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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).

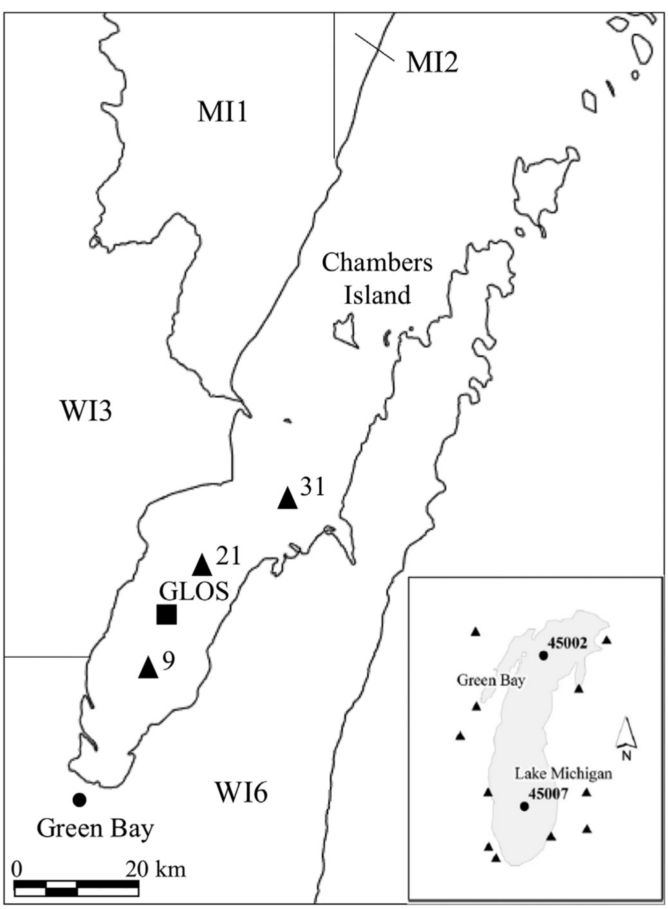

Fig. 1. Moorings (black triangles), GLOS buoy (black square) and NCEI/NESDIS/NOAA climatological divisions used in the current study. Station numbering follows the historic sampling grid as described in (Cahill, 1981) and further described in Klump et al. (2018).

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 from the bottom, depending on the depth of the site, recording temperature to within ±0.53 °C. Some moorings experienced one or more Onset logger failures during a portion of the field season. Contour plots of temperature over depth and time were plotted using Matlab 2016b, with data interpolated using the inpaint_nans function in the Matlab File Exchange Select following a least squares approach that does not alter known values. Missing data is interpolated between adjacent sensors, with no more than one failed sensor at a given station and time.

The 2012 wind direction data was unavailable from the GLOS buoy due to a calibration issue; however, 2013 data were available and were used to determine trends in cold water intrusions with wind speed and direction for that year. In situ wind measurements were compared to data collected by 11 NOAA Automatic Surface Observing System stations within and surrounding Lake Michigan in 2013 (Fig. 1) and displayed relatively good agreement, allowing consideration of interpolated winds at the GLOS buoy for 2012. Winds were interpolated following the nearest neighbor technique with spatial smoothing described in Beletsky and Schwab (2001) and also act as the wind field forcing the nested hydrodynamic model developed for Green Bay (Hamidi et al., 2015).

Air temperature differences between 2012 and 2013 were evaluated using data from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI)/National Environmental Satellite, Data, and Information Service (NESDIS) monitoring service. We considered monthly mean air temperatures for NCEI/NESDIS climatological regions adjacent to Green Bay, using the climatological rankings assigned by NCEI/NESDIS (Table 1, regions indicated in Fig. 1). Due to the large differences in monthly mean air temperature between the years, we did not run a statistical analysis on data grouped by month.

Heat flux

The thermal state of the water column at any given point represents the relative contributions from surface heat fluxes and advection of distinct water masses across that site (Eulerian perspective). In Green Bay, we considered modeled heat flux as the term isolating atmospheric heating/cooling of the water column represented as

$$Q_{NET} = Q_{SW} - Q_{SW\uparrow} + Q_{LW} - Q_{LW\uparrow} - Q_E - Q_H \tag{1}$$

where Q_{SW} is the shortwave radiation incident upon the surface waters, $Q_{SW\uparrow}$ is the shortwave radiation reflected at the surface waters, Q_{LW} is the longwave radiation incident upon the surface waters from the overlying atmosphere, $Q_{LW\uparrow}$ is the longwave radiation emitted by the water body to the overlying atmosphere, Q_E is the latent heat loss, or heat loss due to the evaporation of water, Q_H is the sensible heat loss (or gain) from the heat flux across the air-water interface (due to the difference between air and water temperature), and Q_{NET} is the total heat lost (or gained) during the observed period. We assumed uncertainty in modeled heat flux was low, due to strong agreement with a separate method for calculation, including different input measurements (Grunert, 2013) and agreement between observed and modeled seasonal warming of Green Bay (Hamidi et al., 2015).

Statistical analysis

Cross-correlation analysis was performed on wind velocity and bottom water temperature to determine a relationship between the two parameters. We considered the water column as stratified when a difference of water temperature with depth of 2.5 °C m^{-1} or greater was observed and maintained for >4 h and used this as the basis for further analysis of wind velocity and cold water intrusions. The maximum difference in water temperature with depth was used to define the depth of the hypolimnion and epilimnion from which their volumes were calculated. Cold water intrusions were classified by the onset of stratification and intrusion termination was considered as the breakdown of stratification. We applied a paired *t*-test to determine statistical significance in observed water column heat content, bottom water temperatures (1 m from bottom) and surface water temperatures (1 m depth) between coincident periods in 2012 and 2013. We applied a one-way ANOVA and multiple comparison of means test using Tukey's honest significant difference criterion to determine if wind speeds during pre-intrusion and post-intrusion periods were significantly different.

Results and discussion

Water column thermal structure

Five cold water intrusions were characterized from temperature profile data at the GLOS buoy and Station 21, while only four cold water intrusions were evident at Station 9 in 2012 (Fig. 2a–c). For shallow (<20 m) sites, these intrusions represented the only periods of defined thermocline formation for the entire summer of 2012 (Fig. 2a–b). As sites became deeper and displayed season-long, semi-stable thermoclines, such as Station 31 (Fig. 2d), intrusions resulted in a thicker hypolimnion and stronger stratification (up to 10 °C·m^{-1}). Large thermocline oscillations and thickening of the hypolimnion at sites with stable thermoclines were temporally correlated with cold-water intrusions into shallow southerly sites when tracking changes in bottom water temperature, with a minimum bottom water temperature taking from 1 to 4 days to propagate from Station 31 to the southern-most moorings in 2012 including Station 9.

Four distinct cold water intrusions were observed from the end of June through early September 2013 (Fig. 3), with each intrusion defined by stable and increasing stratification intensity followed by breakdown of stratification and warming of bottom waters. For both 2012 and 2013, we observed a cooling and/or thickening of the hypolimnion during

Table 1
Average monthly air temperature for each NOAA Climate Division adjacent to Green Bay for months from March–August in 2012 and 2013. Colored cells in table follow the color scale (at right hand of table) used by NOAA's NCEI Climatological Rankings, with blue indicating below average air temperatures within the indicated rank (with 1/10 indicating it is in the coolest 10% of observations for that month or 1/3 indicating within coolest 33%), gray indicating an average year and red indicating above average air temperatures. Similar red scale indicates if within warmest 10% or 33% of months. The “1” indicates the warmest monthly average air temperature on record.

	2012				2013				
	MI1	MI2	WI3	WI6	MI1	MI2	WI3	WI6	1/10
March	4.6 °C	3.4 °C	6.1 °C	7.6 °C	-5.9 °C	-4.1 °C	-4.7 °C	-3.4 °C	1/3
April	4.6 °C	4.4 °C	6.2 °C	7.1 °C	0.5 °C	1.4 °C	2.2 °C	4.2 °C	N
May	13.1 °C	12.4 °C	14.4 °C	15.2 °C	9.9 °C	10.5 °C	12.2 °C	12.8 °C	1/3
June	17.6 °C	17.2 °C	18.6 °C	19.8 °C	15.2 °C	15.3 °C	16.8 °C	17.8 °C	
July	21.0 °C	21.3 °C	22.2 °C	24.1 °C	18.6 °C	18.7 °C	19.7 °C	20.6 °C	1/10
August	17.9 °C	18.9 °C	18.6 °C	20.2 °C	17.9 °C	18.2 °C	18.6 °C	19.9 °C	1

