CHAPTER 187

WIND-DRIVEN CIRCULATION OF SAGINAW BAY

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ABSTRACT

A combination of Lagrangian measurements and fixed current meter moorings were used during the summer of 1974 and the winter of 1974-75 to determine the circulation patterns of Saginaw Bay. Because the bay is shallow, the water responds rapidly to wind changes. Distinct circulation patterns were determined for southwest and northeast winds. These directions parallel the major axis of the bay and were the prevailing wind directions during the study. A typical exchange rate between the inner and outer bay during moderate winds aligned with the bay axis is 3700 $m^3 s^{-1}$. If sustained, this flushing rate would completely exchange the water of the inner bay in about 26.5 days. However, winds perpendicular to the axis of the bay cause little water to be exchanged and the residence time of water in the bay is much longer. Comparison of measured currents with the results of an indpendently-developed numerical model for the bay indicates there is good agreement between the observations and the simulation of the circulation in the shallow inner bay. Agreement is poor in the deeper outer bay, where specification of proper boundary conditions at the open mouth of the bay is important for meaningful model simulations. Ice cover during winter shields the water surface from wind stress. Currents are sluggish and driven almost entirely from interactions with the lake-scale circulation of Lake Huron.

INTRODUCTION

Saginaw Bay is a large and important embayment on the southwestern coast of Lake Huron, centered close to 44°00'N latitude and 83°20'W longitude (Figure 1). The mouth of Saginaw Bay (from Point Aux Barques to Au Sable Point) is 42 km wide with an average depth of 27 m. The bay's narrowest constriction is between Sand Point and Point Lookout, with a width of 20 km and a mean depth of only 4 m. A line between these two points forms an approximate boundary between the outer bay (mean depth 16 m) and the much shallower inner bay (mean depth 4.5 m). The bay is 83 km long with its major axis aligned 40° east of north. An important feature of the bay is the relatively deep channel that runs through the inner bay. It is aligned nearly parallel with the major axis of the bay and has a maximum depth of about 14 m.

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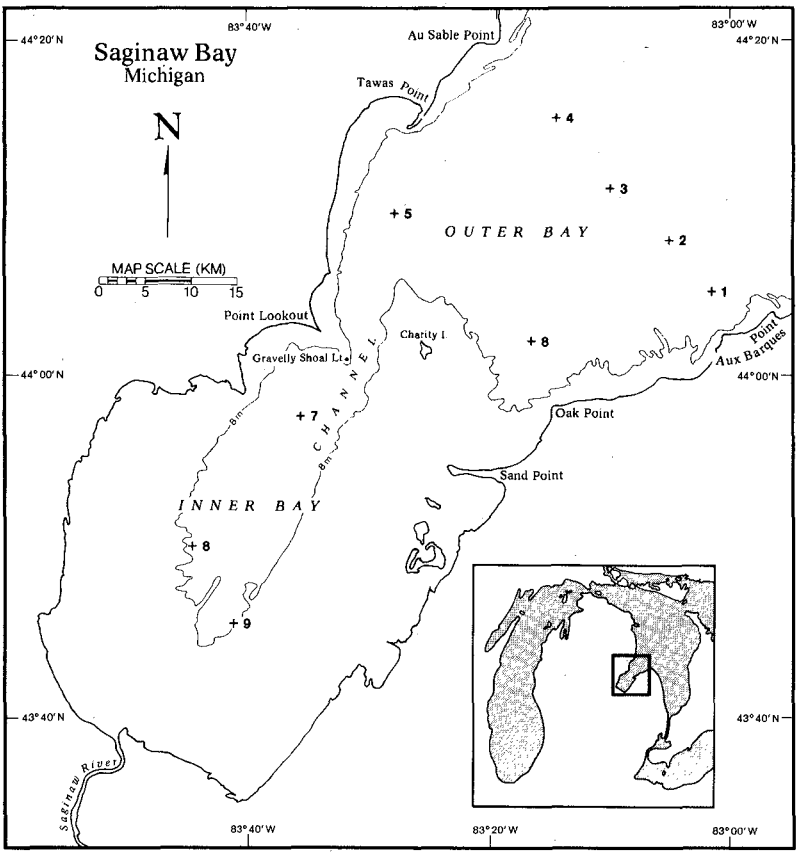

Figure 1. Location map of Saginaw Bay. Current meter moorings were placed at stations numbered 1 - 9, and wind speed and direction was recorded at the Gravelly Shoal Light.

