# Observations of Currents in Saginaw Bay, Lake Huron

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*During June 1991 through June 1994, six current meter moorings were deployed in the outer region of Saginaw Bay, Lake Huron to study the bay's dynamics and interaction with Lake Huron. Two current meters were configured on each subsurface mooring at 14 m below the water surface and 2 m above the bottom, and current speed, direction, and water temperature were recorded at 15 minute intervals. These data represent nearly 1.2 million observations and are the longest continuous set of observations conducted anywhere in Lake Huron and the first extensive set of winter observations conducted in Saginaw Bay. The winter months showed the highest mean currents from the moorings closest to Lake Huron, whereas the stratified season showed high mean currents at the moorings located in the bay proper. There was little consistency in mean flow vectors other than the bottom currents at the southeastern mooring which showed consistent flow from the bay into Lake Huron. Only a small fraction of the kinetic energy was contained in the mean flow. The variability in the orientation of the principal axes of variation on semi-annual to inter-annual time scales suggests using caution in generalizing about circulation patterns based solely upon limited data sets.*

*Keywords:* physical limnology, mean flow, statistics

## Introduction

Saginaw Bay is a large embayment on the western side of Lake Huron encompassing approximately 2,960 km$^2$. The Charity Islands near the middle of the bay roughly mark the boundary separating the inner from the outer bay (Fig. 1). The inner bay is characterized by shallow water depths (average depth 4.5 m) except for a channel running nearly parallel to the main axis of the bay with a maximum depth of 14 m. In contrast, the outer bay (average depth 16 m) deepens from the islands to nearly 40 m where the bay merges into Lake Huron.

There have been few studies of the circulation within the bay, and most of those have been qualitative (Harrington, 1895; Johnson, 1958; Beeton et al., 1967), with Danek and Saylor (1977) providing more quantitative estimates of circulation from field measurements in 1974. Those field experiments involved drifting buoys and several fixed current meter moorings. However, the field experiments were conducted for a relatively brief time period (May–October), and no winter observations were made. This study reports on the results of six fixed current meter moorings with data recorded continuously over a three-year period from 1991 to 1994. This research was part of a larger effort focused on establishing the pre-zebra mussel conditions of Saginaw Bay. Our objectives were to describe the general statistics of the observed currents and their inter-annual variability.

## Methods and results

Six current meter moorings were deployed from June 1991 through June 1994. Four of the moorings span the 42 km wide mouth of the bay, with the other two located nearer to the islands (Fig. 1). All



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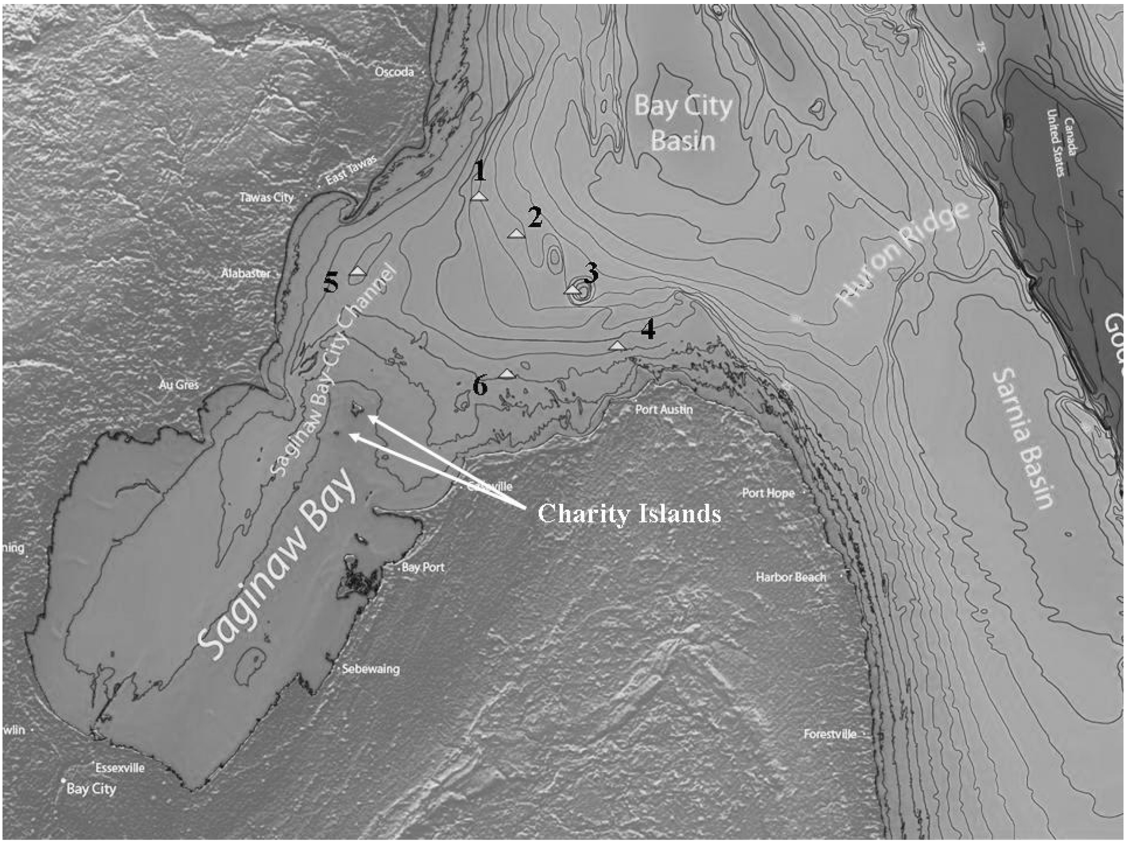


