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Predicting the oscillating bi-directional exchange flow in the Straits of Mackinac

Eric J. Anderson [a,*], David J. Schwab [b]

[a] Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, MI, USA
[b] Water Center, University of Michigan, Ann Arbor, MI, USA

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ABSTRACT

The Straits of Mackinac are a unique feature that connects Lake Michigan and Lake Huron into a single hydraulically linked system. With currents of up to 1 m/s and oscillating volumetric transport up to 80,000 m^3/s, they play an important role in water quality, contaminant transport, navigation, and ecological processes. We present the first three-dimensional hydrodynamic model of the combined Lake Michigan–Huron, including the Straits of Mackinac at high-resolution, that is able to simulate the three dimensional structure of the oscillating flows at the Straits. In comparison with individual lake models for Michigan and Huron (no connection at the Straits), we are able to isolate the effects of the bi-lake oscillation and have found that although the oscillation (Helmholtz mode) is the dominant forcing mechanism, the flow can be modulated when atmospheric systems are in-phase with water level fluctuations. Furthermore, the area of influence of the Straits is found to extend up to 70 km into each lake, underscoring the need for realistic predictions within the Straits. For the first time, this combined-lake hydrodynamic model provides the capability to investigate and accurately predict flow at the Straits of Mackinac and its effect on Lake Michigan and Huron. This model forms the basis for the next generation of real-time hydrodynamic models being developed for the Great Lakes Coastal Forecasting System, a suite of models designed by the National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory (NOAA/GLERL) that predict hydrodynamic conditions such as currents, temperatures, and water levels in three dimensions.

Introduction

Lake Michigan and Lake Huron are hydraulically linked by the Straits of Mackinac. The Straits are deep enough (average depth 20 m) and wide enough (6 km at the narrowest point) to allow for free hydraulic exchange between the lakes yielding a system with identical resting lake level for each lake. The combined Michigan–Huron system forms the largest lake in the world by surface area and the fourth largest by volume (containing nearly 8% of the world's surface freshwater; Fig. 1). The Straits of Mackinac provide an important waterway for commercial shipping of iron ore, coal, cement, limestone, grain and oil to and from ports such as Chicago and Milwaukee. The Straits were formed after deglaciation occurred in 11,200 B.P. (Hansel et al., 1985a,b; Larsen, 1987), leaving an incised river of over 100 km in length that connected the Michigan and Huron basins (Stanley, 1937) after which a water level rise in the Huron basin inundated the fluvial channel and created the Mackinac Straits around 8150 B.P. (Larsen, 1987). Several studies have investigated the flow in the Straits including the net discharge from Lake Michigan to Huron on monthly, seasonal, and annual scales (Judson, 1909; Moll et al., 1976; Mortimer and Fee, 1976; Murty and Rao, 1970; Powers and Ayers, 1960; Quinn, 1977; Saylor and Sloss, 1976). The annual net flow through the Straits is calculated to be on the order of 1100 m^3/s, but is found to be highly variable between years (standard deviation of 26%; Quinn, 1977).

Oscillating flow conditions at the Straits have been described in previous investigations and current measurements have confirmed an oscillation period on the order of 2–3 days due to the combined system and atmospheric conditions (wind and pressure). The amplitude of this oscillation can reach nearly 80 times the annual net discharge (e.g. 80,000 m^3/s), with current speeds near 1 m/s (Mortimer and Fee, 1976; Saylor and Miller, 1991; Saylor and Sloss, 1976). This peak amplitude of the oscillating flow is roughly 50× the discharge in the St. Clair River (the outlet to Lake Huron), or the equivalent of emptying Lake St. Clair in 12 h or Chesapeake Bay in 10 days. Furthermore, current measurements have also revealed that a bi-directional flow can develop in the Straits after the onset of thermal stratification, in which easterly currents (Michigan to Huron) develop in the epilimnion while westerly currents (Huron to Michigan) form in the hypolimnion (Saylor and Miller, 1991). It is suggested that this bi-directional flow profile is established by a horizontal density gradient from Lake Huron to Michigan, where the northern part of Lake Michigan exhibits a deeper thermocline on average than northern Lake Huron. This exchange flow where cold Lake Huron water is pumped into Lake Michigan (and vice-versa, warm Lake Michigan water into Lake Huron), may provide an explanation for the higher water quality observed in northern Lake Michigan, something that is not possible in using averaged or net flow conditions (Saylor and Miller, 1991).

* Corresponding author. Tel.: +1 734 741 2293.
E-mail address: eric.j.anderson@noaa.gov (E.J. Anderson).

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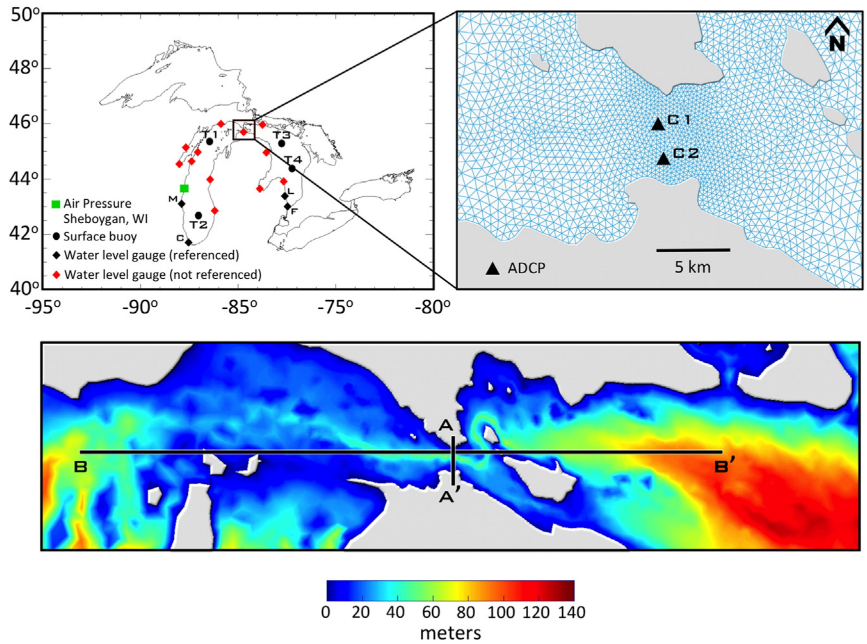

Fig. 1. (Top left) Great Lakes coastline including surface temperature buoys (T1, T2, T3, T4), water level gauges referenced in the paper (M = Milwaukee, C = Calumet, L = Lakeport, F = Fort Gratiot) marked in black, and those not referenced in the paper marked in red; (top right) magnified section of the Straits of Mackinac and model grid, including ADCP locations (C1 and C2); (bottom) 3 arc-second bathymetry of the Straits and lateral transect (A–A′).