The currents of Saginaw Bay and the character of Saginaw Bay-Lake Huron interactions are important because of the heavy load of pollutants entering Lake Huron through the bay. The Saginaw River drains an area of over 16,000 km^2 and discharges the wastes of the industrialized cities of Midland, Bay City, and Saginaw, Michigan. It is the largest tributary source of undesirable materials discharged to Lake Huron. A long residence time and the pattern of water mass movement within Saginaw Bay have adversely impacted parts of the bay. Several other rivers flow into the bay, but their combined discharge is small compared to that of the Saginaw River.

Because the inner reaches of Saginaw Bay are shallow and tidal amplitudes are negligible, currents in the inner bay are closely related to the wind. The outer bay, although also influenced by the local winds, interacts strongly with the large-scale circulation of Lake Huron. Several qualitative studies have been conducted on the circulation of Lake Huron and Saginaw Bay. Harrington (1895) and Johnson (1958) performed drift bottle studies on the lake and bay, and Ayers et al. (1956) used a dynamic height method developed for fresh water to determine the circulation in Lake Huron. Beeton et al. (1967) used chemical distributions to trace the water movements in the bay. These studies were in agreement in that all indicated currents in the bay were strongly dependent on local winds and were highly variable. A more recent study by Allender (1975) used a numerical model to simulate the circulation. This paper presents the results of a study using both Lagrangian and Eulerian current measuring techniques to determine the circulation patterns of the bay. Also presented are representative current speeds and volume transports for various wind conditions and a comparison of these results with the results of Allender's numerical model.

METHOD

Eighteen Geodyne model A-100 film recording current meters were installed in Saginaw Bay during May, 1974, and operated through October, 1974. As many as three of these Savonious rotor current meters were attached to an anchored line and suspended in the water colmn by a subsurface float. A small surface float attached to the end of a ground line 30 to 40 m in length was used to mark the location of the moorings and to aid in the recovery of the meters. Several of the meters failed because of mechanical and electrical problems leaving some holes in the planned sampling grid. Locations and depths of the meters are given in Figure 1 and Table 1. Each current meter sampled the velocity for a 50 s interval every 30 min and accumulated over 7200 data points for the duration of the study.

Drogues were tracked for three 2-week sessions, one session each in June, August, and October of 1974. The drogues consisted of a surface bouy plus a subsurface panel. The bouy was made from a pneumatic float and a radar reflector that extended 1.5 m above the water surface. The panel, a sheet metal current cross with a cross-sectional area of 1.86 m^2, could be set to any desired depth in the water column. During this study the panels were set only at depths of 2 or 5 m and used almost exclusively in the shallow water of the inner bay where the use of moored current meters was impractical. The drogues were followed with a small tending vessel and sequentially positioned by radar with reference to anchored radar reflectors deployed at the site of each released drogue.

Wind speed and direction were measured at the Gravelly Shoal Light near Point Lookout. Data were continuously recorded on a strip chart by the use of a Bendix wind recording system and later digitized as hourly averages. The sensor location was approximately 23 m above the water surface. As the distance to the nearest point of land was 4.5 km, local interferences were minimal.

During the winter of 1974-75 an extensive study of currents and water

Table 1. Current meter locations and dates of operation during the May to October deployments.

Meter No.	Site No.	Latitude (N)	Longitude (W)	Depth (m)	Duration
2A	2	44°05.2'	83°02.4'	10	17 May-15 Oct.
2B	2	44°05.2'	83°02.4'	20	28 May-15 Oct.
2C	2	44°05.2'	83°02.4'	30	17 May-15 Oct.
3B	3	44°11.5'	83°10.9'	20	18 May-15 Oct.
3C	3	44°11.5'	83°10.9'	30	18 May-15 Oct.
4A	4	44°15.3'	83°15.0'	10	18 May-15 Oct.
4B	4	44°15.3'	83°15.0'	20	18 May-15 Oct.
5A	5	44°10.1'	83°28.9'	7	18 May-16 Aug.
5B	5	44°10.1'	83°28.9'	15	18 May- 3 Oct.
6A	6	44°02.3'	83°17.3'	7	17 May- 8 June
6B	6	44°02.3'	83°17.3'	10	17 May-16 Oct.
9A	9	43°45.6'	83°41.4'	7	20 May-18 Oct.

