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CURRENTS AND TEMPERATURES IN GREEN BAY, LAKE MICHIGAN*

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ABSTRACT. Current velocities and water temperatures were measured in the four main passages between Green Bay and Lake Michigan and at several sites within the bay during summer and fall 1977. Monthly resultant currents indicate there is anticlockwise circulation in the bay during dominant southwesterly wind and a reversal of this pattern during episodes of northeasterly wind. It is common for two layers to flow through the mouth of the bay in opposite directions during the stratified season. Cold hypolimnetic lake water entering through the mouth and extending far into the bay maintains stratification and promotes flushing. The effects of resonance of forced and free long wave disturbances are prominent in current records; these oscillations are coherent and in phase across the mouth.

ADDITIONAL INDEX WORDS: Lake circulation, water level, thermal stratification, waves, oscillatory waves.

INTRODUCTION

Green Bay, a relatively shallow bay separated from Lake Michigan by the Door Peninsula, is connected to the Lake by four main channels near the northern end – Martin Island Passage, Rock Island Passage, Porte Des Morts Passage (between the Door Peninsula and Washington Island), and Poverty Island Passage. All but Poverty Island Passage are deeper than 30 m and range in width from 2 to 7 km (Fig. 1). The channels are oriented roughly northwest-southeast. The upper half of Green Bay is generally deeper than 20 m, with a maximum depth of 54 m west of Washington Island, though it becomes very shallow in the extreme northern end. The lower half of the bay, south of Chambers Island, is 30 m deep near the island, but becomes very shallow in the southern end.

The water in the very shallow southernmost part of the bay is severely polluted. This is because inadequately treated waste water (primarily from paper mills and municipalities) is discharged into the nutrient-rich waters of the Fox River, which enters Green Bay at the city of Green Bay, Wisconsin, at the head of the bay. Knowledge of the circulation patterns, the responses of water masses to the forces acting upon them, and the seasonal and temporal temperature structure is necessary in order to determine the distribution and impact of pollutants on the aquatic environment of Green Bay.

A review of limnological research pertaining to Green Bay reveals that, with the exception of water levels, few physical data have been collected. Large amplitude water level oscillations, a conspicuous feature in the bay, have been researched most extensively. Mortimer (1965) explained the oscillations in terms of a double resonance between the first free longitudinal mode of the bay (with a period of about 10.8 h), the semidiurnal tide (12.4 h), and the first free longitudinal mode of Lake Michigan (9.0 h) acting at the bay mouth. Mortimer and Fee (1976) examined power spectra of observed levels and Rao *et al.* (1976) applied a two-dimensional numerical method to characterize these barotropic modes of oscillation. Heaps *et al.* (1982) extended the numerical models to include the dynamics of the bay and computed magnification factors between the mouth and head of the bay. Mortimer (1979) recorded current velocities

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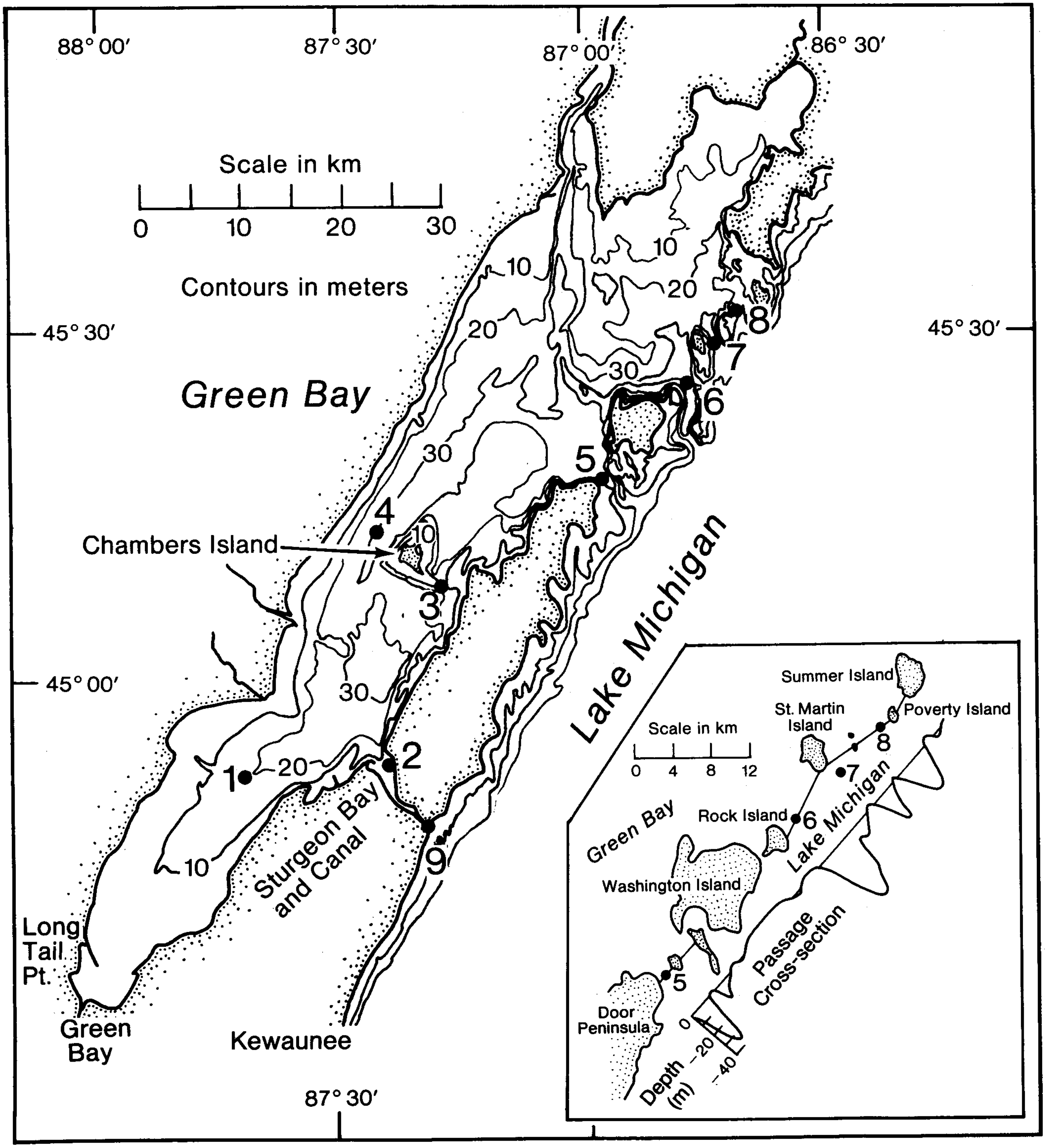


FIG. 1. Green Bay bathymetry, mooring locations, and mouth cross section.

