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Low-Frequency Water Volume Transport Through the Midsection of Green Bay, Lake Michigan, Calculated From Current and Temperature Observations

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ABSTRACT. *Moorings with current meters and temperature recorders were deployed along a mid-bay transect on either side of Chambers Island in Green Bay from September 1988 to October 1989. Daily transport estimates calculated from the current, temperature, and wind data, show temporal and spatial variability. Net summer transport during stratification west of Chambers Island was out of the lower bay (350 m^3s^{-1}) in the epilimnion, into the lower bay (900 m^3s^{-1}) in the hypolimnion, and out of the lower bay (320 m^3s^{-1}) through the passage east of the island. The residence time for the lower bay is reduced to less than 1 year using the above transport compared to a water balance estimate of over 3 years. During the mid-September to May isothermal period, a horizontal transport gradient existed. Under the solid ice cover of winter, transport variability was significantly reduced and was uniformly out of the lower bay (500 m^3s^{-1}). Fluctuations in daily transport were often large (up to 2×10^4 m^3s^{-1}). The temporal and spatial variability of the water volume transport suggests that material mass fluxes between lower and upper Green Bay will be similarly dependent.*

INDEX WORDS: *Water currents, water temperature, water transport, Lake Michigan.*

INTRODUCTION

Green Bay, an elongated freshwater bay, is about 193 km long with an average width of 22 km and a mean depth of 15.8 m (Mortimer 1978) connected to Lake Michigan by four main passages in the northeast corner of the bay. Toxic contaminants, including those attached to particles and dissolved in the water, and nutrients entering the bay, mainly from the Fox River at the city of Green Bay, are primarily responsible for the degraded water quality of the lower bay and the alteration of Green Bay's ecosystem. In the lower bay, wind and Coriolis forces cause the Fox River plume to usually move northward along the eastern shore of the bay for distances of 10 to 40 km (Modlin and Beeton 1970, Ahrnsbrak and Ragotzkie 1970). In the upper bay, significant water volume is exchanged between the bay and Lake Michigan through the island passages north of the Door Peninsula. This complex exchange process is driven by seiche and tidal forces, wind stress, and internal pressure gradients set up by the isopycnal slope between the lake and the bay (Miller and Saylor 1985, Gottlieb *et al.* 1990). Hence, the upper bay water is a mixture of bay and lake water characterized by cool temperatures and high transparency.

Green Bay was selected by the Great Lakes National Program Office, Environmental Protection Agency, as the site for a comprehensive, integrated research effort during 1988-1990. The goal of this effort was to develop a numerical mass balance model for Green Bay. In short, this approach requires that the mass of a material entering the system must equal the quantity leaving the system plus the quantity stored, transformed, and degraded.

Water volume transport is a necessary parameter in these models. In this paper, we present the daily water volume transport between the lower and upper bay calculated using measured current velocities, water temperatures, and over-water winds rather than computing transports by the conventional water balance method. (Lower bay is defined as the area from Chambers Island to the mouth of the Fox River.) We will concentrate on a mid-bay transect at Chambers Island. Previous investigations have indicated a distinguishable, though spatially dynamic, separation in this region between the warmer, more turbid lower bay water and the cooler, clearer upper bay/Lake Michigan water (Lathrop *et al.* 1990, Kennedy 1982, Miller and Saylor 1985). This transect is also a boundary of the contaminant mass balance model.

OBSERVATIONS

The Observational Program

Current velocity and water temperature data through one annual cycle were measured during two deployments. A complete description of the observational program and data collected is presented in Gottlieb *et al.* (1990). This paper focuses on data collected on either side of Chambers Island from 22 September 1988 through 4 May 1989 ("winter") and from 22 May through 9 October 1989 ("summer"). EG&G vector averaging current meters (VACMs) were suspended from subsurface floats with the upper-most meter at the 10 or 12 m depth, another at 5 m above bottom and, where depth permitted, an additional meter near mid-depth. Water temperature data at 2-m intervals from the 5 to 21-m depth and at 4-m spacing from 21 to 29 m were recorded at hourly intervals during the summer deployment at mooring 19. Hourly meteorological data were measured at the Green Bay Harbor Entrance Light approximately 70 km southwest of Chambers Island.