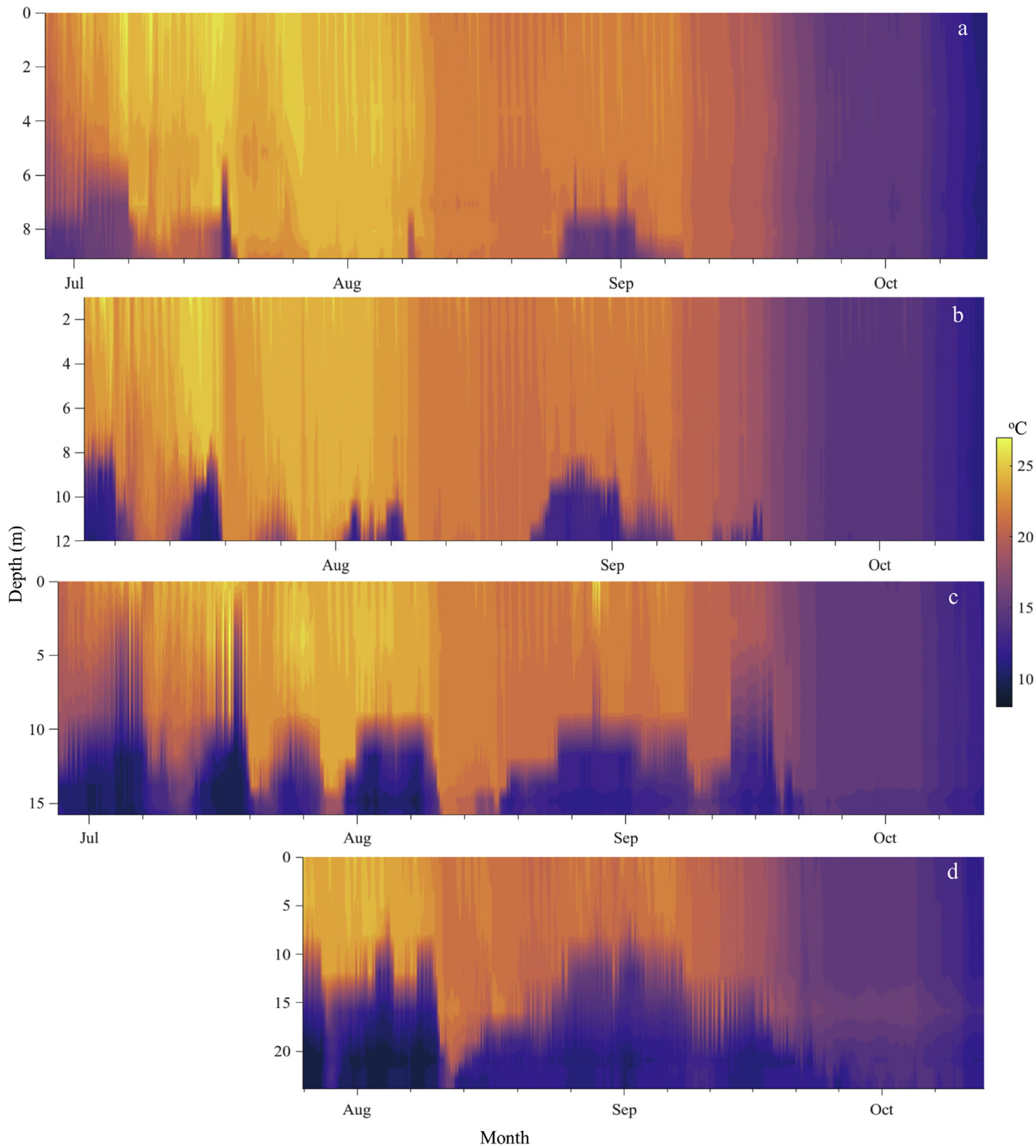

Fig. 2. 2012 water temperature profiles from moorings at stations (a) 9, (b) GLOS buoy, (c) 21 and (d) 31. Colormap from the cmocean project (Thyng et al., 2016).

extended intrusions (>4 days) suggesting either another pulse of cold bottom water or continued tilting of the thermocline.

The water column contained significantly less thermal energy in 2013 than 2012 (paired t-test, $p = 0$). Peak water column energy content in 2012 was 1334 $kJ \cdot m^{-2}$ (July 29) while 2013 water column heat content peaked at 1180 $kJ \cdot m^{-2}$ (July 11). We analyzed the bottom water temperatures from July 4–September 16 for 2012 and 2013 as this was the common record of temperature observations for both years. Mean bottom water temperature (depth = 12 m) for this period in 2012 was 17.6 °C while the mean bottom water temperature for this period in 2013 was significantly cooler at 12.2 °C (paired t-test, $p = 0$). During intrusions, mean bottom water temperature in 2012 was significantly warmer at 14.2 °C compared to 10.9 °C for 2013 (paired t-test, $p = 0$). While the number of intrusions was not significantly different between years, the overall stratified period and average duration for each intrusion was significantly different. Considering the common record of observations, 2012 experienced 51 days of stratification while 2013 experienced 66 days with an average intrusion duration of 7.7 and 16.2 days for 2012 and 2013, respectively (paired t-test, $p = 0$). Additionally, average surface water temperature was significantly different across years, with an average temperature (depth = 1 m) at the GLOS buoy of 23.0 °C and 20.9 °C for 2012 and 2013, respectively.

2013 wind velocity and cold water intrusions

The predominant wind direction for the 2013 study period (May 25–September 16) was southerly, with 36% of all wind directions between 135° and 225° and southwesterly winds (180–225°) accounting for 22% of all winds (Fig. 4). Northeasterly winds between 0° and 45° were also a significant component, accounting for 12% of all winds. Mean wind speed for that same period was 4.6 m s^{-1}, with a maximum wind speed of 16.8 m s^{-1}.

The influence of wind velocity on the thermal structure of the water column was analyzed in detail for 2013, due to direct observations of

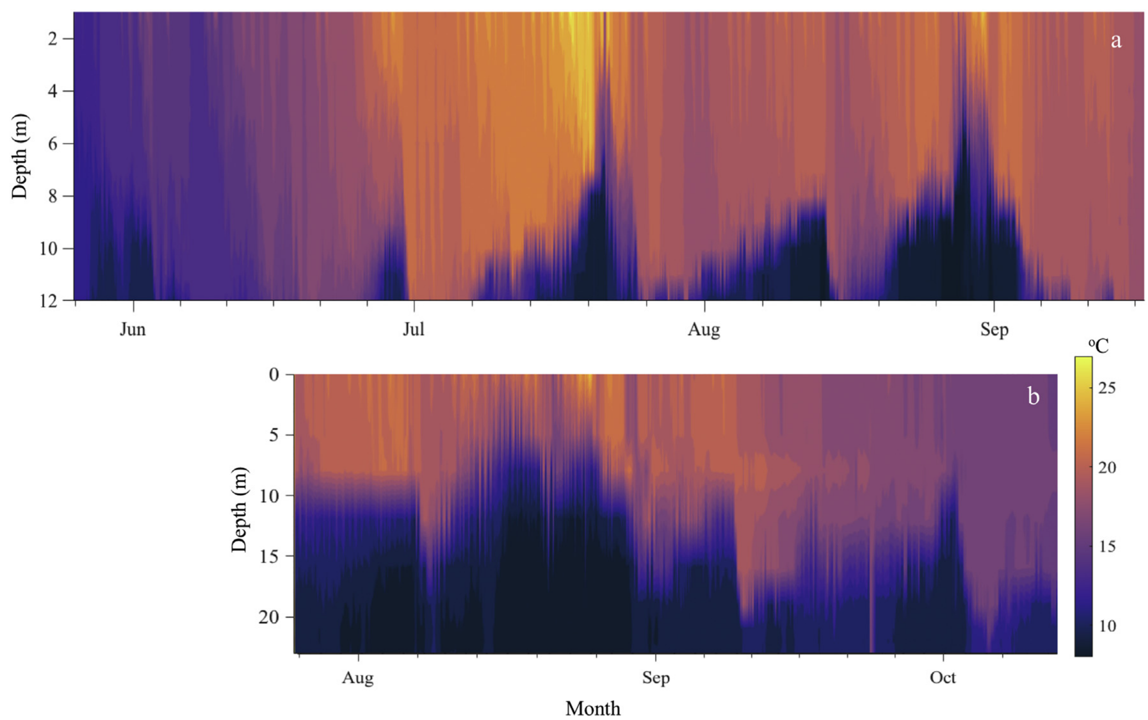

Fig. 3. 2013 water temperature profile at (a) the GLOS buoy and (b) Station 31 mooring. Note difference in observation period between stations.

wind velocity from the GLOS buoy for that year. In 2013 four distinct cold water intrusions were observed at the GLOS buoy during the summer stratification season (Fig. 3). A cross-correlation analysis between bottom water temperature and wind velocity indicated that wind velocity in the 12–60-hour period prior to observations of bottom water temperature was a significant period. From this, we considered wind velocity during this 48 h window before a cold-water intrusion event ("pre-intrusion" period) and 12–60 h prior to bottom waters warming ("post-intrusion" period). Wind roses for these periods are presented for each 48 h period (Fig. 5). Wind speed and direction during intrusions were relatively variable, although two noteworthy features arose: 1) hypolimnion thickening during the intrusion events related to southerly winds with a similar lag period as observed in the cross-correlation analysis, and 2) there were no sustained northerly winds (e.g. north as the predominant direction for >12 consecutive hours) during the intrusion events.