15 m below the surface in Porte des Morts Passage; they correlated well with water level variations, as did earlier current measurements in the Sturgeon Bay Canal (Saylor 1964). Numerical model results for unstratified flow (Heaps *et al.* 1982) agreed with Mortimer's measured currents through Porte des Morts Passage and indicated what flows were to be expected in other regions of the bay.

Limited information on circulation patterns in the lower and middle bay has been inferred from water mass analysis. Moldin and Beeton (1970), using conductivity as a tracer, noted that the Fox River outflow was deflected to the right and flowed northward along the eastern shore as a result of the dominant southwesterly winds and Coriolis deflection. They postulated that there would be compensatory southward flow of diluted Lake Michigan water near the western shore of the bay. Species distribution of diatoms (Holland and Claflin 1975) and zooplankton (Gannon 1974) correlates with the hypothesis that the circulation in the bay is anticlockwise.

Water temperature data are equally sparse. Ahrnsbrak (1971) made two along-the-bay transects in July 1969 and Patterson *et al.* (1975) obtained four cross-bay transects near Sturgeon Bay. The isotherm structure suggested internal wave activity along with the characteristic downward sloping isotherms toward the east. Mortimer (1979) measured temperatures at the current meter site in Porte des Morts Pasage and found oscillations approximately in phase with water level fluctuations.

Because of the many physical questions that remain unanswered and their importance in determining the strategies for improving the quality of Green Bay water, the Great Lakes Environmental Research Laboratory (GLERL) undertook a program to measure currents and temperatures in the four main passages connecting with Lake Michigan and in the interior of Green Bay in an effort to characterize the nature of currents and circulation patterns within the bay, the exchange processes between the bay and Lake Michigan, and the temperature structure. We found that monthly mean currents suggest anticlockwise rotation under prevailing westerly winds. Stratification, extending far into the bay, is maintained by large volume flow into the bay in the hypolimnion with compensating lakeward flow in the upper levels. Large current fluctuations with periodicities of 12.4 and 9.0 h correspond to the semidiurnal (M_2) tide and longitudinal Lake Michigan seiche. These oscillatory currents are in phase across the bay mouth and are coherent with water level fluctuations recorded at the city of Green Bay.

OBSERVATIONS

Eight moorings using 14 EG&G vector-averaging current meters with integral temperature sensors were deployed in May 1977 (Fig. 1). Each mooring consisted of a meter 12 m below the surface and, depending on water depth, a second meter 5 m above the bottom suspended in a taut line beneath a subsurface float. All moorings included an acoustic release just above the mooring anchor and, in the event of release failure, a 180 m ground line that could be hooked with a grapnel. In July 1977, one additional current meter was suspended several meters out from the canal wall at the lakeward end of the Sturgeon Bay Canal (mooring 9).

Because of problems with the acoustic release electronic command equipment, only four moorings and the Sturgeon Bay Canal meter were recovered in October 1977; the remaining four moorings were retrieved in May 1978. The recording capacity for the four moorings retrieved in 1978 was reached in mid-January. Several meters developed electronic problems and the rotor on the Sturgeon Bay Canal meter was apparently fouled much of the time. The sub-surface float on the Porte des Morts Passage mooring was hit by the propeller of a freighter on 9 September and the mooring sank. In spite of these problems, over 80% of all possible data was collected.

Ancillary data were obtained from various sources. Hourly water level data from Green Bay, Sturgeon Bay, and Kewaunee, Wisconsin, were obtained from the National Ocean Survey, National Oceanic and Atmospheric Administration. Tri-hourly wind data from the meteorological stations at Green Bay and Milwaukee, Wisconsin, were taken from National Weather Service published summaries. Tributary inflow values from published data (USGS 1977, 1978) represent gaged flow for approximately 83% of the Green Bay drainage basin.

RESULTS

Monthly Mean Currents and Temperatures

Because shallow bays and lakes respond rapidly to transient forcing, transient effects can dominate over steady low-level forcing for short intervals of time. Averaging on a monthly time scale, steadier patterns of circulation can be inferred by considering net resultant currents. Because the monthly resultants reveal similar flow patterns, we suggest they represent the steady component of bay circulation.

All current meters were deployed by 4 May 1977. Figure 2a shows the resultant current and wind vectors for that month. With the exception of the 5 cm s^{-1} current in Porte des Morts Passage, resultant speeds were less than 1.5 cm s^{-1}. May is characteristically the month when kinetic energy in the Great Lakes is at a minimum (Saylor and Miller 1979, Bennett and Saylor 1974). Strong atmospheric stability develops when warm air flows over cold water bodies, and therefore, the momentum flux to the water surface is minimal. Although the resultant wind from Green Bay was 0.5 m s^{-1} from the southeast, the two prevailing directions were southwest and northeast. These bimodal winds also contributed to the low resultant currents.

The magnitude of the resultant vectors increased during June, and a characteristic flow pattern began to emerge in response to decreased atmospheric stability over the bay and more frequent southwesterly winds (Fig. 2b). Flow through the passages was bayward at all lower levels and generally lakeward at the 12-m depth. West of Chambers Island, flow at 12 m was southwestward, while the 26-m depth resultant current vector oriented perpendicular to the shoreline was the result of bimodal currents. The lower bay current direction at mooring 1 was westward, a feature that persisted throughout the summer. Since the lower bay is shallow (<20 m), the 12-m depth currents are return flows to compensate for northeastward wind-driven surface current. Drift bottle results showed a northeastward surface flow over the southern portion of the bay (Howmiller and Beeton 1971). Temperatures associated with these westward currents at the 12-m depth indicate that the water originated in the northern bay.

The net circulation pattern takes on an anticlockwise rotation with inflow mainly in the lower layers through the passages, flow down the western shore, northward flow along the eastern side of the bay, and epilimnion flow into Lake Michigan through the southern passages. The anticlockwise flow pattern is consistent with previously measured east-west gradients of water properties in the bay, such as conductivity and transparency (Moldin and Beeton 1970).

Currents during July (Fig. 2c) were similar to those observed in June. Two characteristics of the flow regime through the connecting passages are noteworthy. Firstly, the epilimnion flow conforms to the general anticlockwise flow pattern in the bay; net flows were directed lakeward through the southern two passages and bayward in the northern two passages. Secondly, the large magnitude of the resultant currents 5 m above bottom in the southern passages suggests that large volumes of cold lake water (on the order of 4×10^3 m^3 s^{-1}) intrude into the bay. The southward flow in the western half of the bay suggests that the anticlockwise circulation pattern continued with the predominance of southwesterly winds. Current vectors from mooring 2 in Sturgeon Bay are not easily interpreted. The monthly resultants are generally east-northeastward, which may be the result of bimodal currents through the canal or the product of a small-scale circulation pattern within Sturgeon Bay itself.

