Chapter 2
Physical Drivers of the Circulation and Thermal Regime Impacting Seasonal Hypoxia in Green Bay, Lake Michigan

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Abstract The physical processes that drive the circulation and the thermal regime in the bay largely control the duration and persistence of hypoxic conditions in Green Bay. A review of previous studies, existing field data, our own measurements, hydrodynamic modeling, and spectral analyses were used to investigate the effects on the circulation and the thermal regime of the bay by the momentum flux generated by wind, the heat flux across the water surface, the Earth's rotation, thermal stratification and the topography of the basin. Stratification and circulation are intimately coupled during the summer. Field data show that continuous stratification developed at regions deeper than 15–20 m between late June and September and that surface heat flux is the main driver of stratification. Summertime conditions are initiated by a transition in the dominant wind field shifting from the NE to the SW in late June and remain in a relatively stable state until bay vertical mixing in early September. It is during this stable period that conditions conducive to hypoxia are present. Wind parallel to the axis of the bay induces greater water exchange than wind blowing across the bay. During the stratified season flows in the bottom layers bring cold water from Lake Michigan to Green Bay and surface flows carry warmer water from the bay to Lake Michigan. Knowledge of the general patterns of the circulation and the thermal structure and their variability will be essential in producing longer term projections of future water quality in response to system scale changes.

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2.1   Introduction

Green Bay is a large, elongated gulf (190 km × 22 km) in the northern part of the Lake Michigan basin. Physically and biogeochemically the bay can be considered to be divided into two portions, a northern and a southern bay, defined by a dividing line at the Chambers Island cross section. The northern or "upper" bay, open to Lake Michigan, is relatively deep (max. depth >50 m) with water quality similar to that of the open lake and is mesotrophic in character, while the southern or "lower" bay is both shallower (mean depth ∼10 m) and more confined, resulting in a steep trophic gradient from south to north. The bay is fed by a number of rivers draining a watershed that represents approximately one-half of the total drainage basins for the entire lake (Bertrand et al. 1976). The riverine filling time is approximately 6 years, but because of the large exchange of water with Lake Michigan, the actually flushing time for the bay is less than a year (Mortimer 1979; Miller and Saylor 1993). The largest of these rivers, and the major tributary to the bay with ∼50% of the inflow, is the Fox River, entering the bay at the extreme southern end (Fig. 2.1). Once considered one of the most heavily industrialized rivers in the USA as a result of a major regional paper industry and an extensive, largely dairy, agricultural industry within its watershed, the Fox River has a history of excessive loading of nutrients and suspended sediments to lower Green Bay (Klump et al. 1997). As a result, the lower bay has experienced hyper-eutrophic conditions for more than 70 years. The morphology of the lower bay makes it a highly efficient nutrient and sediment trap, with organic-rich sediments that accumulate at rates up to a cm per year and organic carbon contents in excess of 10% by weight (Klump et al. 2009). These sediments quickly become anaerobic and high rates of benthic respiration drive recurring summertime bottom water hypoxia during periods of thermal stratification, generally from late June to early September. The physical processes of circulation and the thermal regime of the bay drive the mixing of tributary nutrients and sediment loads with Lake Michigan waters, affecting the duration and persistence of these hypoxic conditions. The physical drivers of circulation and the thermal regime in the bay are the focus of this chapter.

A review of previous studies, existing field data, our own measurements, hydrodynamic modeling, and spectral analyses were used to investigate the effects on the circulation and the thermal regime of the bay by the momentum flux generated by wind, the heat flux across the water surface, the Earth's rotation, thermal stratification, and the topography of the basin. Stratification and circulation are intimately coupled during the summer.

A brief summary of previous studies on the effects of momentum flux generated by the wind on circulation and thermal regime provides a foundation for our research. Miller and Saylor (1985) analyzed currents and temperatures measured in 1977 in the passages between Green Bay and Lake Michigan (herein referred to as the mouth) and within the bay proper. They found that the direction of circulation
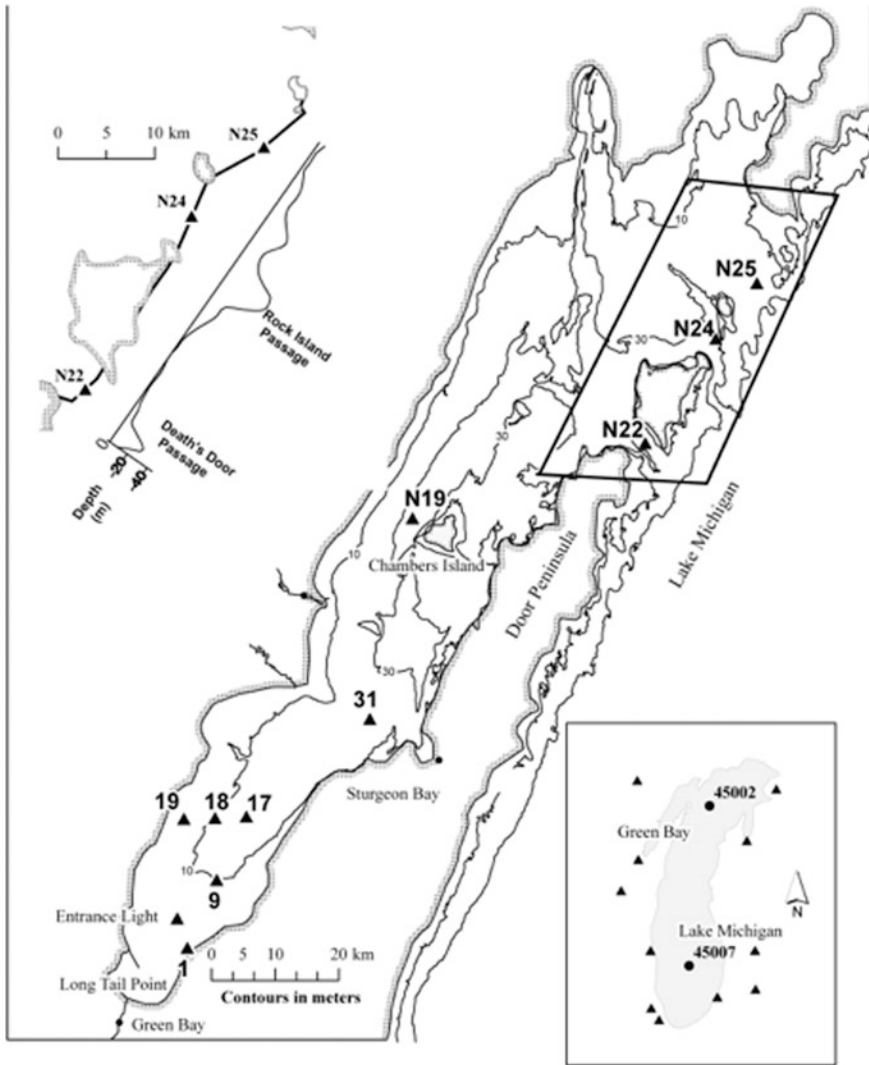
Fig. 2.1 Bathymetric map of Green Bay showing locations of 1989 NOAA measurements, 2011 current and temperature measurements. The *top left inset* shows map and cross section of the passages between Lake Michigan and Green Bay. The *bottom right inset* shows the locations of ASOS meteorological stations and NBDC buoys

reverses with a SW-NE (along-bay) wind direction. Gottlieb et al. (1990) measured currents and temperatures in Green Bay during the 1988–1989 winters and the summer and fall of 1989. Their monthly averaged summer currents showed that the direction of circulation in the bay varied with the wind direction. Gottlieb et al. (1990) found that the power spectrum of their measured currents showed the

surface-mode oscillations computed by Rao et al. (1976), and they attributed the 8-day mode to wind forcing with that frequency. Mortimer (2004) reasoned that: "[t]hese (winds) occurred at intervals ranging from 6 to 12 (average 8) days, apparently regular enough to generate and maintain the internal seiche during the stratified season from mid-July to September." Waples and Klump (2002) analyzed the effect of the wind direction on the water mass exchange between Green Bay and Lake Michigan, and hypoxia in the southern bay. They found a significant shift in the summer surface wind direction over the Laurentian Great Lakes from 1980 to 1999. They showed that in Green Bay the new wind field most likely resulted in a decrease in the water mass exchange with Lake Michigan, leading to an increase in vertical mixing as a result of a less highly stratified water column, a concomitant decrease in the persistence of bottom water hypoxia, warmer bottom water temperatures, and an increase in benthic microbial metabolism, as observed in enhanced methane production from bottom sediments. Recently, Hamidi et al. (2015) analyzed interannual variability in the summer wind direction and the circulation patterns and discussed the relation between multi-year monthly average wind fields and the circulation patterns in Green Bay.