For all intrusions, pre-intrusion periods were characterized by predominantly southerly winds with mean wind speeds of 4.4 m s^{-1}, intrusion periods were characterized by variable wind direction and mean wind speeds of 3.9 m s^{-1} and post-intrusion periods were characterized by predominantly northerly winds with mean wind speeds of 4.6 m s^{-1}. We considered whether the mean wind speeds and group variance

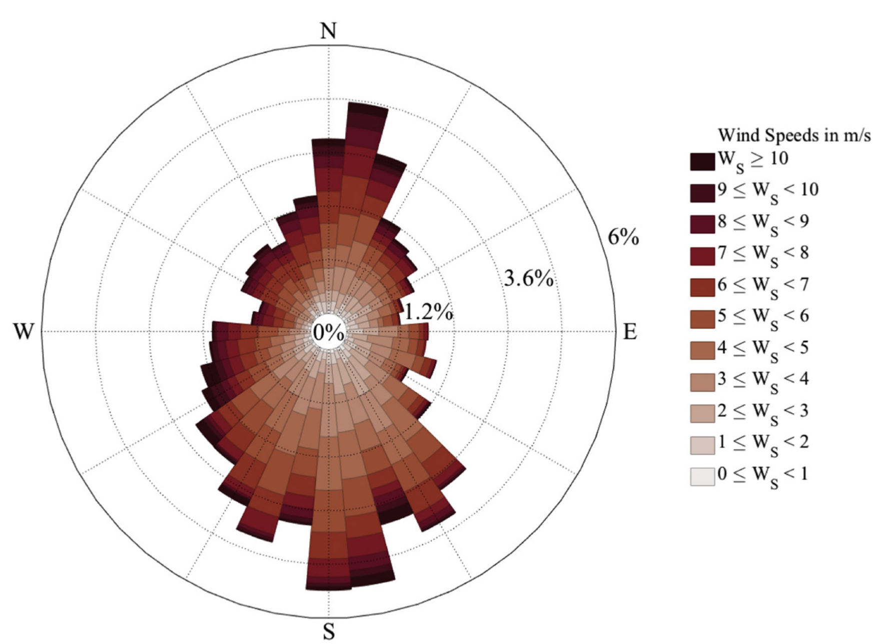

Fig. 4. 2013 wind velocity measured over the entire field season at the GLOS buoy. Colormap from the cmocean project (Thyng et al., 2016).

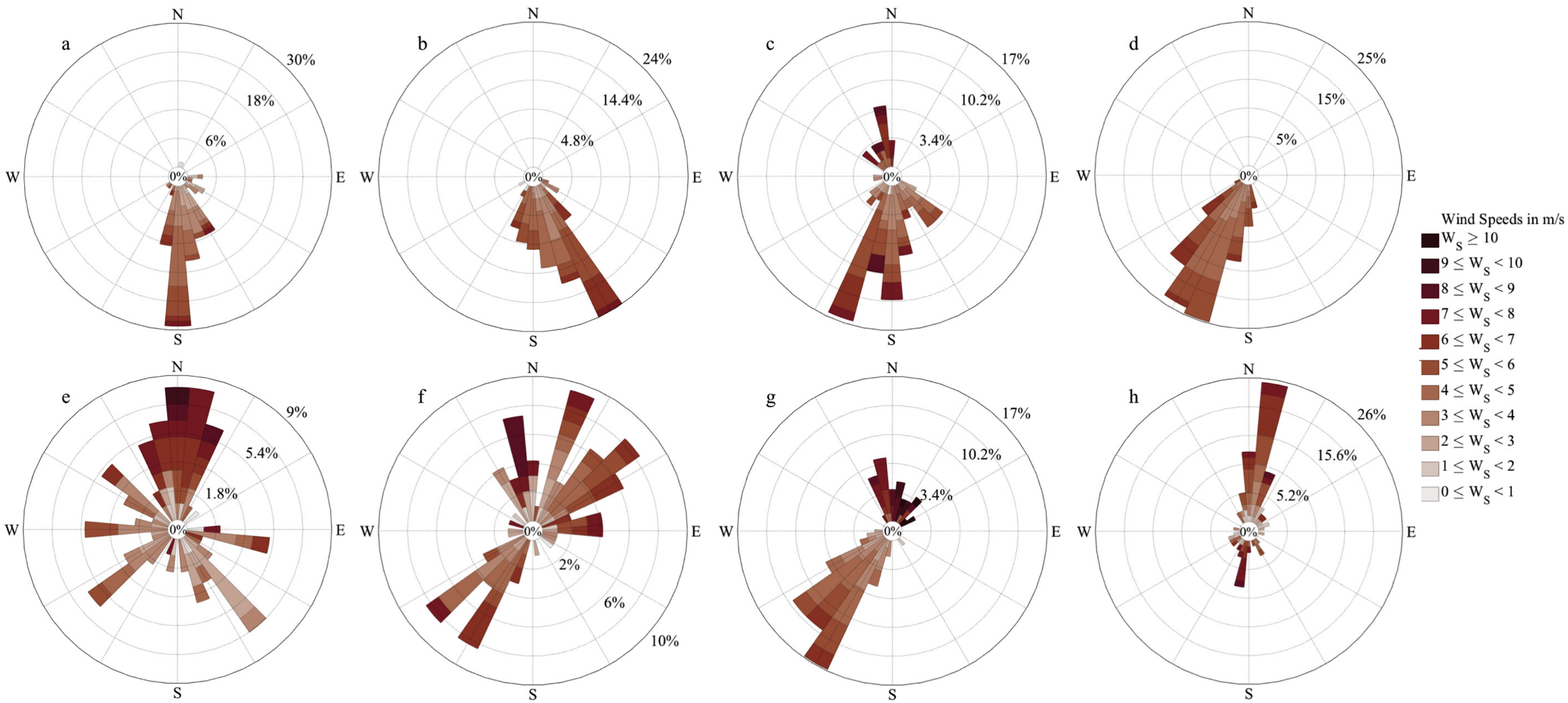

Fig. 5. Comparison of the (a–d) pre-intrusion and (e–h) post-intrusion wind periods measured at the GLOS buoy in 2013. Colormap from the cmocean project (Thyng et al., 2016).

were significantly different using a one-way ANOVA and multiple comparison of means test. Pre- and post-intrusion periods displayed similar mean wind speeds ($p > 0.01$) but were significantly different from mean wind speeds during the intrusion ($p < 0.01$).

Comparison of 2012 and 2013 wind velocity

Considering the relationship between wind velocity and direction and the occurrence of cold water intrusions in southern Green Bay, we compared wind velocity from 2012 and 2013 using the interpolated wind data to maintain consistency between datasets. We considered winds from June 1–October 31, the period over which southern Green Bay has been observed to transition from monomictic to dimictic conditions, before returning to isothermal conditions once again in mid-September to late October. Predominant wind speed over this period was significantly different, with a mean wind speed of 6.35 m s^{-1} in 2012 and 6.12 m s^{-1} in 2013 ($p < 0.01$), while predominant wind direction was not significantly different, displaying a similar overall distribution (Fig. 6). It should be noted that interpolated wind data displayed significantly higher wind speeds than observed data in 2013, with mean wind speeds of 6.2 and 4.6 m s^{-1} for interpolated and observed winds, respectively, over the period of observation. Wind directions were relatively consistent, with a slight westerly bias for interpolated data.

Our analysis is primarily predicated on wind direction; thus, we proceeded with the analysis, breaking down mean wind speed for northerly (315°–45°) and southerly (135°–225°) winds in 2012 and 2013 during the common observation period. Mean northerly wind direction was not significantly different between years; however, northerly wind speed was significantly different between years ($p < 0.01$), 4.83 m s^{-1} and 2.82 m s^{-1} in 2012 and 2013, respectively. Northerly winds were also significantly more frequent in 2012 than 2013, with 14.6% of winds in 2012 versus 4.3% in 2013. Southerly wind direction and speed was significantly different between years ($p < 0.01$), with a mean wind direction of 179.4° and 168.7° and mean wind speed of 6.10 m s^{-1} and 5.54 m s^{-1} in 2012 and 2013, respectively. Southerly wind frequency, however, was not significantly different at 25.8% and 26% for 2012 and 2013, respectively. Thus, while 2012 experienced a mean southerly wind speed of a greater magnitude and direction more closely aligned with the general orientation of Green Bay (generally southwest-northeast orientation, or along-axis winds of ~225°) at a similar frequency, the average northerly wind speed and frequency effectively decreased the physical forcing of cold water into southern Green Bay.

The frequency of distinct stratified periods in 2012 was similar to 2013 (6 vs. 5, respectively). However, the duration and hypolimnetic thickness were quite different during these periods, with intrusions lasting for an average of 7.7 days in 2012 compared to 16.2 days in 2013 and average hypolimnetic thickness during intrusions of 4.1 and 4.9 m in 2012 and 2013, respectively. Based on consideration of the wind field, it was evident that the increase in northerly wind speed and frequency played a large role in bottom water temperatures and duration of stratification. To determine the impact of a warmer climate, we considered water temperature in the mixed layer during the stratified period, as we anticipate this to be the period with the most isolated signal of mixed layer conditions free of impacts from mixing of cold bottom waters. We further considered mixed layer depth alongside temperatures at the GLOS buoy and Station 31 as these two stations represent regions of southern Green Bay that are generally polymictic and dimictic. Mixed layer water temperature was significantly warmer in 2012 than 2013 at both the GLOS buoy and Station 31 (paired *t*-test, $p = 0$), with an average mixed layer temperature of 22.3 and 12.3 °C at the GLOS buoy and 18.6 and 15.5 °C at Station 31 for 2012 and 2013, respectively. The mixed layer depth was not dramatically different between years, with an average thickness of 9.9 and 9.1 m at the GLOS buoy and 16.8 and 15.8 m at Station 31 for 2012 and 2013, respectively.

Considering the wind climatology and significant difference in spring and summer air temperatures between 2012 and 2013, the result was a significantly warmer mixed layer temperature in 2012 relative to 2013 that corresponded to significantly warmer bottom temperatures. This was driven by a difference in northerly wind speed effectively limiting the duration of cold water intrusion when they did occur and air temperatures leading to a significantly warmer mixed layer. More frequent northerly winds of a greater magnitude would reduce the time provided for the thermocline to tilt, leading to less cold water entering and the cold water that enters would presumably be from shallower, warmer waters. However, we did not have observations to deduce the impact of a warmer climate on northern Green Bay waters and cannot limit the change in thermal conditions between years exclusively to wind conditions.