The wind remained southwesterly and again the net flow during August was similar to previous months although there was a general slackening of the current (Fig. 2d). Net flows through the northern passages were small. The middle bay current remained unchanged in magnitude and direction. Although measurements were not collected in the extreme southern part of the bay, sediment samples suggest that the anticlockwise pattern exists down to Long Tail Point. Howmiller and Beeton (1970) reported that highly organic black-brown, foul-smelling mud occupied the extreme southern end of the bay (which is dominated by the Fox River effluent), brown silt northeast from the Fox River along the eastern shore, and sand along the western shore. This distribution is consistent with the current data results.

The resultant currents decreased further in magnitude and the pattern became more unorganized during September (Fig. 2e). Only 8 days of data are available from the Porte des Morts Passage mooring and they are not included on the figure. September was the only month with lakeward flow near the bottom at mooring 6. During this month the thermocline weakens and deepens, resulting in lower shear velocities and more uniform flow from surface to bottom. Therefore, the decrease in current magnitude does not necessarily result in decreased volume transport through the bay mouth.

Of the meters on the four moorings left through the winter, only the two meters on mooring 8 and

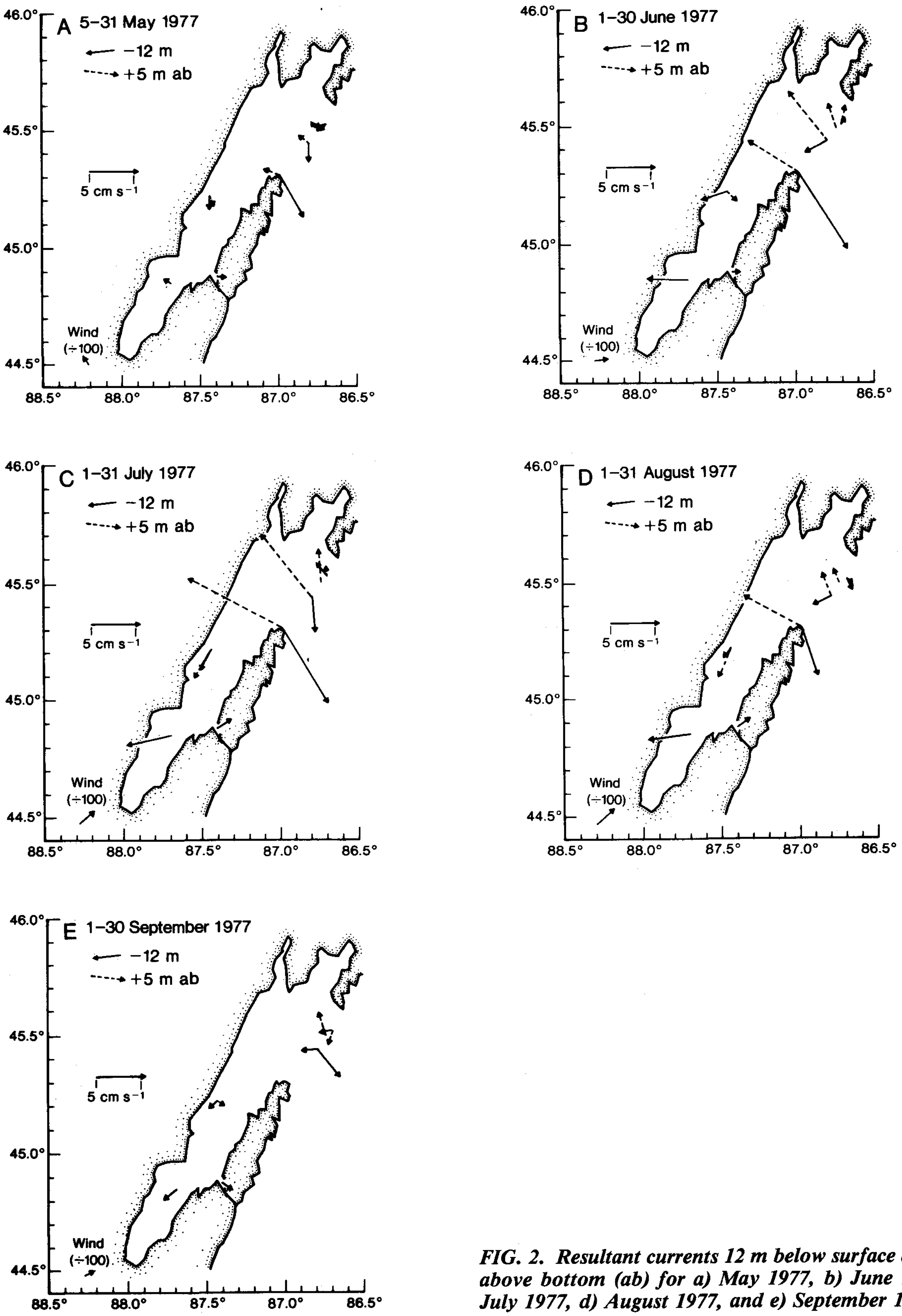


FIG. 2. Resultant currents 12 m below surface and 5 m above bottom (ab) for a) May 1977, b) June 1977, c) July 1977, d) August 1977, and e) September 1977.

the two on mooring 6 recorded current data to mid-January. The resultant current vectors for October through December (not shown) indicate bayward flow at both levels at mooring 6, lakeward flow at the 12-m depth, and weak bayward currents near bottom at mooring 8. Scalar mean speeds were 6-9 cm s^{-1}; however, the resultant speeds were less than 3 cm s^{-1}.

Although the 1977–78 winter was the 12th coldest winter since 1850, ice cover did not extend to the entrance of the bay until 4 January 1978 (Assel *et al.* 1979). For approximately 2 weeks, ice extended across the bay entrance so that moorings 6 and 8 were near the ice boundary; however, effects on currents were not obvious. The mean and resultant speeds for the first 2 weeks in January were similar to those for previous months. Speeds decreased on 5 and 6 January, but with 6-9 m s^{-1} northwesterly winds during 9 and 10 January, bayward currents of 35 cm s^{-1} were measured at both levels at mooring 6. Meanwhile at mooring 8, flow was lakeward at 20-25 cm s^{-1}. The water temperature fell to 0°C at all levels during the storm.

