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The role of circulation and heat fluxes in the formation of stratification leading to hypoxia in Green Bay, Lake Michigan

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ABSTRACT

Summertime bottom water hypoxia has been a recurring water quality issue in Green Bay for decades. Evidence suggests that the magnitude and duration of hypoxia is highly variable from year to year, despite the fact that nutrient loading has been relatively constant for at least 20 years. The bay's size, orientation, and morphology (~20 × 200 km) with high riverine inflow and restricted mixing at the southern end, combined with extensive water mass exchange with Lake Michigan at the northern end, results in a changing hydrodynamic structure that plays a key role in the set up and persistence of stratification that leads to hypoxic conditions. Using both observed and modeled data, this study represents the first attempt to examine the spatial and temporal characteristics of the interactions among the atmospheric heat flux across the water surface, the advective heat flux driven by the circulation, and the intrusion of cold Lake Michigan bottom water into the hypolimnion. With the onset of positive solar heat fluxes in April, stratification generally exists continuously between late June and early September in regions deeper than 15–20 m, and develops discontinuously at depths less than 15 m. Critical improvements in developing realistic simulations of stratification in the bay were obtained via consideration of water clarity conditions that impact heat adsorption and varying default parameters, particularly in the vertical diffusivity, in the Lake Michigan model framework.

Introduction

Green Bay has a long history of hyper-eutrophication, dating back to at least the first half of the last century (Bertrand et al., 1976). The Fox River is the largest single source of phosphorus to Lake Michigan (Dolan and Chapra, 2012), but the bay is a very efficient nutrient trap, sequestering 70–90% of the total inputs via deposition and burial (Klump et al., 1997). This leads to high rates of accumulation of relatively labile, organic-rich sediments in excess of 10% organic carbon by weight (Klump et al., 2009). Consequently, these sediments quickly go anaerobic, and sediment oxygen demand, in conjunction with stratification, is the major cause of hypolimnetic oxygen depletion in the summer (late June–September).

Despite observations of low oxygen concentrations in bottom waters going back decades (Kennedy, 1982; Valenta, 2013), the extent, duration, and processes controlling this hypoxia are not well understood. Kennedy described the occasional intrusion of cool, oxygen-depleted waters into the southern end of the bay, driven presumably by the flow of hypolimnetic waters under conditions in which bottom water flow was sufficiently strong to push into the shallowest regions of the southern bay. The combination of excessive algal blooms, rapid sedimentation, thermal stratification, and wind-driven circulation has made summertime hypolimnetic hypoxia a recurring feature in the shallower southern reaches of the bay where eutrophication is most pronounced (Klump et al., 2009).

As in other systems, the onset of hypoxia is initiated by thermal stratification which, in Green Bay, appears to arise both from direct atmospheric forcing, i.e. low winds, high air temperatures, and increased solar radiation, and from indirect atmospheric forcing that drives circulation patterns resulting in the southerly incursion of cooler bottom waters (Hamidi et al., 2013) onto highly reducing organic-rich sediments. This circulation pattern can re-stratify a well-mixed water column within hours and can set up stable stratified water column conditions that persist for days to weeks during which time sediment oxygen demand rates are sufficient to completely deplete hypolimnetic oxygen (Valenta, 2013). Hence the morphometry, circulation patterns, and the thermal balance of the bay interact to produce conditions that lead to variations in the degree, extent and duration of hypoxia from day to day and from year to year. Modeling hypoxia, therefore, is somewhat more complex than in a system which is driven largely or solely by seasonal thermal fluctuations. Understanding both the general circulation and the onset and duration of stratification in the bay are essential to determining the potential for hypoxic conditions to improve or worsen, particularly in the face of climate change projections of warmer conditions, less ice cover, and an earlier summer (www.wicci.wisc.edu).

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Since the 1970s, several researchers have investigated circulation and thermal regimes in Lake Michigan and in Green Bay. Previous approaches include theoretical and spectral analysis, physical measurements, numerical models, and an examination of the relation between wind fields, water exchange between Lake Michigan and Green Bay, and hypoxia (Heaps et al., 1982). Large-scale circulation forces and the 2-way coupling between stratification and circulation may often be identified through an analysis of the relevant time scales of currents, surface, and internal waves. Examining the theoretical periods of several surface normal modes of Lake Michigan, including Green Bay, and taking into account the lake's topography and the earth's rotation, Rao et al. (1976) showed that there are several dominant modes in the main basin of Lake Michigan and in Green Bay. They also found satisfactory agreement between their theoretically calculated periods and those deduced from spectral analysis of water level data from various stations around the lake. They found 13 normal modes of the main basin of Lake Michigan (not including Green Bay modes) calculated with rotation, and four Green Bay normal modes. Normal modes of free oscillations in Lake Michigan are patterns of motion in which all parts of the system move harmonically with the same frequency and with a fixed phase relation. The water level amplitude of those surface Green Bay modes ranges between 0.25 m and 0.65 m. Saylor et al. (1995) used their summer 1989 measurements to investigate near-resonant wind forcing of internal seiches in Green Bay and found persistent oscillations of the thermocline at the period of the bay's lowest-frequency mode, a closed basin internal seiche, with an 8-day-long period.

