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Quantifying the influence of cold water intrusions in a shallow, coastal system across contrasting years: Green Bay, Lake Michigan

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ABSTRACT

We present water column thermal structure for two climatically different years: 2012, which experienced abnormally warm spring and summer air temperatures preceded by a relatively low ice winter and 2013, which experienced cooler than average spring and average summer air temperatures and preceded by average ice conditions. Mean bottom water temperatures for the season and during cold water intrusions were significantly warmer in 2012 than 2013 leading to a significantly reduced stratified season in 2012. Cold water intrusions were driven into southern Green Bay by southerly winds while intrusions were terminated when winds switched to persistent northerly winds. 2012 observed a significant increase in northerly winds relative to 2013, decreasing cold water intrusion presence and duration but winds did not fully explain the difference in thermal conditions for southern Green Bay. These cold bottom waters drive stratification in polymictic southern Green Bay while dimictic waters were found to have significantly warmer bottom temperatures during 2012 and a deeper mixed layer. Our observations suggest that relatively shallow (<20 m), seasonally stratified systems may not increase in stratification strength and duration under a warming climate; rather, changing wind climatology and surface heat flux can inform the degree to which the mixing regime can be expected to change and impact stratification and thermal structure of coastal systems. We discuss the biogeochemical implications of different thermal regimes, particularly within the context of multiple drivers of physical water column structure in eutrophic, stratified coastal systems.

Introduction

Inland freshwater systems play a disproportionately large role in the global carbon cycle and emission of greenhouse gases despite their relatively small areal contribution to the Earth's surface (Cole et al., 2007; Tranvik et al., 2009) with freshwater methane (CH_4) emissions estimated to account for 25% of land-based carbon uptake on a warming equivalent scale (Bastviken et al., 2011). The physical structure of these systems, in turn, plays a large role in an individual system's biogeochemical cycling, methane emissions and regional climate feedback, presenting a complex interplay between aquatic, terrestrial and atmospheric processes (Giling et al., 2017; Heiskanen et al., 2015; Wik et al., 2014). Properly parameterizing drivers of water column physical structure in stratified inland and coastal waters within this context is increasingly pertinent under a warming climate (Austin and Colman, 2008; Itoh et al., 2015; Trumpickas et al., 2015).

Regional climate assessments for the Laurentian Great Lakes (herein: Great Lakes), in particular Green Bay, Lake Michigan, project warmer conditions, less ice cover and an earlier summer, with less certainty in changes in mean wind speed and direction (WICCI, 2011). The physical structure of large lakes, while quite variable, are highly dependent on atmospheric inputs, currents and surface energy fluxes (Hamidi et al., 2015; Rao and Schwab, 2007; Trumpickas et al., 2015). Wind forcing, in particular, strongly impacts the thermal structure of these systems. Wind stress forces thermocline tilting, upwelling and downwelling processes that strongly impact lake temperature, productivity and oxygen content of the hypolimnion (Chowdhury et al., 2016; Coman and Wells, 2012; Hlevca et al., 2015; Mortimer, 2004; Scully, 2010). Additionally, wind forcing can cause breakdown of stratification through turbulent and convective mixing in shallow zones of the Great Lakes, resulting in a dynamic mixed layer depth and variable thermal conditions that impact the biogeochemistry of these systems (Biddanda et al., 2018; Cossu et al., 2017).

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Green Bay is a relatively shallow (mean depth = 14 m), elongated embayment of Lake Michigan (~160 km × 24 km; Fig. 1). In southern Green Bay (south of Chambers Island), hypoxia is a frequent problem during the summer stratified period due to organic-rich sediments and high oxygen demand (Klump et al., 2018). Sediment oxygen demand also results in sediments that quickly become anoxic (1–2 cm depth), resulting in high levels of methane production and flux into the water column (Buchholz et al., 1995). Stratification at depths of <15 m is dependent on the influx of cold bottom water from northern Green Bay and Lake Michigan proper into southern Green Bay and corresponds with periods of hypoxia. Due to its size, Green Bay displays similar physical processes as large lakes (Gottlieb et al., 1990; Miller and Saylor, 1985; Rao et al., 1976; Saylor et al., 1995) as well as having relatively complex bathymetry and turbid waters. Thus, accurately modeling flows and formation of stratification in Green Bay remains a challenge (Hamidi et al., 2015).

Previous work has suggested that southerly winds drive cold water intrusions into southern Green Bay, consistent with approximations of the impact of wind forcing on the physical structure and upwelling/downwelling behavior of lakes parameterized using Wedderburn or lake number (Miller and Saylor, 1985; Coman and Wells, 2012). This variability in benthic temperature has been linked to significantly different sediment methane production and flux in Green Bay (Waples and Klump, 2002). Waples and Klump (2002) also characterized a multi-decade shift in the predominant wind field over the Great Lakes, suggesting that this shift could lead to profound consequences for hypoxia, methane production and ecological processes in Green Bay (Buchholz et al., 1995; Cossu et al., 2017).