Monthly mean temperatures show the seasonal progression of a dimictic water body (Fig. 3). Temperatures at the time of deployment were about 4°C, and warming was slow during May. Heating accelerated during June, and the characteristic summer stratification developed. Mean monthly temperatures of 16–17°C were reached in August at the 12-m depth. An exception to this progression occurred in the lower bay at mooring 1. After a rapid rise from 7°C in May to 15°C in June, the mean temperature decreased slightly during both July and August. The decrease in warm Fox River inflow from 187 m^3 s^{-1} in May to 102 m^3 s^{-1} in August and the establishment of a persistent circulation pattern bringing cool lake water southward into the lower bay is reflected in the temperature decrease. By September the water column was nearly isothermal in the northernmost passage at mooring 8. However, in the middle bay at mooring 4 in nearly equal water depth, a 5C° gradient similar to that at mooring 6 was still evident. We can infer this stratification also at nearby mooring 5.

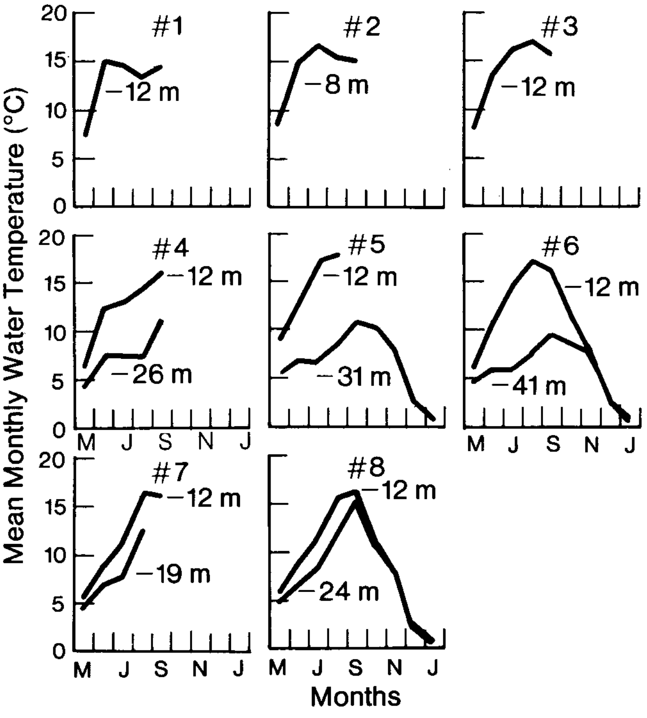
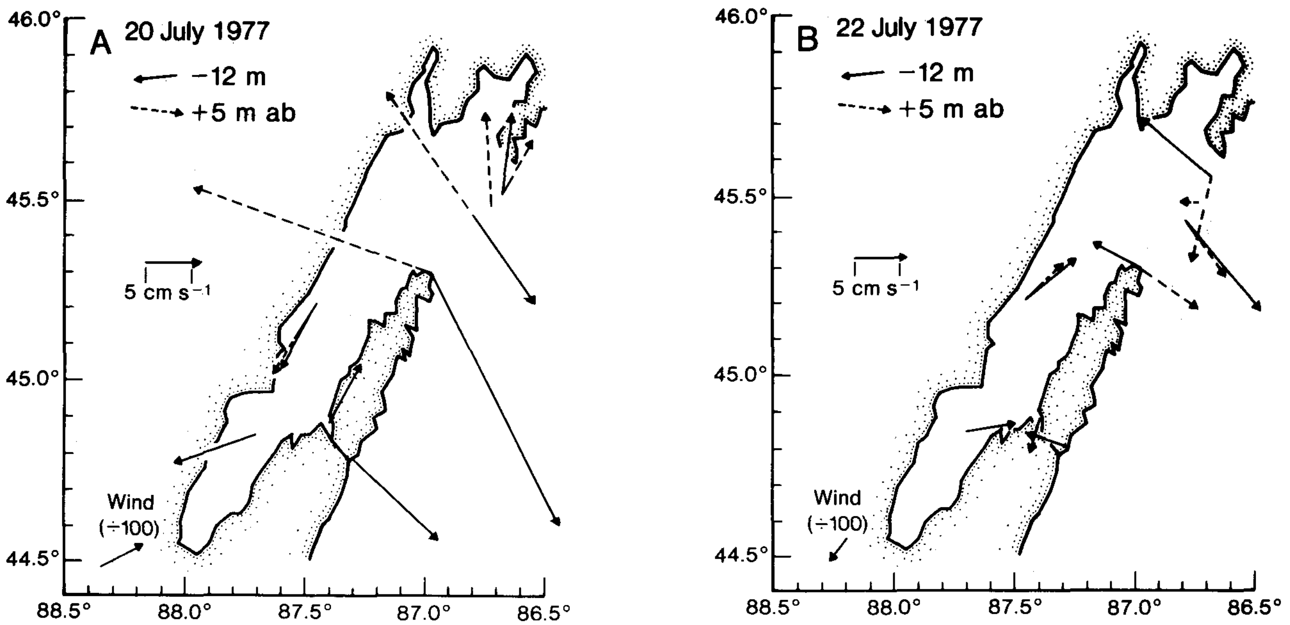


FIG. 3. Mean monthly water temperatures

Current and Temperature Fluctuations

Currents in Green Bay are driven by wind, water level changes at the mouth, and the flow-through of precipitation and tributaries. The response of the currents to varying wind stress and level variations can be seen from examining daily resultant currents. Heaps *et al.* (1982) determined from model results that the circulation in the bay becomes steady within about 12 h of the onset of the wind. An episode of alternating wind from the southwest and northeast with a 2-day periodicity during 19–24 July 1977 illustrates the episodic current response. Current vectors on 20 July (Fig. 4a), during the second day of southwest wind, were very similar to the July and August monthly mean patterns (Figs. 2c and 2d). The water level was steady. During 21 July, the wind veered northeasterly with a speed over 4 m s^{-1}; this continued into the next day (Fig. 4b). The current pattern reversed; the western shore water moved northward, hypolimnion flow through Porte des Morts Passage was lakeward, and epilimnion flow bayward. The wind then returned to the prevailing southwest direction for the next 2 days and by 24 July the familiar circulation pattern seen 4 days earlier was reestablished (Fig. 4c).