temperatures was performed in Lake Huron to determine the large-scale circulation of the lake. In this study many current meter moorings were placed along the west shore of Lake Huron and in the mouth of the bay. The moorings were in place from November, 1974 to May, 1975 and consisted of AMF Vector Averaging Current Meters, again of Savonious rotor design. Thus, the mouth of Saginaw Bay was instrumented for a period of almost one year, although a short gap in the records at the end of October and early November, 1974 exists. The entire bay is usually nearly isothermal so that the water mass is essentially homogeneous. Only during early summer in the deeper water at the mouth of the bay was any density stratification of significance observed.

RESULTS

Drogues

Since most of the inner bay was too shallow for current meter moorings, the drogue studies were concentrated in that area. During 25 days on the bay, 117 drogues were tracked for an average interval of 5 hr each. The

average speed for the drogues was 6.7 cm s^{-1}, while the highest speed measured was over 30 cm s^{-1}; however the speeds in several areas of the bay varied considerably from the average. Near Point Lookout, where the channel has its narrowest constriction, the average speed was 10 cm s^{-1}. Water flow balancing the wind-driven transport in the shallow water southeast of the channel is funneled through this constriction causing the higher average speed. On the other hand, water in the southeast corner of the bay was nearly stagnant, with speeds of less than 4 cm s^{-1}. This is the same area where the highest ion concentrations were reported by Beeton et al. (1967). In the central part of the inner bay the speeds were typically slower in the channel (average speed 6.2 cm s^{-1}) than in the shallow water areas on either side (average speed 8.8 cm s^{-1}). There was no appreciable difference between the average speeds measured at 2 and 5 m depths.

As it was not possible to do a synoptic survey of the entire bay, the drogue data were compiled to present on one chart observations made during similar wind conditions in various parts of the bay thus providing a reasonably accurate picture of the circulation of the inner bay for certain wind directions. Transects for 7 days during which the wind was out of the southwest are shown in Figure 2. The drogue tracks show that the water in the

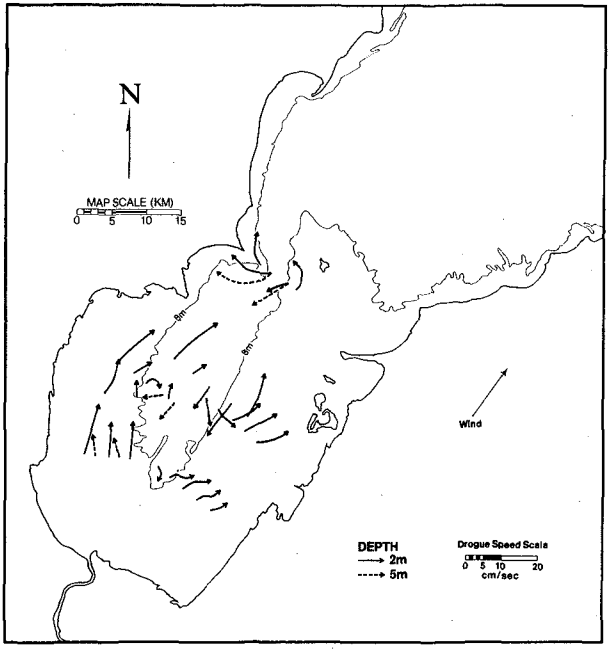

Figure 2. Compilation of drogue tracks observed during southwest wind.

inner bay generally moves to the northeast with the wind, except in the channel, where there is a counterflow to the southwest. The current in the southwest section of the bay, combined with the return flow in the channel, forms a crude clockwise gyre in that region, whereas the current in the shallow southeast area follows the shoreline and flows into the outer bay between Charity Island and Oak Point. Part of the water from the southeastern region of the inner bay also flows northeastward west of Charity Island, a part of this water may be recycled to the inner bay by the return flow southwestward in the channel. The flow distribution near Point Lookout shows that the return flow is confined to a rather narrow stream, with northeastward flow in the shallow water to each side. The drogue trajectories show that the return flow is still well defined further into the bay, although the apparent path of the flow does meander somewhat because of slightly different wind conditions during the separate days of observations.

