Large-Scale Current Measurements in Lake Huron

PETER W. SLOSS AND JAMES H. SAYLOR

Great Lakes Environmental Research Laboratory, NOAA, Ann Arbor, Michigan 48104

Reanalysis of the data from the 1966 Great Lakes-Illinois River Basin Project (GLIRBP) of the Federal Water Pollution Control Administration (FWPCA) reveals 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-August 1966, when some 21 stations returned synoptically significant data from current meters at depths of 10 and 15 m. From this somewhat sparse sample it is deduced that at 10-m depth a counterclockwise circulation dominates the northern two thirds 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 center line 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 component and are dominated by the lunar semidiurnal tide and the seiches of Lake Michigan.

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 of these studies 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 throughout the previous winter at locations near the Lake Michigan shore. Details of typical moorings and meters can be found in the report by the *Federal Water Pollution Control Administration* [1967].

The Lake Huron station network is shown in Figure 1. Winter moorings were located at stations 1 and 4-9, but data from these stations will not be discussed here.

A maximum of 25 of the summer moorings produced simultaneous usable data representing flow at the same depth (10 m) for the interval of mid-June through July 1966. By the middle of August the number of functioning instruments at 10-m depth were 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 were 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 were recorded at 30-min intervals, although some records were timed at 20-, 10-, and 5-min spacings, and data from station 16 include several periods, each of about a week, during which data were taken at 1-min spacings. The purpose of these intensive observations is not known.

DATA ANALYSIS

The velocity time series generated by the current meters were analyzed in two ways, block vector averages over half-month 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 effect of such motions on half-month averages is negligible.

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 thermocline was below 10 m after early July. Figures 2-5 depict the surface layer circulations measured over 14- to 16-day intervals from mid-June through mid-August. Heavy dots 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. Also shown are currents at 30-m depth, which was generally below the thermocline.

Figure 2, representing the second half of June, shows a somewhat disorganized pattern of flow. There is an apparent counterclockwise circulation present in the lake, occupying the area between 44°00'N and 45°20'N latitude, 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 2-3 cm s^{-1} over the lake, being stronger in coastal areas than in the open lake.

During the period of July 1-14 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 northwest quadrant apparently strengthened the southward flow along the western shore, as is shown in Figure 3. The gyre