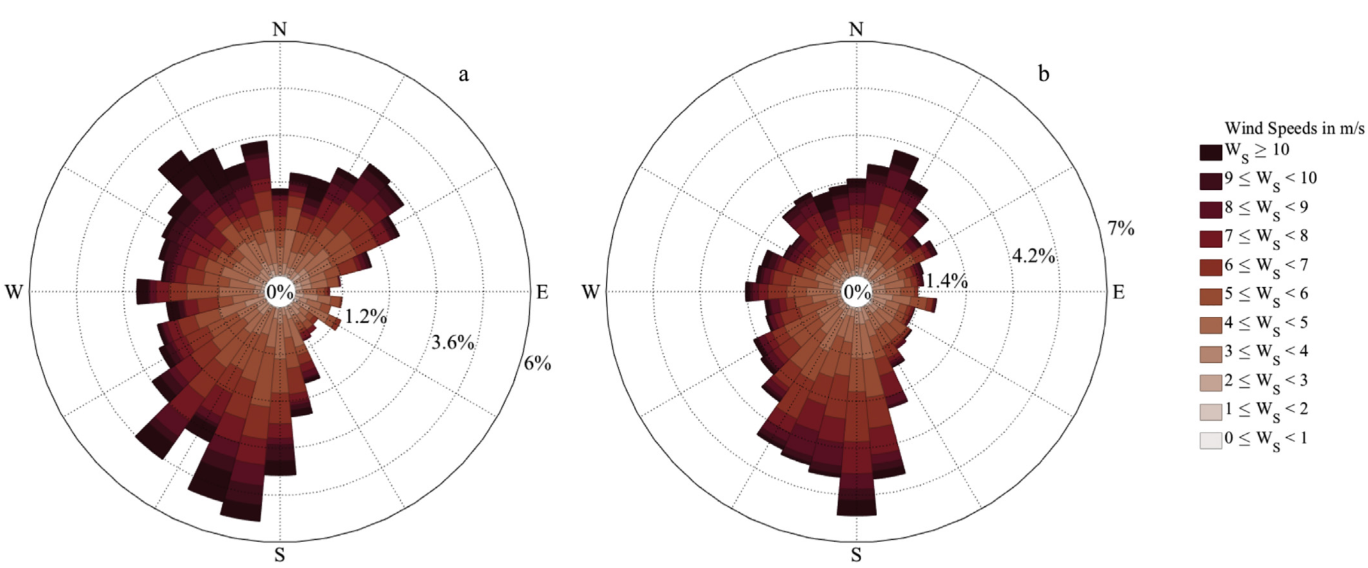

Fig. 6. (a) 2012 and (b) 2013 wind velocity interpolated to the GLOS buoy location from wind measurements at NOAA Automatic Surface Observing System stations identified in Fig. 1. Colormap from the cmocean project (Thyng et al., 2016). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2012 and 2013 modeled heat flux

Net heat flux is calculated from daily averages of the sum of modeled total shortwave and longwave radiation inputs and outputs and the sensible and latent flux terms using the nested Green Bay model described in Hamidi et al. (2015) for 2012 and 2013 (Fig. 7). While the water column in 2012 was considerably warmer than in other years, the net heat flux term was not significantly different from July 1–September 30 between 2012 and 2013. However, the month of July displayed a significant difference between 2012 and 2013 for net heat flux (pair t-test, $p = 0$), longwave radiation (pair t-test, $p = 0$), sensible heat flux (pair t-test, $p < 0.01$) and latent heat flux (pair t-test, $p < 0.01$). Shortwave radiation was not significantly different across years, although the relatively similar values in 2012 across much of July are indicative of the relatively reduced cloud cover observed during that summer. The remaining terms were all predominantly heating the water column at minor levels and are indicative of a stable air-sea boundary layer, likely due to abnormally warm air temperatures remaining above surface water temperatures through July 2012. For the entire observation period, latent and sensible heat flux also displayed significantly different values (paired t-test, $p < 0.01$ and $p < 0.05$, respectively). This is due to a much warmer water column leading to higher evaporation rates and direct exchange of energy with the atmosphere. Mean latent heat flux in 2012 was -117.5 W m^{-2} compared to

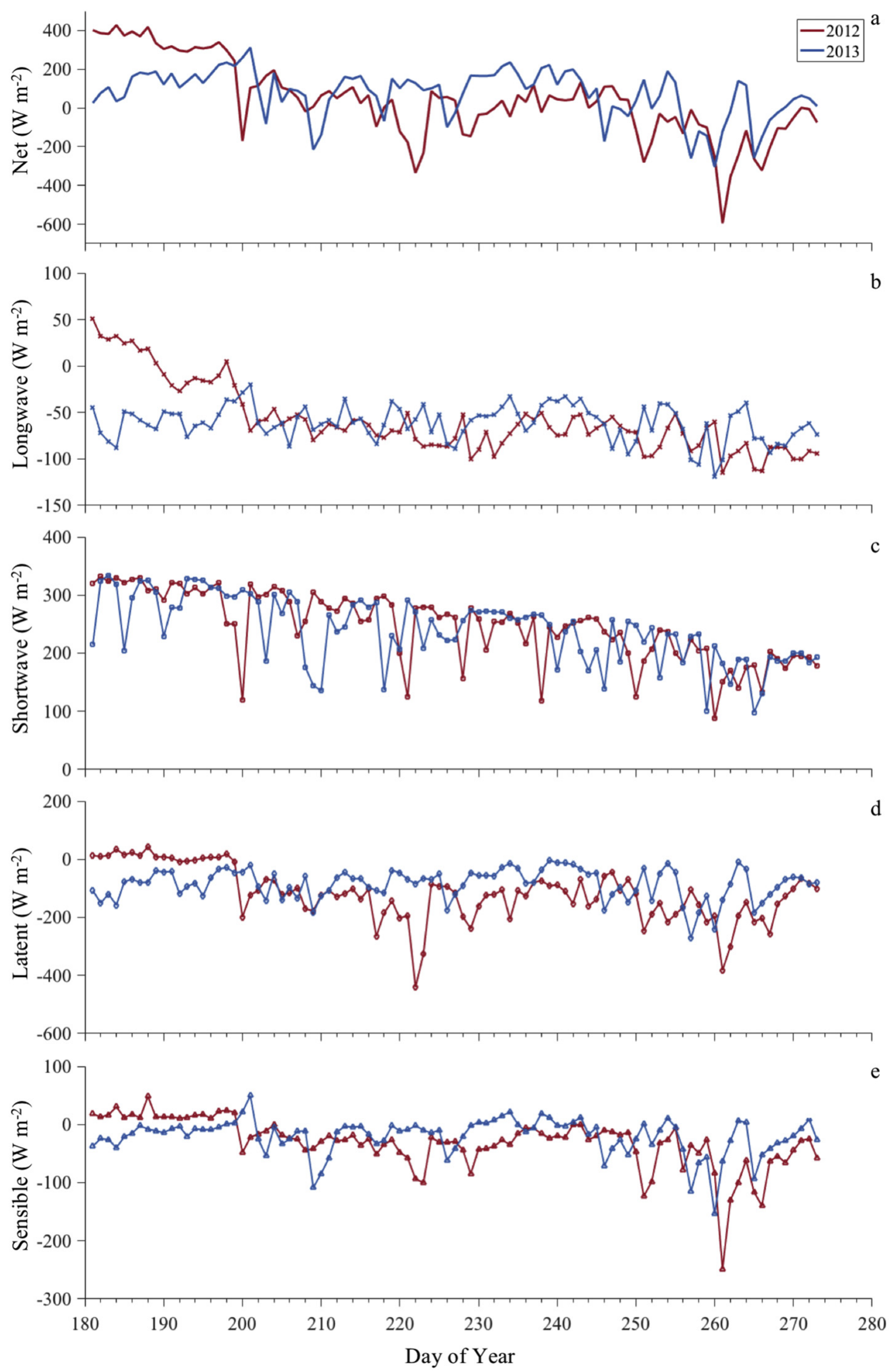

Fig. 7. Average modeled daily (a) net, (b) longwave radiation, (c) shortwave radiation, (d) latent and (e) sensible heat flux terms for 2012 and 2013 from July 1–September 30.

-84.8 W m^{-2} in 2013, suggesting significantly more convective mixing in 2012 relative to 2013. From the flux terms, it appears that the bulk of the additional heat observed was contributed earlier in the year, prior to our period of GLOS buoy observations, evidenced by a warmer water column beginning in July of that year. This is also supported by NOAA average air temperature records showing that 2012 spring and summer air temperatures were abnormally warm over Green Bay (Table 1) and 2012 peak ice cover was significantly lower, suggesting that the warm spring and earlier season for solar insolation "primed" Green Bay to warm above seasonal averages. The significantly different sensible and latent heat flux terms between years were driven by late season trends that favored significantly more convective mixing in 2012 than 2013; this, coupled with wind trends in 2012 likely influenced a much earlier onset of isothermal conditions at Station 31 in 2012 relative to 2013.