On the day that drogues were deployed across the channel near Point Lookout, the wind was out of the southwest with an average speed of 5.8 m s^{-1}. Drogue panels set at 2 and 5 m made it possible to estimate the vertical profile of horizontal velocity and to compute the volume water entering the inner bay through the channel. The estimated transport was 3700 m s^{-1} or 37 times the average flow of the Saginaw River. Since the volume of the inner bay was about 8.5×10^9 m^3 during the time of the study, it would take only 26.5 days for this flow to replace the inner bay water.

On several days the wind changed rather abruptly during the drogue experiments presenting an opportunity to examine the response of the bay to sudden wind changes and to determine the time required for the return flow in the channel to develop. The response for a wind changing to one out of the southwest is that in all areas of the inner bay the water initially flows with the wind; after approximately 8 hr a return flow develops in the central channel. Of course residual currents and the intensity of the wind affect the circulation and the lag time before a return flow develops and a new equilibrium state is established, but this response time is typical for a moderate southwest wind. This result also agrees well with previous work on the bay (Johnson, 1958, and Allender, 1975). The current speed averaged about 3% of the wind speed in shallow water where the currents flow with the wind.

During the Lagrangian current studies the wind was usually out of the southwest, but there were a few occasions of northeast winds. the transects from these days indicate that water enters the inner bay between Charity Island and Oak Point and flows to the southwest in the shallow areas of the bay. The results also show a countercurrent in the channel flowing to the northeast, but there was insufficient data to estimate a volume exchange rate. With flow to the southwest on either side of the channel and a counterflow to the northeast in the channel, the circulation pattern is just reversed from that observed for a southwest wind.

Current meters

Since the largest part of the inner bay was too shallow for current meter moorings, most of the meters were deployed in the outer bay. Histograms of current direction were used to display the summer data. The

histograms were constructed by sorting the current direction into 40^{o} sectors. The percentage of data points that fell into each sector was computed and the average speed for each sector was calculated (percentages of less than 5% are not shown). The average speeds were divided into three categories, low (less than 8 cm s^{-1}), medium (8 to 15 cm s^{-1}), and high (greater than 15 cm s^{-1}), and the results are displayed on the histograms. A similar histogram of wind data was computed, giving the direction toward which the wind was blowing (that is, to be consistent the oceanographic convention was also used for the wind direction so that a wind out of the north was plotted in the south sector).

Since the currents are so highly dependent on the local winds, the nature of the bay circulation during several well-defined meteorological events was examined. Histograms of current direction were computed for periods when the wind was relatively constant for at least two days. Since the two predominant wind directions during the summer of 1974 were out of the southwest and out of the northeast, the response of the bay to winds from these directions was analyzed.

The wind was constant out of the northeast on 22-27 June. Histograms computed for that period are shown in Figure 3. The results of this episode, which are typical of several episodes of northeast wind examined, show that the flow is characterized by a counterclockwise gyre in the outer bay; water enters the bay at the nothern edge of the bay mouth, flushes through the outer bay in one large counterclockwise loop, and flows back into Lake Huron along the southern part of the bay mouth. Meter 9A suggests that a return flow has developed in the channel even that far into the bay, although the return current isn't as well defined as that for a southwest wind. An illustration of this flow pattern, combined with the circulation derived from the drogue results for a northeast wind in the inner bay, is shown in Figure 4. The vectors on the Figure represent a qualitative vertically averaged circulation pattern, with the length of the arrows proportional to flow intensity.

The wind was constant out of the southwest on 3-5 October (Figure 5). The histograms from this episode, which are similar to others computed for a southwest wind, are markedly different than those calculated for a northeast wind. The flow from Lake Huron enters the bay through the southern parts of the bay mouth, circulates through the outer bay in a clockwise direction, and flows out along the edge. Meter 9A shows the prominent return flow in the channel noted in the drogue studies. This circulation pattern, together with the flow pattern determined from the drogue studies for asouthwest wind, is illustrated in Figure 6. The flow past station 5 is usually toward the southwest under both wind conditions, influenced more by the gross circulation and geometry of the bay than by the direct influence of the local winds. This site is in the zone of the return flow in the channel during southwest wind and in the inflow to Saginaw Bay from Lake Huron during northeast wind. Histograms computed for the entire length of the summer current meter records revealed a high variability of flow, with the current direction for some of the meters almost equally distributed around the compass. The meter at site 9, though, showed a dominant flow to the southwest because the prevailing winds during the summer were from the southwest. Wind from directions not nearly parallel to the bay axis drives a local circulation in the inner bay, but does not appear to cause much exchange of water with the outer bay.