A two-dimensional numerical model to investigate the response of the bay to wind stress was developed by Heaps *et al.* (1982). With the forcing of northeasterly wind, model results displayed a flow with the wind along both shores, return flow along the central axis, and anticlockwise flow around Chambers Island, in the northern bay, and



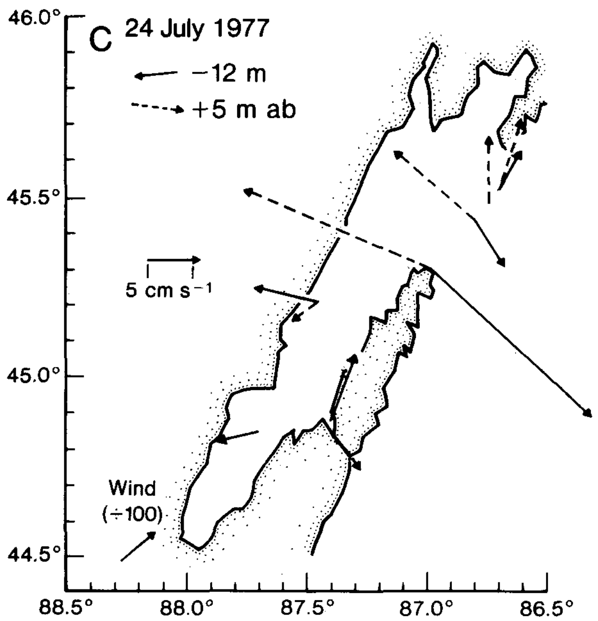


FIG. 4. Daily resultant currents: (a) 20 July 1977, southwest wind, (b) 22 July 1977, northeast wind, and (c) 24 July 1977, southwest wind.

through the mouth. Comparing the model results with measured currents under similar wind forcing (Fig. 4b) yields some similarities. However, it is evident from the large vertical shears measured in the passages that a vertically integrated model will not produce comparable results; stratification plays an important role and must be taken into account.

Time series of selected hourly, low-pass filtered currents, water temperatures, wind, and water level data from July and August 1977 display the range of frequencies present (Fig. 5). The smooth curves are cosine-Lanczos filtered to eliminate periodicities of less than 24 h, and the current components have been rotated to conform to local bathymetry. The filtered data illustrate the slowly varying water elevations in response to mesoscale wind forcing and, in turn, the response of currents and temperatures on a longer than daily scale. Note that the flow reversal in the bay with northeast winds during 21–22 July (Fig. 4b) also markedly affects the water temperature. During this episode of northerly wind, the temperature increased 5C° at mooring 1 and mooring 4 west of Chambers Island (northward flow) and decreased 8C° at mooring 3 east of Chambers Island (southward flow) in response to clockwise rotation. When the thermocline was near the 12-m depth, water temperature fluctuations in the eastern half of the bay were generally in phase (moorings 3 and 5) but out

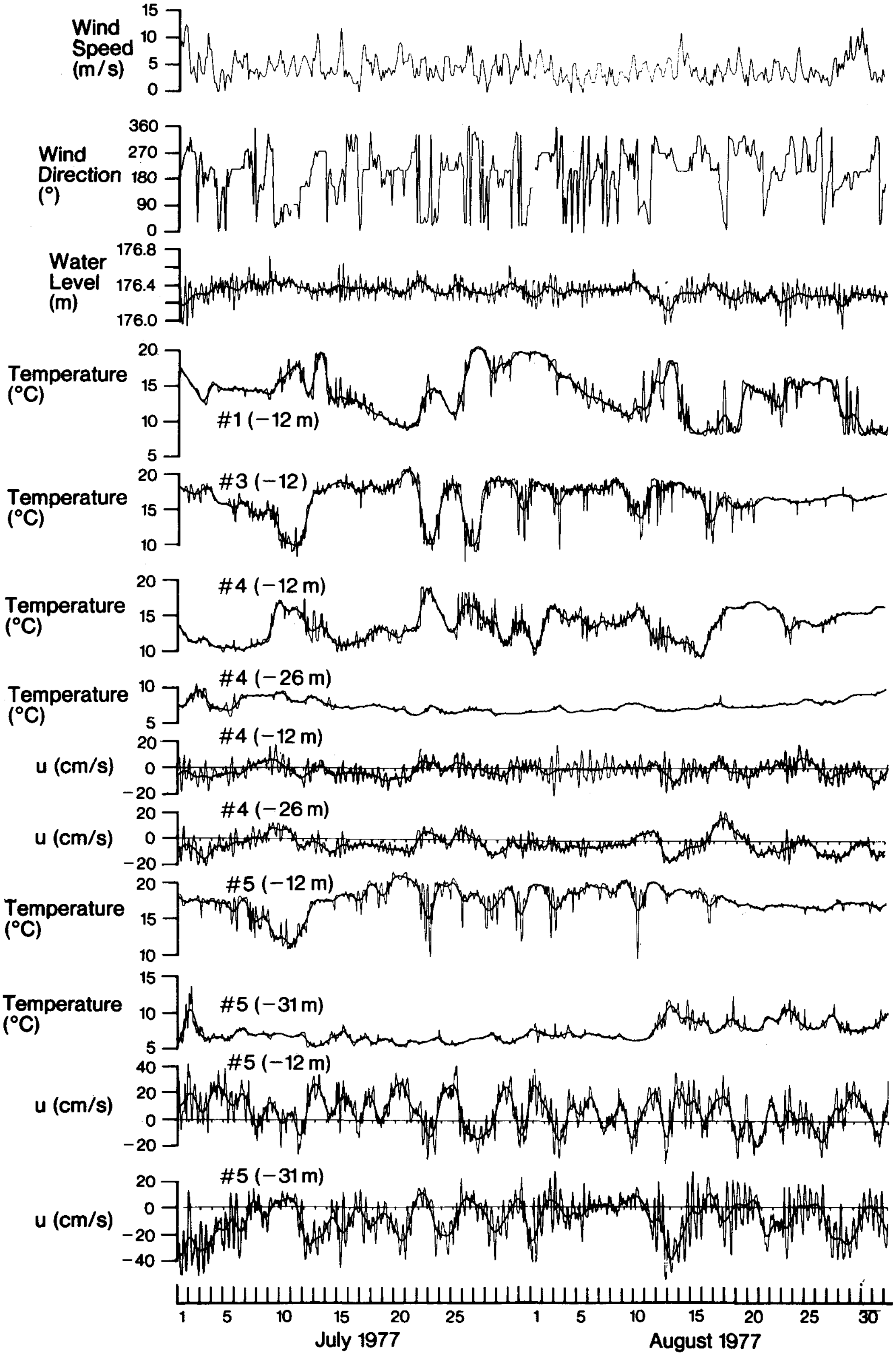


FIG. 5. Hourly and low-pass filtered current and temperature data from selected moorings, Green Bay water levels, and wind velocity, July-August 1977.

of phase with temperatures in the western and northern bay areas (moorings 1, 4, and 8) for oscillations with frequency less than 1 cpd. These water temperatures are clearly correlated with the two circulation patterns illustrated in Figure 4.