Previous studies have also provided physical measurements useful in validating theoretical models. Miller and Saylor (1985) described monthly averaged circulation patterns and water exchange with Lake Michigan between May and September of 1977 from data obtained at eight moorings using vector-averaging current meters with integral temperature sensors. Gottlieb et al. (1990) measured currents and temperatures in Green Bay during the 1988–89 winters, and during the summer and fall of 1989 as part of the U.S. EPA Green Bay Mass Balance project (US EPA, 1989). The winter deployment involved 8 current meters, and summer deployment included 21 moorings, 3 thermistor chains, and 7 tracked drifters. Both studies found that the direction of circulation in the bay is strongly influenced by the wind field and, in particular, reverses with reversals in the along-bay wind direction.

In an attempt to parameterize gas exchange of methane and carbon dioxide, Waples (1998) and Waples and Klump (2002) examined wind direction and speed, bottom temperatures, bottom oxygen concentrations, and calculated air–water gas exchange fluxes of methane during the summers of 1994 and 1995. An analysis of summer surface wind fields over the Laurentian Great Lakes from 1980 to 1999 showed a statistically significant shift in wind direction beginning around 1990 consistent with a southerly migration of the dominant summer storm track across the Great Lakes basin. In Green Bay, this results in a more easterly component to the average summer wind field. They noted that SW winds parallel to the major axis of the bay, like those observed in August of 1994, produce decreases in bottom water temperatures and oxygen concentrations. Conversely, the shifted SE or cross-axial winds observed in August of 1995 caused increases in bottom temperature by as much as 10 °C and an apparent doubling of the air–water methane flux due to temperature-dependent enhanced methanogenesis in the underlying anoxic sediments (Buchholz et al., 1995). They explained the August 1995 increases in bottom temperatures and oxygen concentrations to the reduction in the water mass exchange with Lake Michigan, and a loss of thermal stability in the absence of the intrusion of these cooler bottom waters. Because of its role and importance, modeling this cool water intrusion is a major focus of the current study.

Schwab and Beletsky (2003) analyzed the relative effects of wind stress curl, topography, and stratification on the large-scale circulation in Lake Michigan. They showed that the cyclonic wind stress curl in the winter and the effect of baroclinicity (i.e. stratification causing misalignment between the gradient of pressure and the gradient of density in the water column) in the summer are primarily responsible for the predominantly cyclonic flow in the lake. Topographic effects are also important but are not as significant as wind stress curl and baroclinic effects. Using 10-year averages of model results combined with measurements that validated the model to map basin scale, climatological circulation patterns in Lake Michigan, Beletsky and Schwab (2008) showed a remarkably stable, large-scale cyclonic circulation pattern during both stratified and un-stratified conditions. 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.

The main questions addressed in the current study are the following: 1) What are the main drivers of the thermal regime in Green Bay? 2) Do they produce stable patterns of stratification? 3)Is there a consistent relationship between seasonal patterns of wind fields and circulation in Green Bay? This study includes the use of existing data and acquisition of new field data, development and use of multi-year hydrodynamic modeling, and spectral methods to address those questions. The results reported herein focus on the overall bay-scale circulation and thermal regime patterns that lead to hypoxic conditions. A comprehensive analysis of the relation between hypoxia and small scale physical processes is currently underway.

Methods

Field measurements

Our summer 2011 data collection program 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. 1 and Table 1). Continuous measurements of water temperature at 1- to 3-m depth intervals were collected at four 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 sampling frequency of 2 Hz, cell size 0.5 m, averaging interval 180 s, and 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 no. 45014) located at station 17 (see: glos.us). The 2011 ADCP measurements were done in cooperation with the National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory (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 depths up to 10 m because that is the effective range of the ADCPs.

Historical observations

NOAA GLERL (Hawley, personal communication) provided summer 1989 current and temperature data (Gottlieb et al., 1990) for 21 moorings, including their 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. 1 and Table 1). The model validation used 1989 historical measurements 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 cross-section (station N19). Great Lakes surface water temperature data were obtained from NOAA Coast Watch (http://coastwatch.glerl.noaa.gov/ftp/glsea/). We employed the 1989 data sets, the Coastwatch data, and our own 2011 data in the validation of the model's results.