**Figure 1.** Mooring locations in Saginaw Bay from June 1991 through June 1994.

moorings were deployed in the outer region of the bay near the sites occupied by the Danek and Saylor (1977) study. No moorings were deployed in the inner bay because of the shallow water depths restricting our ability to make year-round observations using subsurface moorings. The moorings were serviced each successive June beginning in 1992 with the old current meters replaced with refurbished equipment. The Vector Averaging Current Meters (VACM) were equipped with a savonius rotor, compass vane, and a thermistor. The VACM recorded speed, direction (+/− 3°), and temperature (+/− 0.1° C) every 15 minutes onto a magnetic tape. Each mooring consisted of two VACMs, a bottom weight, and a subsurface float with adequate buoyancy to maintain a taut line mooring. The top VACM was maintained at a depth of approximately 14 m below the water surface, and the bottom VACM was located at 2 m above the bottom. The use of a subsurface float minimized any ice concerns and any potential damage from passing ships.

A total of 36 VACMs were deployed from 18 June 1991 through 14 June 1994 representing about 1.2 million observations of current and temperature. Six of the VACMs malfunctioned for a variety of reasons ranging from total failure to record any data, to high frequency, rapid oscillations in current speed rendering all data for that meter suspect and not used in any subsequent analyses. Specific details of the deployments and the instruments used in these analyses are shown in Table 1. All data were decomposed from speed and direction to velocity components (u,v), with u being positive to the east and v being positive to the north. The data were then averaged to form hourly records. Also, the year was divided in half to more clearly separate the baroclinic from the barotropic response to wind stress under stratified and non-stratified conditions. The stratified season was defined from 11 May through 10 November (DOY 131–314), and the remaining part of the year was defined as the non-stratified season. Not all days within either period meet the definition of stratified

**Table 1.** Saginaw Bay mooring details.

| Mooring ID & VACM ID T = top VACM, B = bottom VACM | Sensor Depth (m) | Latitude (deg) | Longitude (deg) | Start Date & Time (EST) | End Date & Time (EST) |
|---|---|---|---|---|---|
| 1-91T | 14.6 | 44.2805 | 83.2577 | 18/6/1991, 1900 | 16/6/1992, 0900 |
| 1-92T | " | " | " | 16/6/1992, 1030 | 22/6/1993, 1045 |
| 1-93T | " | " | " | 23/6/1993, 0915 | 14/6/1994, 1400 |
| 1-93B | 26.7 | " | " | " | " |
| 2-91T | 14 | 44.2322 | 83.1865 | 18/6/1991, 1900 | 16/6/1992, 1045 |
| 2-91B | 38.2 | " | " | " | " |
| 2-92T | 14 | " | " | 16/6/1992, 1200 | 23/6/1993,1045 |
| 2-92B | 38.2 | " | " | " | " |
| 2-93T | 14 | " | " | 23/6/1993, 1245 | 14/6/1994, 1400 |
| 2-93B | 38.2 | " | " | " | " |
| 3-91T | 14.8 | 44.1843 | 83.1032 | 18/6/1991, 1900 | 16/6/1992, 1200 |
| 3-91B | 39.2 | " | " | " | " |
| 3-92T | 14.8 | " | " | 16/6/1992, 1315 | 23/6/1993, 1315 |
| 3-92B | 39.2 | " | " | " | " |
| 3-93B | " | " | " | 23/6/1993, 1500 | 14/6/1994, 1400 |
| 4-91B | 26.7 | 44.1223 | 83.0265 | 18/6/1991, 1900 | 16/6/1992, 1330 |
| 4-92T | 14.3 | " | " | 16/6/1992, 1445 | 22/6/1993, 1345 |
| 4-92B | 26.7 | " | " | " | " |
| 4-93T | 14.3 | " | " | 22/6/1993, 1645 | 14/6/1994, 1400 |
| 4-93B | 26.7 | " | " | " | " |
| 5-91T | 14.3 | 44.1767 | 83.4462 | 18/6/1991, 1930 | 16/6/1992, 2045 |
| 5-92T | " | " | " | 16/6/1992, 2130 | 24/6/1993, 0900 |
| 5-92B | 18.9 | " | " | " | " |
| 5-93T | 14.3 | " | " | 24/6/1993, 1045 | 14/6/1994, 1400 |
| 6-91T | 14.6 | 44.0868 | 83.2215 | 18/6/1991, 1900 | 16/6/1992, 1845 |
| 6-91B | 19.2 | " | " | " | " |
| 6-92T | 14.6 | " | " | 16/6/1992, 1945 | 23/6/1993, 1600 |
| 6-92B | 19.2 | " | " | " | " |
| 6-93T | 14.6 | " | " | 23/6/1993, 1730 | 14/6/1994, 1400 |
| 6-93B | 19.2 | " | " | " | " |