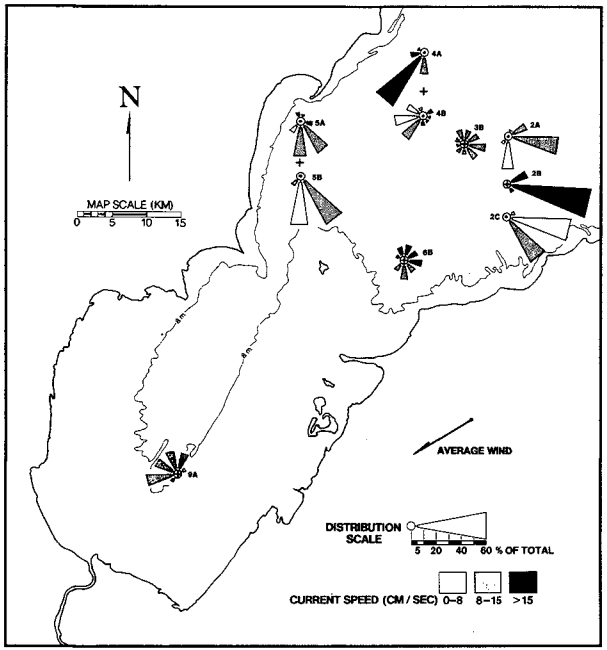

Figure 3. Current direction histograms during northeast wind, 22-27 June, 1974.

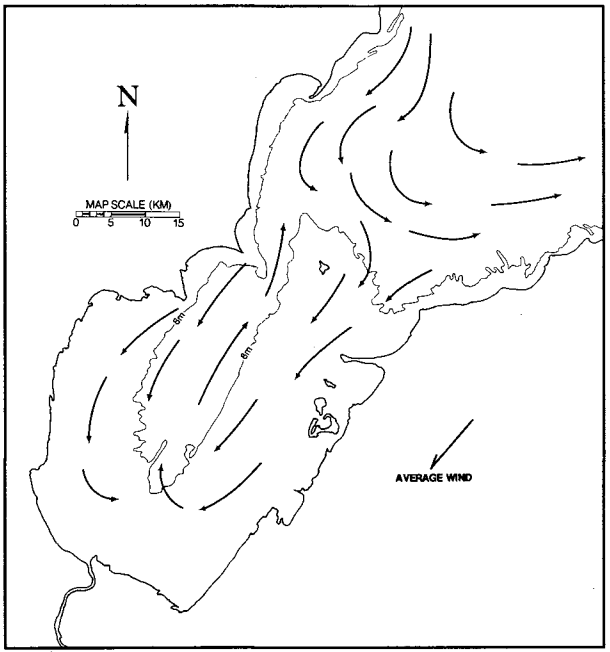

Figure 4. The circulation of Saginaw Bay driven by northeast wind.

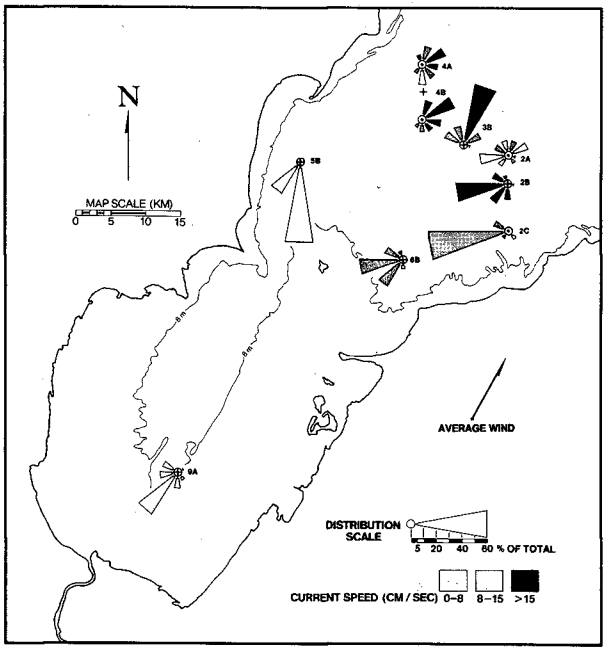

Figure 5. Current direction histograms during southwest wind, 3-5 October, 1974.