The Data

Large amplitude water-level oscillations are a conspicuous feature in Green Bay. Mortimer (1965) demonstrated that the first free mode of Lake Michigan (9.0 hour period) and the lunar (M_2) tide (12.4 hr) are resonantly amplified in the bay and both are evident in the measured current velocities and temperatures (Miller and Saylor 1985, Gottlieb *et al.* 1990). Oscillations with periods less than 24 hours contribute to the mixing and dispersion of solutes and particles, however these periodic oscillations generally have current magnitudes less than 15 cms^{-1} and excursion distances less than 3 km. Hawley (1993), using our transport algorithim with unfiltered current data, found that the transport of total suspended material through a subarea of this cross-section was determined by fluctuations longer than the tidal period. There is no question, however, that tidal mixing at the semidiurnal lunar period and the tidal-like mixing induced by surface seiches of lesser period contribute to the dispersion of dissolved and suspended materials in Green Bay. These motions are barotropic when the bay is unstratified but may have a baroclinic component during stratification (Gottleib 1992). Investigation of these turbulent, short-period mixing processes is outside the scope intended in this paper. The aperiodic circulations induced by boundary geometry, wind events, longer-period internal and surface pressure gradients, and residual currents cause water mass exchanges of at least an order of magnitude larger, and we have limited this analysis to the low-frequency water volume transport through the midsection of the bay. To eliminate oscillations with periods less than 24 hours, hourly current, temperature, and wind data were filtered using a Cosine-Lanczos taper and resampled at 24 hr intervals. The wind measurements, recorded 20 m above the water surface, were adjusted to a 4 m height using the 1/7 power law for wind speed profiles (Schwab and Morton 1984). Currents were rotated such that the v-component is normal to the transect line with the convention that flow out of the lower bay is denoted as positive. Wind vectors were also rotated to align the v-component with the longitudinal bay axis and have the same sign convention as the currents, i.e., positive denotes wind blowing from the lower bay toward the upper bay.

RESULTS

Summer Transport

The transport can be calculated by multiplying the cross sectional area by the current velocity normal to the cross section. The total cross sectional area west of Chambers Island is about 2.4×10^5 m^2 and the area east of the island is an order of magnitude smaller, 2.7×10^4 m^2. The total area was divided into subareas whose initial boundaries were the midpoint between current meters in both the vertical and horizontal (Fig. 1). These subareas were then further partitioned into 1-m-depth layers to permit the horizontal boundaries to vary with fluctuations in thermocline depth. A nearshore shallow area (subarea A1) near the western shore was assumed to be a region where currents are only a function of the wind stress, assumed to equal 0.5% of the v-component of the wind. Current velocity was set to zero in a 1.5 m-thick bottom layer to crudely compensate for effects of bottom friction.

Development of baroclinic current flow with the onset of thermal stratification and the intrusion of