or non-stratified, but the vast majority falls within the specified time frame. The basic statistics of these data are seen in Table 2. One technique to graphically display and efficiently illustrate the characteristics of the data is to locate the preferred axis of variation. The major axis is rotated to be in alignment with the greatest variability of the observations according to the following equation (Emery and Thomson, 2001).

$$\theta_p = -0.5 \tan^{-1}\left[\frac{2\overline{u'v'}}{\overline{u'^2} - \overline{v'^2}}\right] + 90 \tag{1}$$

Where $\theta_p$ is the angle of the principal axis measured clockwise from north, and u′, v′ are the fluctuating velocity components obtained by subtracting the respective component mean from the observations. The minor axis is perpendicular to the major axis. The variances associated with the principal axes are equal to the eigenvalues calculated from formalizing the two-dimensional scatter plot as an eigenvalue problem. The solution is given as:

$$\begin{Bmatrix} \lambda_1 \\ \lambda_2 \end{Bmatrix} = 0.5\{ (\overline{u'^2} + \overline{v'^2}) \pm ((\overline{u'^2} - \overline{v'^2})^2 + 4(\overline{u'v'})^2)^{1/2}\} \tag{2}$$

**Table 2.** General statistics of Saginaw Bay current meter data from June ′91 through June ′94. Symbols in column 2, "s" and "ns" refer to stratified and non-stratified respectively. Mean currents = U, V in cm $s^{-1}$, $u_{std}$ and $v_{std}$ = standard deviation of U, V. $KE_u$ and $KE_v$ = mean kinetic energy of the u and v components, $\theta_p$, $\lambda_1$, $\lambda_2$ are defined in the text and "S" = magnitude of the mean current (cm $s^{-1}$) , "Dir" = direction of the mean current and %V = % of variance explained by the means flow, S.