The effects of heat flux across the water surface on the circulation and the thermal regime has been the subject of important research. Beletsky and Schwab (2001) applied a three-dimensional primitive equation numerical model to Lake Michigan for the periods 1982–1983 and 1994–1995 to study the seasonal and interannual variability of the lake-wide circulation and the thermal structure in the lake. The model was able to reproduce all of the basic features of the thermal structure in Lake Michigan: spring thermal bar, full stratification, deepening of the thermocline during the fall cooling, and finally, overturn in the late fall. They used a bulk aerodynamic formulation to calculate heat and momentum flux fields over the water surface for the lake circulation model. Lately Hamidi et al. (2015) analyzed the relation between the thermal regime in Green Bay, heat flux across the water surface and heat transport by circulation, including the water exchange with Lake Michigan.

Examples of previous studies on the effects of stratification and topography of the basin on the circulation and the thermal regime include Miller and Saylor (1985), Gottlieb et al. (1990), and Saylor et al. (1995). Miller and Saylor (1985) analyzed currents and temperatures measured in 1977 in Green Bay and found flow in two layers and the opposite direction through the mouth of the bay during the stratified period. They reasoned that cold hypolimnetic water maintains stratification and promotes flushing. They also observed oscillations in current records and analyzed coherence between currents and water level fluctuations. Gottlieb et al. (1990) measured currents and temperatures in Green Bay during the 1988–1989 winters and the summer and fall of 1989. Their July and August 1989 current and temperature measurements revealed a strong, persistent, well-defined 8-day-long oscillation associated with seiching of the thermocline. The power spectrum of their measured currents also showed the surface-mode oscillations computed by Rao et al. (1976). Gottlieb et al. (1990) added that the observed period agreed with that of a free standing internal wave (i.e., an internal seiche). Saylor et al. (1995) used summer 1989 measurements (Gottlieb et al. 1990) to investigate near-resonant wind

forcing of internal seiches in Green Bay. Saylor et al. (1995) found persistent oscillations of the thermocline at the period of the bay's lowest-mode, closed basin internal seiche, an 8-day long period.

This chapter is organized as follows. Section 2.2 presents the research methods used and Sect. 2.3 presents the research results. Hamidi et al.'s (2015) results on the effects of surface heat flux and momentum flux generated by the wind on the circulation and the thermal regime are summarized in Sects. 2.3.1 and 2.3.2 of this chapter. In Sect. 2.3.3, we present the results of a numerical experiment on the effect of the wind direction on the water exchange between Lake Michigan and Green Bay. Section 2.3.4 presents a calculation of the water exchange through a midbay section at Chambers Island and the mixing time that shows the effects of stratification and the bay and lake topography. In Sect. 2.3.5, we investigate the effects of wind, stratification, Earth's rotation, and the bay and lake topography on two-layer flows using frequency domain analysis of along-the-bay wind, and top and bottom currents. In Sect. 2.3.6, we analyzed field data on rotating currents to investigate the effects of stratification, Earth's rotation, and the bay and lake topography on the direction of currents. Section 2.4 presents the conclusions of this research study. The main questions explored in this chapter on physical drivers of hypoxia are the relation between the surface heat flux and stratification, the relation between multi-year monthly averages of wind fields and circulation pattern, the relation between the wind direction and the water exchange between Green Bay and Lake Michigan, the residence time in lower Green Bay, and the effect of the Earth's rotation on the currents in the top and bottom layers during the stratified season.

2.2 Methods

2.2.1 New Field Measurements

Our data collection program during the summers of 2011, 2013, and 2014 focused on southern Green Bay. Currents were measured at three stations using Nortek Aquadopp acoustic Doppler profilers (2 MHz) (stations 1, 18, and 19, see Fig. 2.1 and Table 2.1). Continuous measurements of the water temperature at 1–3 m depth intervals were collected at stations 9, 17, 31 and Entrance Light—EL using Onset Hobo temperature data loggers (±0.21 C). The Aquadopp ADCPs were deployed between June 17 and October 5, 2011, and the settings included a sampling frequency of 2 Hz, a cell size 0.5 m, an averaging interval 180 s, and a horizontal velocity precision 0.5 cm/s. Our 2014 field measurements included time series profiles of horizontal velocity and temperature measured at a GLOS Buoy (NOAA # 45014) located at Station 17 (see: glos.us). The 2011 ADCP measurements were done in cooperation with NOAA GLERL as part of an effort to improve nearshore wave climate and beach forecast models within the bay. The 2011 current measurements were obtained at sites with a depth up to 10 m because that is the effective range of the ADCPs employed.

Table 2.1 Locations and characteristics of new and historical field data collection sites

Station	°Lat.	°Lon.	Depth (m)	Data	Year
1	44.60	87.87	4	Current	2011
9	44.70	87.82	9	Temp.	2011
17	44.79	87.76	13	Current/Temp.	2014
18	44.78	87.82	10	Current	2011
19	44.87	87.88	4	Current	2011
31	44.93	87.51	25	Temp.	2011
Entrance Light (EL)	44.65	87.90	6.8	Temp/DO	2011
N19	45.21	87.41	33	Current/Temp.	1989
N22	45.29	86.97	30	Current	1989
N24	45.43	86.80	45	Current/Temp.	1989
N25	45.40	86.75	37	Current	1989

2.2.2 Historical Observations

NOAA GLERL (Hawley, personal communication, 2012) provided summer 1989 current and temperature data (Gottlieb et al. 1990) for 21 moorings, including stations N22, N24, and N25 at the boundary between Green Bay and Lake Michigan at the tip of the Door Peninsula, and station N19 west of Chambers Island (Fig. 2.1 and Table 2.1). The model validation used 1989 historical measurements that were made at sites that are critical to the understanding of the water exchange between the lake and the bay at the northern tip of the Door Peninsula (Stations N22, N24, and N25 at depths larger than 30 m) and between southern and northern Green Bay at the Chambers Island east and west channels (Station N19). Great Lakes surface water temperature data obtained from NOAA Coast Watch (http://www.coastwatch.glerl.noaa.gov/ftp/glsea/) were used to validate modeled temperatures.

2.2.3 Meteorological Forcing

Meteorological data sets were developed to run the Lake Michigan model for years in which new and/or historical observations existed, thus allowing validation against measured currents and temperature data. For 2011, we used a data set prepared by NOAA GLERL, consisting of wind velocities, air temperature, dew point, and cloud cover. For years with historical observations, we used the method described by Beletsky and Schwab (2001) to interpolate to the model grid from the meteorological data available at stations around the lake (Fig. 2.1). To calculate the overwater meteorological fields from land observation data, we first interpolated the data to an hourly basis, then carried out height adjustment and overland/overwater adjustments, and finally interpolated the adjusted data for all

stations spatially over the 2 km grid. Data from 11 NOAA Automatic Surface Observing System (ASOS) stations on land were used. After interpolation over water, results were crosschecked with data at the locations of NBDC buoys 45007 (south) and 45002 (north) in the lake. The accuracy of this interpolation method was verified by comparing interpolated meteorological data with measured data. The comparison (not shown) demonstrated the good accuracy of the method (Hamidi et al. 2015).