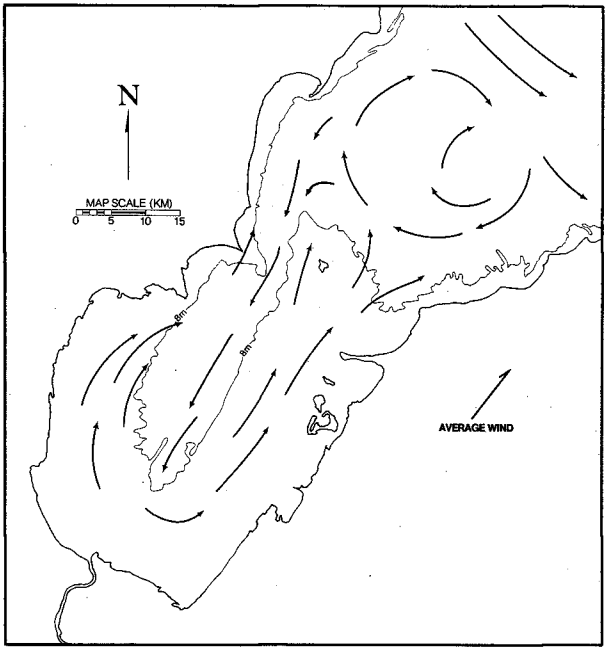

Figure 6. The ciculation of Saginaw Bay driven by southwest wind.

Winter current meters confirmed the same nature of outer bay circulation. Winter studies of Lake Huron have shown that southward flow along the west coast of the lake is the dominant feature of lake circulation. The rest of the lake responds to this flow in the form of one large cyclonic cell, returning water northward along the eastern coast. This persistent southward flow across the mouth of Saginaw Bay interacts strongly with the outer bay and plays a major role in determining its flow characteristics. Figure 7 shows an episode of lake scale current flow during moderate northerly winds in November of 1974. Current roses of water transport past each current meter are shown at the 15 m level. Wind run roses for this episode as recorded at five stations around the perimeter of the lake are shown in usual meteorological fashion here, being wind from the north and northeast at 5 to 6 m s^{-1}. This episode shows, as noted earlier for the summer studies, that north to northeasterly wind drives a counterclockwise loop of Lake Huron water through the outer bay. The average current speeds in the outer bay were 15 to 20 cm s^{-1} during this episode.

Ice cover during its peak development in winter covers the entire surface of Saginaw Bay, extending lakeward past all four current meter moorings placed in the mouth of the bay. Figure 8 shows another episode of wind similar to that of the November case, but during extensive lake ice cover. With ice extending from 10 to 15 km lakeward from the outer bay current meters, the currents in the bay are entirely different in character. Lake Huron retains its cyclonic flow pattern, but under the ice the bay mouth circulation loses its distinctive character. Flow is weak with average current speeds of a few cm s^{-1}. Thus, even the driving force of lake current interactions is lost during extensive winter ice cover, and the bay circulation must be very disorganized and sluggish.

MODEL COMPARISON

Allender (1975) simulated the bay using a finite difference method to solve the linear barotropic equations for two-dimensional motion. Because the development of such a model requires the specification of boundary conditions at the mouth of the bay, he examined water level records from within Saginaw Bay and from Lake Huron near the bay mouth and determined the dominant periods of oscillation of the surface stage. He then specified as boundary conditions periodic functions of the velocity field at the open boundary between Saginaw Bay and Lake Huron at periods of the observed dominant surface oscillations. The intensity of the flow field was adjusted to yield water surface oscillations with amplitudes near those observed on the bay. Figure 9 shows the circulation he calculated for a southwest wind, and Figure 10 shows the flow pattern driven by a northeast wind. A comparison of these results with the results of the field studies shows that there is very good agreement between the flow patterns in the inner bay. Both results show a distinct current in the channel flowing into the wind and flow in shallow water with the wind. The agreement in the outer bay for similar wind conditions is not close, however. The differences between the model and field study circulations are due to the strong influence of Lake Huron currents on the flow in the outer bay, effects which were not included in model development.