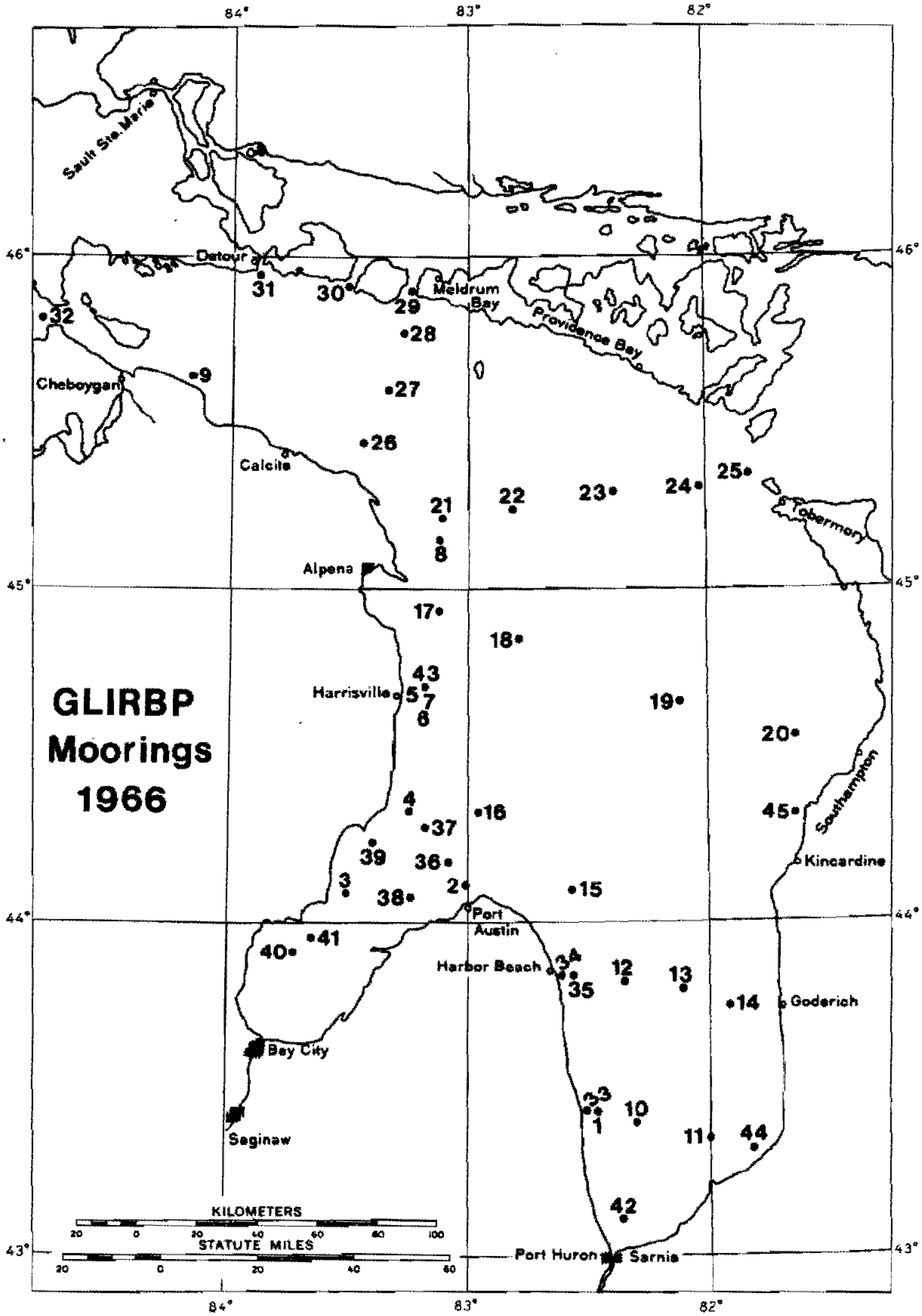

Fig. 1. Location map for 1966 FWPCA current meter moorings in Lake Huron. Stations 1 and 4–9 were deployed for the winter of 1965–1966, and the rest were set from late April through September 1966.

