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# MEASUREMENTS OF THE SUMMER CURRENTS IN SAGINAW BAY, MICHIGAN[1]

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***ABSTRACT.*** *A combination of Lagrangian measurements and fixed current meter moorings were used during the summer of 1974 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 a southwest wind and a northeast wind. Speeds measured in the inner bay were of the order of 7 cm $s^{-1}$, whereas in the outer bay the speeds averaged closer to 11 cm $s^{-1}$. A typical water exchange rate between the inner and outer bay for winds parallel to the axis of the bay is 3700 $m^3s^{-1}$, but winds perpendicular to the axis of the bay cause little water to be exchanged. A comparison with the results of a numerical model for the bay indicates there is good agreement between the data and the simulation of the circulation in the inner bay. However, the agreement is poor in the outer bay, where specification of proper boundary conditions at the open mouth of the bay is important for meaningful model simulations.*

## INTRODUCTION

Saginaw Bay is a large and important estuary on the southwestern coast of Lake Huron, centered close to 44°00'N latitude and 83°20'W longitude (Fig. 1). The mouth of Saginaw Bay (from Point Aux Barques to Au Sable Point) is 42 km wide and has 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. The Saginaw River, which drains an area of over 16,000 $km^2$, enters the bay at the southwestern end near Bay City, Mich. The average discharge of the river is about 100 $m^3s^{-1}$, but it can increase to well over 300 $m^3s^{-1}$ during spring. There are also several other rivers flowing into the bay, but their combined discharge is small compared to that of the Saginaw River.

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 discharges the wastes of the industrialized cities of Midland, Bay City, and Saginaw, Mich., and 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.

Because of the shallow water depths in the inner reaches of Saginaw Bay, currents in the inner bay are closely related to the wind; this situation presents an opportunity to study an estuary where the principal driving force is the wind stress. 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 (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. The above studies are

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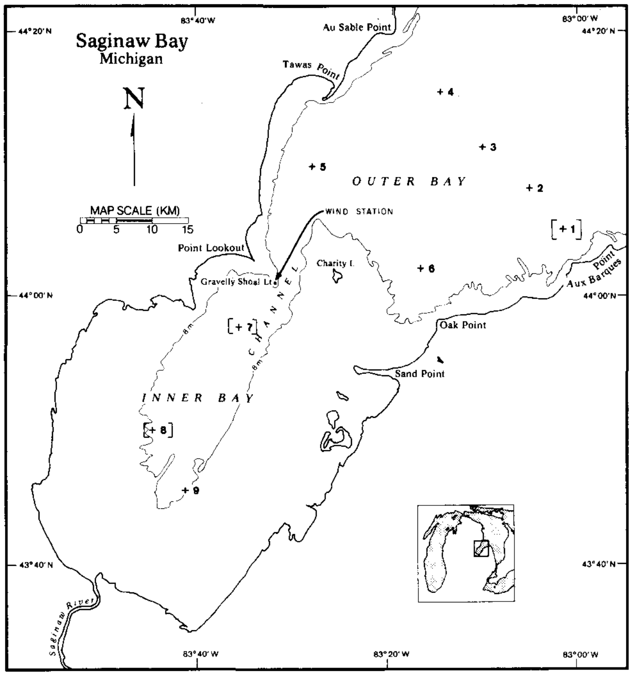


*FIG. 1. The study site showing the locations of the nine current meter moorings and the wind station at Gravelly Shoal Lighthouse. The meters at sites 1, 7, and 8 malfunctioned.*

all in agreement in that they indicate that the currents in the bay are strongly dependent on local winds and are highly variable. A more recent study by Allender (1975) used a numerical model to simulate the circulation.

The present 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 current meters were attached to an anchored line and suspended in the water column 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 meters failed because of mechanical and electrical problems; this left some holes in the planned sampling grid. Locations and depths of the meters are given in Fig. 1 and Table 1.

