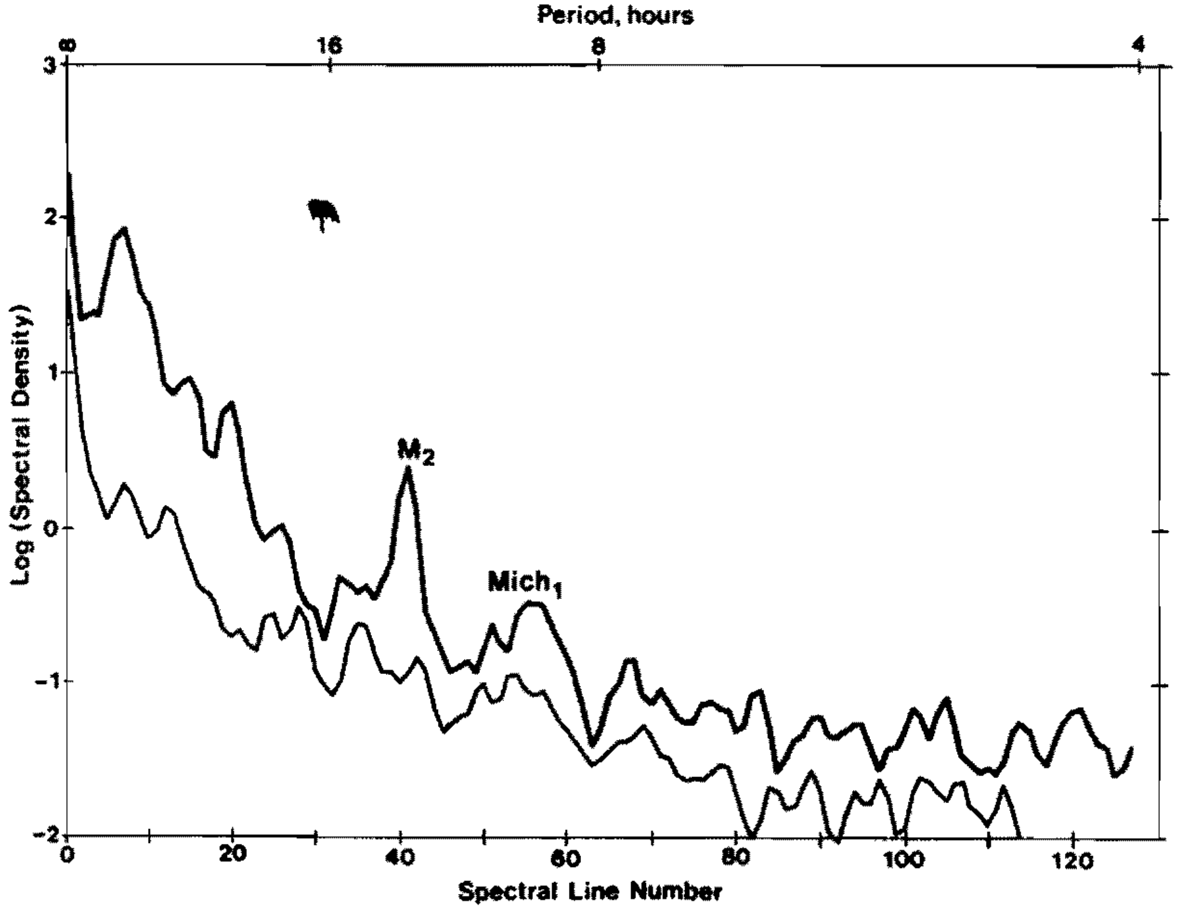

Figure 17. Power spectra of north (heavy line) and east (light line) 2-hourly velocity components at station 32 (Straits of Mackinac), depth 10 m, 15 July-16 September 1966. The strong spectral peak at line 41 is the lunar semidiurnal tide, and the broad peak at lines 55-60 represents the first free seiche of Lake Michigan. The half of the spectrum from 8- to 4-hour periods shows no significant peaks, although the second Lake Michigan seiche may appear around line 105. (Plot ***not*** *truncated.)*

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