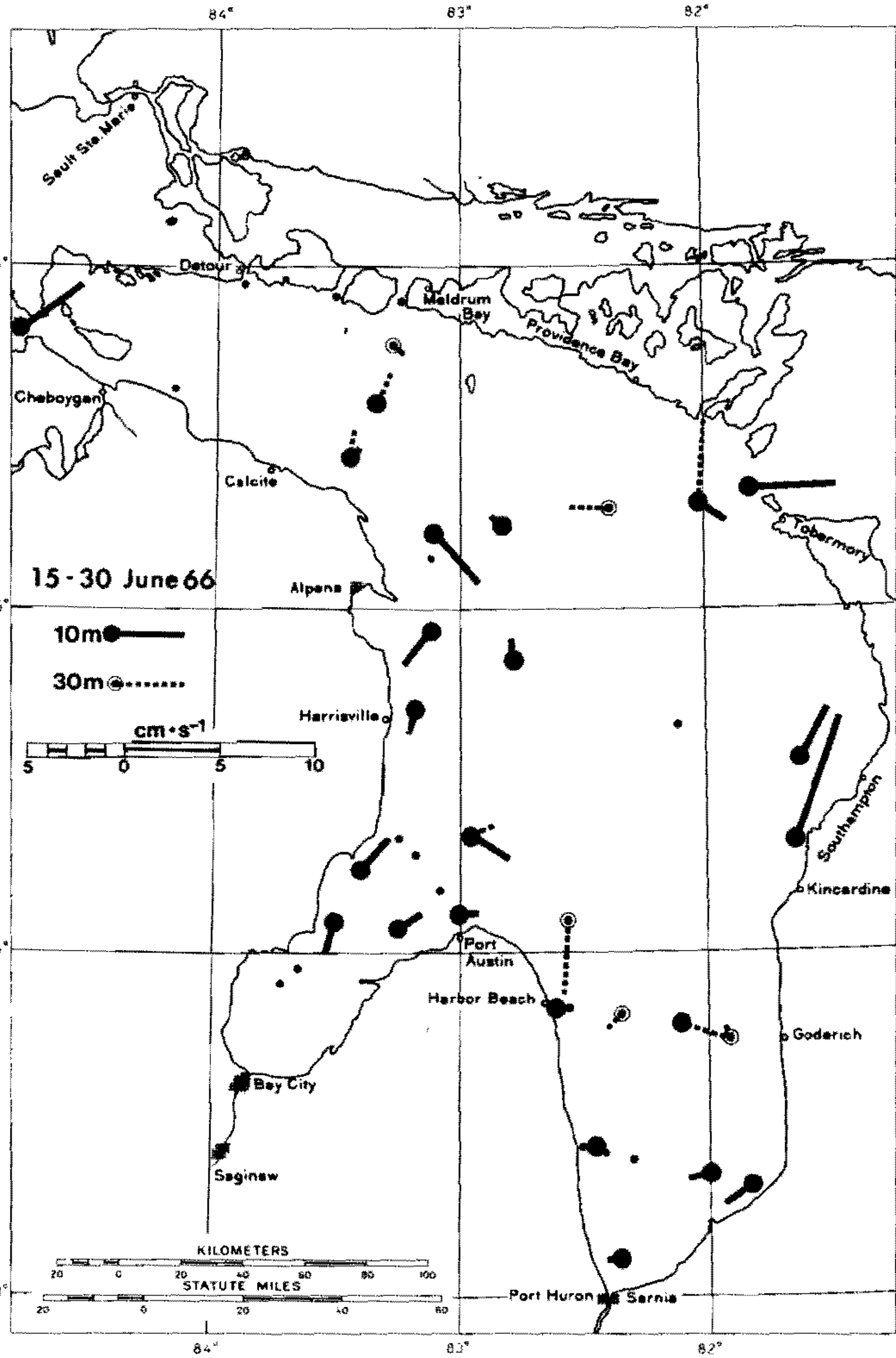

Fig. 2. Half-month average current vectors for June 15–30, 1966. Large solid dots represent operating instruments at 10-m depth, and heavy lines represent flow vectors at 10-m depth. Partially solid circles indicate current vector origins at the 30-m level only.

in the central part of the lake, between 44° and 45° latitude, was less well defined than that 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 flows appear to be responses to the prevailing winds. It should be noted, however, that the direction of surface flow in neither the Straits of Mackinac nor the channel into Georgian Bay necessarily reaches the bottoms of the channels and in fact nearly may be balanced by opposing currents at greater depths (E. B. Bennett, personal communication, 1975).

The second half of July saw three major frontal passages which continued the pattern of prevailing westerly to north-

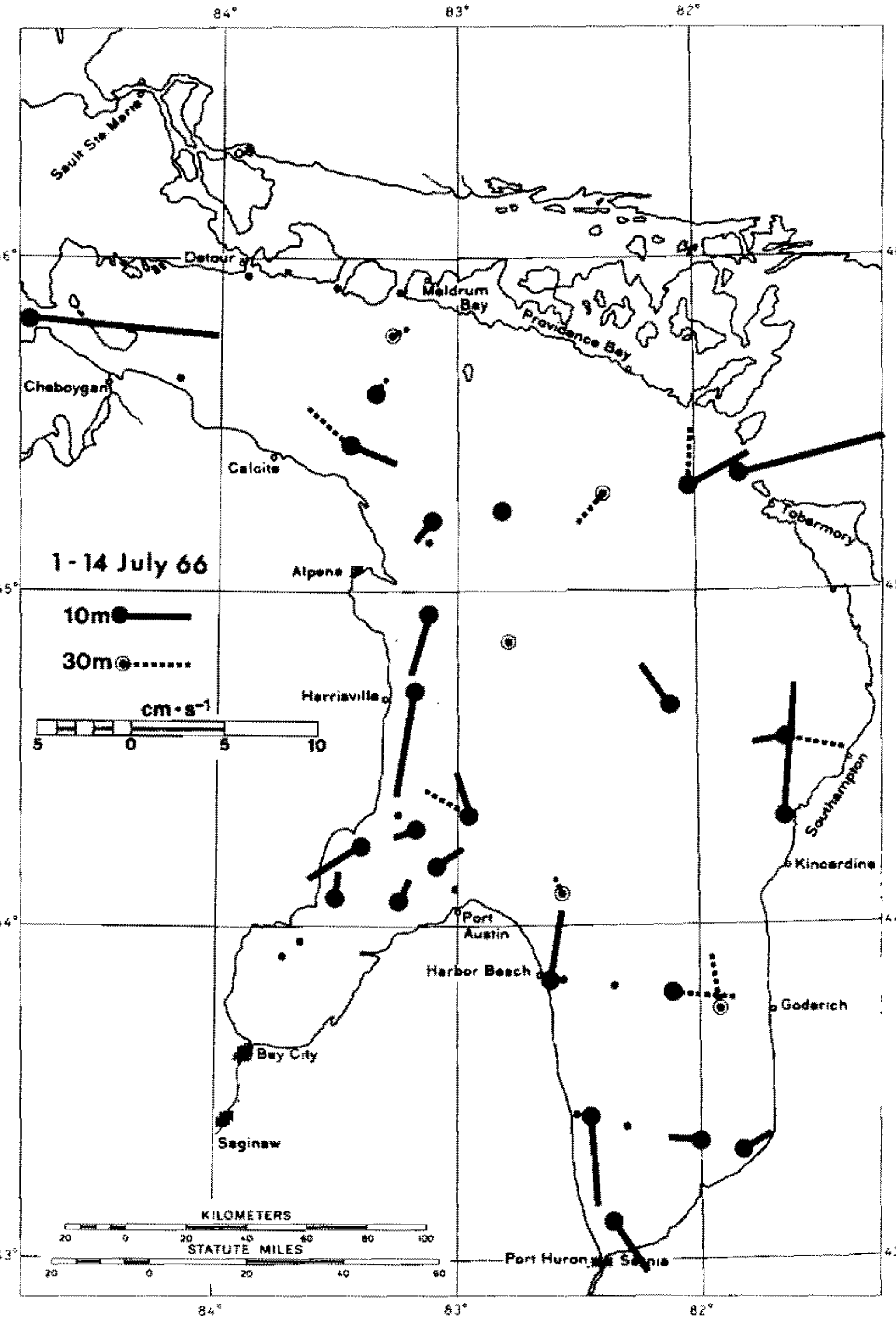

Fig. 3. Half-month currents for July 1–14. Note the reversal between the levels at station 26.