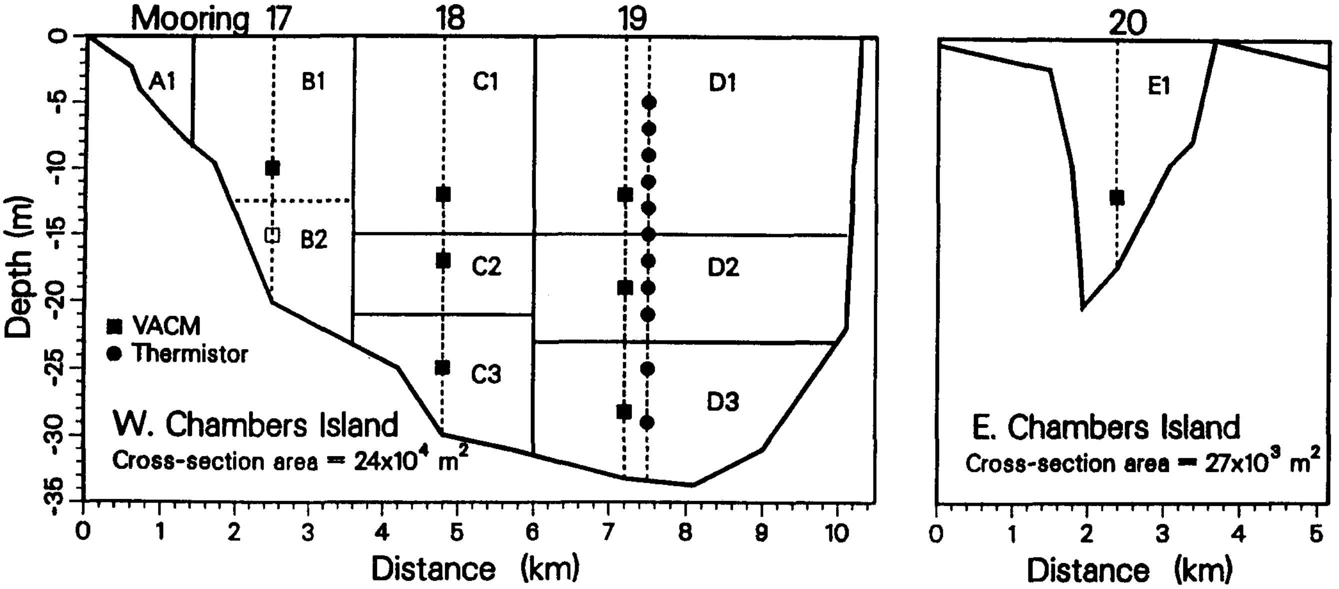

FIG. 1. Schematic drawing of the mid-bay cross section at Chambers Island with a vertical exaggeration of 200:1. Depths of the Vector Averaging Current Meters are denoted by solid squares at the indicated mooring sites (open square indicates no data was recorded), thermistor depths are shown as solid circles. Solid lines denote the subareas.

upper bay/Lake Michigan water into the lower bay is well documented (Miller and Saylor 1985, Lathrop *et al.* 1990), therefore volume transports were computed separately for areas above and below the thermocline. The depth of the 15°C isotherm was assumed to be mid-thermocline and the vertical boundary between eplimnion and hypolimnion flow. The thermocline was confined to depths of 11 to 18 m from July through mid-September with a mean depth of 14.4 m. The cross sectional area assigned to each current meter was a function of the daily thermocline depth rather than the vertical midpoint between the top two current meters during stratification. Because of transverse thermocline slopes associated with upwelling, downwelling, and internal oscillations, the temperatures recorded by individual current meters on moorings 17 and 18 were examined to determine whether the meter was in the epilimnion or hypolimnion, and the area of their respective subsections was adjusted accordingly.

Direct response to wind forcing through Ekman dynamics contributes to the transport process in the near-surface region. The uppermost current meter was at a depth of 10 or 12 m, therefore near-surface wind-generated currents were estimated from the over-water wind data measured 70 km to the south. The current speed in the surface-to-thermocline layer (when the thermocline was above top meter), or in the upper 6 m (thermocline below the top meter) was assumed to be 0.5% of the longitudinal component of the wind. Transport through the smaller east passage was based on the measured current velocities at one depth (-12 m) and no attempt to separate the flow into two layers was made. One-half percent of the wind speed (3 m s^{-1} threshold speed) was added to the measured current through only the top 2 meters because direct wind forcing is more restricted in this confined channel. The lower current meter on mooring 17 did not function, therefore current velocities in this subarea (B2) were assumed to equal the current at the mid-depth meter on mooring 18 when the thermocline was below the upper current meter (-10 m) or, with no thermocline, the velocity was assumed to be 75% of the upper current meter velocity.

The time series of daily net volume transport through the entire Chambers Island transect is shown in Figure 2. Large day-to-day variability (standard deviation = 4,700 m^3s^{-1}) was present throughout the summer months in response to the variable flow fields generated by transient wind events and lake/bay interactions. A more relevant procedure for estimating material mass fluxes separates the daily water volume transport during the summer period into transport above and below the thermocline for the transect west of Chambers Is-

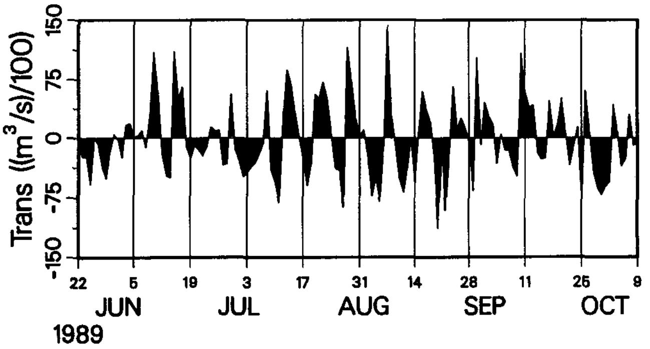

FIG. 2. Net daily transport through the Chambers Island transect for the summer period.

land, and the total transport east of the island (Fig. 3). Transport through the west transect was consistently two layered after stratification developed in June. For the 93 days with baroclinic currents, 22 June–22 September, the net transports were +540, -830, and +250 m^3s^{-1}, above and below the thermocline and the east channel, respectively, and for the 30 days immediately prior to stratification the transport was southward in the lower bay (-470 m^3s^{-1}) west of Chambers Island and northward through the east channel (+550 m^3s^{-1}). An important contributor to the transport is the large amplitude 8-day period oscillations commencing about mid-July that appear more prominently in the daily transport below the thermocline (Fig. 3) (Saylor *et al.* 1993, Gottlieb *et al.* 1990).