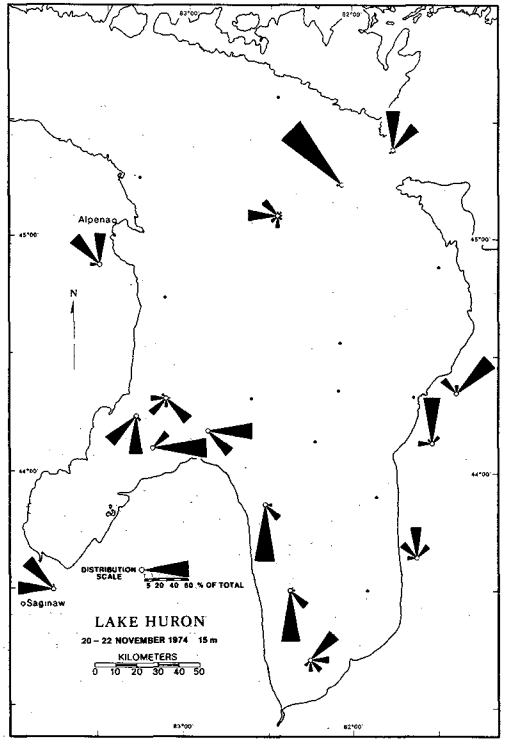

Figure 7. Current roses of water transport at the 15 m level during an episode of northerly wind in November, 1974.

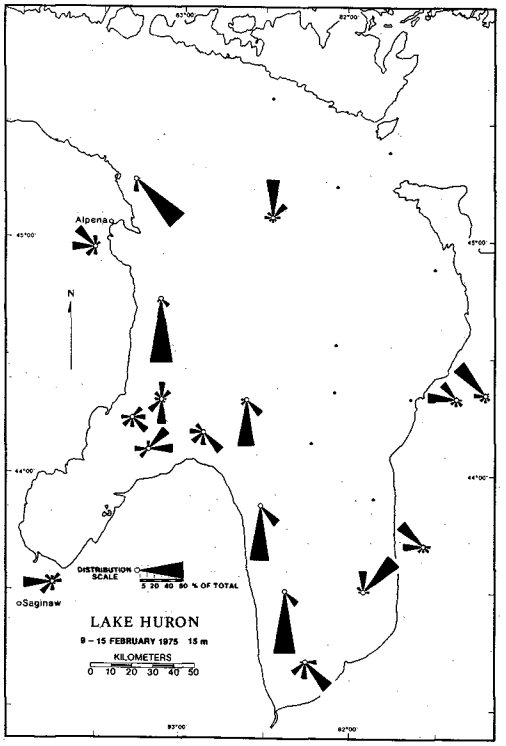

Figure 8. Current roses of water transport at the 15 m level during an episode of northerly wind with extensive ice cover on Saginaw Bay in February, 1975.

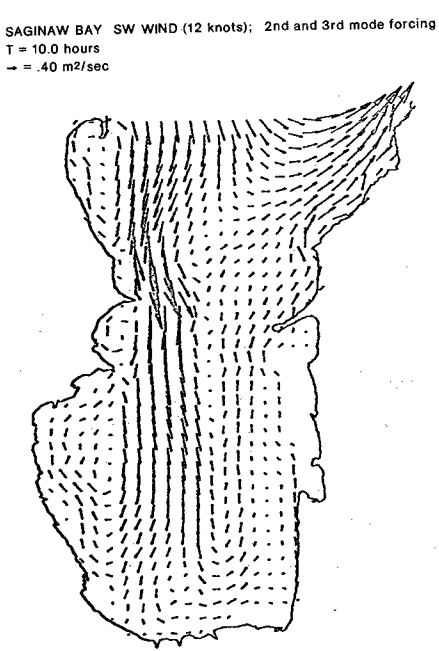

Figure 9. Currents in Saginaw Bay driven by a southwest wind with weak boundary forcing at periods of 3.3 and 2.0 hr (from Allender, 1975).