The free oscillations of Lake Michigan and Huron have been studied extensively in the literature (Mortimer, 1965, 2006; Mortimer and Fee, 1976; Rockwell, 1966; Schwab and Rao, 1977). Several seiche modes for each lake have been computed, where the periods of the first mode are given as 9.1 h for Lake Michigan and 6.7 h for Lake Huron (Mortimer and Fee, 1976). Using the Merian formula (1) to compute the seiche of the combined lakes, given a length of 1000 km and average depth of 75 m, we find the combined-lake to have a period of 20.5 h,

$$T = \frac{2L}{\sqrt{gD}} \tag{1}$$

where T is the period, L is the length of the combined-lake, g is the gravitational constant, and D is the average depth of the combined-lake. Therefore, the bi-lake seiche is clearly not the mechanism behind the 3-day oscillations observed at the Straits. An investigation of the co-oscillation of the lakes by Rockwell (1966) used a one-dimensional channel approach to calculate a period of 47.8 h for the combined Lake Michigan–Huron, which is closer to the period of oscillation measured by Saylor and Sloss (1976). However, the oscillating currents in the Straits may in fact be more closely related to the Helmholtz mode between the lakes.

If we consider Lake Michigan and Lake Huron to be connected by a constriction in the form of the Straits of Mackinac, we can estimate the period associated with a Helmholtz mode between the two basins (Fig. 2) given the surface areas, A_m and A_h, the time-dependent average depths, δ_m and δ_h, the cross-sectional area of the Straits, A_s, and the length of the Straits channel, l. From the continuity Eq. (2), we can relate the rate of change of volume flux into a basin to the rate of change velocity in the channel, assuming a uniform and one-dimensional flow within the channel,

$$\frac{d^2\delta_h}{dt^2} = \frac{A_s}{A_h}\frac{du}{dt} \tag{2}$$

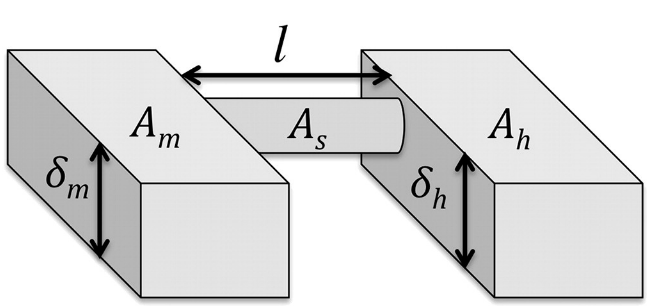

Fig. 2. Idealized schematic for the Lake Michigan and Lake Huron basins, connected by a constricting channel at the Straits of Mackinac. The surface area of Lakes Michigan and Huron are given as A_m and A_h, respectively, δ is the time-dependent depth, A_s is the cross-sectional area of the Straits, and l is the length of the channel.

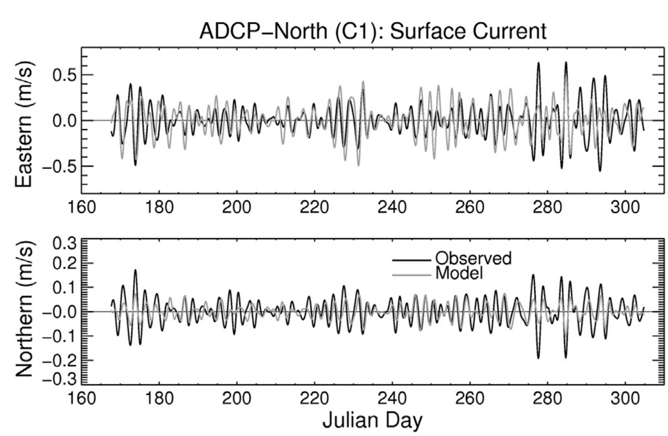

Fig. 3. Observed and modeled surface currents at the Straits of Mackinac for June–December 1990 at the northern ADCP location (C1, representative results).

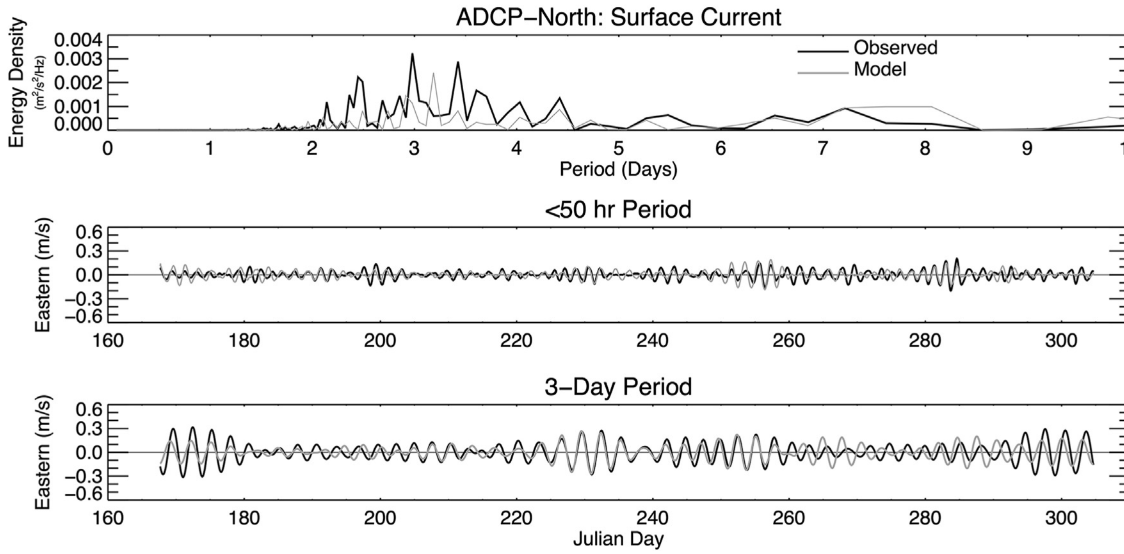

Fig. 4. Power spectra of surface currents at ADCP-North (top) and time-series plots of high-pass filtered (<50 h, middle) and band-pass filtered currents (3 days, bottom). ADCP-North (C1) results and model comparisons are representative of both measurement locations.