2.2.4   Modeling

We employed two hydrodynamic models in this study, namely a Lake Michigan model that is a version of the Great Lakes Coastal Forecasting System (GLCFS) developed and operated by NOAA GLERL, and a high resolution nested model of Green Bay developed for this study. The GLCFS model is based on a Princeton Ocean Model (POM) version adapted to the Great Lakes (Schwab and Bedford 1994). Hydrodynamic models numerically solve the governing equations to predict currents and temperature that result from the combined effects of meteorological forcing functions, the Earth's rotation, and bathymetry. The Princeton Ocean Model (POM) (Blumberg and Mellor 1987) is a time-dependent 3D, non-linear, finite difference model that solves the conservation of heat, mass, and momentum equations, considering the combined effects of the physical drivers listed above. The surface heat flux, hf, is calculated as

$$hf = swr + shf + lhf + lwr \tag{2.1}$$

where *swr* is shortwave radiation from the sun, *shf* is sensible heat transfer, *lhf* is latent heat transfer and *lwr* is long wave radiation. The equations governing the dynamics of coastal circulation contain fast moving external gravity waves and slow moving internal gravity waves. It is desirable in terms of computer economy to separate the vertically integrated equations (external mode) from the vertical structure equations (internal mode). This technique, known as mode splitting (Mellor 2002), permits the calculation of the free surface elevation with little sacrifice in computational time by solving the velocity transport separately from the three-dimensional calculation of the velocity and the thermodynamic properties. The nested model used time steps of 1 s and 20 s for the external and internal time steps, respectively. In this study, simulations started in March–April with Lake Michigan well mixed from top to bottom at temperatures near the temperature of maximum density for freshwater, about 4 °C. For applications to the Great Lakes, the salinity is set to a constant value of 0.2 parts per thousand. The turbulence closure scheme characterizes the turbulence by equations for the turbulence kinetic energy and a turbulence macroscale, according to the Mellor and Yamada 2.5 model (Mellor and Yamada 1982). Full details are given in Beletsky and Schwab (2001).

The Lake Michigan model uses a grid size of 2 km and 131 × 251 cells in the EW and the NS directions, respectively, and 20 vertical depth intervals (sigma layers). The model is driven by the meteorological conditions of wind, air temperature, dew point, and cloud cover developed as described above. Meteorological forcing is distributed over the lake and varies in time every hour. The nested model for Green Bay uses a grid size of 300 m and 132 × 644 cells in the directions along the bay and across the bay, respectively, and 20 vertical depth intervals or sigma layers (Fig. 2.2). The nested model obtains its meteorological forcing, initial and boundary conditions between Green Bay and Lake Michigan from the Lake

Fig. 2.2 Sketch of the grid used for the nested grid model. The model obtains boundary conditions at the mouth region between Green Bay and Lake Michigan from the GLCFS model, and tributary inflows from USGS Web sites. The *dark line* across Chambers Island delineates the grid used for Lower Green Bay model simulations

Michigan model, and tributary inflows from USGS Web sites (http://www.waterdata.usgs.gov/wi/nwis/sw). Monthly averaged winds and currents were calculated for up to five years within the 2004–2008 period from GLCFS results provided by NOAA GLERL.

2.2.5 Model Validation

As described by Hamidi et al. (2015), the hydrodynamic model results were validated against our own 2011 and the historical 1989 measurements, i.e., for two years with available field data and quite different meteorological forcing. As explained in Sect. 2.3.2, we found significant interannual variability in meteorological forcing and circulation patterns. Once the model was validated under different meteorological forcing, we used it in Sect. 2.3.2 to analyze the relation between multi-year monthly average wind forcing and circulation patterns. The goodness of fit between measurements of currents or temperature and model predictions was quantified in terms of the estimated root mean square error (RMSE), the normalized root mean square error (NRMSE), and the correlation coefficient. The NRMSE is equivalent to the Fourier norm, F_n, used by Beletsky and Schwab (2001) and can be thought of as the relative percentage of variance in the observations unexplained by model calculations. The correlation coefficient between the measured and the model-predicted time series is their covariance divided by the product of their individual standard deviations. Blumberg et al. (1999) assessed the skill of their model of the New York Harbor region in terms of the RMSE and the correlation coefficient. We investigated the sensitivity of the model with respect to model parameters and decided to use default values. The sensitivity analysis included varying the horizontal and vertical grid resolution, changing the model parameters such as the dimensionless coefficient (C) that relates velocity gradients to horizontal kinematic viscosity in Smagorinsky's horizontal diffusivity and the turbulent Prandtl number (the relation between diffusivity and viscosity), varying the description of the shortwave radiation penetration, and varying the turbulent vertical mixing. Table 2.2 shows a comparison between the observed and the measured currents at station 1. Verification of the temperature profiles was presented in detail in Hamidi et al. (2015).

Table 2.2 Statistics of the comparison between observed and modeled currents at station 1

Depth avg. currents	Min	Max	Average
RMSE (cm/s)	1.10	2.19	2.10
NRMSE	0.52	0.95	0.82
Correlation coefficient	0.47	0.85	0.62

2.2.6   Spectral Analysis

The time series data collected in Green Bay during 1988–1989 (Gottlieb et al. 1990) and 2011 showed oscillatory patterns in temperatures and currents. Frequency analysis, including the estimation of power spectra, coherency and phase, was applied to uncover the main frequencies in the oscillations of currents and temperature isotherms. Recall that the spectrum of a time series or signal is a function of a frequency variable, which has dimensions of power or energy per frequency unit (such as cycles per day). Intuitively, the spectrum decomposes the content of the time series into different frequencies present in that process and helps identify periodicities. The SSA toolkit was used to estimate the power spectra.

Coherence analysis, or cross-spectral analysis, was used to identify variations that have similar spectral properties (high power in the same spectral frequency bands), i.e., if the variability of two distinct, detrended time series is interrelated in the spectral domain (Von Storch and Zwiers 1999). Squared coherency, the frequency domain analogue of correlation, was estimated in this study following Jenkins and Watts (1968) and Bloomfield (1976). Values of coherency estimates were considered significant at the 95% level of confidence when they were larger than the critical value T derived from the upper 5% point of the F-distribution on (2, d-2) degrees of freedom, where d is the degrees of freedom associated with the univariate spectrum estimates.

2.2.7   Effects of Earth's Rotation

Inertial currents are consequences of the Coriolis effect, caused by the rotation of the Earth and the inertia of the mass experiencing the effect. The effects of the Coriolis force generally become noticeable only for motions occurring over large distances and long periods of time, such as a large-scale movement of water in the ocean. This force causes moving objects on the surface of the Earth to be deflected in a clockwise sense (with respect to the direction of travel) in the Northern Hemisphere. Inertial currents occur in all large stratified basins and oceans, and the theoretical inertial period is 24/(2 sin ϕ), i.e., 17.3 h, for a latitude ϕ = 44°. Inertial oscillations observed in Lake Michigan do not ordinarily reach the theoretical inertial limit. The observed periods are slightly less (but never more) than the theoretical limiting period. Thus one may speak of near-inertial oscillations (Mortimer 2004). The Rossby radius of deformation, or simply the Rossby radius $a = c/f$ (c is the wave speed and f is the Coriolis parameter), is the length scale at which rotational effects become as important as buoyancy or gravity wave effects in the evolution of the flow about some disturbance. For Green Bay, representative values of c for surface and internal long waves are $c_s = 17$ m/s and $c_i = 0.27$ m/s. Therefore, for $f = 10^{-4}$ rad/s, the Rossby radius for surface and internal waves are $a_s = 168$ km and $a_i = 2.6$ km, respectively. Green Bay is "fairly small" for surface

Kelvin waves but "quite large" for internal waves. In Sect. 2.3.6, currents measured west of Chambers Island by Gottlieb et al. (1990) were analyzed using spectral analysis to investigate possible evidence of the Coriolis effect.