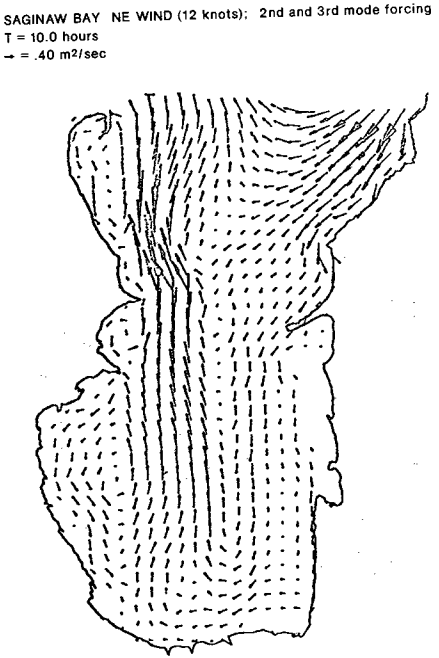

Figure 10. Currents in Saginaw Bay driven by a northeast wind with weak boundary forcing at periods of 3.3 and 2.0 hr (from Allender, 1975).

Spectral analyses of the current meter recordings reveal no significant periodic components in the flow field near the periods specified in model development, although during the density stratified season strong inertial period current flows are prominent near the bay-lake boundary. The dominant interaction between the bay and Lake Huron is controlled by the southward flowing coastal current structure in the lake, so that more realistic model development would necessarily include the dynamical effects of this interaction. Of course, the interaction of the lake and bay cannot be described without detailed field investigation, and the results of these surveys were not available for Allender's work.

SUMMARY

Currents in Saginaw Bay are quite variable and dependent on the local winds. The inner bay is especially susceptible to wind changes, but the circulation patterns developed are predictable for winds from the southwest or northeast, as a stable pattern develops within about 8 hr after a wind shift. Since wind from directions just slightly different than these cause only small perturbations to the flow field, as revealed during several of the drogue tracking intervals, it is felt that the two circulation charts are representative of wind from the southwest and northeast quadrants.

Winds blowing transverse to the longitudinal axis of the bay also cause the circulation pattern to change quickly. The flow pattern is more complex than when the wind is nearly parallel to the axis of the bay, but not enough data were collected under these wind conditions to determine a detailed circulation pattern. The outer bay responds less rapidly to wind changes and the current patterns are strongly influenced by currents in Lake Huron. The dominant southward flowing current along the west shore of Lake Huron frequently flushes through the outer bay. A northeast wind causes part of this current to flow through the outer bay in a counterclockwise loop, whereas the current flows past the mouth of the bay during southwest wind and drives a large clockwise eddy in the outer bay. The existence of such an eddy was suggested by Ayers et al. (1956). Ice cover during winter shields the water surface from wind stress and the bay circulation is very sluggish. Even the outer reaches of Saginaw Bay are decoupled from strong interaction with the currents flowing in Lake Huron as the ice fields grow lakeward of the bay mouth.

The comparison of results of this field study with those of a numerical model developed for the same area demonstrates the usefulness and validity of such modeling techniques. The agreement of the model with the actual data is excellent in the shallow water of the inner bay. However, the comparison also illustrates the importance and difficulty of prescribing proper boundary conditions at the open mouth of the bay. The model agrees well with the data far from the bay mouth, but breaks down near the open boundary. The choice of realistic boundary conditions is essential for the prediction of meaningful flow patterns, especially in this region where currents in Lake Huron are so important in influencing the circulation.

REFERENCES

Allender, J.H.
1975. Numerical simulation of circulation and advection-diffusion processes in Saginaw Bay, Michigan. Ph. D. Thesis, University of Michigan, Ann Arbor.

Ayers, J.C., D.V. Anderson, D.C. Chandler, and G.H. Lauff
1956. Currents and water masses of Lake Huron. Ontario Dept. of Lands and Forests, Res. Rept. No. 35, and Great Lakes Res. Institute, University of Michigan, Ann Arbor, Tech. Paper No. 1, 101 pp.

Beeton, A.M., S.H. Smith, and F.F. Hooper
1967. Physical limnology of Saginaw Bay, Lake Huron. Great Lakes Fisheries Commission, Ann Arbor, Michigan, Tech. Rept. No. 12, 56 pp.

Harrington, M.W.
1895. Surface currents of the Great Lakes, as deduced from the movements of bottle papers during the seasons of 1892, 1893, and 1894. U.S. Dept. of Agriculture, Wash., D.C, Weather Bur. Bulletin B, 14 pp.

Johnson, J.H.
1958. Surface current studies of Saginaw Bay and Lake Huron. U.S. Fish and Wildlife Service, Special Scientific Rept. - Fisheries No. 267, 84 pp.