*TABLE 1. Current meter locations and dates of operation.*

| Meter No. | Site No. | Lat (N) | Long (W) | Depth (m) | Duration |
|---|---|---|---|---|---|
| 2A | 2 | 44°5.2′ | 83°2.4′ | 10 | 17 May–15 Oct. |
| 2B | 2 | 44°5.2′ | 83°2.4′ | 20 | 28 May–15 Oct. |
| 2C | 2 | 44°5.2′ | 83°2.4′ | 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°2.3′ | 83°17.3′ | 7 | 17 May– 8 June |
| 6B | 6 | 44°2.3′ | 83°17.3′ | 10 | 17 May–16 Oct. |
| 9A | 9 | 43°45.6′ | 83°41.4′ | 7 | 20 May–18 Oct. |

Each meter sampled the velocity for a 50-s interval every 30 min and accumulated over 7200 data points for the duration of the study. The Savonius rotors on the meters have a threshold speed of 2.5 cm $s^{-1}$ and an accuracy of 2.5 cm $s^{-1}$ for speeds less than 50 cm $s^{-1}$. The sensitivity of the direction vane is alignment within 10° of the current direction at a current speed of 2.5 cm $s^{-1}$ and within 2° at 10 cm $s^{-1}$, with a resolution of 2.8°. The meters recorded the velocity in binary code on standard 16 mm photographic film.

Drogues were tracked for three 2-week sessions, one session each in June, August, and October of 1974. The drogues consisted of a surface buoy plus a subsurface panel. The buoy was made from a pneumatic float and a radar reflector that extended 1.5 m above the water surfaces. 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 m or 5 m. The drogues were followed with a vessel and sequentially positioned by radar with reference to the anchored reflectors.

Wind speed and direction were measured at the Gravelly Shoal Lighthouse 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.

## 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 $s^{-1}$, and 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 $s^{-1}$. Apparently the water entering or leaving the bay was funneled through this constriction, causing the higher speeds. On the other hand, the water in the southeast section of the bay was nearly stagnant, with speeds 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 m and 5 m.

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 water circulation of the inner bay for certain wind directions. The transects for 7 days during which the wind was out of the southwest are plotted on Fig. 2. The drogue tracks show that the water in the inner bay generally moves to the northeast with the wind, except in the channel, where there is a counter flow moving 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 enters the outer bay between Charity Island and Oak Point. Part of the water from the southeast area also flows out of the inner bay to the west of Charity Island, and some of the water may be recycled in the return flow down the channel. The transect near Point Lookout illustrates the water exchange between the inner and outer bays with water outflow in the shallow areas on either side of the channel and return flow through the channel. The drogue trajectories show that the return flow is still well defined further into the bay, although the path of the flow does meander somewhat because of slightly different wind conditions during the drogue studies.

On the day the drogues were deployed across the channel near Point Lookout, the wind was out of the southwest with an average speed of 5.8 m $s^{-1}$.

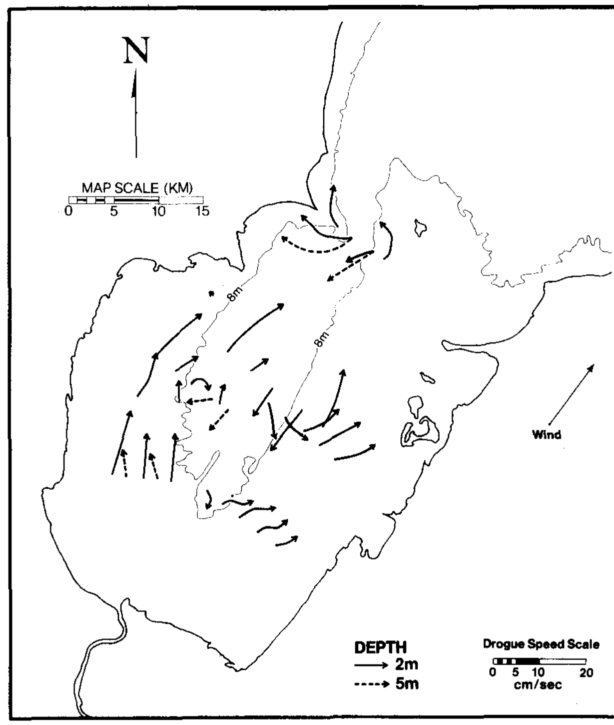


*FIG. 2. Compilation of drogue tracks for a southwest wind.*

Drogue panels set at 2 m and 5 m made it possible to estimate the vertical profile of horizontal velocity and to compute the volume of water entering the inner bay through the channel. The estimated transport was 3700 $m^3$ $s^{-1}$ or 37 times the average flow of the Saginaw River. Since the volume of the inner bay was about 8.5 x $10^9$ $m^3$ during the time of the study, it would take 26½ days for this flow to fill the inner bay.