westerly 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, while the winds recorded at stations 11 and 29 had a more north-south bias. It should be noted that for the interval of July 15–31, some 30% 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 July 15–31 reflected the dominance of northwesterly flow, with a strengthening of the southward flow along the Michigan shore, and mean speeds up to 8 cm s^{-1}. The gyre in the central region of the lake retained its identity, while 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},

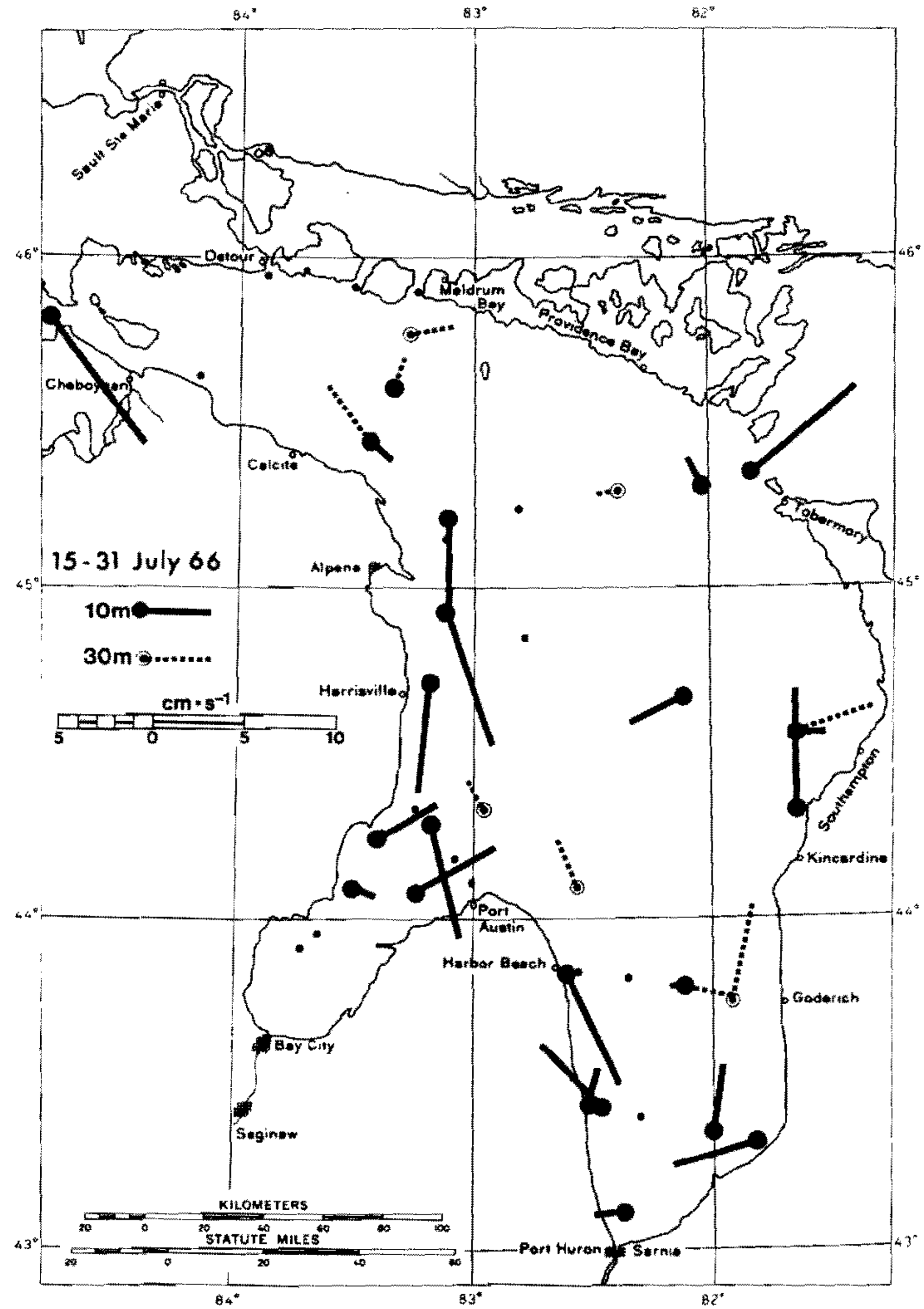

Fig. 4. Half-month currents for July 15–31. Thirty-m flow at stations 15 and 16 runs opposite apparent 10-m depth flow.

alternately eastward and westward, confused the picture. The meter at mooring 32 (Straits of Mackinac) at 22-m depth 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 depth.