where t is time and u is the water velocity in the Straits channel. From the momentum equation, we can write the relate of change of velocity to the time-dependent depths of each basin,

$$\frac{du}{dt} = -\frac{dP}{dx} = -g\frac{(\delta_h - \delta_m)}{l} \tag{3}$$

where P is pressure and x is the coordinate in the channel direction. Substituting this into (2), we find

$$\frac{d^2\delta_h}{dt^2} = -\frac{A_s}{A_h}\frac{g}{l}(\delta_h - \delta_m). \tag{4}$$

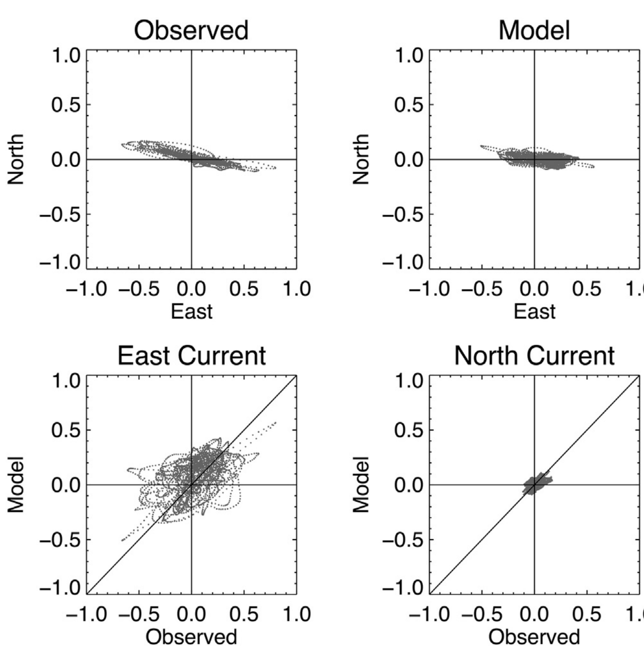

Fig. 5. Scatter plot comparisons of observed and modeled hourly surface currents (m/s) at the ADCP-North location (C1, representative of both ADCP locations).

Given that the volume of the combined system is a constant, C, we can write the total water volume as the sum of Lake Michigan, Straits of Mackinac, and Lake Huron

$$A_m\delta_m + A_s l + A_h\delta_h = C. \tag{5}$$

Solving for one of the basin depths and substituting it into (4), we find an equation in the form of a simple harmonic oscillator

$$\frac{d^2\delta_h}{dt^2} = -\frac{A_s g}{l}\left[\frac{1}{A_m} + \frac{1}{A_h}\right]\delta_h + C \tag{6}$$

with frequency, f,

$$f = \frac{1}{2\pi}\sqrt{\frac{A_c g}{l}\left[\frac{1}{A_m} + \frac{1}{A_h}\right]}. \tag{7}$$

Therefore, the period related to the Helmholtz mode is found to be

$$T = 2\pi\sqrt{\frac{l}{A_c g\left[\frac{1}{A_m} + \frac{1}{A_h}\right]}} \tag{8}$$

or if the surface areas of the two basins are equal (i.e. $A_m = A_s = A$), we can rewrite (8) as

$$T = 2\pi\sqrt{\frac{Al}{2A_c g}}. \tag{9}$$

Using a basin surface area of 6×10^{10} m^2, channel length of 60 km, and channel cross-sectional area of 1.2×10^5 m^2, the period of the Helmholtz mode between Lake Michigan and Lake Huron is 2.8 days, giving strong support to the notion that it is the primary forcing mechanism behind the oscillations in flow at the Straits as measured by Saylor and Sloss (1976).

The spectral analyses of water levels and currents at the Straits have illustrated the correlation between flow and the bi-lake oscillation, as well as higher-order oscillations in the current field that overlap with the frequency of meteorological systems in the Great Lakes (As-Salek and Schwab, 2004; Mortimer, 2006; Rockwell, 1966; Saylor and Sloss,

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Table 1
Statistical measures of surface currents at two locations in the Straits. Current comparisons are based on hourly surface currents (band pass filtered, 2–5 day oscillations), where U is the eastern current direction, V is the northern current direction, and |U| and |V| are the mean current amplitudes (ADCP locations C1, C2). Values of the mean, standard deviation (SD), root mean square difference (RMSD), and residual are given in units of m/s. The central frequency (CF) is computed for the error limit of one standard deviation. The positive outlier frequency (POF) and negative outlier frequency (NOF) are computed for the error limit of two standard deviations. The maximum duration of positive outliers (MDPO), maximum duration of negative outliers (MDNO), and mean duration of outlier (MDO) are computed for two standard deviations and represent the duration of outlier events in hours.

Mean amplitude (m/s)		Observed	Model
ADCP-North (C1)	|U|	0.168	0.164
	|V|	0.053	0.030
ADCP-South (C2)	|U|	0.195	0.173
	|V|	0.165	0.032

Observed vs. model

		RMSD	Residual	SD	CF	POF	NOF	MDPO	MDNO	MDO
ADCP-North (C1)	U	0.160	0.001	0.160	0.724	0.023	0.024	23.0	22.0	12.8
	V	0.041	0.000	0.041	1.000	0.000	0.000	0.0	0.0	0.0
ADCP-South (C2)	U	0.188	0.001	0.188	0.722	0.022	0.025	21.0	21.0	12.1
	V	0.031	0.000	0.031	1.000	0.000	0.000	0.0	0.0	0.0

1976; Schwab and Rao, 1977). The Straits lie at the northern end of each lake and would presumably be near the nodal point of the combined system. The phase relationships between flow direction and the water levels at the northern end of the lakes have shown peak eastward flow to be in phase with high water level at the Straits (peak westward flow to be out of phase with water level at the Straits). However, the correlations between water levels and flow have not been adequate to develop accurate predictions of flow magnitude and direction at the Straits, resulting in an on-going gap in real-time hydrodynamic prediction for a critical location in the Great Lakes.

Several hydrodynamic models have been developed for Lake Michigan and Lake Huron, though most have not included flow through the Straits as part of the model construction (Beletsky and Schwab, 2001; Schwab and Beletsky, 2003; Beletsky et al., 2006; Birchfield and Murty, 1974; Murty and Freeman, 1973; Schwab and Bedford, 1994; Sheng and Rao, 2006). In particular, the three-dimensional hydrodynamic models developed for the Great Lakes Coastal Forecasting System (GLCFS), a real-time operational system maintained by the National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory (NOAA/GLERL) that provides hourly predictions of currents, water levels, temperature, waves, and ice to the public, uses a zero-flow boundary condition at the Straits (Beletsky and Schwab, 2001; Schwab and Bedford, 1994). Since a combined-lake model is not presently available for real-time operation, there is no method to predict the flow at the Straits available for historical record (hindcast) or forecasted conditions. This gap in modeling exposes the vulnerability in the areas of water quality prediction and spill transport, both of which could benefit considerably from accurate forecasts of the flow conditions at the Straits (Alexander and Wallace, 2012; Chapra and Dolan, 2012; Dolan and Chapra, 2012).