On several days the wind changed rather abruptly, 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 surface water initially flows with the wind and after approximately 8 hr a return flow develops in the central channel. For example, on 20 August the wind became southwesterly at about 0200 hr. The surface current in the channel initially followed the wind, but between 1000 and 1100 hr it reversed direction and flowed to the southwest. Thus it took between 8 and 9 hr for the return flow to form. 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 the above response is typical for a southwest wind. This result also agrees well with previous work on the bay (Johnson 1958, and Allender 1975).

During the drogue 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 Isalnd and Oak Point and flows to the southwest in the shallow areas of the bay. The results also suggest that there is a countercurrent in the channel flowing to the northeast, but there are 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 display the data. The histograms were constructed by sorting the current direction into 40° 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 (< 8 cm $s^{-1}$), medium (8 to 15 cm $s^{-1}$), and high (> 15 cm $s^{-1}$), and the results are displayed on the histograms. A similar histogram of the wind data was computed, giving the direction toward which the wind was blowing (i.e., 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).

Histograms computed for the entire length of the current meter records (Fig. 3) show a high variability of flow, with the current direction for some of the meters almost equally distributed around the compass. This is due not only to variable winds, but also to the importance of inertial currents in certain parts of the bay. One exception to this variability occurs at meter 9A where the dominant flow is to the southwest. This is in agreement with the drogue results where a return flow in the channel was found during southwest wind episodes. Strong southwesterly flow also prevails at station 5 near the mouth of the channel, as the observations here indicate that this location is in the area of return flow for a southwest wind and in the inflow to Saginaw Bay from Lake Huron during a northeast wind.

The average speed computed for all the current meter data was 10.6 cm $s^{-1}$. The highest averages

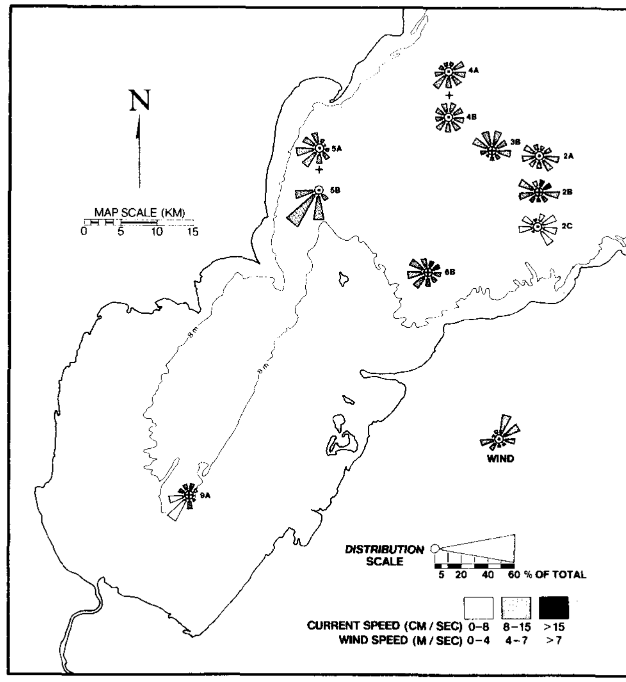


*FIG. 3. Histograms of current direction for entire period of study.*

were recorded by meters 6B (13.7 cm $s^{-1}$) and 5A (13.0 cm $s^{-1}$), located near the division between the inner and outer bays. The only meter in the inner bay (meter 9A) recorded an average speed of 7.9 cm $s^{-1}$. The speed recorded at the 30-m level near the mouth of Saginaw Bay averaged only 7.7 cm $s^{-1}$ (meters 2C and 3C). The direction measured at the 30-m level was much more stable than the direction recorded closer to the water surface, indicating that the flow along the bottom near the mouth is rather slow and relatively free of large fluctuations. Meter 6B on the other hand is located in an area of high variability. Large fluctuations in direction, a high variance calculated for the velocity components plus large amounts of energy in the high frequency range of computed power spectra indicate that this is an area of strong interaction. This meter is located near the division of the inner and outer bay, and apparently the water from the inner region mixes with the water in the outer bay in this area and causes these highly variable currents.