| ID | Season | U | V | $u_{std}$ | $v_{std}$ | $KE_u$ | $KE_v$ | $\theta_p$ | $\lambda_1$ | $\lambda_2$ | S | Dir | %V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1-91T | s | 1.4 | 0.8 | 7 | 7 | 23 | 27 | 40 | 77 | 19 | 1.6 | 61 | 2.7 |
| 1-91T | ns | −0.7 | −2.2 | 4 | 5 | 8 | 15 | 35 | 36 | 6 | 2.3 | 198 | 12.6 |
| 1-92T | s | 1.2 | 1.3 | 4 | 5 | 10 | 14 | 36 | 34 | 11 | 1.7 | 42 | 6.4 |
| 1-92T | ns | −0.7 | −1.9 | 3 | 5 | 6 | 14 | 32 | 33 | 3 | 2.1 | 201 | 12.3 |
| 1-93T | s | 0.5 | −1.2 | 6 | 8 | 20 | 34 | 35 | 90 | 16 | 1.3 | 155 | 1.6 |
| 1-93T | ns | −0.1 | −1.4 | 3 | 5 | 6 | 15 | 28 | 35 | 5 | 1.4 | 185 | 4.9 |
| 1-93B | s | −0.2 | −1.2 | 4 | 4 | 6 | 10 | 27 | 20 | 11 | 1.2 | 190 | 4.6 |
| 1-93B | ns | −0.3 | −0.7 | 2 | 3 | 2 | 5 | 22 | 11 | 2 | 0.7 | 201 | 3.8 |
| 2-91T | s | 0.3 | −0.5 | 5 | 6 | 14 | 17 | 32 | 37 | 26 | 0.6 | 145 | 0.6 |
| 2-91T | ns | 0.6 | −2.2 | 3 | 4 | 4 | 12 | 20 | 20 | 7 | 2.3 | 165 | 19.6 |
| 2-91B | s | 0.6 | −0.1 | 4 | 4 | 9 | 8 | 84 | 18 | 16 | 0.6 | 104 | 1.1 |
| 2-91B | ns | 0.3 | −1.1 | 3 | 3 | 5 | 6 | 35 | 11 | 9 | 1.1 | 167 | 6.1 |
| 2-92T | s | −0.5 | −1.5 | 5 | 5 | 11 | 15 | 23 | 30 | 20 | 1.5 | 198 | 4.5 |
| 2-92T | ns | 0.9 | −1.9 | 3 | 5 | 5 | 16 | 5 | 29 | 9 | 2.1 | 155 | 11.6 |
| 2-92B | s | 0.5 | −0.2 | 4 | 4 | 8 | 7 | 68 | 15 | 14 | 0.5 | 114 | 0.9 |
| 2-92B | ns | 0.6 | −1.2 | 3 | 4 | 5 | 8 | 1 | 14 | 9 | 1.3 | 152 | 7.3 |
| 2-93T | s | 0.4 | −0.8 | 5 | 6 | 12 | 20 | 14 | 41 | 24 | 0.9 | 151 | 1.2 |
| 2-93T | ns | 1.2 | −0.8 | 3 | 4 | 4 | 8 | 11 | 15 | 7 | 1.5 | 126 | 10.2 |
| 2-93B | s | 0.6 | −0.6 | 5 | 4 | 10 | 9 | 77 | 21 | 18 | 0.8 | 132 | 1.6 |
| 2-93B | ns | 0.7 | −0.3 | 4 | 4 | 7 | 7 | 31 | 13 | 12 | 0.8 | 112 | 2.6 |
| 3-91T | s | −0.2 | −0.3 | 5 | 4 | 13 | 7 | 95 | 25 | 15 | 0.4 | 223 | 0.4 |
| 3-91T | ns | 0.5 | −1.1 | 3 | 3 | 6 | 4 | 117 | 13 | 6 | 1.2 | 156 | 7.6 |
| 3-91B | s | −1.1 | 0.1 | 6 | 3 | 18 | 5 | 96 | 35 | 11 | 1.1 | 273 | 2.6 |
| 3-91B | ns | 0.2 | −0.5 | 5 | 3 | 11 | 4 | 89 | 23 | 7 | 0.6 | 158 | 1.2 |
| 3-92T | s | −0.6 | −0.7 | 6 | 5 | 17 | 13 | 99 | 33 | 26 | 0.9 | 222 | 1.4 |
| 3-92T | ns | 0.6 | −1.9 | 6 | 4 | 18 | 11 | 116 | 41 | 13 | 2 | 163 | 7.4 |
| 3-92B | s | −0.3 | −0.1 | 5 | 3 | 13 | 5 | 93 | 25 | 10 | 0.3 | 256 | 0.3 |
| 3-92B | ns | 0.6 | −0.9 | 6 | 3 | 19 | 5 | 96 | 38 | 10 | 1.1 | 149 | 2.5 |
| 3-93B | s | −0.6 | −0.3 | 5 | 3 | 15 | 6 | 77 | 30 | 10 | 0.6 | 243 | 0.9 |
| 3-93B | ns | −0.2 | −0.2 | 5 | 3 | 13 | 4 | 77 | 27 | 6 | 0.3 | 232 | 0.3 |
| 4-91B | s | 0.9 | 0.9 | 5 | 3 | 12 | 6 | 72 | 25 | 9 | 1.3 | 46 | 5.0 |
| 4-91B | ns | 2.1 | 0.7 | 6 | 2 | 18 | 3 | 79 | 33 | 3 | 2.2 | 71 | 13.4 |
| 4-92T | s | −0.5 | 0 | 5 | 2 | 15 | 3 | 86 | 30 | 6 | 0.5 | 271 | 0.7 |
| 4-92T | ns | 1.8 | 0.1 | 6 | 1 | 19 | 1 | 89 | 34 | 2 | 1.8 | 87 | 9.0 |
| 4-92B | s | 0.7 | 0.9 | 4 | 3 | 10 | 6 | 68 | 22 | 9 | 1.1 | 35 | 3.9 |
| 4-92B | ns | 1.5 | 0.6 | 6 | 2 | 17 | 2 | 81 | 33 | 4 | 1.6 | 69 | 6.9 |
| 4-93T | s | −0.4 | 0 | 8 | 4 | 31 | 9 | 72 | 67 | 14 | 0.4 | 269 | 0.2 |
| 4-93T | ns | 0.6 | 0.2 | 5 | 3 | 12 | 3 | 76 | 25 | 5 | 0.7 | 68 | 1.6 |
| 4-93B | s | 0.7 | 1 | 5 | 4 | 12 | 9 | 53 | 31 | 9 | 1.2 | 35 | 3.6 |
| 4-93B | ns | 0.4 | 0.5 | 5 | 3 | 11 | 4 | 67 | 24 | 4 | 0.6 | 39 | 1.3 |
| 5-91T | s | −1.8 | 0.7 | 6 | 3 | 18 | 6 | 95 | 33 | 12 | 1.9 | 290 | 8.0 |
| 5-91T | ns | −1.2 | 0.6 | 5 | 2 | 11 | 3 | 86 | 22 | 5 | 1.3 | 299 | 6.3 |
| 5-92T | s | −1.9 | 1.1 | 6 | 4 | 20 | 8 | 97 | 36 | 15 | 2.2 | 299 | 9.5 |
| 5-92T | ns | −1.7 | 0.5 | 5 | 3 | 15 | 4 | 89 | 27 | 8 | 1.8 | 288 | 9.3 |