Table 2
Statistical measures of water level and surface temperature comparison between the model and observed conditions. Water level differences between the model and observed values are computed hourly at four gauging stations (M, C, L, F). Surface temperature differences are computed hourly at four buoys (T1, T2, T3, T4). (RMSD = Root mean square difference).

Water level (m)	RMSD	Residual	SD
Milwaukee (M)	0.029	−0.009	0.027
Calumet (C)	0.036	−0.012	0.034
Lakeport (L)	0.035	−0.025	0.024
Fort Gratiot (F)	0.037	−0.027	0.025
Temp. (°C)	**RMSD**	**Residual**	**SD**
45002 (T1)	2.52	−1.72	1.85
45007 (T2)	1.92	−1.12	1.56
45003 (T3)	2.90	−2.37	1.68
45008 (T4)	3.37	−2.98	1.57

In this study, we develop the first hydrodynamic model of the combined Lake Michigan–Huron that includes the Straits of Mackinac at high resolution. Meteorological conditions (wind, air temperature, dew point temperature, cloud cover) are used to predict the three-dimensional hydrodynamics (currents, temperature, water level) within the lakes and in the Straits on an hourly time-scale. The validation of currents at the Straits is carried out using measurements from a previous field study (Saylor and Miller, 1991). For the first time, we are able to predict the oscillating and bi-directional flows observed at the Straits of Mackinac, providing more accurate hydrodynamic predictions within the lakes and filling the gap in the physical predictions necessary for studies of water quality and contaminant spill transport. This model also provides the basis for a real-time hydrodynamic forecasting system of the combined Lake Michigan–Huron for the Great Lakes Coastal Forecasting System (GLCFS), a research product developed by NOAA/GLERL that predicts three-dimensional hydrodynamics for the Great Lakes and connecting channels.

Methods

Hydrodynamic modeling

A three-dimensional, unstructured mesh hydrodynamic model is created that extends over Lake Michigan and Lake Huron, including

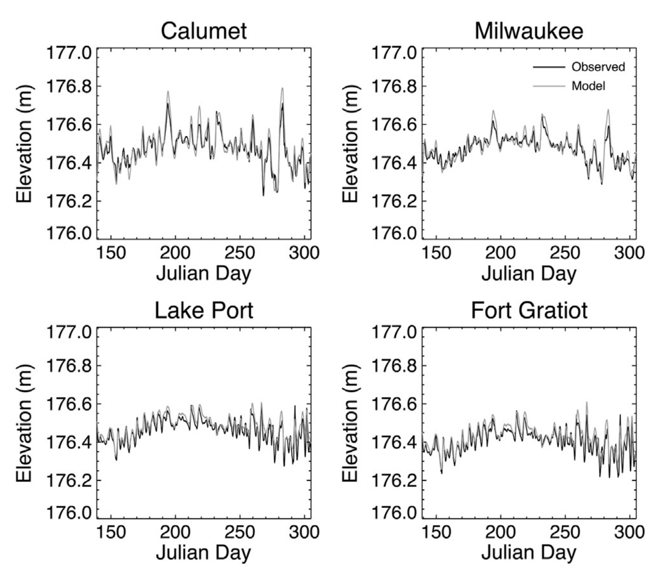

Fig. 6. Water level observations and model predictions at Calumet (C), Milwaukee (M), Lakeport (L), and Fort Gratiot (F) for 1990 (24-hour smoothing).

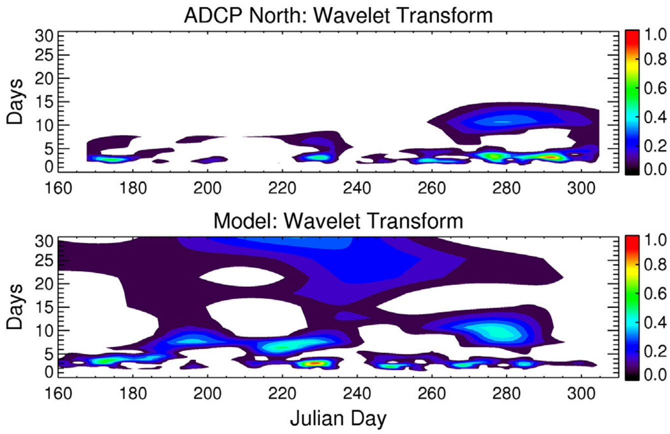

Fig. 7. Morlet wavelet transform (normalized) for the observed and modeled surface currents at ADCP-North location (C1).

the Straits of Mackinac. The model is based on the Finite Volume Coastal Ocean Model (FVCOM; Chen et al., 2006), a free-surface, hydrostatic, primitive-equation hydrodynamic model that solves the continuity, momentum, and energy equations in three-dimensions on an unstructured, sigma-coordinate (terrain-following) mesh. The horizontal diffusion and sub-grid mixing are parameterized by the Smagorinsky scheme with a coefficient of 0.1 (Smagorinsky, 1963). Vertical mixing in the model is handled by the Mellor–Yamada Level-2 turbulence closure scheme (Mellor and Yamada, 1982). FVCOM has been validated and implemented successfully in several coastal ocean applications (Chen et al., 2003, 2007; Huang et al., 2008) as well as in the Great Lakes and connecting channels (Anderson and Phanikumar, 2012; Anderson and Schwab, 2011; Anderson et al., 2010; Bai et al., 2013; Luo et al., 2012; Read et al., 2012; Shore, 2009). For the combined-lake model, three arc-second bathymetric and coastline data are obtained