Relative role of wind and climate on Green Bay thermal structure

The abnormally warm seasonal average air temperatures in all climate divisions lying adjacent to Green Bay in 2012 appeared to extend summer water conditions (defined as a water column warm enough to have stable stratification), decrease stratification and increase the total heat content of the water column (Fig. 1, Table 1; NCEI/NESDIS/NOAA Climatological Rankings, 2017). It should be noted that the rankings are based on the continuous climate record dating back to 1895; thus, while we are only comparing two years of water column temperature data they are presented within the context of a climatically-relevant air temperature dataset (e.g. Free et al., 2002). This agrees quite well with regional projections for future climate (WICCI, 2011). However, full consideration of the impact of climate variability requires consideration of the separate impacts of wind on water column structure.

To consider the impact of wind speed and direction on thermal variability in southern Green Bay, we ran a cross-correlation between wind velocity and bottom water temperature, then separately characterized wind speed and direction for this period. This analysis suggested that wind velocity from 60 to 12 h correlated with observed bottom water temperature. This relationship agrees quite well with the description of a 2-day periodicity of bay water temperature and currents between alternating wind from the southwest and northeast as well as a 12 h steady state period between the onset of wind and bay circulation (Heaps et al., 1982; Miller and Saylor, 1985). While winds directly force Green Bay, the bathymetry and elongated nature of the bay make water exchange complex and difficult to model (Hamidi et al., 2015). Cold water from northern Green Bay is forced into southern Green Bay through the deep channel west of Chambers Island and does not spread across Green Bay in a consistent manner but rather follows along the predominant cyclonic flow of southern Green Bay (Grunert, 2013; Miller and Saylor, 1985, 1993). Thus, beyond being primarily forced through wind, the distribution and extent of these waters is also forced by circulation, riverine inputs to Green Bay and bathymetry (Gottlieb et al., 1990; Lathrop et al., 1990). Inflow from Lake Michigan is significant, resulting in a relative water residence time of <1 year compared to a residence time of ~3.5 years when only considering riverine flows (Miller and Saylor, 1993).

From this set of drivers, we would anticipate warmer years would exhibit an increase in stratification duration and intensity in southern Green Bay; however, observations did not support this. A factor in this is the role of winds in driving cold water intrusions into southern Green Bay. 2012, despite displaying a significantly warmer climate and water column, also exhibited stronger and more frequent northerly winds, effectively shutting down upwelling of cold bottom waters into the southern bay. However, we also found that the temperature of cold water intrusions was significantly warmer in 2012 than in 2013. From this, we cannot exclusively claim winds as the primary driver of Green Bay thermal structure. The water displaced in 2012 and upwelled into southern Green Bay was also warmer by approximately 2 °C, suggesting that a warmer climate played a role in decreased stratification duration and depth of the hypolimnion across southern Green Bay in 2012. Beyond simply considering predominant wind climatology as discussed in Waples and Klump (2002), it seems that the periodicity of wind shifts and atmospheric factors controlling those, as well as climate, play a combined role in thermal variability and temperature-dependent biogeochemical processes in Green Bay. This highlights the importance of accurately projecting temperature, storm intensity and changes in wind climatology when assessing the impact of climate change on the aquatic environment.

While it is known that a variety of factors account for the observed stratification in a given system, projected changes in lake stratification attributed to climate change tend to focus on increases in air temperature and, subsequently, water temperature (Adrian et al., 2009; Mortsch and Quinn, 1996), with some studies considering secondary drivers in small lakes such as water clarity (Palmer et al., 2014). We found that spring air temperatures and reduced winter ice cover resulted in a significantly warmer water column in 2012 relative to 2013; however, we posit that warmer air temperatures and reduced ice cover will not necessarily translate to more stable stratification and a longer stratified period for systems where thermal variability is also dependent on wind forcing (e.g. Trumpickas et al., 2015; Chowdhury et al., 2016).

Previous studies have pointed out the lack of regional coherence between air temperature and lake stratification due to variables such as wind velocity, sheltering, water clarity and surface heat fluxes (Benson et al., 2000; Read et al., 2014). Variability in mixed layer depth due to internal processes of large lakes and lake morphology have been observed (Cossu et al., 2017; Stainsby et al., 2011; Wells and Parker, 2010) while changes in wind velocity and air-sea interactions due to climate change have also been addressed (Austin and Colman, 2007; Desai et al., 2009; Waples and Klump, 2002). Despite the propensity to consider stratification stability and duration as increasing with climate warming, we argue that a more nuanced approach is needed to better assess how food web and biogeochemical processes will change due to climate change. Modeling studies have shown the importance of accurately representing the impact of competing variables on thermal structure and its effect on hypolimnetic oxygen depletion in Lake Erie (Liu et al., 2014), as well as the importance of individual lake characteristics in mediating the onset of stratification (Read et al., 2014). While our system is not representative of many stratified freshwater systems due to the periodic introduction of cold bottom waters that initiate or maintain stratification, our observations suggest that a warming epilimnion coupled with divergent wind patterns and a warming hypolimnion can lead to conditions not well-predicted when considering air temperature alone. Additionally, we did not find that a change in the southerly wind trajectory significantly impacted the presence or duration of cold water intrusions, as predicted by Waples and Klump (2002). Rather, despite 2012 exhibiting stronger southwest wind forcing, warmer bottom waters and stronger and more frequent northerly winds led to a warmer water column and shorter duration of stratification.

Studies considering the impact of climate on warming lake surface temperatures have observed that large lakes display more rapid warming than over-land warming, with deeper lakes displaying the greatest magnitude of change (Austin and Colman, 2007; Piccolroaz et al., 2013). Some studies have suggested that a change in ice cover is the primary driver due to increased solar heating from a lower albedo, with Hanrahan et al. (2010) observing a correlation between winter ice cover and summer lake surface temperature in Lake Michigan. This could be the primary cause for a warmer water column in 2012, as ice cover in Green Bay, peaking at 100% coverage for most years, peaked at 75% coverage for much of the bay in the winter preceding 2012 observations (NOAA GLERL/U.S. National Ice Center). However, Zhong et al. (2016) suggested that the impact of decreases in ice cover may be limited due to competing impacts of ice albedo (cooling effect) and ice insulating effects (warming effect), while Toffolon et al. (2014) found that air temperatures dominate surface water temperature warming in small, shallow lakes and present a more muted surface water warming signal in deeper lakes.

Green Bay undoubtedly behaves like a large lake but is quite shallow relative to its surface area, posing as a system with a fixed mixed layer depth for much of the southern bay in the absence of cold water intrusions. Kravtsov et al. (2018) describe a basis for observed warming trends in large lakes, finding that shallow regions of the Great Lakes will display more convoluted signals as thermal regime changes are driven by short-term atmospheric variability while deeper regions switch thermal regimes following the long-term warming trend. Considering this, the fact that the thermal inertia of Green Bay across most sites is relatively low due to shallow depths, and observations of mixed layer depth between a warm (2012) and relatively average (2013) year, it is likely that thermal stratification in many regions of Green Bay will be largely dependent on forcing of cold water into the bay from Lake Michigan and deep regions of northern Green Bay and the temperature of this upwelled water. This is demonstrable in the thermal profiles at Station 31 between 2012 and 2013, where isothermal conditions setup by October 1 in 2012; however, the water column maintains stratification well into October in 2013, suggesting that conditions producing cold water intrusions persisted well into October despite a smaller thermal gradient between the epilimnion and hypolimnion. Hamidi et al. (2015) also found that accurately modeling the mixed layer depth and intensity of stratification in Lake Michigan was critical for modeling the presence of cold water intrusions in southern Green Bay. This suggests that cold water intrusions will be significantly impacted by warming of Lake Michigan as well. Observations of warmer surface water temperature accompanied by increasing wind speeds and evaporation favor water column mixing (Desai et al., 2009; Hanrahan et al., 2010), a factor that could also explain the earlier onset of isothermal conditions in 2012. Thus, accurately characterizing the physical drivers of Green Bay, including climate-driven variability in Lake Michigan proper, is crucial to forecast the future biogeochemical conditions of the bay to best inform current and future management decisions.

Implications for temperature-dependent biogeochemical processes

Our observations that southwesterly, along-axis winds push surface water northwards, resulting in a reciprocal flow of bottom water observed as a cold water intrusion agrees with previous hypotheses about the mechanisms for these observed water masses (Kennedy, 1982; Waples and Klump, 2002), with the caveat that winds initiating the intrusion do not need to be aligned with the along-axis component of the bay but rather from a generally southerly direction. The intrusions initiate stratification in southern Green Bay, with prolonged stratification setting up conditions for rapid consumption of hypolimnetic oxygen and seasonal hypoxia observed in the bay for decades (LaBuhn and Klump, 2016; Valenta, 2013). Other eutrophic Great Lakes systems have observed similar phenomena where hypoxia is dependent on periodic stratification formed by intrusions of cold water (Biddanda et al., 2018). Beyond the benthos, pelagic oxygen consumption within the hypolimnion has been shown to account for nearly 50% of total hypolimnetic oxygen consumption (Brunner, unpublished data), suggesting that warmer water column temperatures will extend beyond benthic impacts. Green Bay also shares many similar features with Chesapeake Bay, including seasonal hypoxia influenced by physical forcing and nutrient loading (Lee et al., 2013; Li et al., 2016; Scully, 2010, 2013; Vaquer-Sunyer and Duarte, 2008). While the primary setup for hypoxia is stratification, sediment oxygen demand in Green Bay fueled by loading of organic matter (terrestrial and autochthonous) leads to distinct, recurrent patterns of hypoxia that largely mirror circulation and organic matter deposition dynamics (Klump et al., 2018; Klump et al., 2009). This suggests that effective management of complex coastal systems requires an understanding of multiple drivers.