(Continued on next page)

**Table 2.** General statistics of Saginaw Bay current meter data from June ′91 through June ′94. Symbols in column 2, "s" and "ns" refer to stratified and non-stratified respectively. Mean currents = U, V in cm s$^{-1}$, $u_{std}$ and $v_{std}$ = standard deviation of U, V. $KE_u$ and $KE_v$ = mean kinetic energy of the u and v components, $\theta_p$, $\lambda_1$, $\lambda_2$ are defined in the text and "S" = magnitude of the mean current (cm s$^{-1}$), "Dir" = direction of the mean current and %V = % of variance explained by the means flow, S. *(Continued)*

| ID | Season | U | V | $u_{std}$ | $v_{std}$ | $KE_u$ | $KE_v$ | $\theta_p$ | $\lambda_1$ | $\lambda_2$ | S | Dir | %V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5-92B | s | −1.4 | 0.4 | 6 | 3 | 18 | 4 | 89 | 34 | 8 | 1.4 | 287 | 4.7 |
| 5-92B | ns | −1.2 | 0.3 | 5 | 3 | 13 | 3 | 89 | 24 | 7 | 1.2 | 286 | 4.6 |
| 5-93T | s | −2.3 | −0.2 | 5 | 4 | 16 | 7 | 88 | 27 | 13 | 2.3 | 265 | 13.2 |
| 5-93T | ns | −0.9 | 0 | 3 | 2 | 6 | 3 | 73 | 11 | 5 | 0.9 | 272 | 5.1 |
| 6-91T | s | −1.8 | −0.6 | 7 | 4 | 25 | 7 | 103 | 49 | 12 | 1.9 | 253 | 5.9 |
| 6-91T | ns | 0.7 | −1 | 5 | 2 | 11 | 3 | 91 | 22 | 6 | 1.3 | 144 | 6.0 |
| 6-91B | s | 0.4 | −0.6 | 6 | 3 | 19 | 4 | 96 | 39 | 8 | 0.7 | 148 | 1.0 |
| 6-91B | ns | 0.8 | −0.4 | 5 | 2 | 12 | 3 | 81 | 23 | 5 | 0.9 | 118 | 2.9 |
| 6-92T | s | −2.4 | −0.2 | 6 | 3 | 20 | 6 | 101 | 34 | 10 | 2.4 | 266 | 13.1 |
| 6-92T | ns | 0.7 | −0.7 | 5 | 3 | 14 | 4 | 89 | 27 | 8 | 0.9 | 136 | 2.3 |
| 6-92B | s | −0.3 | −0.2 | 4 | 3 | 10 | 3 | 87 | 20 | 6 | 0.4 | 242 | 0.6 |
| 6-92B | ns | 0.7 | −0.1 | 4 | 2 | 10 | 3 | 78 | 20 | 4 | 0.7 | 98 | 2.0 |
| 6-93T | s | −1.3 | −0.7 | 6 | 3 | 21 | 4 | 89 | 39 | 8 | 1.5 | 242 | 4.8 |
| 6-93T | ns | 0 | −0.3 | 4 | 2 | 7 | 2 | 87 | 14 | 4 | 0.3 | 185 | 0.5 |
| 6-93B | s | 0 | −0.6 | 6 | 3 | 16 | 5 | 74 | 34 | 8 | 0.6 | 179 | 0.9 |
| 6-93B | ns | −0.2 | −0.4 | 4 | 2 | 7 | 2 | 77 | 15 | 4 | 0.4 | 210 | 0.8 |