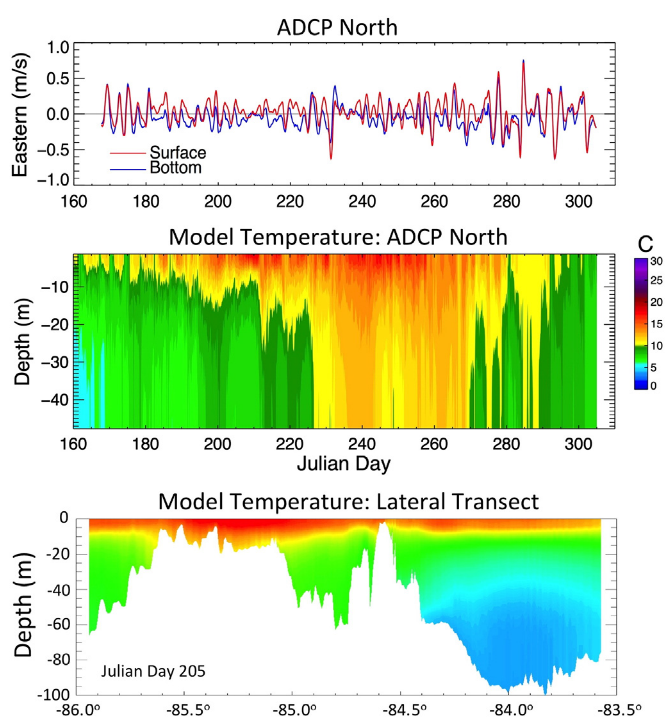

Fig. 8. (Top) observed bi-directional currents for surface and mid-depths at C1, (middle) model temperature profile at ADCP North (C1), (bottom) model temperature along a lateral (A–A′) transect on day 205 showing the tilted thermocline across the Straits.

from the NOAA National Geophysical Data Center (NGDC) and interpolated to the unstructured mesh. The horizontal grid resolution ranges from 100 m in the Mackinac Straits to 2.5 km in the center of the lakes (Fig. 1) with vertical resolution provided by 20 uniformly distributed sigma layers.

Simulations are carried out for the period April–December 1990, during which hourly meteorology (wind speed/direction, air temperature, dew point temperature, cloud cover) is interpolated from all available surface weather stations around the lakes to the model grid using a natural-neighbor interpolation scheme derived for the GLCFS (Schwab and Bedford, 1994). Model validation is provided by the NOAA/NOS water level gauges from 4 locations (C = Calumet, M = Milwaukee, F = Fort Gratiot, L = Lakeport; 6-minute water levels), NOAA/NOS buoys (T1 = 45007, T2 = 45002, T3 = 45003, T4 = 45008) for hourly surface temperatures at 4 locations, and current measurements from two Acoustic Doppler Current Profilers (ADCP; hourly) deployed at the Straits during the simulation period (Saylor and Miller, 1991). A statistical analysis and spectral analyses are carried out for the observed and modeled variables. In addition, a Morlet wavelet transform is employed for the comparison of measured and predicted currents at the ADCP locations.

The model is applied in two configurations: (i) the combined-lake model with unrestricted flow at the Straits, and (ii) a closed-boundary, zero-flow Straits condition. Both configurations use identical forcing conditions, unstructured grids, and simulation parameters. The only difference is the boundary condition at the Straits, where the boundary is treated as a wall with no flow, and hence the individual models are independent from each other. In the zero-flow configuration (ii), the combined-lake model is actually split into two individual lake models for Michigan and Huron, similar to the operational GLCFS hydrodynamic models. The purpose for investigating both configurations is to highlight the differences between the modeling approaches and delineate the area of influence of the Straits on hydrodynamic predictions within each lake. In addition, by subtracting the model results of the zero-flow Straits simulation from the open-boundary Straits model results, we can remove the effects of atmospheric forcing on water level fluctuations, since they are present in both approaches, and essentially isolate the effects of the bi-lake oscillation. This approach also provides a basis from which to decide when an open-boundary condition is necessary or when a closed-boundary will be sufficient for investigations into water quality, spill transport, and other topics.

Current measurements

In June 1990, Saylor and Miller (1991) deployed two ADCPs in the Straits of Mackinac (Fig. 1) in order to measure hourly currents throughout the water column (1-meter intervals). These measurements were carried out to investigate the bi-directional and oscillating flows in the Straits as well as seasonal variations. In addition, these deployments were the first use of the ADCP technology in the Straits. However, due to the limited amount of data at the Straits and the scarcity of meteorological observations during previous studies (Saylor and Sloss, 1976), this period of measurement (June–December 1990) serves as the only calibration data set used here. For the entire period, modeled currents at the ADCP locations (C1 and C2) are compared to the recorded current velocities using data for the entire water column. In an effort to verify the model's ability to predict the oscillating flow at the Straits, a particular focus is placed on the predicted phase and amplitude of volumetric flow over the dominant oscillation period.

Results and discussion

Current comparisons and model performance

Current measurements in the Straits reveal an oscillating flow oriented primarily in the east–west direction with amplitudes between 0.2 and