Coastal and lake systems are increasingly influenced by human activities, with urbanization and eutrophication often the common theme in regions experiencing hypoxia, as highlighted above. The impact of hypoxia on pelagic and benthic communities is well-documented (Diaz and Rosenberg, 1995; Vaquer-Sunyer and Duarte, 2008), including a mass beaching event of invasive round gobies on the eastern shore of Green Bay in 2005 (Qualls et al., 2013). The combined impact of eutrophication and hypoxia also alters benthic communities, microbial processing of organic matter and relative complexity of buried material (Middelburg and Levin, 2009; Wrede et al., 2017). In Green Bay, sediment has shifted to a finer, fluidized mud that prevents mayflies from forming stable burrows (Groff and Kaster, 2017). The lack of mayfly presence in Green Bay for the past half century has very likely impacted bioirrigation of the sediments and sediment oxygen levels, which in turn impact microbial processing pathways (Banks et al., 2013; Michaud et al., 2005; Pastor et al., 2011). Even if nutrient loading is reduced, finer grained sediment is more easily resuspended, sequestration of organic matter in the sediments is altered and sediment oxygen exchange is altered, further impacting species richness and functioning (Cai and Sayles, 1996; Middelburg and Levin, 2009; Wrede et al., 2017). The coupling of eutrophication and hypoxia has been observed to lead to a new regime for system biogeochemistry, more tightly coupling aquatic primary productivity into a recycling regime due to the generally low transfer of bacterial carbon to upper trophic levels (Howarth et al., 2011; Orita et al., 2015; van Oevelen et al., 2006). While restoration efforts are typically focused on upper trophic levels, including the muskellunge fishery in the lower Fox River and Green Bay, failure to restore the original ecosystem structure and function at all trophic levels leads to the absence of keystone species and continued poor water quality (Lotze et al., 2006; Törnroos et al., 2015). Water column structure also influences the role of sediments in achieving a steady state between nutrient loading and system trophic state (Soetaert and Middelburg, 2009). Understanding the complex interactions between physical drivers, nutrient loading and ecosystem functioning, particularly as it relates to species richness, is critical for managing Green Bay water quality (Beauchard et al., 2017; Bremner, 2008). Thus, current management strategies in Green Bay may not be adequate for restoration of original system functioning – a key goal of the Remedial Action Plan put in place for the lower Fox River and southern Green Bay – and should consider the role of lower trophic levels and physical forcing of system biogeochemistry (Last, 2013).

The coupling of hypoxia, temperature and methane production is well-documented (Schulz et al., 1997; Yvon-Durocher et al., 2014; Zhang et al., 2010). The link between a changing climate, changing physical structure of lakes and coastal systems and concomitant changes in methane production, the proverbial positive feedbacks due to a warming climate (Walter et al., 2006), however, is a more recent observation (Wik et al., 2014). Bastviken et al. (2011) estimated that methane production in freshwater systems will increase under a warming climate. Our results suggest that for some systems, this increase could be much more marked than under a gradual increase in average temperature if the physical structure of the system is significantly changed due to a warming climate and changes in wind climatology, a result consistent with the findings of Wik et al. (2014). In Green Bay, even when the water column is not well stratified, bottom water oxygen concentrations are relatively low, at or below 50% saturation (Klump et al., 2018). Low oxygen conditions, even in the absence of hypoxia, alter species diversity, distribution and behavior and favor reducing pathways that fundamentally alter the biogeochemistry of coastal systems (Gray et al., 2002; Middelburg and Levin, 2009; Vaquer-Sunyer and Duarte, 2008). A shift to anaerobic pathways leads to increased methane production, a shift to opportunistic species (e.g. oligochaetes) and a reduction in re-oxidation pathways for reduced metabolites (Carter et al., 2006; Naqvi et al., 2010). Overall, energy transfer to higher trophic levels is disrupted with an apparent net effect of a tighter feedback between microbial degradation of organic matter and primary productivity creating a system for sustained eutrophication and hypoxia even in the absence of limited nutrient loading (Howarth et al., 2011; Orita et al., 2015). A shift to a microbial loop and trophic transfer through this element can also strongly shape food web structure and energy transfer efficiency (Christoffersen et al., 1990; Jansson et al., 2007). Our observations, although limited to two years, suggest the possibility of a warmer, thinner hypolimnetic layer in warmer years during stratified periods and a much warmer benthos in southern Green Bay during isothermal water column conditions. This, coupled with decreased oxygen saturation at warmer temperatures, suggests that hypoxia may be exacerbated and methane production will likely increase in a warmer climate.

Conclusions

We considered thermal structure in southern Green Bay between two significantly different years: 2012, which experienced abnormally warm spring and summer air temperatures, and 2013, which experienced cooler than average spring and average summer air temperatures. This difference in seasonal climate resulted in a peak water column heat content of over 150 $kJ \cdot m^{-2}$ more in 2012 approximately 3 weeks later in the summer season. Mean bottom water temperatures were significantly warmer in 2012 by 5.4 °C for the entire season, and 3.3 °C warmer during cold water intrusions. Intrusion duration was significantly shorter due to more frequent and intense northerly winds, despite a concomitant increase in mean southerly winds that were more closely aligned with the predominant axis of the bay. Cold water intrusions, a frequent feature in southern Green Bay waters, strongly influence the thermal regime of southern Green Bay and stratification; however, forecasting future biogeochemistry of the bay will depend on understanding how a warming climate impacts seasonal evolution of water column temperatures in all of Green Bay, as well as Lake Michigan proper. Cold bottom water displaced into southern Green Bay in 2012 was significantly warmer while intrusion duration was shorter due to northerly winds. Thus, understanding future climate impacts on thermal structure, hypoxia and methane production requires an understanding of the propagation of atmospheric warming into these waters, how the timing of this warming impacts seasonal progression of stratification and how wind climatology alters system biogeochemistry alongside a warmer climate.

Cold water intrusions have been observed in southern Green Bay for decades and are known to provide the physical set up for hypoxia and anoxia in the system (Klump et al., this issue). Here, we showed that climate and wind patterns significantly impact the presence and persistence of these features with profound impacts on biogeochemical processes in the benthos. The cold water intrusions are initiated by persistent southerly winds, typically over 4 $m \cdot s^{-1}$ for a 48 h period, while the intrusions are terminated when the winds switch to persistent northerly winds. While these features strongly drive stratification in southern Green Bay, our observations also suggest that relatively shallow (<20 m), seasonally stratified systems may not increase in stratification strength and duration under a warming climate. Rather, how multiple drivers of physical structure in these systems change with a warming climate should be considered. It is likely that the volume of the hypolimnion will decrease and temperature will increase during stratified periods in a warmer climate, creating more rapid onset of hypoxia and a greater magnitude of variability in oxygen conditions for the benthos. Understanding how changes in atmospheric temperatures and wind climatology impact the biogeochemistry and ecosystem functioning of coastal and lake systems impacted by eutrophication and hypoxia is crucial for creating effective restoration and management plans.

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References

Adrian, R., O'Reilly, C.M., Zagarese, H., Baines, S.B., Hessen, D.O., Keller, W., Livingstone, D.M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G.A., Winder, M., 2009. Lakes as sentinels of climate change. Limnol. Oceanogr. 54, 2283–2297.

Austin, J.A., Colman, S.M., 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: a positive ice-albedo feedback. Geophys. Res. Lett. 34.

Austin, J., Colman, S., 2008. A century of temperature variability in Lake Superior. Limnol. Oceanogr. 53, 2724–2730.

Banks, J.L., Ross, D.J., Keough, M.J., Macleod, C.K., Keane, J., Eyre, B.D., 2013. Influence of a burrowing, metal-tolerant polychaete on benthic metabolism, denitrification and nitrogen regeneration in contaminated estuarine sediments. Mar. Pollut. Bull. 68, 30–37.

Bastviken, D., Tranvik, L.J., Downing, J.A., Crill, P.M., Enrich-Prast, A., 2011. Freshwater methane emissions offset the continental carbon sink. Science 331, 50.

Beauchard, O., Veríssimo, H., Queirós, A.M., Herman, P.M.J., 2017. The use of multiple biological traits in marine community ecology and its potential in ecological indicator development. Ecol. Indic. 76, 81–96.

Beletsky, D., Schwab, D.J., 2001. Modeling circulation and thermal structure in Lake Michigan: annual cycle and interannual variability. J. Geophys. Res. Oceans 106, 19745–19771.

Benson, B.J., Lenters, J.D., Magnuson, J.J., Stubbs, M., Kratz, T.K., Dillon, P., Hecky, R.E., Lathrop, R.C., 2000. Regional coherence of climatic and lake thermal variables of four lake districts in the Upper Great Lakes region of North America. Freshw. Biol. 43, 517–527.

Biddanda, B.A., Weinke, A.D., Kendall, S.T., Gereaux, L.C., Holcomb, T.M., Snider, M.J., Dila, D.K., Long, S.A., VandenBerg, C., Knapp, K., Koopmans, D.J., Thompson, K., Vail, J.H., Ogdahl, M.E., Liu, Q., Johengen, T.H., Anderson, E.J., Ruberg, S.A., 2018. Chronicles of hypoxia: time-series buoy observations reveal annually recurring seasonal basin-wide hypoxia in Muskegon Lake – a Great Lakes estuary. J. Great Lakes Res. 44, 219–229.