The weather maps for August 2, 8, and 14 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 to function. Prevailing winds at station 16 were westerly and southwesterly, while winds at station 11 were largely from the south until a deepening storm over Quebec caused winds to shift around to

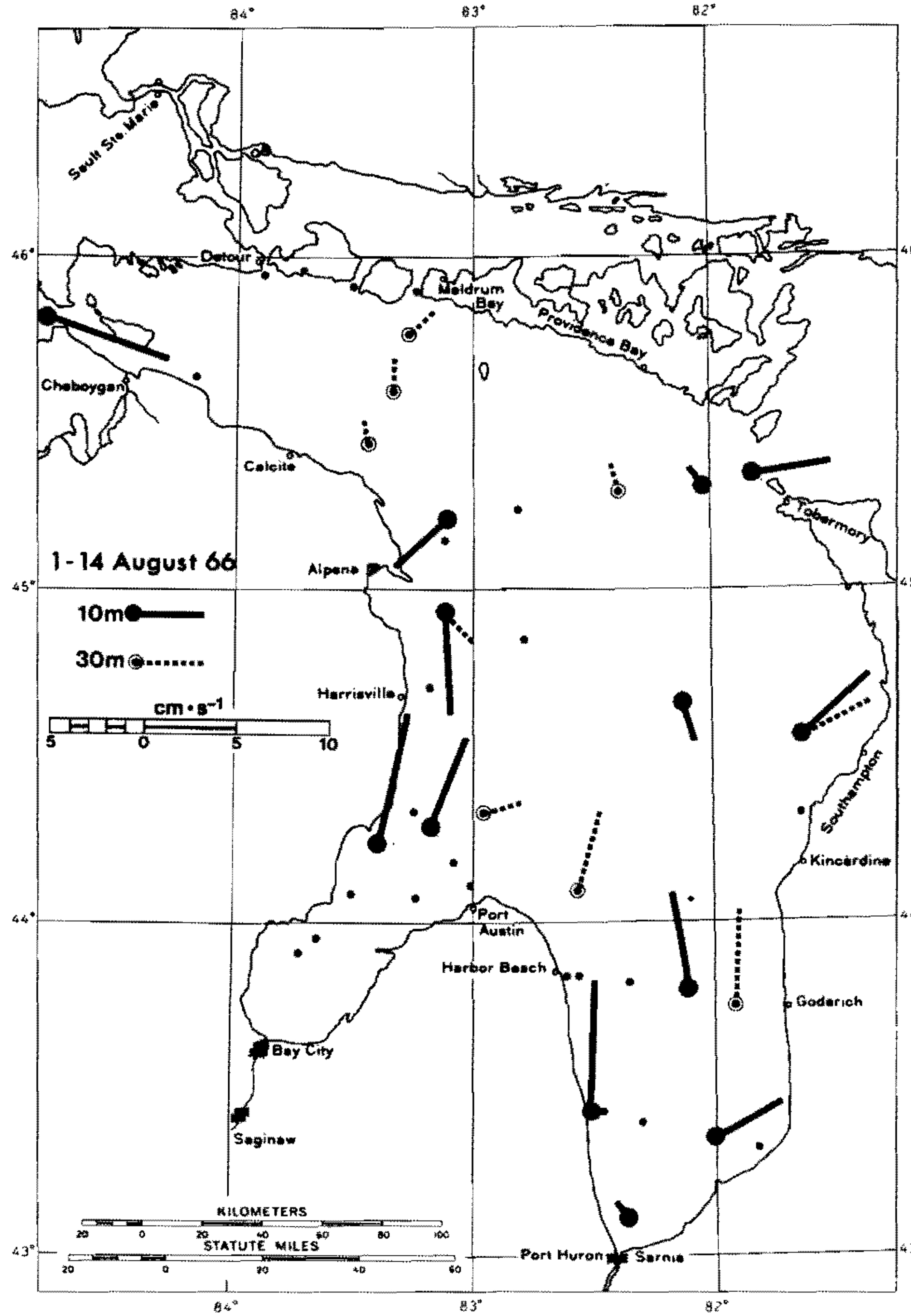

Fig. 5. Half-month currents for August 1-14. Flows at 30-m depth more closely follow the shallow level. The northward flow at moorings 26-28 persists, while the southern part of the lake responds to continued south winds.

the north on August 12. The lack of northerly wind components at station 16 gives cause for the suspicion that the data are not entirely reliable from that meter.

Current patterns determined from the 13 meters still operating during the first half of August show the effects of the more southerly wind flow. In the southern basin, flow was northward along both shores, as was the flow out of Saginaw Bay. There remained evidence of the gyre in midlake, indicated principally by vectors at stations 17, 20, and 21.