Since the currents are so highly dependent on the local winds, the character of the bay circulation during several meteorological events was examined. Histograms of current direction were computed for periods when the wind was relatively constant for at least 2 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 plotted on Fig. 4. The results from this episode, which are typical of several episodes examined for a northeast wind, show that the flow is characterized by a counterclockwise gyre in the outer bay: water enters the bay at the northern edge of the mouth, flushes through the outer bay, and flows back into Lake Huron along the southern part of the bay mouth. The observations at meter 9A suggest that a return flow has developed in the channel even that far into the inner bay, although the return current isn't as well defined as that for a southwest wind. An illustration of this flow pattern, plus the circulation derived from the drogue results for a northeast wind in the inner bay, is shown in Fig. 5. The vectors on this illustration represent a qualitative vertically averaged circulation pattern.

The wind was constant out of the southwest on 3-5 October (Fig. 6). 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 part of the mouth, flushes through the outer bay in a clockwise direction, and flows out along the northern edge. Observations at meter 9A show the prominent return flow in the channel as indicated during the drogue studies. This circulation pattern, plus the flow pattern determined from the drogue results for a southwest wind, is illustrated in Fig. 7. As noted earlier, the flow past site 5 is usually to 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.

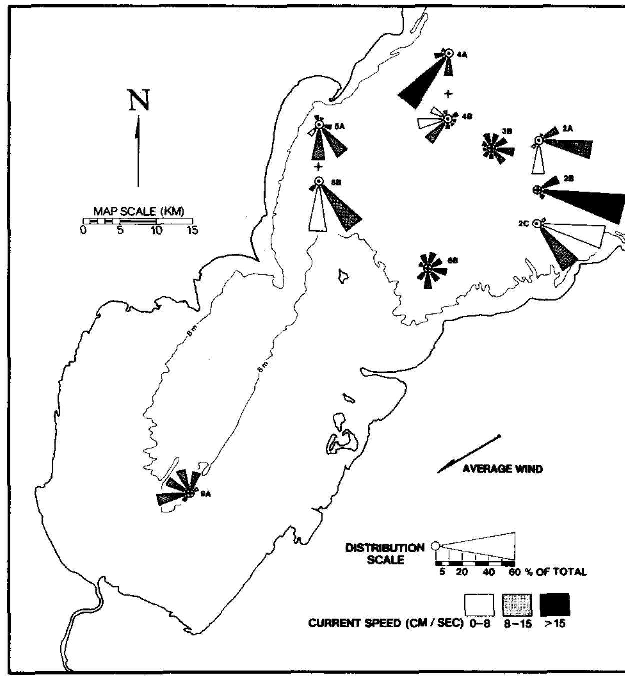


*FIG. 4. Histograms from 22-27 June – northeast wind.*

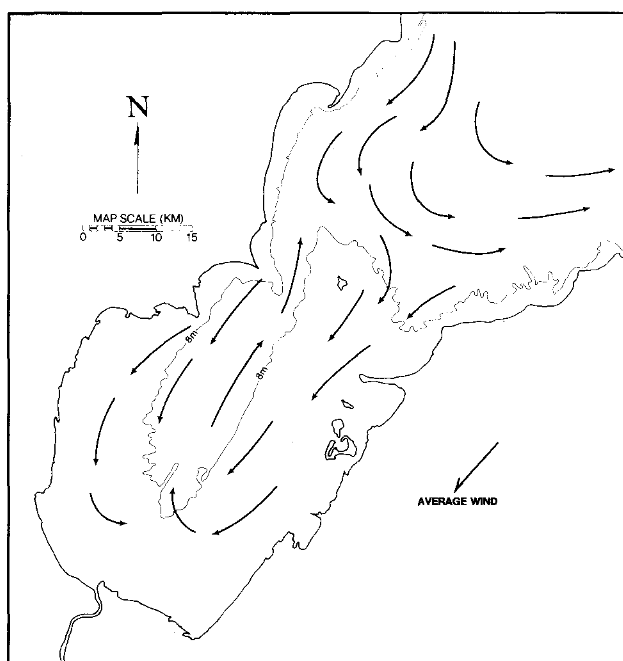


*FIG. 5. The circulation of Saginaw Bay driven by a northeast wind.*

### *Model Comparison*

In Allender's numerical model (1975), a finite difference method was used for solving 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. Fig. 8 shows the circulation he calculated for a southwest wind, and Fig. 9 shows the flow pattern driven by a northeast