2.3 Results and Discussion

2.3.1 Relation Between the Surface Heat Flux and Stratification

Gottlieb et al.'s (1990) temperature measurements and our own 2011 measurements had a resolution sufficient to characterize stratification. The net heat flux across the water surface of Green Bay was calculated for those two years in order to explore its relation with stratification. Figure 2.3a, c show the calculated net heat flux, and its components of shortwave radiation, sensible heat transfer, latent heat transfer, and long wave radiation, for 1989 and 2011, respectively. The meteorological forcing files have an hourly time step, and the calculated heat flux varies hourly. Heat flux terms are displayed in Fig. 2.3 with a daily time step for readability reasons. The figure shows that the net heat flux is consistently positive between mid-June and September. Shortwave radiation from the sun was the largest single component of the surface heat flux. The calculated heat fluxes compared very well with heat flux measurements made in 2011 (Grunert 2013), and with Beletsky and Schwab's (2001) calculated annual cycles of the net heat flux for Lake Michigan during 1982–1983 and 1994–1995, which ranged from -400 W m^{-2} in winter to 200 W m^{-2} in summer.

Figure 2.3b, d show measured temperature profiles at Stations N19 and 31 (see locations in Fig. 2.1 and Table 2.1) during the summers of 1989 and 2011, respectively. Continuous stratification developed at regions deeper than 15–20 m between late June and September. A positive surface heat flux heats the surface waters, and Fig. 2.3 shows that stratification in the measured temperature profiles follows the surface heat flux cycle, indicating that the surface heat flux is the main driver of stratification in Green Bay.

2.3.2 Relation Between Wind Fields and Circulation Pattern

Previous descriptions of the general circulation in Green Bay were based on the field measurements made within one-year period (Miller and Saylor 1985; Gottlieb et al. 1990). Examining the more general description of circulation patterns contained in the 1988–1989 data supplied by NOAA GLERL, our own 2011 current measurements, and model simulations for 1989 and 2011, revealed considerable differences between the 1989 monthly averaged wind field and circulation patterns,
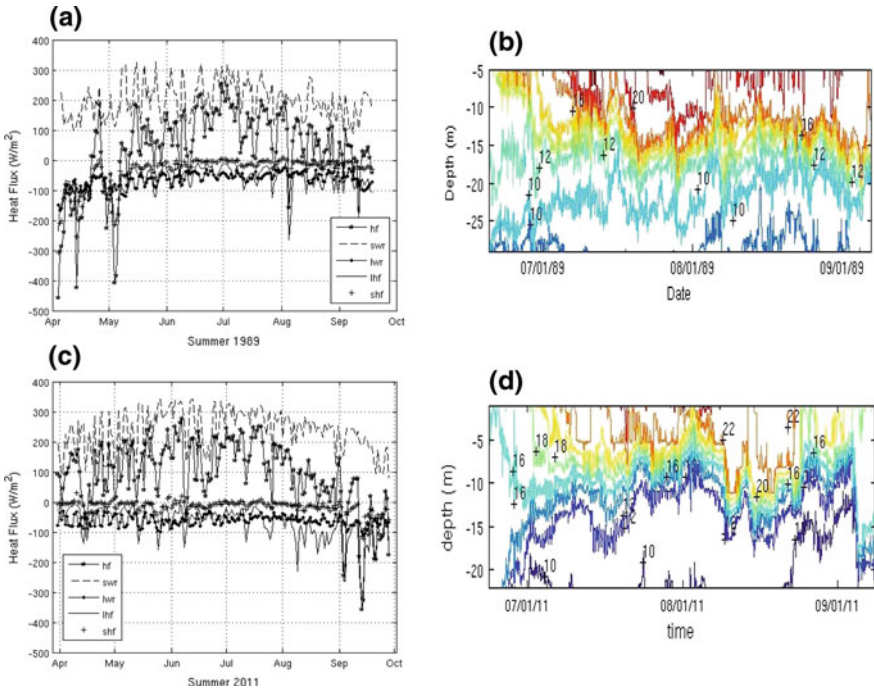
Fig. 2.3 **a** and **c** calculated net heat flux across the water surface of Green Bay, and its components, for 1989 and 2011, respectively. **b** and **d** measured temperature profiles (C) at Stations N19 and 31 during the summers of 1989 and 2011, respectively

and those in 2011. The monthly averaged wind was northerly in August 1989 and westerly in August 2011. The circulation pattern in August 1989 was very different than that in August 2011, particularly across the region between Green Bay and Lake Michigan. Results based on the single-year measurements can give incomplete descriptions of longer term conditions.

The relation between summer wind fields and circulation was therefore studied using multi-year averages. Mean summer circulation patterns were determined by calculating multi-year averages of wind shear fields and depth-averaged currents in the bay, for each month from May to September, starting with two-year averages and successively increasing the number of years included. The circulation patterns remain unchanged beyond a four-year average. Five-year averages of wind shear fields and currents are illustrated in Figs. 2.4 and 2.5, respectively, for the 2004–2008 period. The circulation in the bay depends on the wind field over the whole lake. Figures 2.4 and 2.5 show the wind and current fields in Green Bay and the immediately adjacent area of Lake Michigan.

Even though there is significant variability from one year to another, maps of climatological circulation in Green Bay are useful because they describe the general circulation patterns in the bay and can show the patterns of seasonal progression in
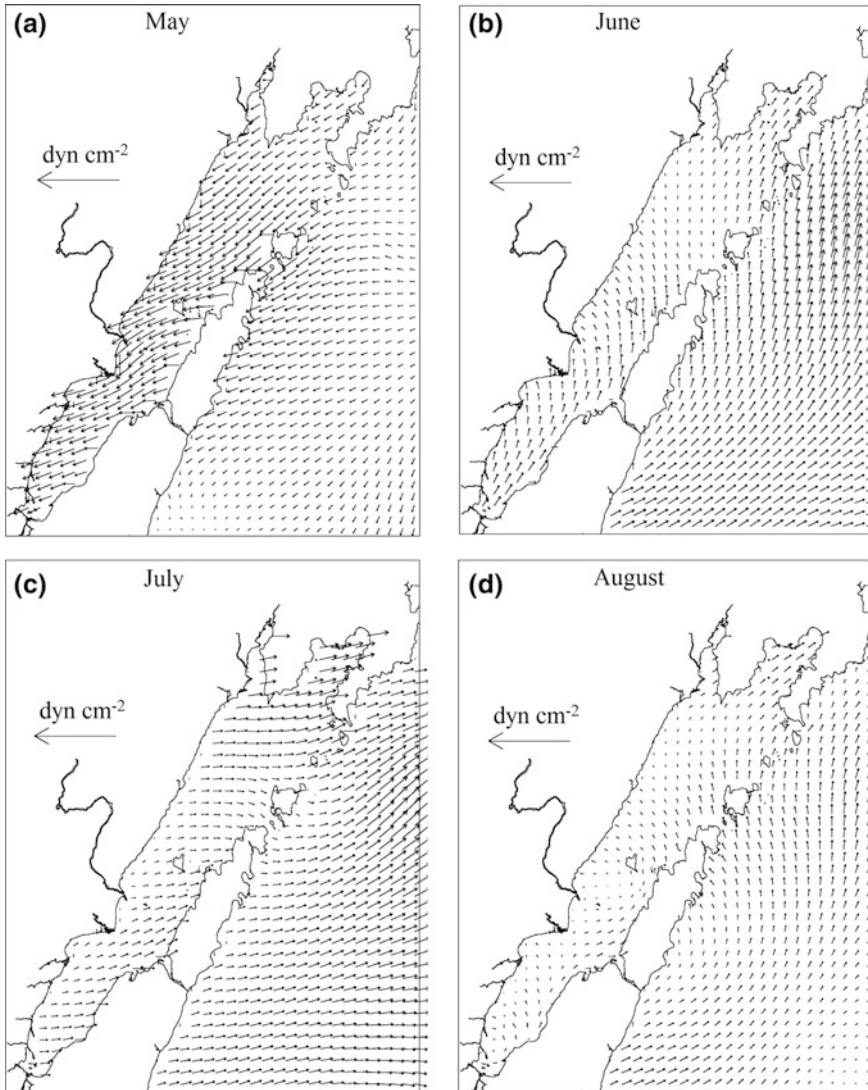
Fig. 2.4 Monthly averaged wind stress for May through August for the 2004–2008 five-year period