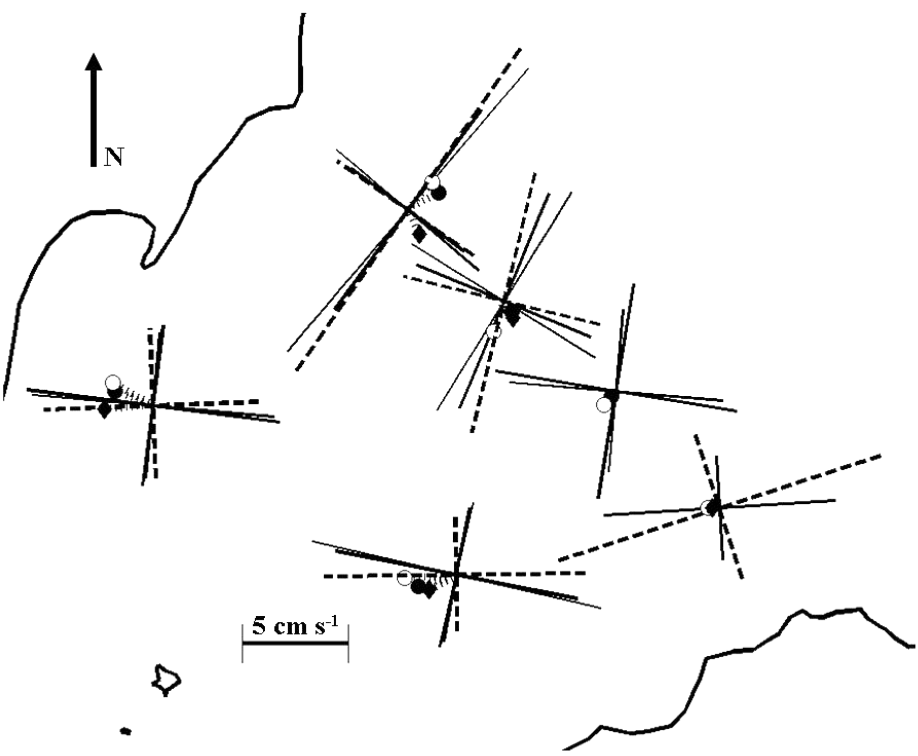


**Figure 2.** Principal axes of variation for the stratified season (DOY 131 - 314) for the near surface current meter data (14 m) in Saginaw Bay. The axes origin corresponds to the mooring locations in Figure 1. The axis length from the origin is one standard deviation of the rotated velocity components. The thin line is ′91–′92, the thick line is ′92–′93, and the dashed line is ′93–′94. The mean current vectors are also displayed with • = ′91–′92, ○ = ′92–′93, and ♦ = ′93–′94.

where the positive sign is used for $\lambda_1$ which describes the variance along the major axis, and the minus sign is used for the variance $\lambda_2$ and the minor axis. Additional details and derivations of these equations can be found in Emery and Thomson (2001).

Figures 2–5 show the principal axes of variation for the top (14 m below the water surface) and bottom (2 m above the bottom) current meters calculated according to equation 1 for both the stratified and non-stratified periods for all years. The length of the major axis from the origin is equal to $\sqrt{\lambda_1}$, and correspondingly the length of the minor axis from the origin is $\sqrt{\lambda_2}$. The mean current vectors were also calculated and are depicted in Figures 2–5 as well.

## Discussion

Each mooring location had at least one occasion of a mean current greater than or equal to 2 cm s$^{-1}$ (Table 2). There were nine such occurrences from June ′91 to June ′94 with the peak means occurring during the non-stratified season at the outer four moorings, whereas peak means occurred at stations 5 and 6 during the stratified period. There was only one occurrence of a peak mean current at a bottom current meter (mooring 4), and the remaining eight peaks all occurred at the top current meter. There was significant directional variability to the mean flows, with the greatest inter-annual variability occurring at mooring 1 during the stratified period (Fig. 2). In ′91 and ′92 the mean surface flow at station 1 was directed out of the bay, whereas in ′93 the mean flow was directed into the bay. In fact, variability in the magnitude and direction of the mean flow field was often significantly different between years, between the top and the bottom current meter, and between the stratified and non-stratified seasons, with the most consistent site being the bottom current meter at station 4 which consistently showed the mean flow to be directed out of the bay. The importance of the mean flow relative to current variability (%V, Table 2) was calculated by squaring the mean flow, S, dividing it by $\lambda_1 + \lambda_2$, and multiplying the result by 100. The percentage of the variance explained by the