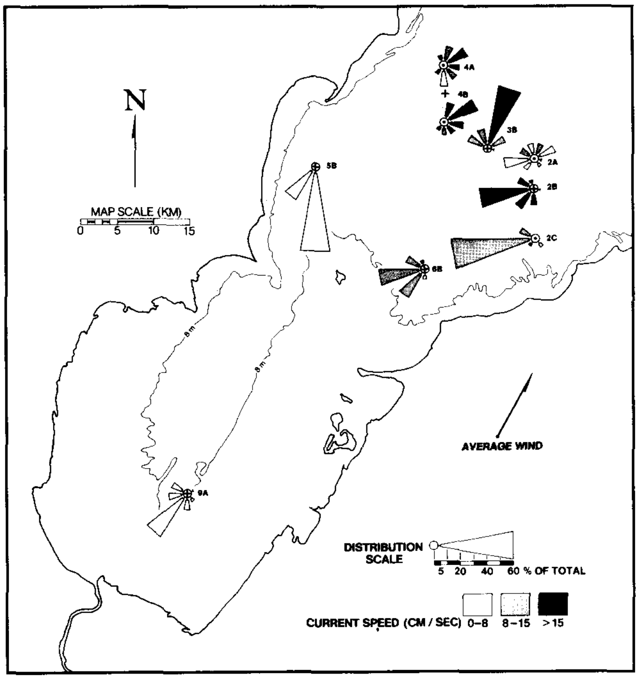


*FIG. 6. Histograms from 3-5 October–southwest wind.*

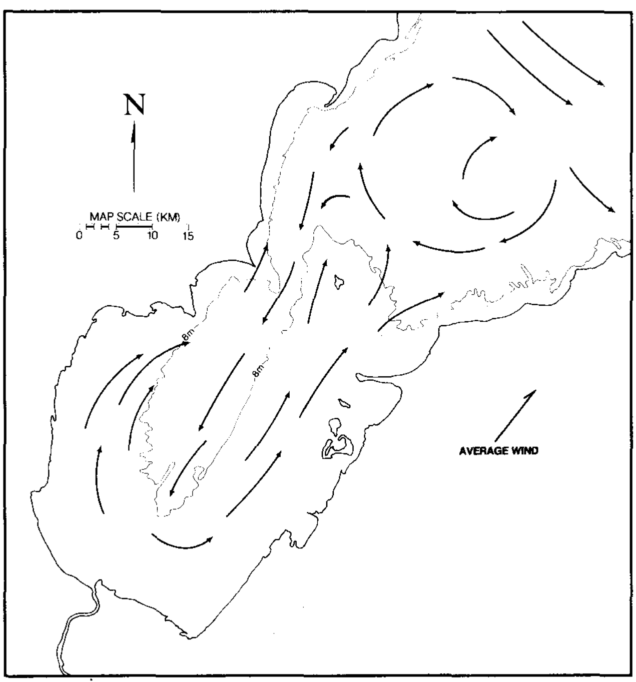


*FIG. 7. The circulation of Saginaw Bay driven by a southwest wind.*

wind. A comparison of these results with the results of the field studies (Figs. 5 and 7) shows that there is strong agreement between the circulation patterns in the inner bay. Both results show a distinct current in the channel flowing into the wind and flow in the shallow water regions moving with

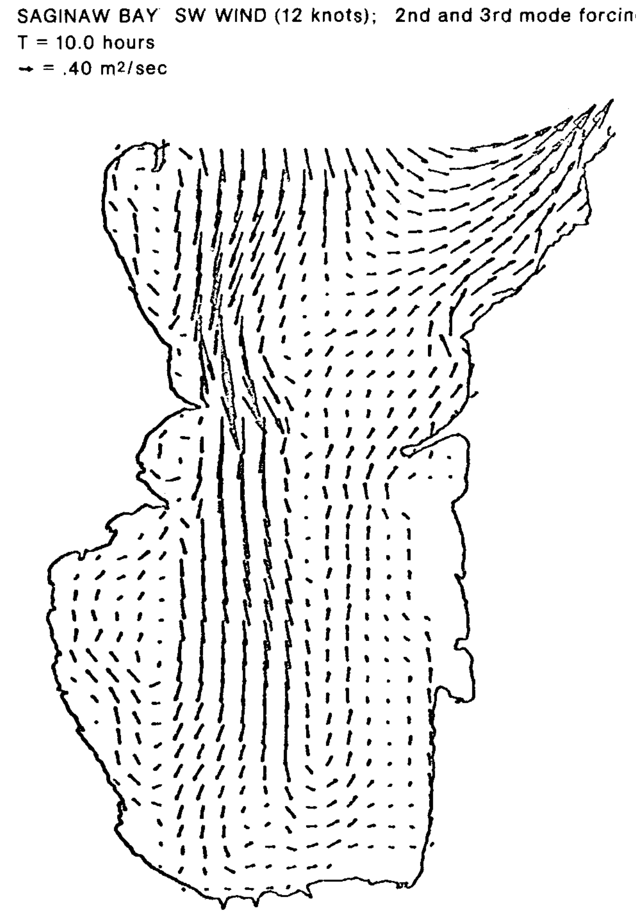


*FIG. 8. Currents in Saginaw Bay driven by a southwest wind with weak boundary forcing at periods of 3.3 hr and 2.0 hr [from Allender (1975)].*

