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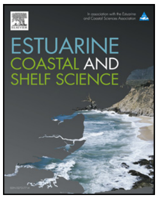

Modeling reveals the role of coastal upwelling and hydrologic inputs on biologically distinct water exchanges in a Great Lakes estuary

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ABSTRACT

Freshwater estuaries everywhere are under stress from anthropogenic activities and climate change. Muskegon Lake Estuary (MLE) is a freshwater estuary along the eastern shore of Lake Michigan characterized by algal blooms and hypoxia during the summer and designated as an Area of Concern (AOC) by the EPA. We developed a 3-D hydrodynamic model using the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) to study the hydrodynamics of MLE with a focus on the cold-water intrusions from Lake Michigan into MLE. Substantial water exchange process was validated by comparisons with observations in the near-shore region of Lake Michigan and in the navigation channel between Lake Michigan and MLE. The model found that the cold-water intrusions from Lake Michigan to MLE occur during summer stratification, amounting to as much as 10% of MLE's total volume during one single episodic event. The intrusion was accompanied by a stronger surface outflow in the opposite direction, which may accelerate the delivery of MLE water to Lake Michigan. Through process-oriented model experiments, we examined the cold-water intrusion's responses to hydrological shift under climate change, and found that the increase in riverine input during upwelling weakens the intrusion. In addition, an increase of navigation channel width strengthens the cold-water intrusion, and that intrusion strength as well as intrusion period was directly related to wind speed. Our observation-modeling based findings would provide a good reference for the future study of biophysical interactions between coastal ocean and estuaries.

1. Introduction

Estuaries are an ecologically active interface between riverine systems and coastal waters, which provide unique habitats for many varieties of plants and animals, are highly productive systems, and undergo several complex biological and physical processes. Similar to brackish estuarine systems, freshwater estuaries involve mixing of chemically and biologically distinct waters, as they receive hydrologic inputs with carbon and nutrients from terrestrial sources and heavily urbanized population centers, and as a result can have large spatial variability in dissolved oxygen, conductivity, and turbidity (Fisher et al., 2015). Such land-water interface ecosystems are greatly affected by anthropogenic activities and climate change (Borja et al., 2010).

Though extremely large, the Laurentian Great Lakes, are quite vulnerable to anthropogenic stressors and climate driven changes in physical or biogeochemical conditions such as thermal stratification, precipitation and runoff, and timing of the hydrometeorological cycle (Allan et al., 2012; Larson et al., 2013; Cotner et al., 2017). In addition, lakes are highly reactive sites for carbon metabolism and play a critically important role in the global carbon cycle because of the enhanced rates of carbon respiration and burial within them (Cole et al., 2007; Tranvik et al., 2009; Biddanda, 2017). As climate projections reveal intensification of extreme precipitation events over the next century (Donat et al., 2016; Wang et al., 2017), and subsequent shifts in riverine inputs to estuarine systems, an important concern arises regarding the impact of these changes on estuarine function – such as rising coastal eutrophication worldwide (Sinha et al., 2017).

Extensive studies have focused on the mechanisms that control estuarine dynamics, including the exchange flow in different brackish estuarine systems (Chen et al., 2012), the generation of estuarine front (Geyer and Ralston, 2015; Liu et al., 2016a; b), turbulent mixing in estuaries and the resulting variations in water exchange (Simpson et al.,

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1990; Rong and Li, 2012; Liu et al., 2017), and biologically distinct water exchange during coastal upwelling (Roegner et al., 2011). Roegner et al. (2011) found that the coastal upwelling supplies oxygen-depleted water to the Columbia River estuary and therefore deteriorates the estuarine habitats. Similarly, upwelling along the central California coast supports Harmful Algal Blooms (HABs) in some open embayments by delivering nutrients from the bottom of the coastal ocean to the embayments but sustaining its stratification (Pitcher et al., 2010). Along the California coast, in 2007, an inshore anoxia over a 5 km stretch of coastline at Erendira is believed to be caused by a strong upwelling region off Baja California, killed many animals, including tons of lobsters (Levin et al., 2009). Intrusions of saline hypoxic water to estuaries are commonly found, for example, from the ocean to Puget Bay (Deppe et al., 2017), from Gulf of Mexico to its embayments (Rabalais et al., 2002), and from Chesapeake Bay to the lower reaches of the Choptank River (Breitburg, 1992, 2002; Sanford et al., 1990). Similar intrusions of cold, dense oxygenated waters have also been found to occur in the freshwater estuaries of the Great Lakes; e.g., Lake Michigan water into Green Bay (Grunert, 2013) and Lake Ontario water into Hamilton Harbor (Lawrence et al., 2004), and the Muskegon Lake Estuary (MLE; Biddanda et al., 2018), the investigation area in this study.

In the Great Lakes, where tides are weak, winds become the dominant mechanism for water exchange between the Great Lakes and freshwater estuaries. However, there is little information on the drivers of exchange in a freshwater estuary and in particular, how the mechanisms that control important ecological variables such as dissolved oxygen are impacted by shifts in precipitation or meteorology due to a changing climate. To investigate the dominant mechanisms behind freshwater estuary exchange and the sensitivity of spatiotemporal variability of dissolved oxygen to these controls, this study focuses on the MLE, one of the several drowned river-mouth estuaries along the eastern coastline of Lake Michigan (Larson et al., 2013).