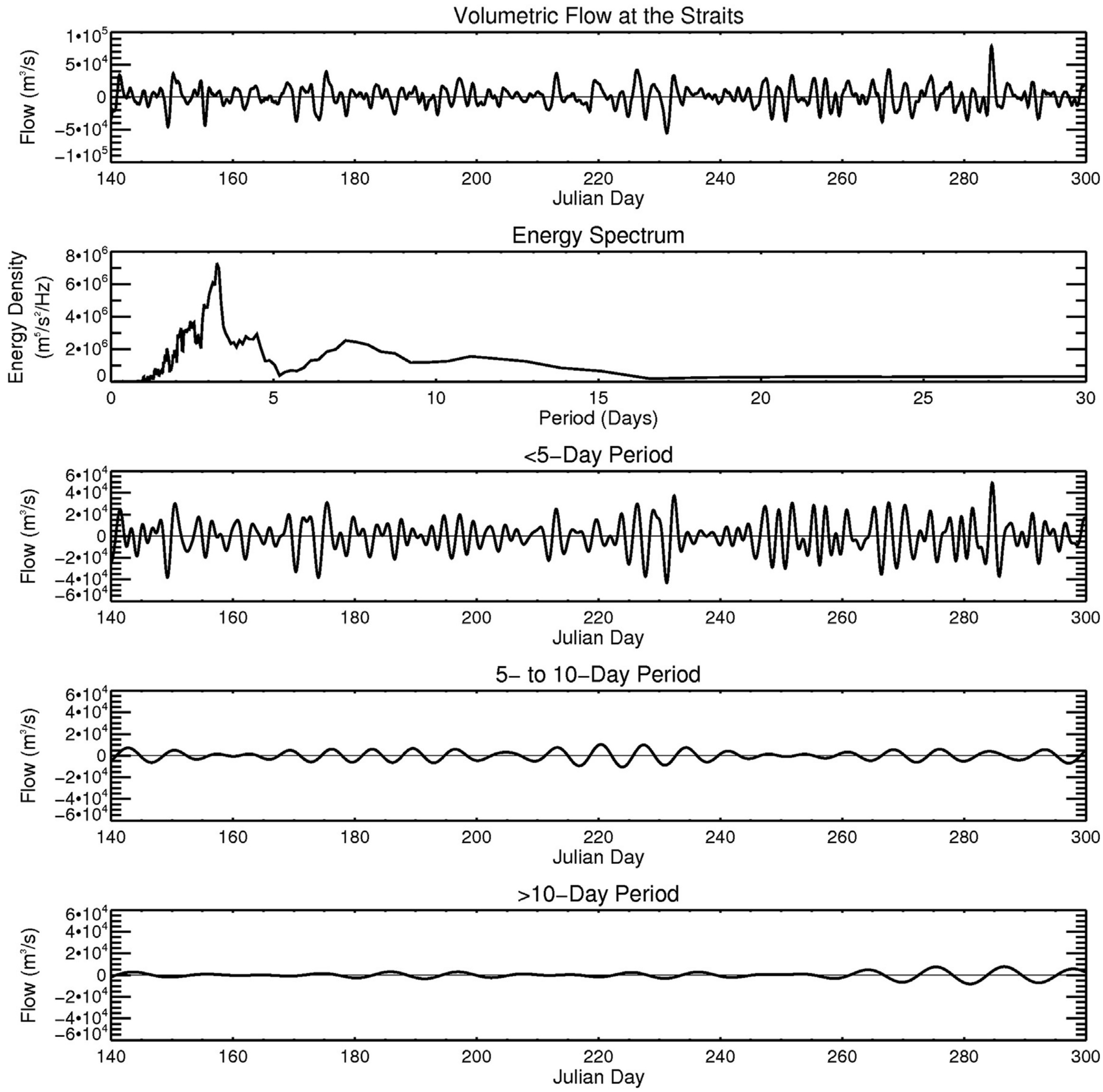

Fig. 9. Volumetric flow at the Straits of Mackinac as computed from the model currents, including the power spectrum and band-pass filtered discharges. Positive values represent flow into Lake Huron, while negative flow values represent flow into Lake Michigan.

0.5 m/s for both ADCP locations (C1, C2), however the unfiltered raw-data have revealed speeds that approach 1 m/s at a few points during the year. Observed and predicted currents are similar for both locations (C1 and C2), and therefore results are only shown and discussed for the ADCP-North location (C1) as a representative data set (Figs. 3–4). Shorter period (16–17 h) oscillating currents occur in the lakes during the stratified period (inertial oscillations), however some longer period (greater than 3 days) flow oscillations at the Straits occur year-round, with the greatest current magnitudes occurring in the fall, likely due to weather intensity in combination with thermal conditions in the lake. A spectral analysis reveals that most of the energy lies near the 3-day period, although oscillations also occur at 2-day (Saylor and Miller, 1991; Saylor and Sloss, 1976) and greater than 5-day periods. An ideal band-pass filter is used to isolate the 2–5 day oscillations and the 2.5–3.25 day oscillations (referred to as the 3-day oscillation) in the current analysis (Figs. 3, 4, 5). The observed mean current amplitude at ADCP-North (C1) is 17 cm/s in the primary flow direction (U, east–west), and 5 cm/s in the north–south (V) component (Table 1).

The model simulation for June–December 1990 predicts currents, water levels, and temperature in three-dimensions. Current comparisons between the model and observations at the two ADCP locations yield root mean square deviations (RMSD) of 16 cm/s and 19 cm/s for the ADCP-North (C1) and ADCP-South (C2) locations, respectively (Table 1). Water level comparisons are carried out for all available gauging stations, although four stations at the southern end of the lakes (C, M, L, F) are highlighted as representative results and serve as good descriptors of the oscillations. Results show that modeled water level displacements are able to track seiche- and Helmholtz-period fluctuations at all locations, where the computed RMSD between the model and observed levels are near 3 cm (standard deviation of 2 to 3 cm) but slightly under predict the largest events (Table 2, Fig. 6). The comparisons of surface temperatures at 4 buoy locations (T1, T2, T3, T4) show the model to under predict the surface temperature by 1 to 2 °C, with an average RMSD of 2.7 °C (Table 2).

Similar to the observed currents, the model predictions exhibit oscillating currents at the Straits with the highest energy density near 3.25 days, slightly longer than the observed oscillation period, and of similar amplitude of 16 cm/s in the east–west (U) component and 3 cm/s in the north–south (V) component (Table 1). For the primary flow direction (U, east–west), the root-mean-square deviation (RMSD) between the

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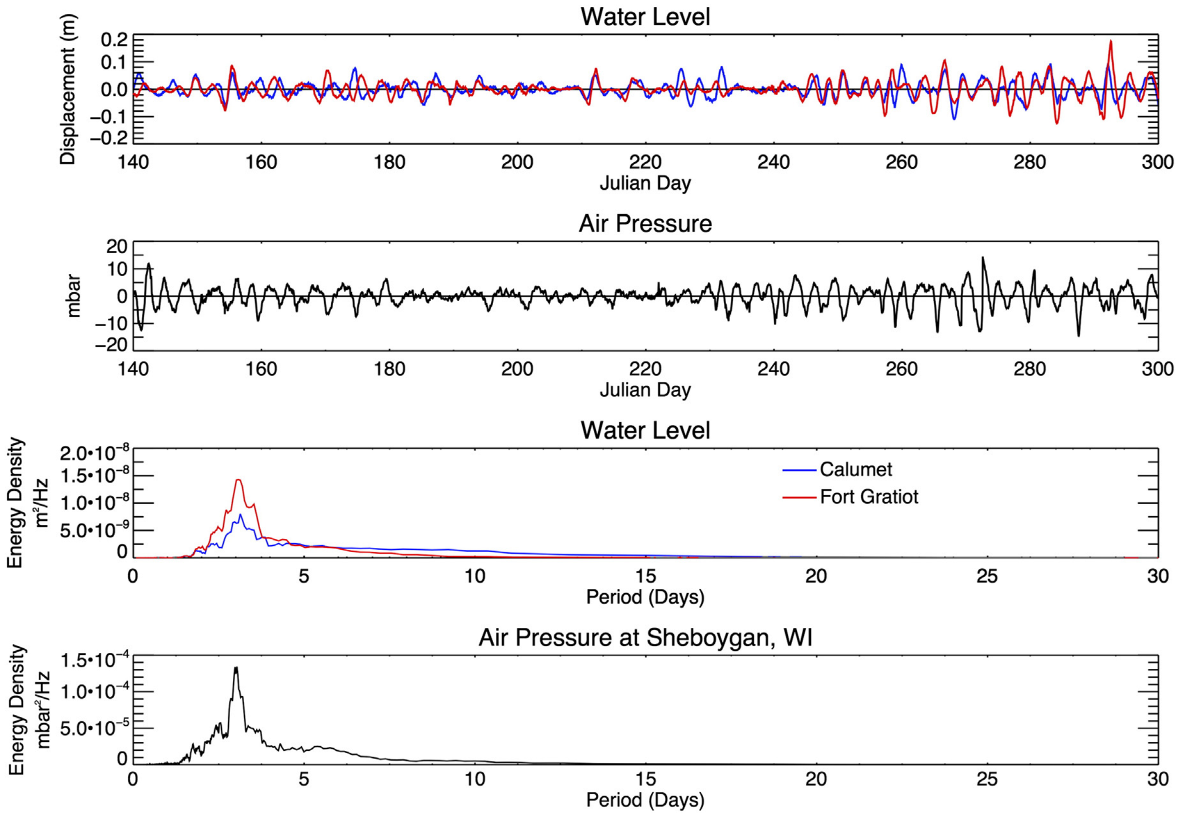