An important feature, seen also in the monthly resultant currents, is the out-of-phase two-layered flow through the mouth, particularly through Porte des Morts Passage (mooring 5) and Rock Island Passage (mooring 6). Epilimnetic water flows lakeward and is compensated for by cold hypolimnetic water moving into the bay. There are sometimes current shears to 60 cm s^{-1} between the 12 and 31-m depth at mooring 5. The level of zero flow cannot be determined from our data, but is assumed to be near the thermocline. The constancy and intensity of the two-layered flow during the stratified season is shown in Table 1. The means of the positive and of the negative longitudinally directed component of current velocity and the percentage of occurrence for each direction are tabulated for each mooring in the bay mouth and for mooring 4 west of Chambers Island. The persistent velocity shear and the large mean speeds illustrate the large volume flux through the Porte des Morts Passage. Using the cross-section area and assuming that the zero-current depth is at the thermocline and that the thermocline is at a normal depth for the season, the estimated mean inflow of cold lake water through Porte des Morts Passage for June, July, and August is roughly 800 m^3 s^{-1}. Similarly, the hypolimnion bayward flow rate at mooring 6 is computed to be about 2,100 m^3 s^{-1}. The northern two passages exhibit very small bayward currents and the mean cold water inflow is about 350 m^3 s^{-1}. At midbay west of Chambers Island, flow at both levels was southward for the same three summer months at roughly 4,000 m^3 s^{-1} flow through the cross section. This estimate may be a little high since near-surface currents are possibly directed northeastward by the prevailing winds. The large volume of cold water entering the bay, traced by both water temperatures and flows, has important implications, particularly for flushing rates.

The "emptying time" for Green Bay was computed to be 6.0 yr using mean annual tributary inflow of 336 m^3 s^{-1} and an excess of 18 m^3 s^{-1} from precipitation-evaporation (Mortimer 1979). When the hypolimnetic inflow through the mouth region (which we have estimated to be about 3,300 m^3 s^{-1}) is added, the emptying time is reduced by a factor of ten to 0.6 yr. Of course this emptying time concept may not be realistic because all of this water may not be resident in the bay long enough for full mixing, but it does give a yardstick by which the effect of communication with Lake Michigan can be gaged. Moldin and Beeton (1970) computed a flushing time of 261 days for Fox River water from conductivity measurements throughout the bay in July 1969. Their computation, based on estuarine methods, assumes that the spatial conductivity reflects the mixing between two distinct water masses—the Fox River and Lake Michigan. In Green Bay, however, this method becomes more complex because other tributaries have vastly different conductivities than Fox River (400 μmhos) or Lake Michigan water (270 μmhos). For exam-

TABLE 1. Frequency of occurrence and mean speed of bayward (−) and lakeward (+) currents (1977).

Mooring	depth	May				June				July				August				September			
		+		−		+		−		+		−		+		−		+		−	
		FO*	V†	FO*	V†	FO*	V†	FO*	V†	FO*	V†	FO*	V†	FO*	V†	FO*	V†	FO*	V†	FO*	V†
8	−12	51	3.3	49	−4.1	54	3.8	46	−4.1	34	5.3	66	−4.8	53	6.7	47	−5.4	53	5.7	47	−7.5
	−24	47	4.5	53	−4.0	47	4.1	53	−4.9	46	4.8	54	−5.1	53	5.5	47	−5.3	58	4.8	42	−5.4
7	−19	40	2.2	57	−2.9	30	2.2	70	−4.2	24	3.4	76	−5.2	37	3.7	63	−4.4	No data			
6	−12	59	4.7	41	−4.0	44	5.2	56	−4.7	61	8.0	39	−5.1	46	4.4	54	−4.4	43	4.2	57	−4.4
	−41	43	4.7	57	−5.4	30	5.4	70	−11.0	23	5.5	77	−12.2	47	7.2	53	−10.6	70	9.8	30	−11.8
5	−12	73	10.7	27	−11.2	79	13.5	21	−6.7	74	15.3	26	−9.4	63	12.9	37	−9.7	No data			
	−31	43	8.0	57	−8.4	34	8.5	66	−13.4	30	5.7	70	−17.8	38	8.1	62	−15.6	No data			
4	−12	38	3.5	56	−4.2	34	3.3	66	−4.5	35	4.4	65	−5.9	48	4.6	52	−6.1	45	4.0	55	−4.1
	−26	42	4.4	56	−4.1	46	6.7	54	−6.2	28	5.2	72	−6.8	28	6.0	72	−6.8	50	5.4	50	−5.7

*Frequency of occurrence (%).

†Mean speed (m s^{-1}).

ple, the Menominee River has nearly the same flow rate as the Fox River but one-half the specific conductivity (Moldin and Beeton 1970). Even with the simplifying assumptions though, the flushing time computed from the mixing model is very close to the renewal time calculated on the basis of volume and inflow.

Large amplitude oscillations with periods shorter than 24 h present in all nonfiltered hourly data (Fig. 5) are the result of free long wave disturbances in water level originating in Lake Michigan and forced tidal modes that act at the bay's entrance. Mortimer (1965) demonstrated that Green Bay resonates with the first free mode of Lake Michigan (9.0 h) and with the M_2 semidiurnal tide (12.4 h), producing large amplitude water level variations that have been noted from the time of the early explorers. Heaps *et al.* (1982) computed that the magnification factors at the head of the bay are 9.8 for the first longitudinal lake mode and 3.5 for the M_2 tide, with phase increases of 166° and 5°, respectively.

Spectral analysis was performed on measured current velocities; selected spectra are presented in Figure 6a,b. Current components were rotated to coincide with the local bathymetric orientation except for mooring 1 where the north-south component was used. Record lengths generally extended from May through September 1977. Included on the figure are vertical lines identifying the frequencies of the normal models of Lake Michigan (LM_i) and Green Bay (GB_i), the M_2 tide, and the inertial frequency (f) (Rao *et al.* 1976). The most obvious features displayed in all current spectra are energy peaks corresponding to the lowest barotropic Lake Michigan mode and the semidiurnal tide. The second lake mode is prominent in all spectra except mooring 4. The second Green Bay mode is immersed in this peak and identifiable as a small peak or shoulder in several spectra. Energy at near-inertial frequency ($f = 0.058$ cph) verifies the presence of Poincaré type waves within the bay. Rotary spectral techniques clearly reveal the characteristic clockwise rotating inertial period currents seen at mooring 1.