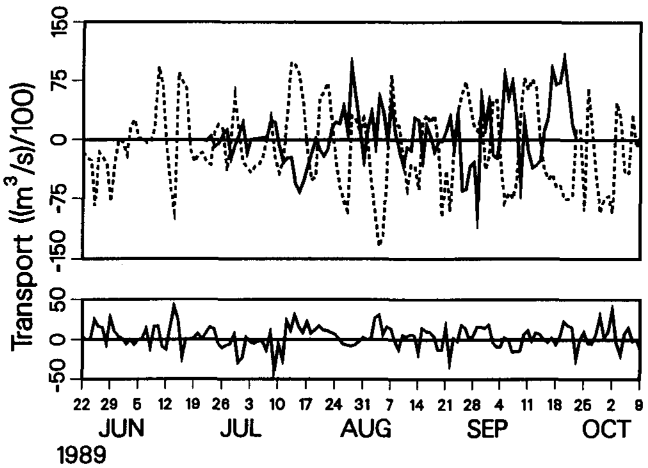

FIG. 3. Transport above (solid) and below (dashed) the thermocline west of Chambers Island in the upper panel and transport through the transect east of Chambers Island in the lower panel.

Winter Transport

Transport calculations during winter are based on measurements at moorings 4 and 5 west of Chambers Island and mooring 6 east of the island (Fig. 4). These currents, the first to be observed during winter in Green Bay, can be categorized into two types. In October through December, the v-component of the current at moorings 4 and 5 west of Chambers Island were similar in magnitude to those recorded during summer, while east of the island the low-pass filtered currents were greater than during summer occasionally exceeding 30 cms^{-1}. Ice covered most of the lower bay by 19 December and by 11 January, 100% unconsolidated pack covered the bay. An unusually warm episode during the last half of January temporarily decreased the ice cover, but by 6 February 1989, consolidated pack extended over the entire bay (Gottlieb *et al.* 1990). It was not until consolidated pack formed, i.e., 100% concentration with the floes frozen together to form a solid sheet, that the low-pass filtered current speeds dropped markedly at all locations. Currents returned to typical open water magnitudes as the ice pack began to break up. It should be noted, however, that the water mass is not at rest during maximum ice cover. Strong oscillatory currents generated by tidal forcing and interactions with water level oscillations in Lake Michigan, and atmospheric pressure gradients on the ice surface itself continued throughout the ice-cover period as displayed in non-filtered data (Gottlieb *et al.* 1990).

We again subdivided the cross sectional area at the approximate midpoints between current meters (Fig. 4). Note that the bottom meter on mooring 5 (-27.5 m) did not function and that mooring 4 was at approximately the same location as summer mooring 18. Winter transport estimates were computed using the same technique as for summer, except the subarea boundaries were fixed and no wind contribution was added during ice cover. During the period of ice consolidation, 11 January through 1 April (Gottlieb *et al.* 1990), a linearly increasing current profile was assumed through the upper 6 m of water. Figure 5 shows that the winter net daily transports were again highly variable, with significantly lower magnitudes during solid ice cover. Net transport for the entire "winter" period, 22 September 1988 through 4 May 1989, was +360 m^3s^{-1}. The standard deviation, 4,100 m^3s^{-1}, is nearly equal to