Fig. 10. Water level observations at Calumet (C) and Fort Gratiot (F) gauges (displacements) and recorded air pressure at the Sheboygan, WI air station. Power spectra for water levels and pressure computed for high-pass filtered measurements (<6 days).

model and the observations is 16 cm/s (residual of 0.1 cm/s, standard deviation of 16 cm/s), arising from the slight difference in phase and the large current magnitude at the Straits. For errors greater than two standard deviations, the durations of these events are computed for positive and negative outliers. The mean duration of outlier events is computed to be 12.8 h. Given that the typical oscillation period is 3 days, this time difference is quite reasonable, however the maximum duration is found to be 23 h. Using a band-pass filter to isolate the 3-day oscillation, differences between modeled currents and observed currents show the phase lag at the dominant period (Fig. 4), where differences between the model and observations are illustrated by scatter plot comparisons of the hourly currents (Fig. 5).

The wavelet power spectra (based on a Morlet wavelet) of the observed and modeled currents reveal oscillations in the observations and modeled currents with distinct episodes of high energy at the 3-day oscillation period in late June, mid August, and September/October (Fig. 7). During the fall, the observed currents also exhibit energy near the 6-day oscillation period (and greater) that exists throughout the months of September and October. The modeled currents reveal this 6-day oscillation as well, though to a lesser extent.

In addition to the east–west flow oscillations, a vertically bi-directional flow also develops at the Straits at several points during the stratified period (Fig. 8). Saylor and Sloss (1976) and others have suggested that the bi-directional flow forms as a result of an internal

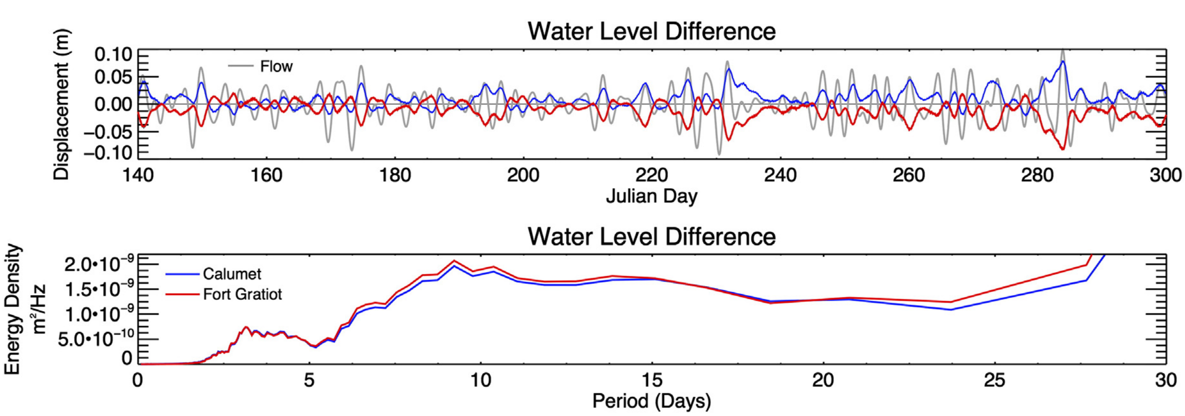

Fig. 11. (Top) difference in water level between the combined-lake model and the individual-lake models for the Calumet (C) and Fort Gratiot (F) gauge locations with a 6-hour phase shift overlay of the volumetric discharge at the Straits. (Bottom) power spectrum of water level differences at each gauge.

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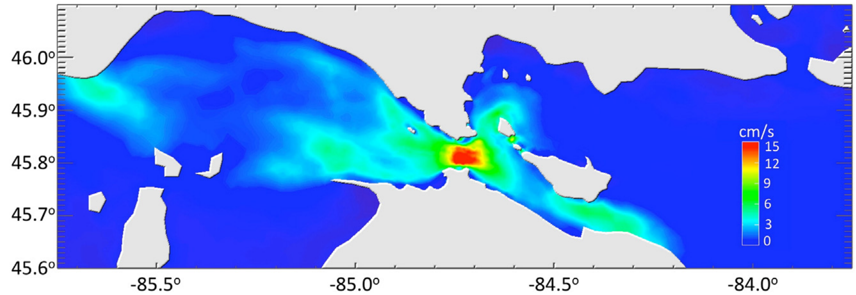

Fig. 12. The area of influence of the Straits of Mackinac as represented by differences in mean surface current (magnitude) between the combined-lake model and the individual models computed for the period June–December 1990. Values over 15 cm/s are shown in red and values of 0 cm/s (meaning no difference between models) are shown in blue.

pressure gradient between Huron and Michigan that occurs due to the deeper thermocline in northern Lake Michigan. During this period, the warm surface waters tend to flow eastward (Michigan to Huron) while a return flow is established in the sub-surface layers bringing cold Lake Huron water into Lake Michigan (Saylor and Miller, 1991). Although vertical temperature profiles were not measured in 1990, model temperatures show stratification beginning in late June and continuing until mid-September, corroborating the presence of bi-directional flow during several time periods in the stratified months. Model results also reveal a tilted thermocline along an east–wes transect (A–A′) through the Straits, as was suggested by Saylor and Sloss (1976) as the mechanism for sub-surface return flows (Fig. 8). However, as no observations of the tilted thermocline have been made within the Straits, we cannot confirm these results and therefore refrain from further analysis.