the wind field and the resulting mean flows. Beletsky and Schwab (2008) used 10-year averages of model results combined with measurements that validated the model, to map basin scale, climatological circulation patterns in Lake Michigan. They pointed out that maps of climatological circulation are extremely useful for a variety of issues ranging from water quality predictions to sediment transport and ecosystem modeling.
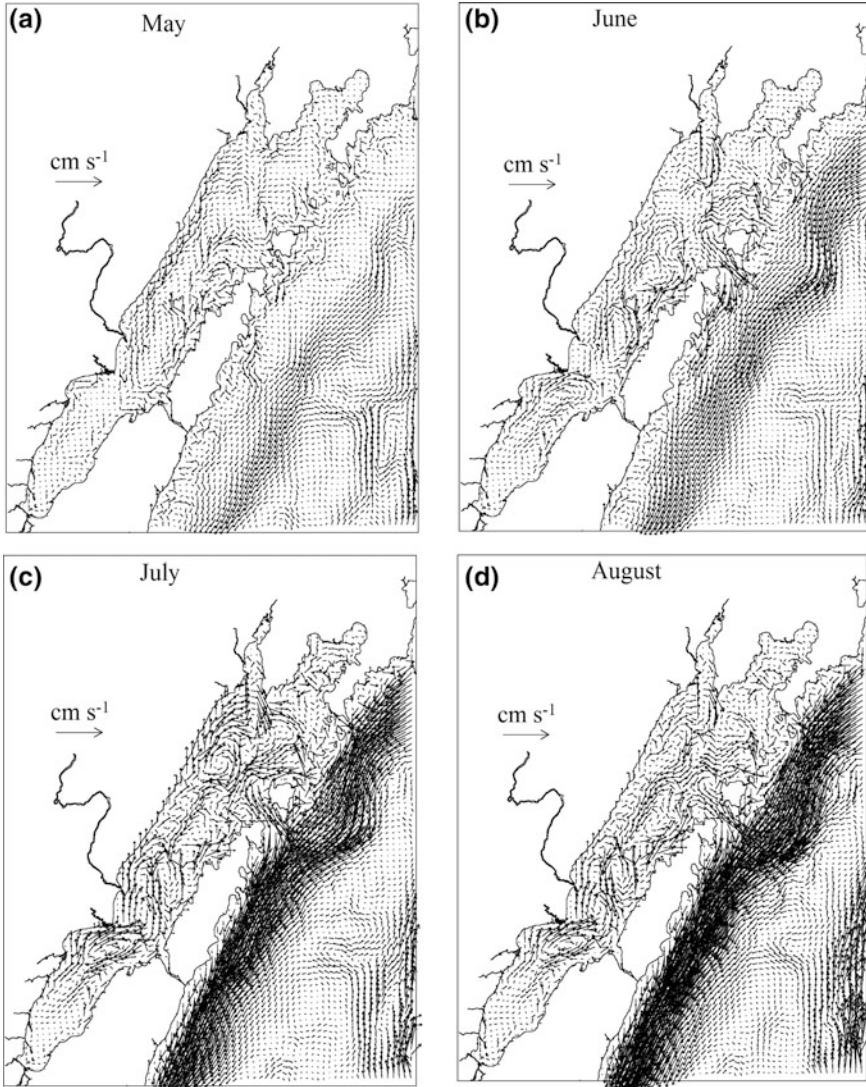
Fig. 2.5 Monthly averaged circulation for May through August for the 2004–2008 five-year period

In May, the monthly averaged wind is predominantly NE. In June, it rotates to the SW and keeps the same monthly average direction for the rest of the summer. The switch in wind direction in May and the consistent wind direction during the summer occurs over the whole lake. Analysis showed a consistent relationship between the monthly average wind shear direction and the monthly average currents and circulation. At the beginning of summer in May, the average circulation

pattern responds to a changing wind climate, which transitions from a predominantly NE to a SW wind direction in June. During July, August, and September while the wind blows from the SW the circulation patterns remain similar (Figs. 2.4 and 2.5). Figure 2.4 also shows that the average magnitude of wind shear in June is smaller than that later in the summer as the variability in the direction of the winds cancels one another and reduces the mean. Water circulation patterns change in June as a result of changes in the wind direction, and as more persistent wind conditions become established, a more stable circulation pattern develops during the rest of the summer. Hypoxia is typically observed from late June to early September. Results are shown for the months of May to August to demonstrate the May to June switch in the dominant winds and the subsequent period of consistent average wind associated with stratification. Figure 2.5 shows depth-averaged currents to illustrate general circulation patterns. Figure 2.3b, d show the relevance of bottom currents during the inception of stratification, when the transport of colder water by into-the-bay bottom currents induces a decrease in bottom temperatures.

Circulation varies from year to year depending on wind forcing, yet it was possible to find persistent, monthly average patterns in wind forcing and consequent circulation patterns. Schwab and Beletsky (2003) clearly explained the relation between transport vorticity and the curl of the wind stress in Lake Michigan. When the dominant wind field shifts from NE to SW in late June there is a change in the wind curl, which in turn results in a change in transport vorticity and circulation patterns, as shown in Fig. 2.5. Furthermore, conditions conductive to hypoxia are present during the July–September period of consistent circulation.

This description complements the climatological maps of summer and winter circulation in Lake Michigan developed by Beletsky and Schwab (2008), who found consistent overall cyclonic circulation in Lake Michigan. Maps of climatological circulation are useful for understanding water quality and ecosystem issues and patterns of sediment transport.

2.3.3 Relation Between Wind Direction and Water Exchange Between Green Bay and Lake Michigan

The water exchange between Green Bay and Lake Michigan varies continuously and depends on several of the physical drivers considered in this chapter. The effect of wind direction alone was explored by estimating the water exchange between Lake Michigan and Green Bay under idealized conditions consisting of summer 2011 atmospheric forcing, except for steady uniform wind with a velocity of 5 m s^{-1} parallel or perpendicular to the main Green Bay axis. This experiment tested the effect of the wind direction alone and it did not reflect real time variability in wind speed and direction. The purpose of the experiment was to compare the

water exchange induced by along-bay and cross-bay winds. An estimation of the water exchange with a historical unsteady wind is described in Sect. 2.3.4.

This idealized condition is intermediate between the barotropic model with a steady uniform wind used by Beletsky (2001) to study the circulation in Lake Ladoga and the general case of a baroclinic model with a spatially variable wind. In this idealized condition, the wind curl is zero because the wind field is steady and spatially uniform (Schwab and Beletsky 2003). The model was run in each case for about one month, when it was verified that the circulation and the thermal regime approached steady conditions. A steady uniform wind parallel to the axis of the bay (NNE and SSW) induces roughly a 25% greater water exchange (11,670 and 10,080 m^3 s^{-1}, respectively) than wind blowing across the bay (ESE and WNW, 9,900 and 7,200 m^3 s^{-1}, respectively). In addition, wind blowing from the lake to the bay (NNE) induces a greater water exchange than wind blowing from the bay to the lake (SSW).