2. Study area

The MLE is a mesotrophic drowned river mouth along the eastern shore of Lake Michigan (Fig. S1 in Supplementary Material), with a surface area of 17 km^2, a water volume of 119 million m^3, a mean water depth of 7 m, a maximum depth of 21 m (Fig. 1; Steinman et al., 2008; Marko et al., 2013) and an average hydraulic residence time of 23 days. The estuary drains the second largest watershed in Michigan (approximately 7302 km^2) including 53.2% forested, 23.0% agricultural, and 4.2% urban lands (Marko et al., 2013), and connects to an oligotrophic Lake Michigan through a 1 km long and 100 m wide navigation channel.

Historical observations show that the MLE is under the effects of anthropogenic activities and climate change (Steinman et al., 2008). The proportion of urbanized land within the Muskegon River watershed is projected to increase by 11.5% by the year 2040 (Tang et al., 2005), which changes the nature and quantity of nutrients, major ions, and dissolved organic carbon (DOC) inputs to the estuary. The US Geological Survey (USGS; http://waterdata.usgs.gov/nwis) has recorded stream flows within the watershed since the early 20th century. Over most of that period, gauged flow of the Muskegon River from USGS, which is the primary input to the estuary, shows an increase of 34% in mean flow, 16% in low flow, and 10% in peak flow since monitoring began in 1935. Wiley et al. (2010) showed an increase in the base flow, storm flow, and median discharge by 15–20% in BAU (end of century with business as usual land management) scenario under the current climate regime.

The MLE was listed as an EPA AOC in 1985 due to historical contamination and habitat degradation. Recent observations in the MLE and previous annual samplings have revealed an annually recurring lake-wide hypoxia (Biddanda, 2012; Biddanda et al., 2018), and the potential for hypolimnetic habitat degradation and increased eutrophication due to sediment phosphorus release (Steinman et al., 2008; Weinke and Biddanda, 2018).

Preliminary results from observations suggest that hypoxia in the estuary is mitigated by episodic cold-water intrusion from Lake Michigan during coastal upwelling events under certain wind conditions (Biddanda et al., 2018). Water temperature and dissolved oxygen throughout the water column were measured by the Muskegon Lake Observatory (MLO; Fig. 1a) each year from April/May to November/December since 2011 (Biddanda, 2012; Biddanda et al., 2018; www.gvsu.edu/buoy). Physically, MLO observations revealed that the cold-water intrusion strengthens MLE's stratification in the middle of July, August, and early September as shown in Fig. S3a. Ecologically, the dissolved oxygen saturation (Fig. S3b) showed that the hypoxia is mitigated by the cold-water intrusion with increased dissolved oxygen concentrations during the intrusion.

The cold-water intrusion's influence on the ecosystem is more complex than what is revealed from a single station due to the spatial variations in nutrients and seston from the Muskegon River to Lake Michigan. Observations at five fixed stations in MLE and the near shore zone of Lake Michigan from March to October 2003 exhibited explicit spatial variations in nutrient concentrations and seston stoichiometry from the Muskegon River to Lake Michigan (Marko et al., 2013). Much of the terrestrial material from the Muskegon River was intercepted and processed by MLE before flowing into Lake Michigan. Therefore, generally, levels of organic matter (including dissolved organic carbon and particulate organic carbon), total suspended matter, and total phosphorus contained in the fine-grain sediment is consistently lower in Lake Michigan than those observed in MLE (Marko et al., 2013). Stratification combined with the high amount of organic matter in MLE leads to episodic hypoxia in the estuary (Biddanda et al., 2018), while such an event is infrequent in Lake Michigan. As another major spatial difference, because Lake Michigan has phosphorus limitation to phytoplankton growth (Hecky et al., 1993), the mean C:P ratio was much higher in Lake Michigan than MLE due to the lower phosphorus concentrations in Lake Michigan. Thus, water exchange between the Great Lakes and freshwater estuaries is closely associated with nutrients/organic matter redistribution.

In light of the significance of cold-water intrusions to water exchange between the Great Lakes and freshwater estuaries, modeling of cold-water intrusions and its response to different factors is valuable for the understanding of estuarine ecosystems. In this work, we investigate the processes that govern exchange in a freshwater estuary. Through the combination of a long record of observations in the MLE and the development of a hydrodynamic model, we explore the dynamics behind dense water intrusion to freshwater estuaries during coastal upwelling, as well as the intrusion's response to shifts in hydrologic inputs that would result under changing precipitation patterns as a result of climate change. Finally, we test the sensitivity of the dense water intrusion to anthropogenic activities such as alterations to the navigation channel that connects the estuary to the coastal waters.

3. Methods

3.1. Model description

To understand the physical processes that govern exchange in the MLE, a three-dimensional hydrodynamic model has been developed for MLE, which extends from the mouth of the Muskegon River to the offshore of Lake Michigan (Fig. 1). The model is based on the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM; Zhang et al., 2011, 2015, 2016), an open-source community-supported modeling system based on unstructured grids, derived from the early SELFE model (Zhang and Baptista, 2008). It employs a highly efficient and accurate semi-implicit finite-element/finite-volume method with Eulerian-Lagrangian algorithm to solve the Navier-Stokes equations, and has been widely applied to bays and estuaries around the world