the wind. The agreement in the outer bay for similar wind conditions, however, is not very good. The differences between the circulation patterns as determined by Allender's model and those as determined by field studies are due in part to the strong influence of the Lake Huron coastal currents, which were not included in the computer model.

Spectral analyses of the current meter recordings reveal no significant periodic components in the flow field near the periods specified in the 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 more realistic model development would necessarily include the dynamical effects of this interaction. Of course, the interaction of lake and bay cannot be described without detailed field investigation, and these surveys were not available for Allender's work.

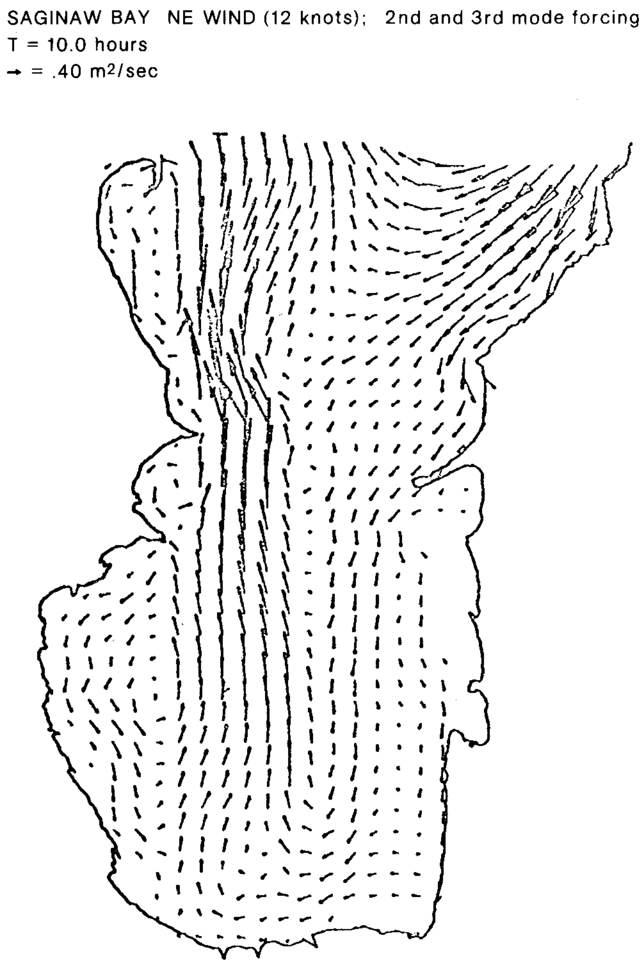


*FIG. 9. Currents in Saginaw Bay driven by a northeast wind with boundary forcing at periods of 3.3 hr and 2.0 hr [from Allender (1975)].*

## SUMMARY

Currents in Saginaw Bay are quite variable and highly dependent on the local winds. The inner bay circulation is especially susceptible to wind changes, but the circulation patterns in the inner bay are predictable for winds out of the southwest or northeast, as a stable pattern develops in approximately 8 hr after a wind shift. Since wind from directions just slightly different than these will 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 essentially representative of wind from the southwest and northeast quadrants.

Winds blowing transverse to the longitudinal axis of the bay (i.e., from the northwest or southeast) also cause the circulation pattern to change quickly. The flow pattern is more confused 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 general circulation. The outer bay responds less rapidly to wind changes and the circulation patterns are less predictable because the flow is 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 under a southwest wind and drives a large clockwise eddy in the bay. The existence of such an eddy was suggested by Ayers et al. (1956). The flow in the outer bay may be further complicated by temporal variations in the circulation pattern in Lake Huron.

The comparison of the results of the field study with those of the numerical model 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 inner region of the bay; however, the comparison also illustrates the importance and difficulty of prescribing the proper boundary conditions at the open mouth of the bay. The model agrees well with the data far from the 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.

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