In summary, 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 44°N

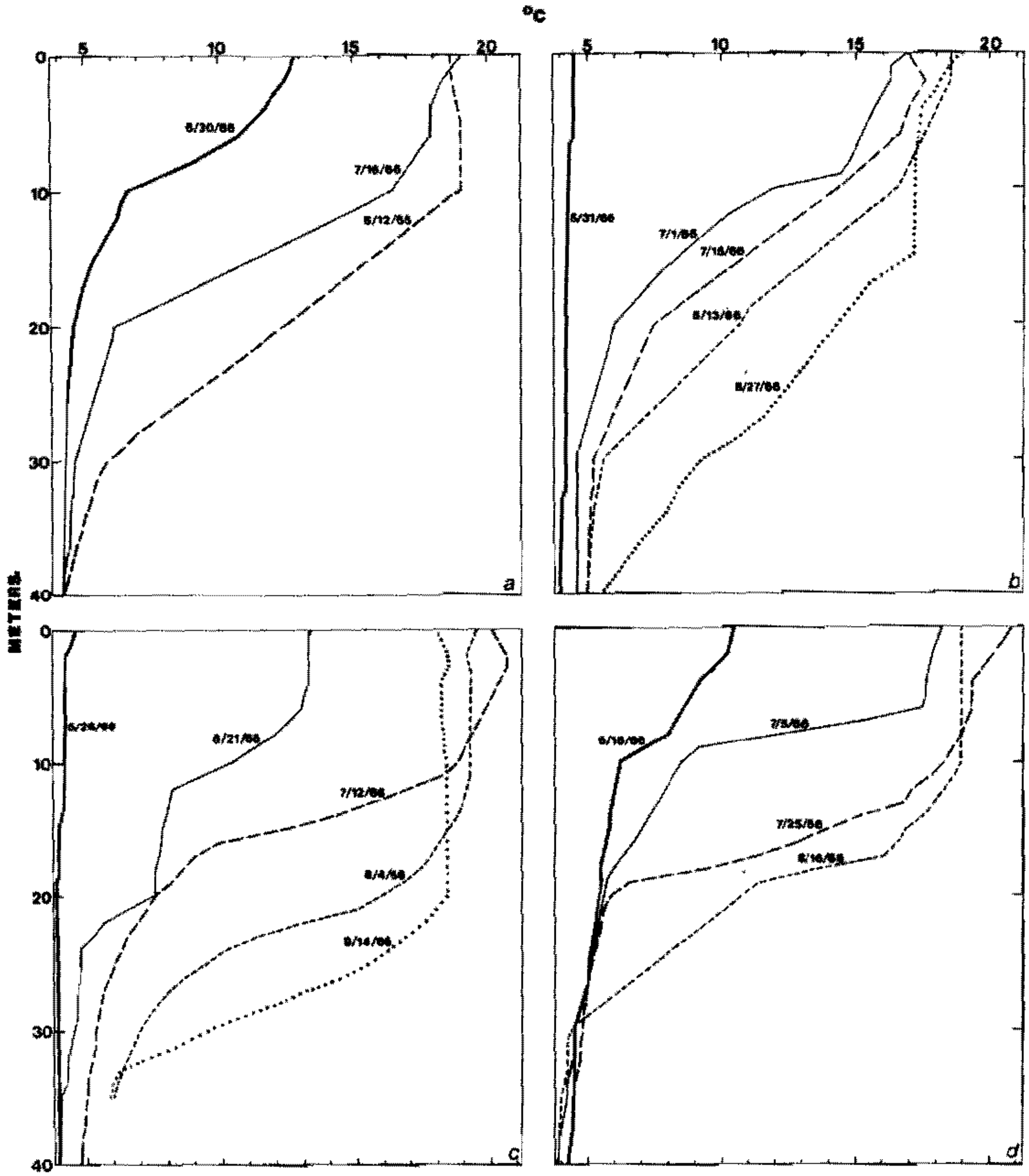

Fig. 6. (*a*) Temperature profiles (bathythermograph) from *R. V. Shenehon* taken near mooring 27. The thermocline passed 10 m in early July but had not reached 30 m by the last date shown. The maximum temperature gradient was 1.0°C m^{-1}. (*b*) Temperature profiles from near mooring 18. The thermocline first touched the 30-m depth at the end of the analysis period. The maximum temperature gradient was 0.7°C m^{-1}. (*c*) Temperature profiles from near mooring 16. The epilimnion first included the 10-m depth at the end of the analysis period. The maximum temperature gradient was 1.6°C m^{-1}. (*d*) Temperature profiles from near mooring 13. The epilimnion reached 10 m in mid-July. The maximum temperature gradient was 2.8°C m^{-1}.

latitude, 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 *Ayres et al.* [1956], and while the response of the lake to meteorological inputs created significant differences, such features as the persistent southward current along the Michigan shore at 45°N latitude and a southwestward (alongshore) flow at the south end of the lake on the Canadian side are common to both sets of observations.