Bremner, J., 2008. Species' traits and ecological functioning in marine conservation and management. J. Exp. Mar. Biol. Ecol. 366, 37–47.

Bridgham, S.D., Cadillo-Quiroz, H., Keller, J.K., Zhuang, Q., 2013. Methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. Glob. Chang. Biol. 19, 1325–1346.

Buchholz, L.A., Klump, J.V., Collins, M.L.P., Brantner, C.A., Remsen, C.C., 1995. Activity of methanotrophic bacteria in Green Bay sediments. FEMS Microbiol. Ecol. 16, 1–8.

Cahill, R.A., 1981. Geochemistry of recent Lake Michigan sediments. Illinois State Geol. Sur. Div. Circ. 517.

Cai, W.-J., Sayles, F.L., 1996. Oxygen penetration depths and fluxes in marine sediments. Mar. Chem. 52, 123–131.

Carter, G.S., Nalepa, T.F., Richard, R.R., 2006. Status and trends of benthic populations in a coastal drowned river mouth lake of Lake Michigan. J. Great Lakes Res. 32, 578–595.

Chowdhury, M.R., Wells, M.G., Howell, T., 2016. Movements of the thermocline lead to high variability in benthic mixing in the nearshore of a large lake. Water Resour. Res. 52, 3019–3039.

Christoffersen, K., Riemann, B., Hansen, L.R., Klysner, A., Sorensen, H.B., 1990. Qualitative importance of the microbial loop and plankton community structure in a eutrophic lake during a bloom of cyanobacteria. Microb. Ecol. 20, 253–272.

Cole, J.J., Prairie, Y.T., Caraco, N.F., McDowell, W.H., Tranvik, L.J., Striegl, R.G., Duarte, C.M., Kortelainen, P., Downing, J.A., Middelburg, J.J., Melack, J., 2007. Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. Ecosystems 10, 172–185.

Coman, M.A., Wells, M.G., 2012. Temperature variability in the nearshore benthic boundary layer of Lake Opeongo is due to wind-driven upwelling events. Can. J. Fish. Aquat. Sci. 69, 282–296.

Cossu, R., Ridgway, M.S., Li, J.Z., Chowdhury, M.R., Wells, M.G., 2017. Wash-zone dynamics of the thermocline in Lake Simcoe, Ontario. J. Great Lakes Res. 43, 689–699.

Cyr, H., 2012. Temperature variability in shallow littoral sediments of Lake Opeongo (Canada). Freshw. Sci. 31, 895–907.

Desai, A.R., Austin, J.A., Bennington, V., McKinley, G.A., 2009. Stronger winds over a large lake in response to weakening air-to-lake temperature gradient. Nat. Geosci. 2, 855–858.

Diaz, R., Rosenberg, R., 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioural response of benthic macrofauna. Oceanogr. Mar. Biol. 33, 245–303.

Free, M., Durre, I., Aguilar, E., Seidel, D., Peterson, T.C., Eskridge, R.E., Luers, J.K., Parker, D., Gordon, M., Lanzante, J., Klein, S., Christy, J., Schroeder, S., Soden, B., McMillin, L.M., Weatherhead, E., 2002. Creating climate reference datasets: CARDS workshop on adjusting radiosonde temperature data for climate monitoring. Am. Meteorol. Soc. 891–899.

Giling, D.P., Nejstgaard, J.C., Berger, S.A., Grossart, H.P., Kirillin, G., Penske, A., Lentz, M., Casper, P., Sareyka, J., Gessner, M.O., 2017. Thermocline deepening boosts ecosystem metabolism: evidence from a large-scale lake enclosure experiment simulating a summer storm. Glob. Chang. Biol. 23, 1448–1462.

Gottlieb, E.S., Saylor, J.H., Miller, G.S., 1990. Currents and Water Temperatures Observed in Green Bay, Lake Michigan.

Gray, J.S., Wu, R.S.-S., Or, Y.Y., 2002. Effects of hypoxia and organic enrichment on the coastal marine environment. Mar. Ecol. Prog. Ser. 238, 249–279.

Groff, C.M., Kaster, J.L., 2017. Survival, growth, and production of Hexagenia bilineata mayflies in fluidized sediment from lower Green Bay, Lake Michigan. J. Great Lakes Res. 43, 102–107.

Grunert, B.K., 2013. Evaluating the Summer Thermal Structure of Southern Green Bay, Lake Michigan. School of Freshwater Sciences. University of Wisconsin-Milwaukee, Milwaukee, WI.

Hamidi, S.A., Bravo, H.R., Val Klump, J., Waples, J.T., 2015. The role of circulation and heat fluxes in the formation of stratification leading to hypoxia in Green Bay, Lake Michigan. J. Great Lakes Res. 41, 1024–1036.

Hanrahan, J.L., Kravtsov, S.V., Roebber, P.J., 2010. Connecting past and present climate variability to the water levels of Lakes Michigan and Huron. Geophys. Res. Lett. 37 (n/a-n/a).

Heaps, N.S., Mortimer, C.H., Fee, E.J., 1982. Numerical models and observations of water motion in Green Bay, Lake Michigan. Phil. Trans. R. Soc. Lond. 306, 371–398.

Heiskanen, J.J., Mammarella, I., Ojala, A., Stepanenko, V., Erkkilä, K.-M., Miettinen, H., Sandström, H., Eugster, W., Leppäranta, M., Järvinen, H., Vesala, T., Nordbo, A., 2015. Effects of water clarity on lake stratification and lake-atmosphere heat exchange. J. Geophys. Res. Atmos. 120, 7412–7428.

Hlevca, B., Cooke, S.J., Midwood, J.D., Doka, S.E., Portiss, R., Wells, M.G., 2015. Characterisation of water temperature variability within a harbour connected to a large lake. J. Great Lakes Res. 41, 1010–1023.

Howarth, R., Chan, F., Conley, D.J., Garnier, J., Doney, S.C., Marino, R., Billen, G., 2011. Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. Front. Ecol. Environ. 9, 18–26.

Itoh, M., Kobayashi, Y., Chen, T.-Y., Tokida, T., Fukui, M., Kojima, H., Miki, T., Tayasu, I., Shiah, F.-K., Okuda, N., 2015. Effect of interannual variation in winter vertical mixing on CH_4 dynamics in a subtropical reservoir. J. Geophys. Res. Biogeosci. 120, 1246–1261.

Jansson, M., Persson, L., De Roos, A.M., Jones, R.I., Tranvik, L.J., 2007. Terrestrial carbon and intraspecific size-variation shape lake ecosystems. Trends Ecol. Evol. 22, 316–322.

Kennedy, J.A., 1982. Water-mass Structure and Exchanges in Green Bay, Lake Michigan. University of Wisconsin-Milwaukee, Milwaukee, WI.

Klump, J.V., Fitzgerald, S.A., Waples, J.T., 2009. Benthic biogeochemical cycling, nutrient stoichiometry, and carbon and nitrogen mass balances in a eutrophic freshwater bay. Limnol. Oceanogr. 54, 692–712.

Klump, J.V., Brunner, S.L., Grunert, B.K., Kaster, J.L., Weckerly, K.A., Houghton, E.W., Kennedy, J.A., Valenta, T., 2018. Evidence of persistent, recurring summertime hypoxia in Green Bay, Lake Michigan. J. Great Lakes Res.

Kravtsov, S., Sugiyama, N., Roebber, P., 2018. Role of nonlinear dynamics in accelerated warming of Great Lakes. In: Tsonis, A.A. (Ed.), Advances in Nonlinear Geosciences. Springer, pp. 279–295.

LaBuhn, S., Klump, J.V., 2016. Estimating summertime epilimnetic primary production via in situ monitoring in an eutrophic freshwater embayment, Green Bay, Lake Michigan. J. Great Lakes Res. 42, 1026–1035.

Last, L., 2013. Remedial Action Plan Update for the Lower Green Bay and Fox River Area of Concern. Wisconsin Department of Natural Resources.

Lathrop, R.C., Vande Castle, J.R., Lillesand, T.M., 1990. Monitoring river plume transport and mesoscale circulation in Green Bay, Lake Michigan, through satellite remote sensing. J. Great Lakes Res. 16, 471–484.

Lee, Y.J., Boynton, W.R., Li, M., Li, Y., 2013. Role of late winter–spring wind influencing summer hypoxia in Chesapeake Bay. Estuar. Coasts 36, 683–696.

Li, M., Lee, Y.J., Testa, J.M., Li, Y., Ni, W., Kemp, W.M., Di Toro, D.M., 2016. What drives interannual variability of hypoxia in Chesapeake Bay: climate forcing versus nutrient loading? Geophys. Res. Lett. 43, 2127–2134.

Liu, W., Bocaniov, S.A., Lamb, K.G., Smith, R.E.H., 2014. Three dimensional modeling of the effects of changes in meteorological forcing on the thermal structure of Lake Erie. J. Great Lakes Res. 40, 827–840.

Lotze, H.K., Lenihan, H.S., Bourque, B.J., Bradbury, R.H., Cooke, R.G., Kay, M.C., Kidwell, S.M., Kirby, M.X., Peterson, C.H., Jackson, J.B.C., 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312, 1806–1809.