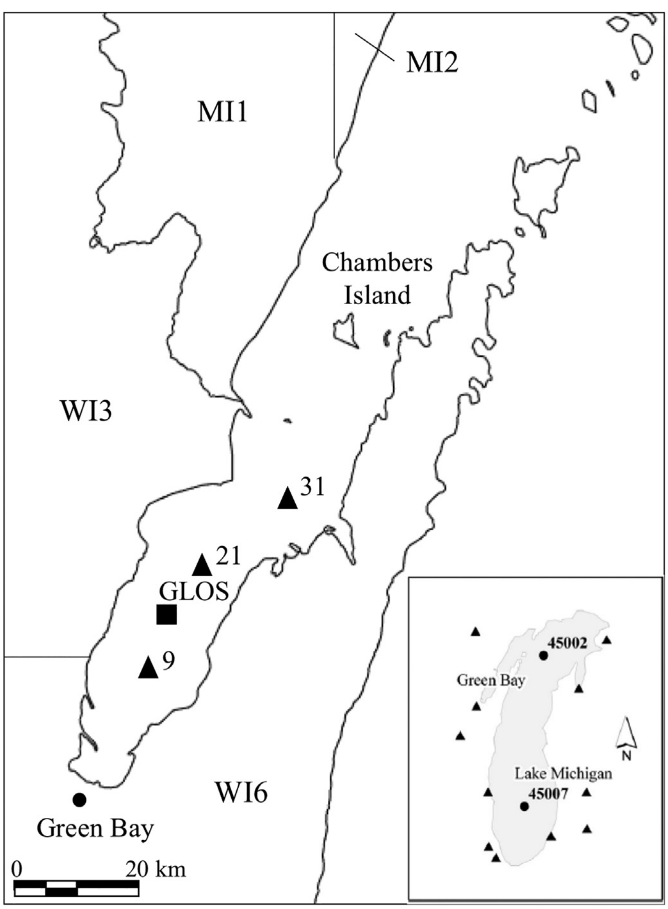

Fig. 1. Moorings (black triangles), GLOS buoy (black square) and NCEI/NESDIS/NOAA climatological divisions used in the current study. Station numbering follows the historic sampling grid as described in (Cahill, 1981) and further described in Klump et al. (2018).

The mechanics of how the thermocline forms and breaks down, as well as its stability and interaction with surface and meteorological conditions, is arguably the most critical physical process to understand when evaluating how Green Bay and other polymictic environments will respond to climate change (Cyr, 2012; Trumpickas et al., 2015; Wilhelm and Adrian, 2008). Increases in temperature increase oxygen demand and production of methane within the sediments while cool bottom waters provide the setup for hypoxic conditions in the southern bay (Schulz et al., 1997; Waples and Klump, 2002), displaying the strong role of thermal variability on biogeochemical processes as observed in other lake systems (LaBuhn and Klump, 2016; Piccolroaz et al., 2013; Wik et al., 2014). Additionally, variability in stratification drives the occurrence of hypoxic and anoxic bottom waters and sediment temperature (LaBuhn and Klump, 2016; Waples and Klump, 2002). Understanding how Green Bay thermal structure responds to climate and meteorological variability is critical for modeling and forecasting hypoxia in Green Bay as well as assessing how climate variability will impact production and flux of methane, a potent greenhouse gas, in Green Bay (Buchholz et al., 1995; Wik et al., 2014). Globally, aquatic CH_4 emissions are expected to increase considerably (Bridgham et al., 2013) with inter-seasonal and inter-annual variability directly impacted by water temperature (Pokrovsky et al., 2013).

The role of water column structure and benthic temperature on Green Bay hypoxia and methane production is relatively well understood. However, how meteorological and climate variability impact these processes has not been formally addressed. Observing and understanding how this variability drives the thermal structure of Green Bay will provide unique insight into the formation of hypoxia under varying climate conditions, including forecasting hypoxia in biogeochemical models of the bay. Additionally, understanding physical drivers of benthic temperature alongside changes in climate will assist in predicting the role of Green Bay in the regional climate budget based on established relationships between temperature and methane production and flux in Green Bay (Buchholz et al., 1995; Waples, 1998; Waples and Klump, 2002). In light of this, we present wind and temperature data for 2012 and 2013, two years characterized by distinct meteorological regimes and a unique difference in wind forcing. We find that predominantly southerly winds drive cold water intrusions, while northerly winds rapidly shut them down, analogous to a bathymetrically constrained upwelling event. We isolate the role of cold water intrusions on the thermal balance of southern bay waters through modeled heat flux terms, showing that southern Green Bay acts as a dynamic, elongated wash-zone similar to that observed in other lake systems (e.g. Chowdhury et al., 2016; Cossu et al., 2017). Finally, we discuss the impact of wind and climate on the thermal variability of Green Bay as it relates to hypoxia and methane production in Green Bay based on the findings of previous work.

Methods

Observations

All in situ observations were collected on three seasonal moorings at Stations 9, 21 and 31 collecting data every 3 or 6 min from June or July through October and NOAA/Great Lakes Observing System (GLOS) buoy 45014 (herein: GLOS buoy) collecting data every half hour (Fig. 1). The GLOS buoy was equipped with a Lufft WS501-UMB Compact Weather Station (Santa Barbara, CA) measuring temperature (±0.2 °C), relative humidity (±2%), global radiation (310–2800 nm, resolution <1 W m^{-2}), air pressure (±1.5 hPa), mean wind speed (average wind speed over a 2 min period) and wind gust speed (3% or ± 0.3 m s^{-1}), a YSI (Dayton, OH) 6600 series multi-parameter sonde measuring temperature, fluorescence, turbidity, pH, dissolved oxygen, and conductivity, and a Nexsens (Dayton, OH) temperature string with thermistors (±0.1 °C) every 1 m from 2 to 12 m. Wire moorings were equipped with Onset (Bourne, MA) temperature loggers at varying distances