Flows at Depths Below 10 m

Flows at 15-m depth (not shown) generally seem to follow the shallower layer, but the density of observations was not great enough to define circulations. There was a particularly problematical lack of simultaneous reliable data from 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 six moorings provided data at both 10- and 15-m depths in July, and only 11 moorings gave any usable 15-m depth data at all. Missing data are attributable to instrument failures and possible inadequacies in the automated data reduction hardware and processing methods [*Mehr*, 1965, 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 depth

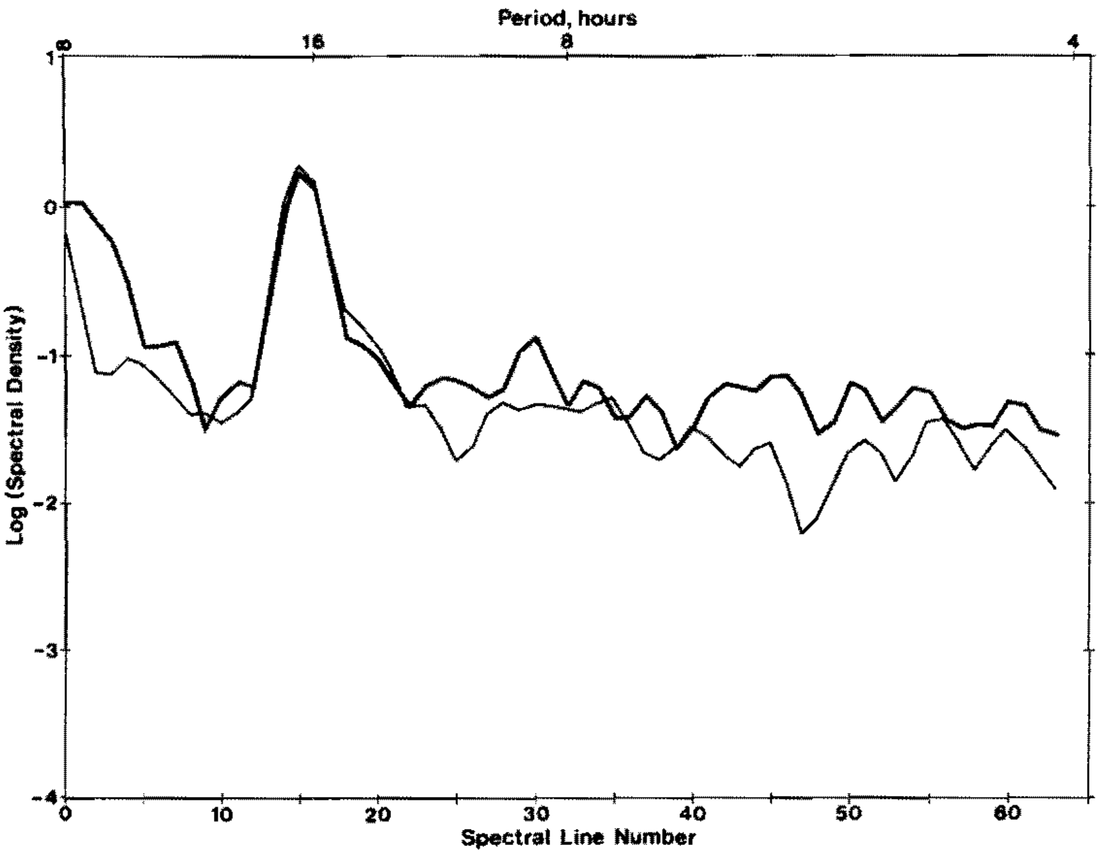

Fig. 7*a*. Power spectra of northward (heavy line) and eastward (light line) hourly velocity components at station 13 at 10-m depth for July 1–16. Only the first half of the computed spectrum is shown; no significant peaks appeared in lines 65–128. The spectral density (power) scale is logarithmic.

set. Half-month flows could be computed at a maximum of 12 moorings for a 30-m depth, and only for the second half of June were that many available. (A more comprehensive synopsis of the available data is presented by *Sloss and Saylor* [1975].)

Existing 30-m depth 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 stream or downstream of this region, but the prevailing winds would have favored upwelling inshore of station 26.

EFFECTS OF THERMAL STRUCTURE

Figures 6*a*–6*d* show temperature profiles taken from the *R. V. Shenehon* of the U.S. Lake Survey Center as part of a separate study. The profiles show that stratification started in early June, 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 are near mooring 27, Figure 6*a*; near mooring 18, Figure 6*b*; near mooring 16, Figure 6*c*; and near mooring 13, Figure 6*d*.

Examination of even these few selected profiles reveals some reasons for the behavior of the current vectors. Figure 6*d*, 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 depth 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 was predominantly northward at station 13 although the inertial component remained. (Spectral 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 happened at mooring 26 throughout July and at mooring 20 in the first half of July.