Michaud, E., Desrosiers, G., Mermillod-Blondin, F., Sundby, B., Stora, G., 2005. The functional group approach to bioturbation: the effects of biodiffusers and gallery-diffusers of the *Macoma balthica* community on sediment oxygen uptake. J. Exp. Mar. Biol. Ecol. 326, 77–88.

Middelburg, J.J., Levin, L.A., 2009. Coastal hypoxia and sediment biogeochemistry. Biogeosciences 6, 1273–1293.

Miller, G.S., Saylor, J.H., 1985. Currents and temperatures in Green Bay, Lake Michigan. J. Great Lakes Res. 11, 97–109.

Miller, G.S., Saylor, J.H., 1993. Low-frequency water volume transport through the midsection of Green Bay, Lake Michigan, calculated from current and temperature observations. J. Great Lakes Res. 19, 361–367.

Mortimer, C.H., 2004. Lake Michigan in Motion. University of Wisconsin Press, Madison, WI.

Mortsch, L.D., Quinn, F.H., 1996. Climate change scenarios for Great Lakes basin ecosystem studies. Limnol. Oceanogr. 41, 903–911.

Naqvi, S.W.A., Bange, H.W., Farías, L., Monteiro, P.M.S., Scranton, M.I., Zhang, J., 2010. Marine hypoxia/anoxia as a source of CH_4 and N_2O. Biogeosciences 7, 2159–2190.

NCEI/NESDIS/NOAA Climatological Rankings, 2017. https://www.ncdc.noaa.gov/cag/national/rankings/110/tavg/201806.

van Oevelen, D., Middelburg, J.J., Soetaert, K., Moodley, L., 2006. The fate of bacterial carbon in an intertidal sediment: modeling an in situ isotope tracer experiment. Limnol. Oceanogr. 51, 1302–1314.

Orita, R., Umehara, A., Komorita, T., Choi, J.-W., Montani, S., Komatsu, T., Tsutsumi, H., 2015. Contribution of the development of the stratification of water to the expansion of dead zone: a sedimentological approach. Estuar. Coast. Shelf Sci. 164, 204–213.

Palmer, M.E., Yan, N.D., Somers, K.M., 2014. Climate change drives coherent trends in physics and oxygen content in North American lakes. Clim. Chang. 124, 285–299.

Pastor, L., Deflandre, B., Viollier, E., Cathalot, C., Metzger, E., Rabouille, C., Escoubeyrou, K., Lloret, E., Pruski, A.M., Vétion, G., Desmalades, M., Buscail, R., Grémare, A., 2011. Influence of the organic matter composition on benthic oxygen demand in the Rhône River prodelta (NW Mediterranean Sea). Cont. Shelf Res. 31, 1008–1019.

Piccolroaz, S., Toffolon, M., Majone, B., 2013. A simple lumped model to convert air temperature into surface water temperature in lakes. Hydrol. Earth Syst. Sci. 17, 3323–3338.

Pokrovsky, O.S., Shirokova, L.S., Kirpotin, S.N., Kulizhsky, S.P., Vorobiev, S.N., 2013. Impact of western Siberia heat wave 2012 on greenhouse gases and trace metal concentration in thaw lakes of discontinuous permafrost zone. Biogeosciences 10, 5349–5365.

Qualls, T.M., Harris, H.J., Harris, V., 2013. The State of the Bay: The Condition of the Bay of Green Bay, Lake Michigan.

Rao, Y.R., Schwab, D.J., 2007. Transport and mixing between the coastal and offshore waters in the Great Lakes: a review. J. Great Lakes Res. 33, 202–218.

Rao, D.B., Mortimer, C.H., Schwab, D.J., 1976. Surface normal modes of Lake Michigan: calculations compared with spectra of observed water level fluctuations. J. Phys. Oceanogr. 6, 575–588.

Read, J.S., Winslow, L.A., Hansen, G.J.A., Van Den Hoek, J., Hanson, P.C., Bruce, L.C., Markfort, C.D., 2014. Simulating 2368 temperate lakes reveals weak coherence in stratification phenology. Ecol. Model. 291, 142–150.

Saylor, J.H., Miller, G.S., Gottlieb, E.S., 1995. Near-resonant Wind Forcing of Internal Seiches in Green Bay.

Schulz, S., Matsuyama, H., Conrad, R., 1997. Temperature dependence of methane production from different precursors in a profundal sediment (Lake Constance). FEMS Microbiol. Ecol. 22, 207–213.

Scully, M.E., 2010. Wind modulation of dissolved oxygen in Chesapeake Bay. Estuar. Coasts 33, 1164–1175.

Scully, M.E., 2013. Physical controls on hypoxia in Chesapeake Bay: a numerical modeling study. J. Geophys. Res. Oceans 118, 1239–1256.

Soetaert, K., Middelburg, J.J., 2009. Modeling eutrophication and oligotrophication of shallow-water marine systems: the importance of sediments under stratified and well-mixed conditions. Hydrobiologia 629, 239–254.

Stainsby, E.A., Winter, J.G., Jarjanazi, H., Paterson, A.M., Evans, D.O., Young, J.D., 2011. Changes in the thermal stability of Lake Simcoe from 1980 to 2008. J. Great Lakes Res. 37, 55–62.

Thyng, K.M., Greene, C.A., Hetland, R.D., Zimmerle, H.M., DiMarco, S.F., 2016. True colors of oceanography: guidelines for effective and accurate colormap selection. Oceanography 29, 9–13.

Toffolon, M., Piccolroaz, S., Majone, B., Soja, A.-M., Peeters, F., Schmid, M., Wüest, A., 2014. Prediction of surface temperature in lakes with different morphology using air temperature. Limnol. Oceanogr. 59, 2185–2202.

Törnroos, A., Bonsdorff, E., Bremner, J., Blomqvist, M., Josefson, A.B., Garcia, C., Warzocha, J., 2015. Marine benthic ecological functioning over decreasing taxonomic richness. J. Sea Res. 98, 49–56.

Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P., Finlay, K., Fortino, K., Knoll, L.B., Kortelainen, P.L., Kutser, T., Larsen, S., Laurion, I., Leech, D.M., McCallister, S.L., McKnight, D.M., Melack, J.M., Overholt, E., Porter, J.A., Prairie, Y., Renwick, W.H., Roland, F., Sherman, B.S., Schindler, D.W., Sobek, S., Tremblay, A., Vanni, M.J., Verschoor, A.M., von Wachenfeldt, E., Weyhenmeyer, G.A., 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnol. Oceanogr. 54, 2298–2314.

Trumpickas, J., Shuter, B.J., Minns, C.K., Cyr, H., 2015. Characterizing patterns of nearshore water temperature variation in the North American Great Lakes and assessing sensitivities to climate change. J. Great Lakes Res. 41, 53–64.

Valenta, T., 2013. Oxygen Depletion in Green Bay. University of Wisconsin-Green Bay, Green Bay, WI.

Vaquer-Sunyer, R., Duarte, C.M., 2008. Thresholds of hypoxia for marine biodiversity. Proc. Natl. Acad. Sci. 105, 15452–15457.

Walter, K.M., Zimov, S.A., Chanton, J.P., Verbyla, D., Chapin 3rd, F.S., 2006. Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature 443, 71–75.

Waples, J.T., 1998. Air-water Gas Exchange and the Carbon Cycle of Green Bay, Lake Michigan. University of Wisconsin-Milwaukee.

Waples, J.T., Klump, J.V., 2002. Biophysical effects of a decadal shift in summer wind direction over the Laurentian Great Lakes. Geophys. Res. Lett. 29 (43-41-43-44).

Wells, M., Parker, S., 2010. The thermal variability of the waters of Fathom Five National Marine Park, Lake Huron. J. Great Lakes Res. 36, 570–576.

WICCI, 2011. Potential climate change impacts on the bay of Green Bay - An assessment report. https://www.wicci.wisc.edu/report/Green-Bay.pdf.

Wik, M., Thornton, B.F., Bastviken, D., MacIntyre, S., Varner, R.K., Crill, P.M., 2014. Energy input is primary controller of methane bubbling in subarctic lakes. Geophys. Res. Lett. 41, 555–560.

Wilhelm, S., Adrian, R., 2008. Impact of summer warming on the thermal characteristics of a polymictic lake and consequences for oxygen, nutrients and phytoplankton. Freshw. Biol. 53, 226–237.

Wrede, A., Dannheim, J., Gutow, L., Brey, T., 2017. Who really matters: influence of German Bight key bioturbators on biogeochemical cycling and sediment turnover. J. Exp. Mar. Biol. Ecol. 488, 92–101.
Yvon-Durocher, G., Allen, A.P., Bastviken, D., Conrad, R., Gudasz, C., St-Pierre, A., Thanh-Duc, N., del Giorgio, P.A., 2014. Methane fluxes show consistent temperature dependence across microbial to ecosystem scales. Nature 507, 488–491.
Zhang, J., Gilbert, D., Gooday, A.J., Levin, L., Naqvi, S.W.A., Middelburg, J.J., Scranton, M., Ekau, W., Peña, A., Dewitte, B., Oguz, T., Monteiro, P.M.S., Urban, E., Rabalais, N.N., Ittekkot, V., Kemp, W.M., Ulloa, O., Elmgren, R., Escobar-Briones, E., Van der Plas, A.K., 2010. Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. Biogeosciences 7, 1443–1467.
Zhong, Y., Notaro, M., Vavrus, S.J., Foster, M.J., 2016. Recent accelerated warming of the Laurentian Great Lakes: physical drivers. Limnol. Oceanogr. 61, 1762–1786.