A water exchange through the mouth region of 11,550 m^3 s^{-1} was estimated for wind from the WSW (30° south from W), which approximates the monthly average wind direction during August 1994. The ESE wind direction described above approximates the monthly averaged wind direction in August 1995. Across-bay wind from the ESE induced a substantially smaller water exchange (9,900 m^3 s^{-1}) than wind from the WSW. Waples and Klump (2002) found that SW wind (parallel to the major axis of the bay) in August of 1994 produced decreases in bottom temperature and oxygen concentration, while SE (cross-axial) winds in August of 1995 caused increases in bottom temperature and oxygen concentration. They explained the 1995 effect by saying that the water mass exchange with Lake Michigan slowed under more easterly winds. The comparison performed in this study is not based on modeling the circulation and thermal regime during August 1994 and 1995 using the actual meteorological forcing, yet confirms Waples and Klump's (2002) finding about the important effect of the wind direction on the water exchange between Green Bay and Lake Michigan. One of the long-term impacts hypothesized as potentially important for this system is a regime change in the propagation of storm tracks through the Laurentian Great Lakes basin in response to large-scale climate change patterns that have pushed summertime storm tracks further to the south.

Miller and Saylor (1985) estimated at 3,300 m^3 s^{-1} the average water exchange during June, July, and August of 1977, and at 0.6 yr the "emptying time" for Green Bay. The monthly average wind direction was from the SWW in June and from the SW in July and August of 1977. Our estimate for idealized steady uniform wind shown above is almost three times larger than Miller and Saylor (1985) estimate. The water exchange rates presented above are realistic estimates because they were obtained using a model that was positively tested against 1989 measurements (Hamidi et al. 2013), assuming an idealized uniform wind with normal speed. The water exchange flow rates presented here are therefore comparable with Miller and Saylor's (1985) estimates based on 1977 measurements.

2.3.4 Estimation of Water Transport Between Lower and Upper Green Bay

The water transport between lower and upper Green Bay was estimated based on model simulation of the circulation and the thermal regime during the summer of 1989, using actual meteorological forcing. This water transport was calculated by integrating the modeled currents through the cross section at Chambers Island (Fig. 2.2). During the stratified season, a complex two-layer transport oscillated out of and into lower Green Bay. Figure 2.6 shows that summer 1989 net transport varied continuously over time. The three-month (June–August) average in and out flows were practically equal with a value of 1,500 m^3 s^{-1}. This means that exchange between the upper and lower bay is ∼15% of the exchange of the upper bay with the open lake, i.e., the flushing or exchange attenuates significantly as water penetrates into the southern bay. The model estimation is almost double the water transport values of 790 m^3 s^{-1} and 830 m^3 s^{-1} out of and into lower Green Bay, respectively, estimated by Miller and Saylor (1993) for the 93 days with baroclinic currents, June 22–September 22, 1989. Miller and Saylor's (1993) estimation was based on actual current measurements along four vertical profiles. The model estimation presented here is based on simulation of the circulation and the thermal regime in the whole bay, using actual summer 1989 meteorological forcing. Dividing the volume of lower Green Bay (23.7 km^3) by the estimated average flow rate of 1,500 m^3 s^{-1} yields a "mixing time" for the lower bay across the Chambers Island section of ∼0.5 year. Concomitantly, a mixing time for the upper bay would be on the order of 50 days.

The values of average transport estimated from the data and model are within a factor of two. The comparison of estimations seems reasonable given that the former value resulted from measurements made along four vertical profiles, while the latter values were estimated independently by a model driven by reconstructed meteorological conditions, as explained in Sect. 2.2.3. Spectral analysis was used to investigate additional evidence of the physical drivers investigated in this chapter. Figure 2.6b shows the estimated spectrum for the net transport out of or into lower Green Bay during summer 1989 across the Chamber Island cross section. The spectrum shows peaks for the first surface mode of Green Bay GB_1 (0.097 h^{-1}), the first surface mode of Lake Michigan LM_1 (0.108 h^{-1}), and the first internal mode of Green Bay, GB_{i1} (0.005 h^{-1} or 0.12 d^{-1}). This means that the water exchange between upper and lower Green Bay shows relevant timescales that demonstrate the effects of stratification (GBi1), and the bay and lake topography (GB_1 and LM_1). This result confirms the important contribution to the transport of the 8-day period oscillations reported, based on a qualitative analysis of the currents' data, by Miller and Saylor (1993).
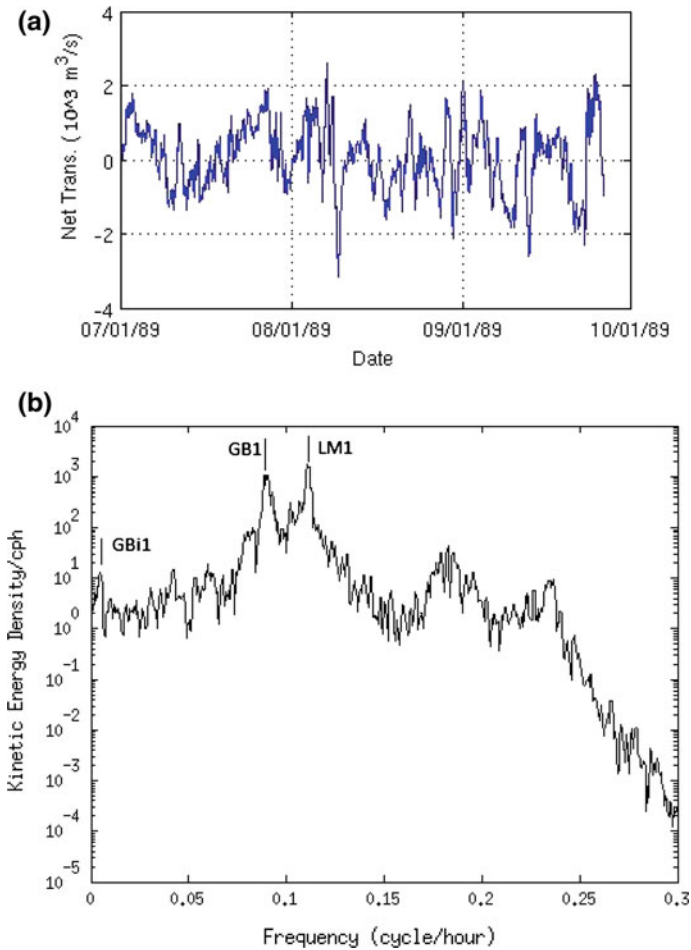
Fig. 2.6 a Model-estimated net transport out of (+) or into (−) lower Green Bay during summer 1989 across the Chambers Island midbay cross section. **b** Spectrum of the net flow out or into lower Green Bay during summer 1989