The first free Green Bay mode (0.093 cph) observed by Mortimer (1965) and Rao *et al.* (1976) does not appear in our water level spectra or in the current spectra. Mortimer (1965) pointed out that excitation may be restricted to occasions when the forcing function is limited mainly to the bay and does not set the main lake into motion. Therefore, in the spectra from long data records, an accumulation of energy at this frequency tends to be immersed in the broad M_2 tidal and first lake mode frequency band. The water level spectrum from Sturgeon Bay, Wisconsin, at the lakeward end of the canal, showed a strong semidiurnal peak and significant coherence with Green Bay, lesser peaks at 9 and 5 h, and no energy at 4.1 h.

The partitioning of spectral energy was nearly identical during summer stratification and isothermal conditions in fall and early winter (Fig. 6b, mooring 8). Vertically the spectra are nearly identical, e.g., mooring 6 at depths of 12 and 41 m. Wind velocity spectra (not shown) computed using tri-hourly data from Green Bay and Milwaukee indicate that energy is concentrated at long periods—153, 96, and 60 h—and at the diurnal frequency similar to all land station wind spectra at midlatitudes. Water temperature spectra characteristics depend on the location of the sensor relative to the thermocline. When the thermocline was near the sensor depth, the temperature spectra showed energy peaks at the same frequencies as the current and water level. Temperature spectra sensors near the bottom showed much less total energy and no peaks at specific frequencies.

In addition to computing the resonance magnification and response of the bay to wind forcing, Heaps *et al.* (1982) investigated the water level and current responses to excitation by long wave disturbances entering the bay from Lake Michigan. To summarize their findings, for the 9.0 h first free lake mode the water level variations at the mouth are out of phase with levels at the head and the currents at the north end of the mouth are in unison with mouth elevation changes but with progressively later phase (up to 90%) when proceeding southward across the mouth. The 10.8 h mode is nearly in phase over the entire length of the bay. The currents across the mouth again change in phase from north to south and lead the in-phase levels by 90°-180°. The tidal mode (12.4 h) is very similar to the 10.8 h wave with in-phase elevations along the bay's length. Although their model performed reasonably well, discrepancies were encountered in the comparisons of modeled and measured water levels. These discrepancies were attributed to inaccurate wind stress estimates over the bay and underestimates of the inflow-outflow of the whole bay.

The 1977 experiment did not include water level measurement at the mouth; however, phase relationships between measured water levels at Green Bay and currents in the mouth are qualitatively

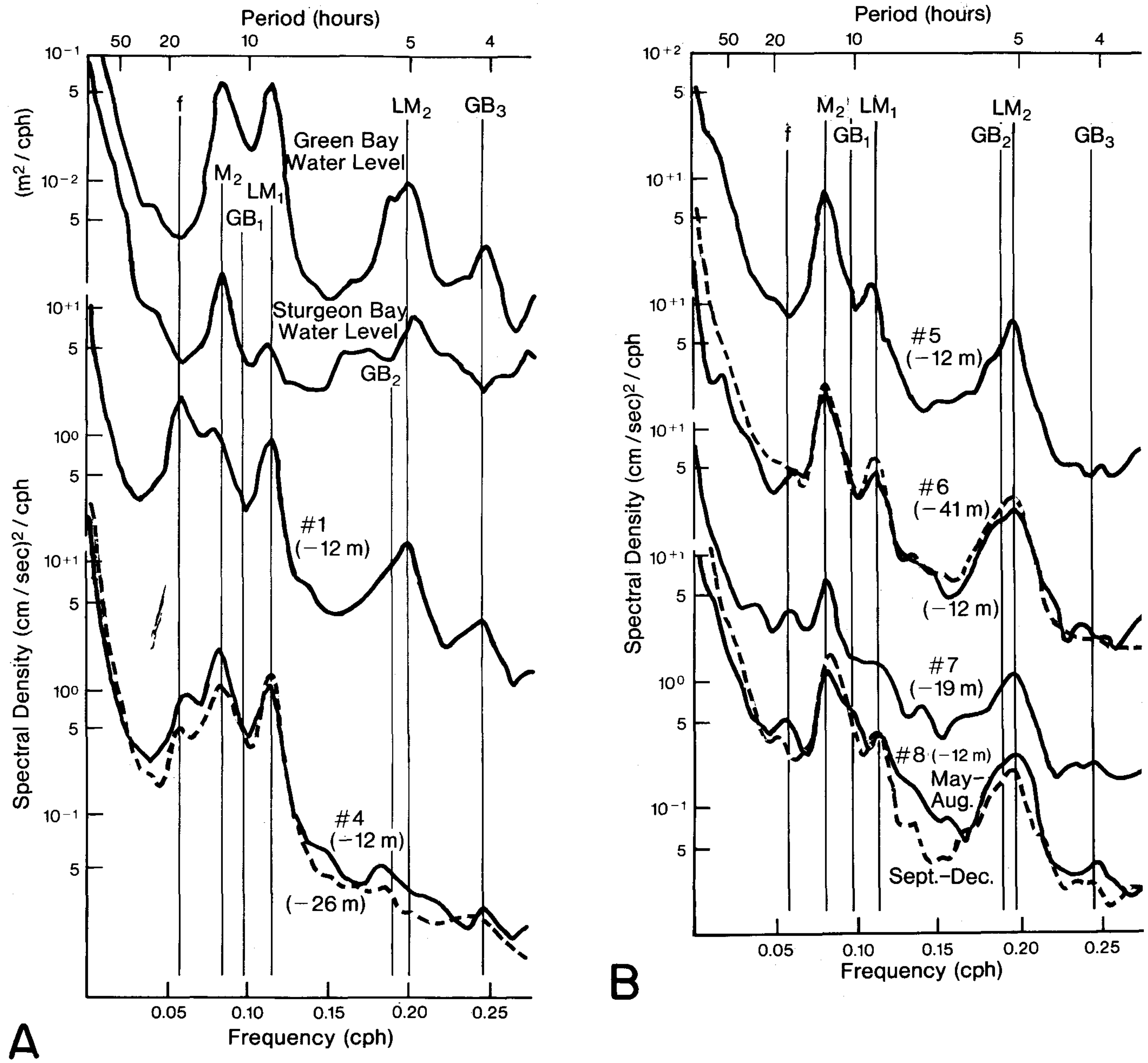


FIG. 6. Spectra estimates from: (a) Green Bay and Sturgeon Bay water levels and moorings 1 and 4; (b) moorings 5, 6, 7, and 8. Vertical lines indicate Lake Michigan modes (LM_1, LM_2, LM_3) and Green Bay modes (GB_1, GB_2, GB_3). M_2 is the semidiurnal tide and f is the inertial frequency. Dashed spectral curves from deep meters on moorings 4 and 6, and fall-winter spectrum from mooring 8.