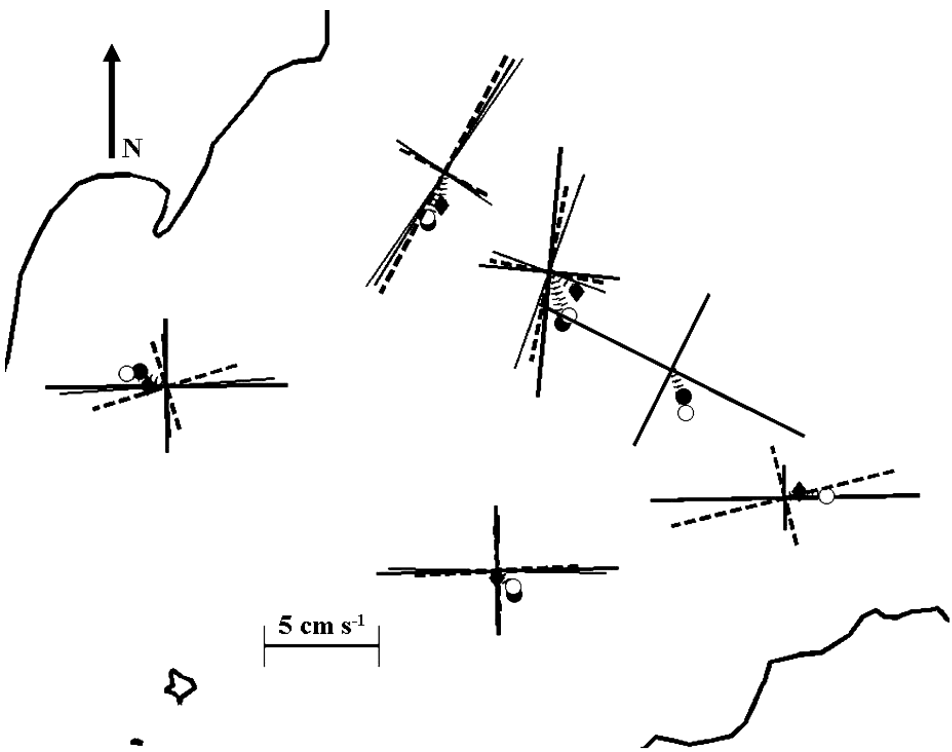


**Figure 3.** Principal axes of variation for the non-stratified season (DOY 315–130) for the near surface current meter data (14 m) in Saginaw Bay. All graph elements correspond to those described in Figure 2.

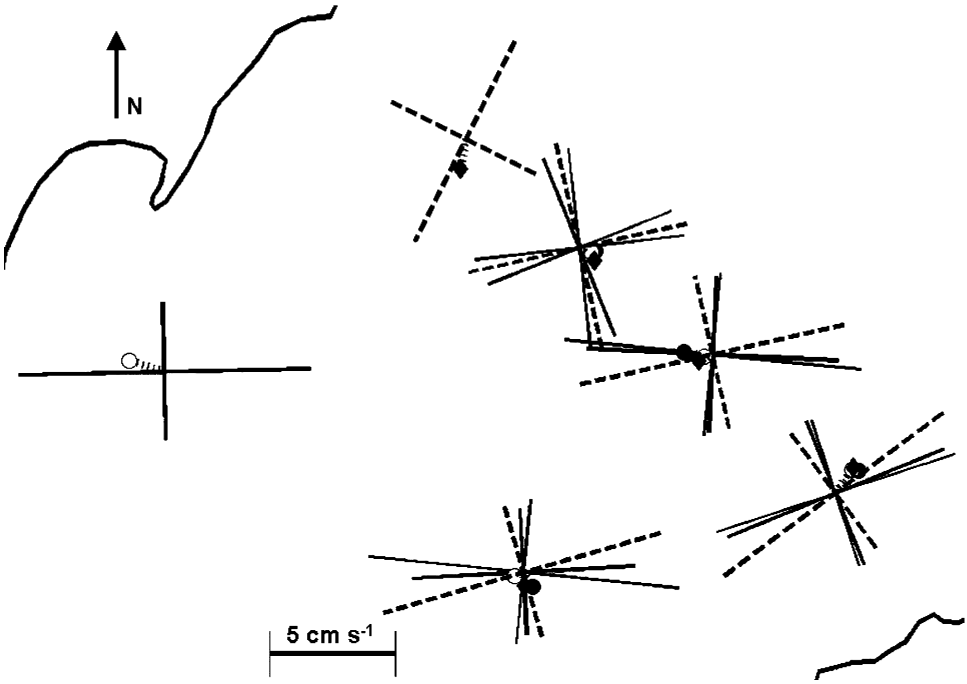


**Figure 4.** Principal axes of variation for the stratified season (DOY 131–314) for the bottom current meter data in Saginaw Bay. All graph elements correspond to those described in Figure 2.