Volumetric flow, bi-lake oscillation, and spectral analysis

A transect across the Straits is used to compute the volumetric flow between the lakes using the three-dimensional modeled currents (Fig. 9). A spectral analysis reveals the dominant 3-day oscillation as well as some longer period oscillations in the exchange flow between Michigan and Huron. Using a bandpass filter, the volumetric flow is split into time-series plots of less than 5-day, 5-10 day, and greater than 10-day signals. The primary oscillation is near the 3-day period. The 5-10 day oscillations exhibit amplitudes of roughly one quarter the amplitude of the dominant 3-day oscillation. The greater than 10-day oscillations reveal a seasonal dependence with higher amplitude in the fall (Sept–Nov).

The analysis of the water level fluctuations at the southern ends of Lake Michigan (gauges C, M) and Lake Huron (gauges F, L) reveals a similar distribution of energy, where 3-day oscillations are dominant for both gauges (Fig. 10). If we consider changes in air pressure as a proxy for weather systems moving across the lakes, we can compare the frequency of these systems to the observed oscillation and volumetric flow at the Straits. Although water levels at the extremities of the lakes and flow at the Straits are governed primarily by patterns of wind speed and direction over the lakes, the pressure signal can be used as a simple proxy to examine possible connections between weather, Helmholtz oscillations, and exchange flow. For this analysis, air pressure is taken from the Sheboygan, WI airport station during the observation/simulation period. The spectral analysis of air pressure suggests that weather systems move across the lake near a frequency of 3 days, although atmospheric changes at other frequencies are certainly present.

Using open- and closed-Straits models, we can isolate the effects of the bi-lake oscillation on exchange flow. For this analysis, individual models of Lake Michigan and Huron are simulated for the same period as the combined-lake model (and same meteorological forcing), where the only difference is that a closed-basin condition (i.e. a wall) is imposed at the Straits for each lake. This approach mimics the present state of the hydrodynamic models for Lake Michigan and Huron in the Great Lakes Coastal Forecasting System, where a closed boundary is defined at the Straits for each individual lake model. As a result of this closed-boundary, no flow is computed through the Straits and water levels are independent for each model. In this case, the results from the individual models are subtracted from the combined-lake model predictions. The difference between the results from the two model simulations isolates the component of water level fluctuations due only to the bi-lake oscillation. We then compare the water level differences at the southern ends of the lakes (e.g. $WL_{combined\text{-}model}$–$WL_{Michigan\text{-}model}$) to each other in Fig. 11. The results show a clear mirror image signal between the Calumet and Fort Gratiot water levels with an oscillation period of roughly 3 days. If the volumetric flow at the Straits is shifted by 18 h and superimposed onto the water-level difference plot (since the flow should be ¼ period out of phase with water level at the ends of the lakes), we can illustrate the relationship between the Helmholtz oscillation and the exchange flow. It appears that flow is not perfectly correlated with water level differences (or the bi-lake oscillation), suggesting that atmospheric forcing, essentially the wind and pressure fields, could be modulating the flow at the Straits. In other words, although the Helmholtz mode is the primary mechanism behind the oscillating exchange flow at the Straits of Mackinac, when the meteorological forcing is in-phase with these oscillations the flow is modified. As a result, water level analysis alone will not provide accurate flow predictions, pointing toward the importance of atmospheric forcing conditions and the need for a hydrodynamic model.

Finally, in using this same approach of model subtraction, the area of influence of the Straits is delineated. In this case, if the individual-lake model currents are subtracted from the combined-lake model results, a spatial representation of current differences due to the presence of the Straits is acquired (Fig. 12). These differences are greatest within the Straits themselves, as expected, but also extend 50 km eastward into Lake Huron, hugging the southern coast of Lake Huron, and up to 70 km northwestward into Lake Michigan. This spatial representation highlights the area where a combined-lake model with open-flow at the Straits will differ from the closed-flow models. This detail may be particularly helpful in choosing whether an investigation needs to include the open-flow condition at the Straits even when the oscillating flow may not be the point of interest.

Conclusions

A hydrodynamic model is presented for the combined Lake Michigan–Huron including the Straits of Mackinac, an area that contains oscillating flow conditions that are unique within the Great Lakes and critical to understanding water quality and contaminant transport in the lakes. Using interpolated meteorology, the model predicts oscillating flow at the Straits with a period of 3.25 days, and also simulates the bi-directional currents that appear during the stratified period. The observed dominant flow oscillation occurs at a period of 3 days, close to the computed Helmholtz period of 2.8 days, where current speeds reach up to 1 m/s with a volumetric flow of 80,000 m^3/s. The comparison of the water level records and atmospheric pressure changes,

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which indicate the passage of weather systems across the lakes, yields similar periods for each.

When the combined-lake model is compared to individual lake models, where a zero-flow condition exists at the Straits as in the present set of hydrodynamic forecasting models of Lakes Michigan and Huron, the effect of the co-oscillation can be isolated. Using this approach, we can see that the flow at the Straits depends not only on the oscillations associated with the Helmholtz mode but also on atmospheric forcing. When the meteorological conditions are such that systems moving across the lakes are in-phase with water level fluctuations due to the bi-lake oscillation, it's possible that the flow at the Straits is modulated. This underscores the importance of a hydrodynamic model in predicting flow, as water level fluctuations at the extremities of the lakes do not perfectly correlate with the oscillating currents found in the Straits and are not adequate to develop a predictive relationship. In addition, the model allows for the delineation of the area of influence that the open-boundary condition at the Straits has on the northern ends of the lakes, where current differences due to flow through the Straits are found up to 70 km into northern Lake Michigan and 50 km along the southern coast of Lake Huron.

Overall, the ability of the combined Michigan–Huron model to predict the oscillating flow at the Straits of Mackinac in real-time bridges a major gap in Great Lakes hydrodynamics and is integral to understanding water quality in the region, residence times, and spill transport within the Straits (Alexander and Wallace, 2012; Chapra and Dolan, 2012; Dolan and Chapra, 2012; Quinn, 1992). The combined-lake hydrodynamic model is able to reproduce observed oscillations and bi-directional conditions consistent with suggested mechanisms and phenomena for flow within the Straits region. This effort produces the first combined-lake model to include the Straits at high-resolution which will become the basis for the next generation of real-time prediction in the NOAA/GLERL Great Lakes Coastal Forecasting System (GLCFS).

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