2.3.5 Effects of Wind, Stratification, Earth's Rotation, and the Bay and Lake Topography on Two-Layer Flows

We used frequency domain analysis of field data to further investigate the effects of wind, stratification, the Earth's rotation, and the topography of the bay and the lake topography on the observed two-layer flows. Specifically, we investigated common timescales of top and bottom currents and along-bay wind, and whether the relevant timescales indicate evidence of the effects of basin topography, the Earth's rotation, and stratification.
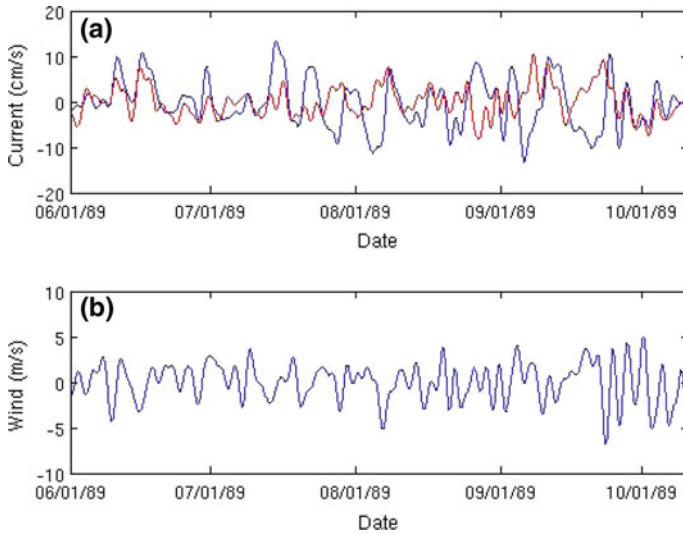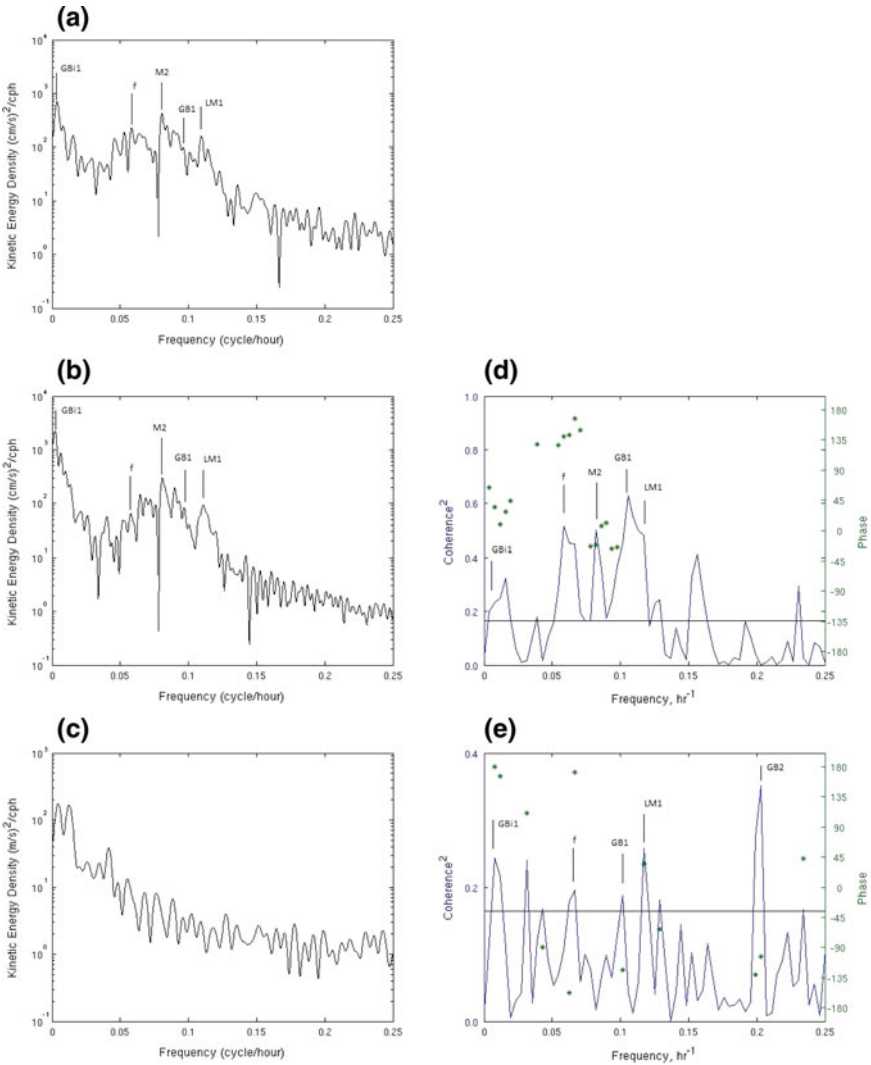
Fig. 2.7 a along-bay currents measured at station N19 (Chambers Island west) in the top (*blue*) and bottom (*red*) layers (Gottlieb et al. 1990), and **b** along-bay wind speed during summer 1989. *Positive values* denote currents and wind flowing out of the bay

Typical two-layer flows occur during the stratified season. Flows in the bottom layers bring cold water from Lake Michigan to Green Bay and surface flows carry warmer water from the bay to Lake Michigan. Figure 2.7a shows along-bay currents measured at Station N19 (Chambers Island west) in the top and bottom layers (Gottlieb et al. 1990), and Fig. 2.7b shows along-bay wind speed during the summer of 1989. The figure shows that during the stratified season (between late June and September) along-bay surficial and bottom currents vary out of phase.

The time series were analyzed in the frequency domain to uncover relevant timescales. Figure 2.8a–c show the power spectral density estimates for summer 1989 along-bay currents measured at station N19 (Chambers Island west) in the top (a) and bottom (b) layers, and along-bay wind (c). The frequencies of the significant peaks in Fig. 2.8a (top currents) and b (bottom currents) include the inertial frequency f ($0.058 \ h^{-1}$), the M_2 tide ($0.081 \ h^{-1}$), the first surface mode of Lake Michigan, LM_1 ($0.108 \ h^{-1}$), the first surface mode of Green Bay GB_1 ($0.097 \ h^{-1}$), and the first internal mode of Green Bay, GB_{i1} ($0.005 \ h^{-1}$ or $0.12 \ d^{-1}$). The M2 tidal constituent, the "principal lunar semi-diurnal," was observed in field data and is not considered by the POM model.

Figure 2.8d presents the squared coherency and phase between top and bottom currents. The figure shows that surface and bottom currents are significantly coherent (above the 95% confidence level shown in the figure) at several frequencies, including the first internal mode of Green Bay, GB_{i1}, the inertial frequency f caused by the Earth's rotation, the M_2 tide, the first surface mode of Green Bay GB_1, and the first surface mode of Lake Michigan LM_1. In other words, the
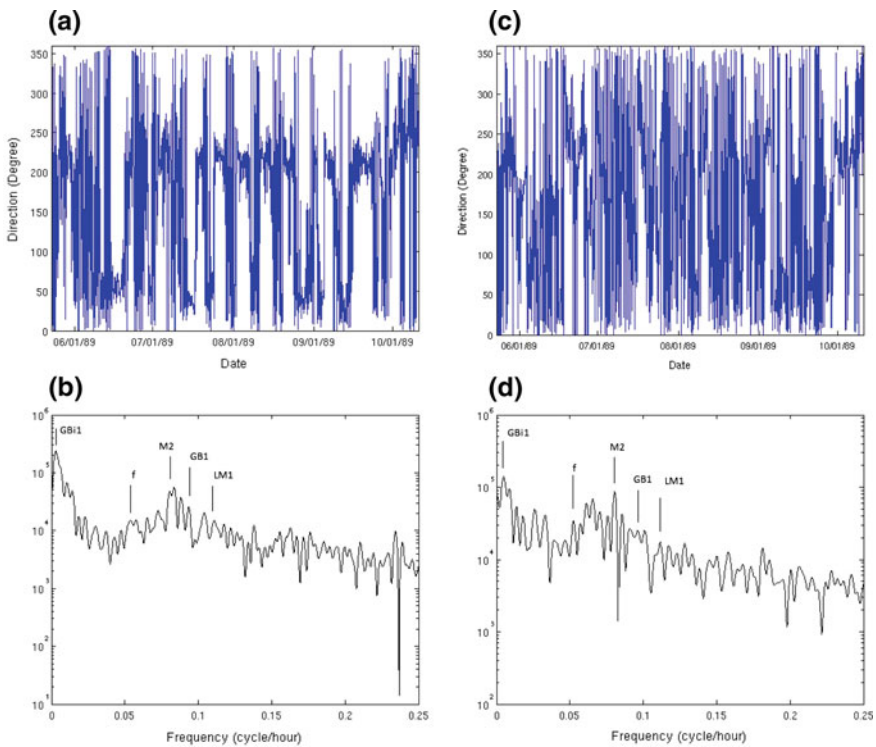
Fig. 2.8 Power spectral density estimates for along-bay currents measured at Station N19 (Chambers Island west) in the top (**a**) and bottom (**b**) layers, **c** power spectral density estimates for along-bay winds, **d** squared coherency and phase between top and bottom currents, **e** squared coherency and phase between top currents and wind. The horizontal lines in parts **d** and **e** show the threshold for coherency to be significant at the 95% level of confidence

squared coherency in Fig. 2.8d confirms the information conveyed by the spectra in Fig. 2.8a and b, showing that top and bottom currents have common relevant timescales that demonstrate the effects of stratification (GBi1), the Earth's rotation (f), and the bay and lake topography (GB_1 and LM_1). Figure 2.8d also shows that at the inertial frequency top and bottom currents are out of phase by about 135°.