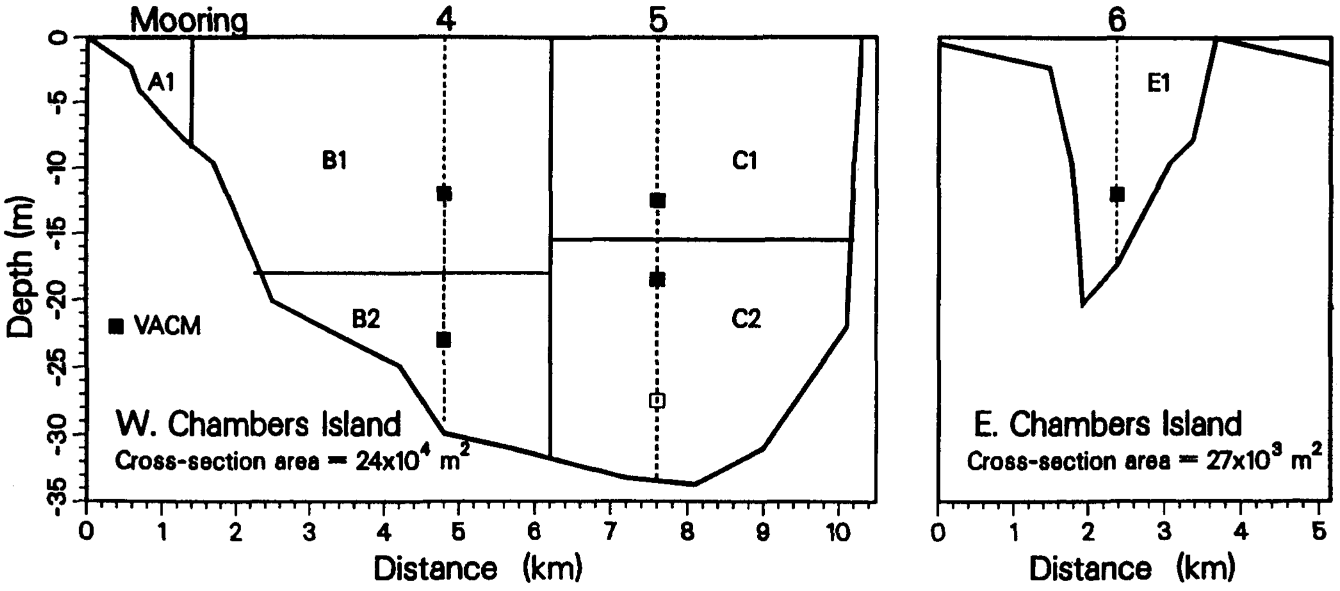

FIG. 4. Schematic drawing of the winter cross sectional subareas, Chambers Island transect.

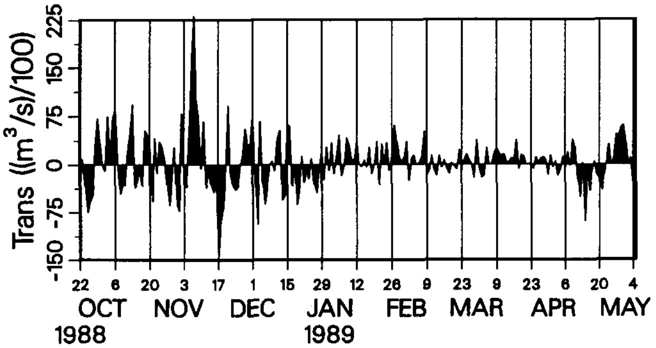

FIG. 5. Net transport through the Chambers Island transect for the September 1988 to May 1989 period.

the summer value. Transport during 100% consolidated pack was northward, into the upper bay, across the whole transect averaging +520 m^3s^{-1} over the 54-day ice period. The transport was larger than expected during this low tributary inflow period (<200 m^3s^{-1}) and there was negligible change in storage which indicates that regions of lesser or reversed flow were not detected by our winter sampling grid. During winter, there was no significant vertical transport gradient since the current was barotropic, however, significant horizontal variability existed as illustrated by the net transport time series for the individual cross-sectional areas (Fig. 6). Prior to ice consolidation, transport in the western half of the west transect (B subareas) was northward (+2,130 m^3s^{-1}), while southward transport (-1,400 m^3s^{-1}) dominated the eastern half (C subareas) and the channel east of Chambers Island (-520 m^3s^{-1}).

DISCUSSION

The transport through the midsection of Green Bay has been shown to be highly variable on a daily time scale. Errors inherent in the input data and through the assumptions used to compute the daily transport are difficult to quantify. Inaccuracies in the magnitude of the cross-sectional area would lead to a bias in the net values but not contribute to day-to-day variablity. Spatial variability in current velocities, as noted earlier, suggests that the selection of the subarea boundaries, based on the midpoints both vertically and horizontally, may not provide adequate resolution but was limited by the finite number of observation points. Estimates of wind generated surface currents and their depth of influence resulted in a net positive (out of the lower bay) component to the transport (+165 m^3s^{-1} for the 141-day summer period, +270 m^3s^{-1} during winter). The flux estimates are most sensitive to errors in current velocity. For example, a 1 cms^{-1} error in current velocity throughout the cross section translates into about a 2,500 m^3s^{-1} change in transport. Vertical and horizontal current shears are a noted feature in the bay, and profiles based on, at most,