illustrated by a 9-day period in June (Fig. 7). The water level at the head lags the mouth currents by 2-3 h. Across the mouth from mooring 5 in the south to mooring 8 in the north, the currents are exactly in phase horizontally and vertically. Cross-spectral computations from Green Bay water levels and currents at moorings 8 and 4 (12-m depth) for the entire measurement season show greater than 99% coherency throughout the 0.117-0.075 cph frequency range, with the water level leading the current by 130° (Fig. 8). (Rotating the coordinates to correspond with the Heaps *et al.* [1982] convention of the positive current component bayward then translates to a phase of −50°; that is, the

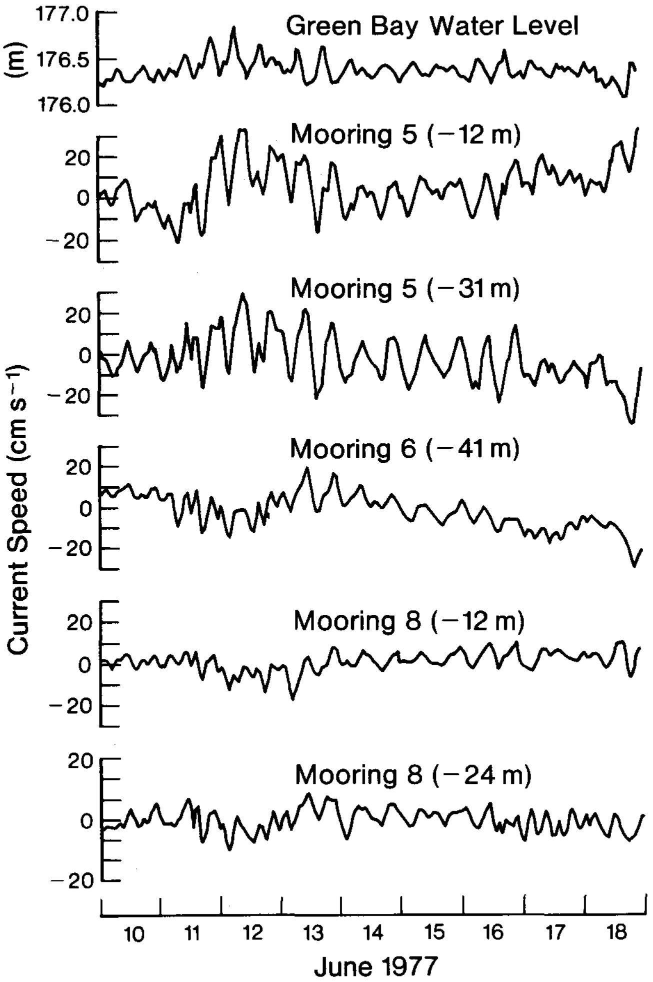


FIG. 7. Hourly currents through the mouth and Green Bay water levels, 10–18 June 1977.

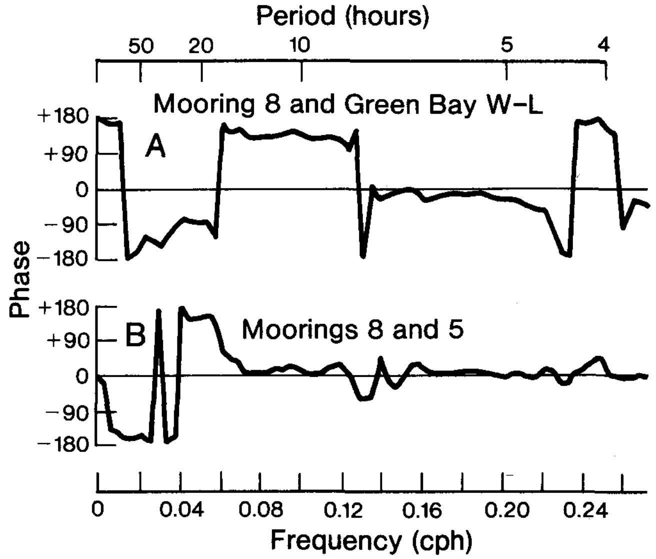


FIG. 8. Phase angles between mooring 8 currents and (a) Green Bay water levels and (b) mooring 5 currents.

current leads the water level.) The fact that our measurements show the same phase throughout this frequency range suggests that the nodal line, or amphidromic point, associated with the 9-h oscillation, is outside the bay mouth, contrary to the model computations of Rao *et al.* (1976) and Heaps *et al.* (1982). Our data also show that the phase difference across the mouth is very near zero throughout the same frequency band (Fig. 8b).

SUMMARY

Current and water temperature recordings made during 1977 constitute the first long-term data set of this type from Green Bay. Anticlockwise water movements hypothesized from earlier indirect data were also indicated in our current data. Cool water flows southward along the western shore while warmer water returns in the eastern part of the bay. This cyclonic pattern is disrupted and reversed during northeasterly winds. An unexpected discovery was the large and consistent water volume transfer through Porte des Morts Passage and Rock Island Passage. Measurements showed the upper half of the water column egressing from the bay while cold hypolimnetic lake water entered the bay in the lower half. This intruding cold water, with an estimated flow rate of 3,300 m^3 s^{-1} during summer, supplies cool water well into the middle bay southward of Chambers Island. This cold-water inflow is not an infrequent episodic phenomenon, nor is the flow seasonally dependent. October through mid-January currents from Rock Island Passage, for example, continued to be directed into the bay at both levels. Flushing is enhanced dramatically by the infusion of additional water.

Periodic components are present in all currents and are highly coherent with water level fluctuations. Energy concentrated at 12.5 h and 9.0 h corresponds to the M$_2$ tide and lowest mode of the Lake Michigan seiche. Also, an accumulation of energy at around 5 h includes the second free mode of both Lake Michigan and Green Bay. Near-inertial period oscillations were identified in currents in the middle of the bay. Currents through the mouth associated with water level oscillations at the bayhead illustrated that the phase was constant within the frequency band of the semidiurnal tidal wave and co-oscillating 9-h wave, contrary to model predictions. In addition, the phase of currents across the mouth was near zero for these oscillating components, suggesting that the modeled bottom friction may require adjustment. As pointed out by Heaps *et al.* (1982) and demonstrated by our data, three-dimensional models capable of treating stratification and lake-bay interactions are necessary to adequately model dynamic processes in Green Bay.

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