The squared coherency and phase between wind and top currents (Fig. 2.8e) shows that wind and surface currents are significantly coherent at several frequencies, including the first internal mode of Green Bay, GB_{i1}, the inertial frequency f caused by the Earth's rotation, the first surface mode of Lake Michigan LM_1, and the first two surface modes of Green Bay GB_1 and GB_2 (0.207 h^{-1}). In other words, wind and top currents show common relevant timescales that demonstrate the effects of stratification (GB_{i1}), the Earth's rotation (f), and the bay and lake topography and the Earth's rotation (GB_1, GB_2, and LM_1).

2.3.6 Effects of Stratification, Earth's Rotation, and the Bay and Lake Topography on the Direction of Currents

Currents measured in the top and bottom layers, west of Chambers Island during summer of 1989, were analyzed to investigate evidence of the effect of the Earth's rotation. Top and bottom currents rotated clockwise (as shown by Fig. 2.9a for the

Fig. 2.9 Direction of **a** bottom and **c** top currents measured at Chambers Island west during summer 1989; spectra of **b** bottom and **d** top currents direction
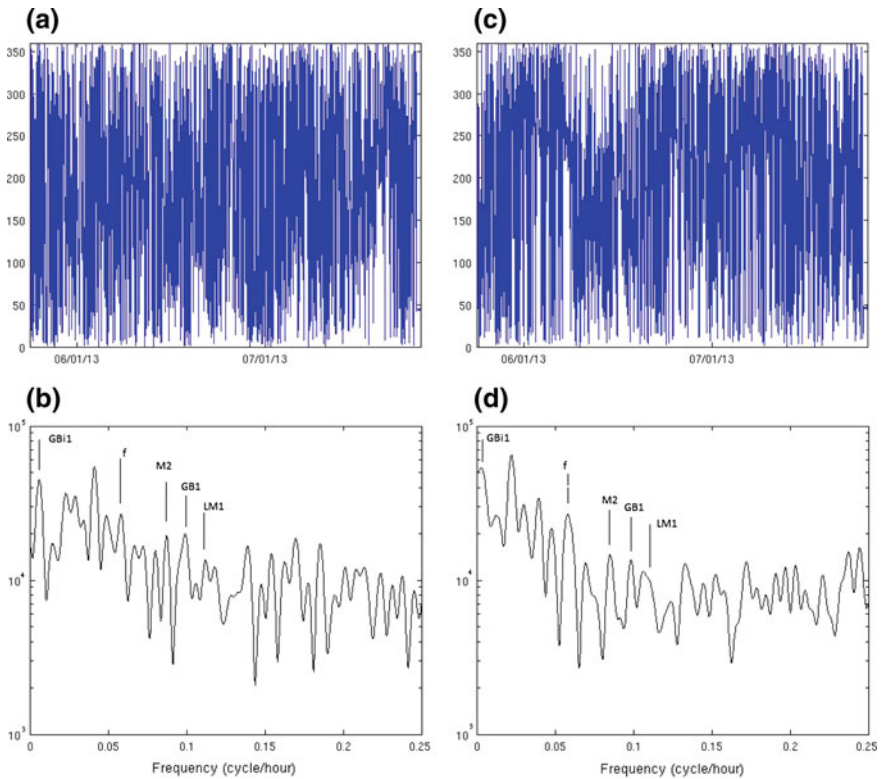
Fig. 2.10 Direction of **a** bottom and **c** top currents measured at Station 17 during summer 2013; spectra of **b** bottom and **d** top currents direction

near bottom currents) with distinct periodicity during the stratified season (between late June and September).

Figure 2.9b, d show the power spectral density estimates for the direction of summer 1989 bottom and top currents, respectively, measured at station N19 (Chambers Island west). The frequencies of the significant peaks in Fig. 2.9b, d include the first internal mode of Green Bay, GB_{i1} (0.005 h^{-1} or 0.12 d^{-1}), the inertial frequency f (0.058 h^{-1}), the M_2 tide (0.081 h^{-1}), the first surface mode of Lake Michigan, LM_1 (0.108 h^{-1}), and the first surface mode of Green Bay GB_1 (0.097 h^{-1}). In other words, the rotation of top and bottom currents shows time-scales that demonstrate the effects of stratification (GBi1), the Earth's rotation (f), and the bay and lake topography and the Earth's rotation (GB_1 and LM_1). The first internal mode of Green Bay, GBi1, is the frequency of persistent oscillations of the thermocline at the period of the bay's lowest-mode, a closed basin internal seiche, an 8-day long period found by Saylor et al. (1995). The observed inertial period f was very close to the theoretical limiting period. Mortimer (2004) used the term near-inertial oscillations to describe this phenomenon. The passage west of

Chambers Island is about four times the Rossby radius for internal waves (estimated at 2.6 km); i.e., it is wide enough to observe the effect of the Earth's rotation.

A similar analysis of our 2013 current measurements at Station 17 showed results that are very similar to those just described. These results, shown in Fig. 2.10, demonstrate that the effects of the Earth's rotation are also observable in the lower Green Bay circulation.

2.4 Conclusions

The thermal regime in Green Bay is determined by the combination of the heat flux across the water surface and heat transport by circulation, including the water exchange with Lake Michigan. The analysis of the calculated heat flux across the water surface and measured, stratified temperature profiles showed a clear cause-effect relationship in regions deeper than 15–20 m between late June and September.

Green Bay exhibits significant interannual variability in the summer wind direction and the circulation patterns. Hence, descriptions of circulation based on single-year field data or modeling may represent incomplete pictures or may miss the range of variability present. The existence of persistent, monthly average patterns in wind forcing and consequent circulation patterns is an important finding of this study. The monthly average wind direction in May is from the NE and rotates to the SW in June, producing changes in the circulation pattern. Summertime conditions are initiated by this transition in the dominant wind field shifting from the NE to the SW in late June, and conditions remain relatively stable until bay vertical mixing in early September. It is during this stable period that the stratified conditions conducive to hypoxia are present. Wind direction has a significant effect on the water exchange between Lake Michigan and Green Bay. A computational experiment for an idealized steady uniform wind parallel or perpendicular to the bay showed that the former condition induces a greater water exchange than the latter condition, with a difference as much as 60%.

The water exchange between upper and lower Green Bay yields a measure of the mixing between those water bodies. The hydrodynamic model was used to simulate, fairly closely, the water exchange measured by Miller and Saylor (1993) and to estimate a "mixing time" for the lower bay across the Chambers Island section of ~0.5 year. Spectral analysis of the net water exchange between upper and lower Green Bay showed relevant timescales that demonstrate the effects of stratification, the bay and the lake topography and the Earth's rotation.

Frequency domain analysis of wind and measured currents' data revealed the effects of wind, stratification, the Earth's rotation, and the topography of the bay and the lake topography on the observed two-layer flows in Green Bay. This two-layered flow, particularly the southerly propagation of cooler, denser waters, establishes and reestablishes the conditions most susceptible to the onset and persistence of hypoxia in the lower bay. This cooler hypolimnetic water mass becomes

progressively depleted of oxygen as it moves south, at times reaching complete anoxia. Top and bottom currents rotated clockwise with distinct periodicity during the stratified season. Frequency domain analysis of top and bottom currents clearly showed the effects of stratification, Earth's rotation, and the bay and lake topography on the direction of currents.

The general patterns of the circulation and thermal structure and their variability as related to the changing wind regimes and the thermal climate will be essential in producing longer term projections of future water quality in response to system scale changes, e.g., changes in seasonality, duration of summertime conditions, climate forcing mechanisms, nutrient loading, habitat restoration and alteration, and long-term changes in predicted lake levels.

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