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Simulating the effect of nutrient reduction on hypoxia in a large lake (Lake Erie, USA-Canada) with a three-dimensional lake model

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ABSTRACT

Hypoxia, or low dissolved oxygen (DO) concentrations, in lakes is commonly linked to eutrophication caused by excessive nutrient loadings. While nutrient-driven eutrophication creates a potential for hypoxia, the full realization of this potential, as well as its location, ultimate size, and duration, is to a large degree dependent on the lake's physics. Herein, we employed a three-dimensional coupled hydrodynamic and ecological model of Lake Erie to explore the potential for spatial and temporal developments of hypoxia and its response to nutrient load reductions. Reducing loads by 40 to 50% relative to the 2008 load will result in significant reductions (~50%) of hypoxia in terms of its maximum and mean areal extents and duration, as well as providing significant improvements in mean hypolimnetic DO. We also explored the impact of different DO threshold concentrations to characterize hypoxia, and found that responses at lower thresholds are most sensitive to variation in nutrient loads.

Introduction

Productive and thermally/chemically stratified lakes, estuaries and coastal systems are susceptible to developing hypoxic conditions (low dissolved oxygen concentrations) and sometimes reaching their more severe conditions, anoxia (absence or very low dissolved oxygen), with implications at both global and local levels. Under very low oxygen conditions, aquatic respiration becomes successively based on nitrate, manganese, iron (hydr)oxides and sulfate, thus altering key biogeochemical cycles (Pena et al., 2010). Moreover, anoxic conditions contribute to formation of methane (CH_4), a strong green-house gas, rather than carbon dioxide (CO_2), a weaker green-house gas produced when more oxygen is present (Bastviken et al., 2004). The areal flux of CH_4 can be a significant source in large and shallow systems like Lake Erie (Bastviken et al., 2004). Elevated concentrations of manganese mobilized from anoxic sediments also require additional drinking water treatment for its removal (Sly et al., 1990). However, one of the most significant local effects manifests through altering survival, behavioral, physiological, growth, and reproductive responses of aquatic biota including shellfish, benthic invertebrates and fishes (Carlson et al., 1980; Roberts et al., 2009; Vanderploeg et al., 2009; Arend et al., 2011; Roberts et al., 2011).

Lake Erie has a long history of eutrophication linked to excessive nutrient loads, with especially high loads occurring in the 1960s through 1980s (Electronic Supplementary material (ESM) Fig. S1). In response, the 1978 Great Lakes Water Quality Agreement (GLWQA) between United States and Canada established target loads for phosphorus (P) for each of the Great Lakes (IJC, 1978). The target load for Lake Erie total phosphorus (TP) was 11,000 MTA (metric tons per annum) that, at that time, was thought to be sufficient to improve areas of low dissolved oxygen (DO) and reduce or eliminate harmful algal blooms. As a result, annual TP loads were reduced from nearly 30,000 MTA in the late 1970s to about 11,000 MTA, with an average load over the past 20 years of about 9,000 MTA (ESM Fig. S1). However, despite the significant reduction in nutrient loads since the mid-1990s, Lake Erie began to experience a resurgence of large hypoxic zones (Hawley et al., 2006; Zhou et al., 2013, 2015; Scavia et al., 2014; Bocaniov and Scavia, 2016), including a recent record-breaking hypoxic extent in 2012 (Zhou et al., 2015). In response, the 2012 GLWQA agreement (IJC, 2012) called for a review and, if necessary, revision of the 1978 targets.

Previous efforts to simulate bottom water dissolved oxygen concentrations in Lake Erie included a wide range of models; from simplified box-reactor-type models (e.g. Di Toro et al., 1987; Lam et al., 1987, 2008) to more complex and spatially resolved 1-dimensional (1D) and 2D models (e.g. Rucinski et al., 2014; Boegman, 2006; Zhang et al., in this issue). While these efforts improved our understanding and

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predictability of hypoxia, their simplified representations of physical processes, bathymetry and atmospheric forcing limited their ability to explore the complex lake thermodynamic and hydrodynamic processes and patterns, including the effects of density currents, Coriolis force, and enhanced mixing due to actions of internal waves and boundary mixing.

The earlier models were thus not designed to simulate spatial development and location of hypoxia. Yet, observations of Lake Erie's hypoxic conditions (e.g. Kraus et al., 2015) suggest a highly dynamic hypoxic zone that can be patchy and driven by dynamic physical processes such as general lake circulation (Beletsky et al., 2012), near-inertial internal waves (Bouffard et al., 2012), and extreme events such as upwelling-induced mixing (e.g. Rao et al., 2014; Bocaniov et al., 2014b). Resolving these processes requires a model capable of representing in-lake physical processes, basin topography and, heterogeneous atmospheric conditions. Thus, the major objective of this study was to employ a coupled hydrodynamic-ecological 3D model to develop a relationship between external phosphorus loads and the spatial and temporal dynamics of hypoxia in Lake Erie.