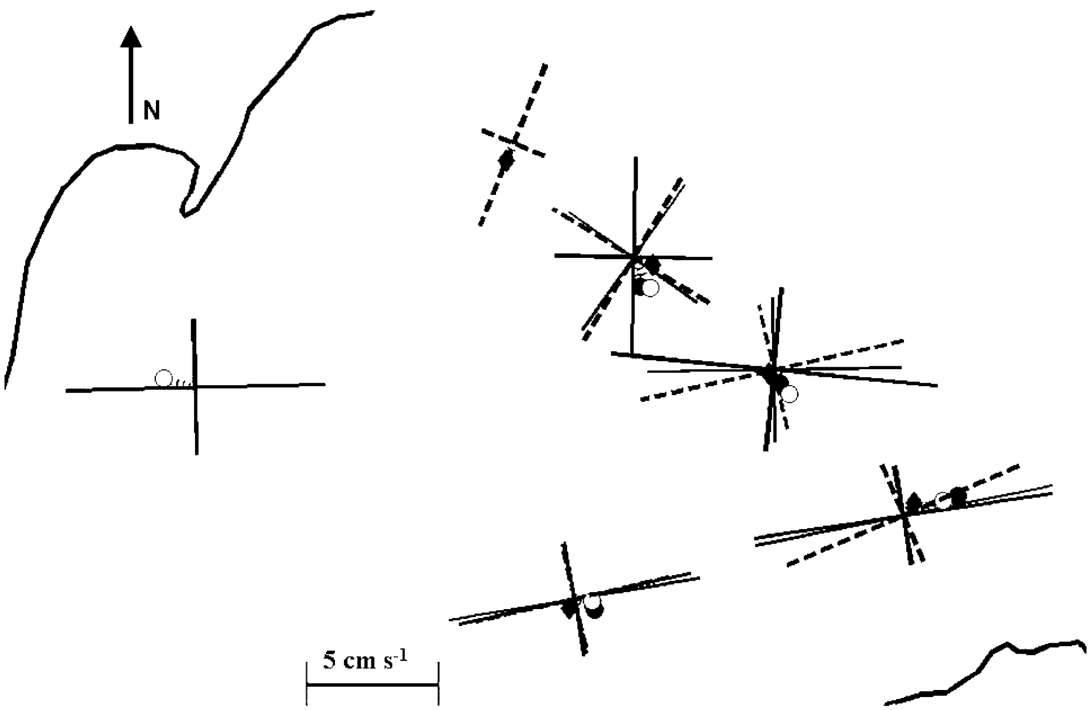


**Figure 5.** Principal axes of variation for the non-stratified season (DOY 315–130) for the bottom current meter data in Saginaw Bay. All graph elements correspond to those described in Figure 2.

mean flow ranged from (1–13%) and (1–20%) for the stratified and non-stratified seasons, respectively. The overall mean during stratification was 3%, increasing to 6% during the non-stratified portion of the year. Although the mean flows are small in terms of their contribution to instantaneous circulation pattern, their very existence indicates that there is a significant net exchange of water between the bay and lake.

The principal axes of variation (Figs. 2–5) provide information on preferred flow orientation by the alignment of the major axis parallel to the direction showing the greatest variance or energy of the current meter data under examination. The top 12 data sets in terms of mean kinetic energy ($KE_u + KE_v \geq 25$ cm$^2$ s$^{-2}$, Table 2) all occur at the top current meter and 11 of them happen within the stratified season. Each mooring location had at least one season with high kinetic energy except for station 2 which in ′92–′93 had mean high kinetic energies of 30 and 29 cm$^2$ s$^{-2}$ for the stratified and non-stratified periods, respectively. The energy levels were nearly equal between seasons, yet the energy was more evenly distributed during stratification with 56% of the total variance contained in $\lambda_1$, as opposed to the non-stratified season when 76% of the total variance was aligned along the major axis. The distribution of variance between the major and minor axes for the top 12 most energetic records ranged from 56 to 85% with an overall mean of 73% demonstrating anisotropy in the flow field but not necessarily a preferred orientation to the flow. If there were a preferred flow orientation, as is likely with bathymetric steering of currents, then the principal axes of variation should be time invariable. For example, in general, the ′93–′94 current meter data show a cyclonic rotation of the principal axes compared to the previous two years, suggesting a similar rotation in the wind stress pattern which should be discernible in the over-lake meteorology.

# Conclusions

The following four points summarize our major findings. (1) The winter months showed the highest mean currents at the outermost bay stations, whereas the stratified season showed high mean currents further into the bay, in more shallow waters, at stations 5 and 6. (2) The bottom currents at station 4 were the most consistent over time showing a mean flow directed out of the bay into Lake Huron. (3) Only a small fraction of the kinetic energy was contained in the mean currents. And, finally, (4) the variability in the orientation of the principal axes on semi-annual to inter-annual time scales suggests caution in generalizing about circulation based solely upon limited data sets. Future efforts will be directed at more extensive comparisons between these data and output from whole-lake hydrodynamic model simulations, as well as examining the coupling of the surface meteorology driving the system.

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