OSCILLATORY CURRENTS

Spectral computation 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. By following the method of *Gonella* [1972], rotary spectra also were computed. A multispectral averaging technique was employed rather than the prefiltering and subsampling techniques employed 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.

Results of one spectral computation are shown in Figures 7*a* and 7*b*, representing the period of July 1–16 at station 13 at 10-m depth. From Figure 6*d* it appears that the meter in this example was in the thermocline for at least part of the July 1–16 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% lower and 80% higher. The energy of motions with periods of 16–18 hours was almost 60% greater than the energy of all motions

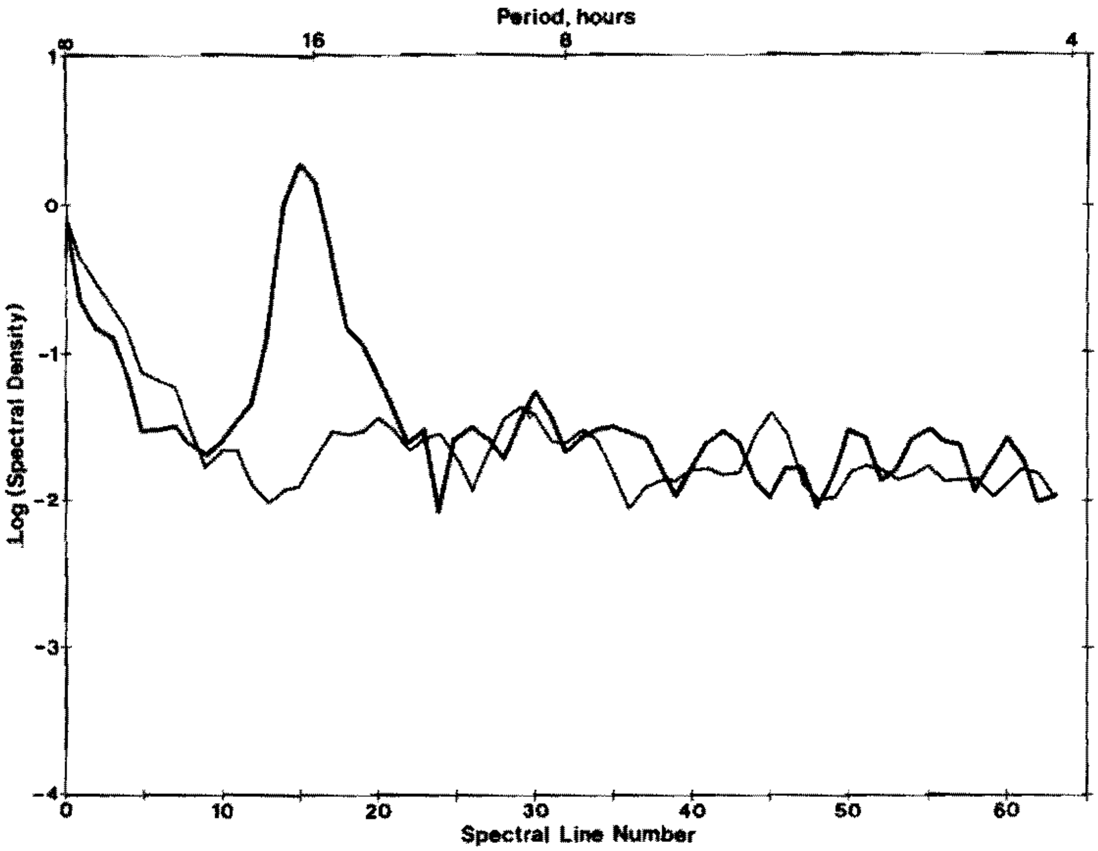

Fig. 7b. Rotational spectra for the case in Figure 7a. The inertial band contains 100 times as much energy in clockwise motions as in counterclockwise motions. (Clockwise motion is denoted by the heavy line, and counterclockwise motion is denoted by the light line on rotary spectra.)

with periods longer than 50 hours. For the interval from July 17 to August 3, energy in the inertial range (16–18 hours) exceeded the energy in long-period motions by 25%. 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.

In contrast to these inertially dominated oscillations the Straits of Mackinac currents were driven by meteorologic scale (about 3 day) oscillations [*Saylor and Sloss*, 1976], the lunar semidiurnal tide, and the seiches of Lake Michigan (8.9 hours) and Lake Huron (6.7 hours) [cf. *Rockwell*, 1966].

SUMMARY AND CONCLUSIONS

The summertime surface circulation of Lake Huron is dominated by a counterclockwise gyre which occupies most of the northern two thirds 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, which are dependent on weather. A ridge separates the southern basin from the deeper main basin, and this bottom feature is followed by the southern boundary of the main gyre, indicated principally by flows at mooring 13. 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; for example, 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 these 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.

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(Received July 18, 1975;
revised January 9, 1976;
accepted January 13, 1976.)