Methods and materials

Study site

Lake Erie is a very large, shallow lake (mean depth = 18.9 m) with a surface area of 25,657 km^2 and a volume of 484 km^3 (Bolsenga and Herdendorf, 1993) located in the temperate zone of North America between latitudes [41–43°N] and longitudes [79–83.5°W]. The lake has three distinct basins (Fig. 1). Its central basin is the largest with a volume of 305 km^3 and an area of 16,138 km^2 (Bolsenga and Herdendorf, 1993), stretching 213 km in length and 92 km in width, with a very flat bottom and mean and maximum depths of 18.5 and 25.6 m, respectively. The water retention capacity of the central basin is 1.74 years, compared with 2.76 years for the entire lake (Bolsenga and Herdendorf, 1993). The central basin experiences extensive, seasonally re-occurring hypoxia (Zhou et al., 2013, 2015), particularly during the period of late September through early October when it is interrupted by autumnal lake overturn as a result of the combined effects of the weakened water column stability due to lower surface water temperatures and increased intensity of mixing due to autumnal storms. For our purposes, we set the western boundary of the central basin as a straight line from Pelee Point to the edge of Sandusky Bay and the eastern boundary as a line along the natural ridge separating east and central basins, called Long Point Lake Erie Ridge (Fig. 1).

Hydrodynamic and ecological model

The model we used is the 3D coupled hydrodynamic and ecological model ELCOM-CAEDYM. The hydrodynamic Estuary and Lake COmputer Model (ELCOM; Hodges et al., 2000; Hodges and Dallimore, 2006) is designed for numerical simulation of hydrodynamics/thermodynamics of stratified inland and coastal waters. It accounts for baroclinic effects, earth's rotation (Coriolis force), meteorological forcing, inflows and outflows. It is dynamically coupled with the Computational Aquatic Ecosystem DYnamics Model (CAEDYM; Hipsey, 2008) to simulate water and sediment chemical and biological processes. ELCOM provides CAEDYM with temperature, solar radiation, mixing, advection, and diffusion, while CAEDYM provides ELCOM with variations in light attenuation due to concentrations of dissolved and particulate organic matter, phytoplankton, and suspended solids. ELCOM-CAEDYM (ELCD) has been applied to Lake Erie to investigate nutrient and phytoplankton dynamics (e.g. Leon et al., 2011), ice extent and thickness and their effects on spring phytoplankton and DO concentrations (Oveisy et al., 2014), the effects of atmospheric forcing on thermal structure (Liu et al., 2014), the impacts of mussel grazing on phytoplankton biomass (Bocaniov et al., 2014a), and hypoxic extent as a function of bottom water DO concentration (Bocaniov and Scavia, 2016).

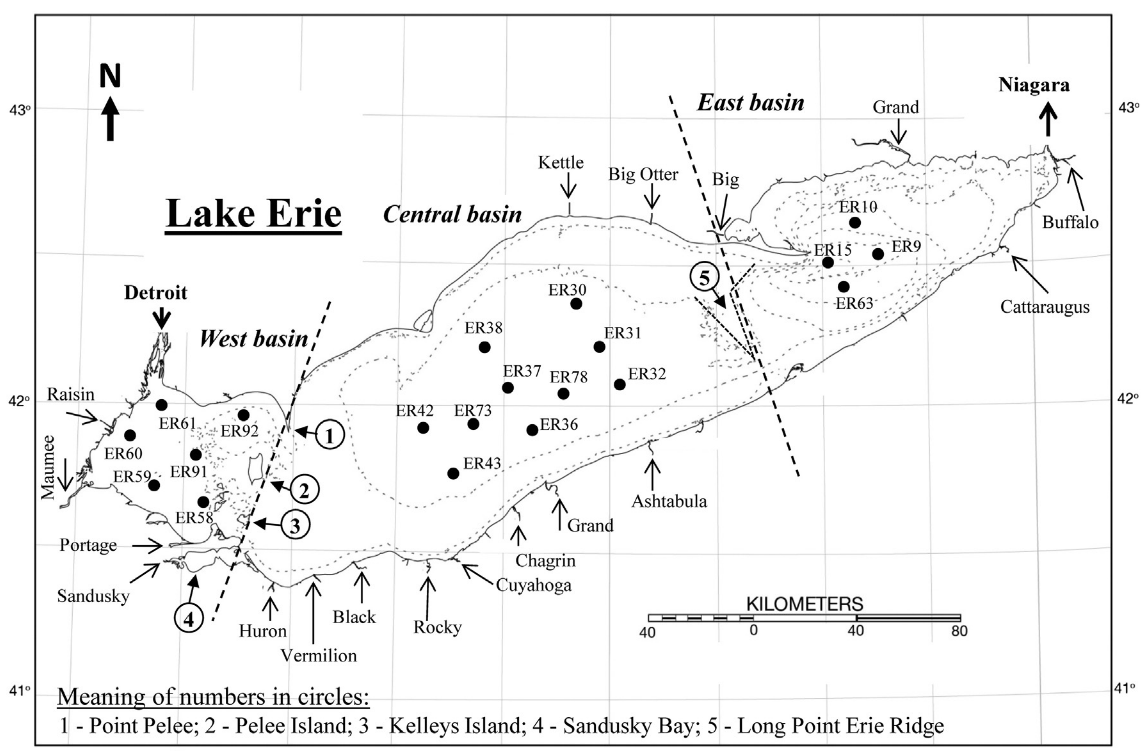

Fig. 1. Map of Lake Erie showing the central basin boundaries, included outflow and inflows (indicated by arrows), and the locations of the United States EPA stations (black solid circles). Dotted lines represent 10-m contours.

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