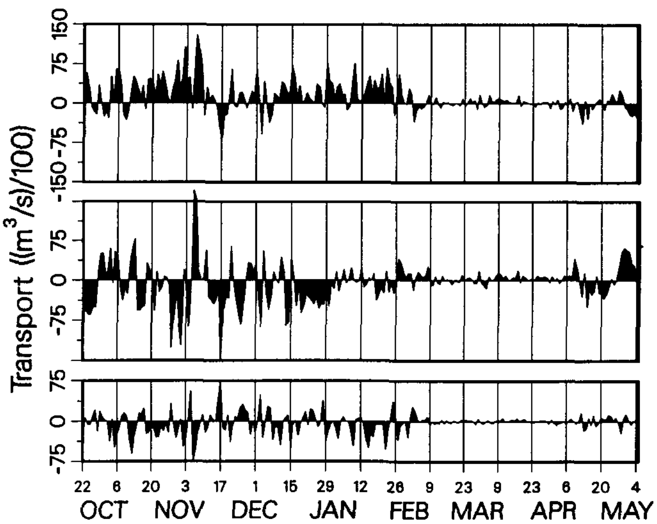

FIG. 6. Transport for subareas during the winter season for the Chambers Island transect. Transport through subareas B1+B2 is presented in the upper panel, subareas C1+C2 in the middle panel, and through the transect east of the Chambers Island, E1, in the lower panel. (See Fig. 4 for the subarea locations.)

three points will induce variability, particularly when the thermocline is near the depth of a current meter. The presence of islands, shoals, and shoreline prominences create wakes and eddies that are not well understood but which contribute to transport variability. In light of the variety of uncertainites possible in these transport calculations, the values computed are surprisingly consistent and mass conserving, albeit with large daily variability.

An independent assessement of the validity of our assumptions and criteria can be estimated by computing transports using only current velocity data measured by an Acoustic Doppler Current Profiler (ADCP) located near mooring 19. The ADCP measured current velocities at 1 m intervals from 5 meters above bottom to 6 meters below the surface during the summer months. These data were processed in the same manner as the VACM data with the assumption that the current magnitude measured at the 6 m depth extends to the surface. Transport was computed only for subarea D (Fig. 1). The 137-day mean computed from the VACM and ancillary data, -20 m^3s^{-1}, compares favorably with the ADCP computed value of +40 m^3s^{-1}. The standard deviation of the daily difference, 3,200 m^3s^{-1}, was caused mainly by large differences that occurred during days when the thermocline level was very near the upper VACM.

Although the daily transport values show much variability, the long-term influence of inflow of upper bay/Lake Michigan water into the lower bay can be qualitatively visualized by computing the residence time of the lower bay. The lower bay contains about 22 km^3 of water. A net outflow of approximately 200 m^3s^{-1}, the average tributary inflow to the lower bay, yields a residence time of about 3.5 years. From the inflow and outflow values calculated in this study during the stratified season, the residence time would be reduced to 0.8 years.

SUMMARY

This study represents the first effort to compute a time series of water volume transport between lower and upper Green Bay using observed current velocities and water temperatures during one annual cycle. Transport values, computed at daily time intervals, show small temporal and spacial variability during consolidated ice cover. During the isothermal period, October through May, the water volume flux was vertically uniform but with significant horizontal shear across the transect with transport generally southward (into lower bay) through the passage east of Chambers Island and the east half of the west passage and northward through the west half of the west passage. Summer thermal stratification and the associated baroclinic currents produced bidirectional two-layer or vertically sheared, but horizontally consistent, flow. Transport was directed out of the lower bay above the thermocline and into the lower bay below the thermocline through the transect west of Chambers Island and out of the lower bay east of the island. The net transport for the entire data collection period, +130 m^3s^{-1}, compares favorably with the tributary inflow to the lower bay, roughly 200 m^3s^{-1} (U.S. Geological Survey 1990). The large concurrent transports into and out of lower Green Bay reduce the flushing time from 3.5 years to less than 1 year. These transport gradients also suggest that the mass flux of materials between the lower and upper bay is highly dependent on the temporal and spatial distribution of these materials.

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