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Three dimensional modeling of the effects of changes in meteorological forcing on the thermal structure of Lake Erie

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ABSTRACT

A three dimensional hydrodynamic model, the Estuary and Lake Computer Model (ELCOM), validated by field data collected in 2008, is used to investigate the thermal structure response in Lake Erie to changes in air temperature and wind speed. We define spatially and temporally varying regions for the epilimnion, thermocline, and hypolimnion. Increasing the air temperature warms up the epilimnion but has little effect on the hypolimnion. The stratification forms earlier and breaks down later. The thermocline is raised modestly in the warmer air temperature scenario. Stronger winds cool the epilimnion slightly, but warm up the hypolimnion with much larger temperature changes. The stratification duration is shortened, and the thermocline depth is noticeably deepened. Due to the large differences in depths and layer thicknesses of the three basins, the responses to changes in meteorological forcing vary among the basin. Exploiting the power of the three dimensional model to provide a more authentic characterization of thermal stratification in large lakes, it is shown that patterns inferred from simple isotherm dynamics when studying the stratification period as typically done with one dimensional models are not always accurate. The present results for Lake Erie show the potential for complicated and interactive effects of climate forcing on important biogeochemical processes, especially hypolimnetic oxygen depletion.

Introduction

The mean global surface air temperature has increased by about 0.5–0.9 °C during the 20th century, and the change is likely to exceed 1.5 °C by the end of the 21st century relative to the 1850 to 1900 period for most scenarios (Intergovernmental Panel on Climate Change, 2013). Climate warming is anticipated to have great influence on the Laurentian Great Lakes ecosystem (Lam and Schertzer, 1999), including hydrology (Mortsch et al., 2000), plankton (Lehman, 2002), and fisheries (Lynch et al., 2010). Recently Trolle et al. (2011) applied a one dimensional ecosystem model to three morphologically different lakes, and suggested that a warmer climate can produce effects similar to increased nutrient loading. By contrast Rucinski et al. (2010) used a coupled one dimensional temperature-dissolved oxygen model to argue that changes in the production of organic matter, rather than climate variability, is the dominant factor in dissolved oxygen changes in the central basin of Lake Erie. With the complexities inherent in modeling and predicting ecological effects, it is important that we start with an accurate account of the most direct influence of climate variations, notably changes in thermal structure.

The thermal structure includes two fundamental variables, water temperature and the depth of the seasonal thermocline. Temperature determines the solubility of many substances, influences organism distributions based on thermal habitat preferences (Lynch et al., 2010), and affects the rate of chemical reactions and biological processes such as photosynthesis and respiration (Falkowski and Raven, 2007). The epilimnion depth influences sedimentation losses (Diehl et al., 2002), phytoplankton biomass concentration (Kunz and Diehl, 2003), and availability of light and nutrients in the surface mixed layer (Kunz and Diehl, 2003) while also playing an important role in the severity of hypolimnetic hypoxia (Lam and Schertzer, 1987). The epilimnion depth also affects the production to respiration balance of plankton communities (Bocaniov and Smith, 2009) and thus the potential for export of organic matter to support other trophic levels or hypolimnetic consumption. Hydrodynamic processes and upwelling events can also be important influences on plankton production and respiration (Bocaniov et al., 2012).

Mortsch and Quinn (1996) developed a series of climate change scenarios for the Great Lakes Basin using general circulation models (GCMs), and stated that the direct effects of climate change would occur through higher air and water temperatures. Hayhoe et al.

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(2010) applied a statistical downscaling method to an Atmosphere–Ocean General Circulation Model (AOGCM) and projected an estimate of air temperature change across the US Great Lakes Region for the 21st century. Robertson and Ragotzkie (1990) applied the one dimensional hydrodynamical model Dynamic Reservoir Simulation Model (DYRESM) and a statistical regression approach to investigate the response of the thermal structure to changes in air temperature in Lake Mendota, Wisconsin. More recently Austin and Allen (2011) studied the sensitivity of the summer thermal structure in the western end of Lake Superior to meteorological forcing using the Regional Ocean Modeling System (ROMS) model run in a one dimensional mode, and Rao et al. (2012) conducted sensitivity experiments to investigate the effect of climate changes on the thermal structure of Great Bear Lake using the Princeton Ocean Model (POM). Using a 40-year record of water temperature and meteorological data Huang et al. (2012) investigated the recent climatic trends and discussed the thermal response in Lake Ontario. Previous work leaves room for uncertainty about how the physical effects of climate change will be manifested in large lakes, and what they will mean for the ecology. From Austin and Allen (2011) and Huang et al. (2012) we expect that higher air temperatures will make the epilimnion shallower and increase its temperature, while higher winds will tend to have the opposite effect. However, three dimensional processes such as upwelling, inter-basin advection, and near-shore–offshore exchange may be expected to influence the predicted sensitivity of the thermal structure to atmospheric forcing. Lake or basin depths will also affect the situation by changing the rate of equilibration between lake and atmosphere (Austin and Allen, 2011).

Hydrodynamical modeling of the Great Lakes has been ongoing since the 1960s using many numerical tools. The first three dimensional hydrodynamic model for the Great Lakes used finite difference methods and was based on the hydrostatic and Boussinesq approximations (Simons, 1974). Schwab and Bedford (1994) developed an experimental Great Lakes forecasting system using the POM. An unstructured grid, finite-volume, sigma-coordinate terrain following ocean model (FVCOM) was applied to Lake Ontario by Shore (2009) and Wilson et al. (2013). The Estuary and Lake Computer Model (ELCOM) has been successfully applied to several large lakes including Lake Erie (Leon et al., 2005) and Lake Ontario (Huang et al., 2010).

Here we use ELCOM to explore the sensitivity of the thermal structure in Lake Erie to changes in air temperature and wind. The Methods section briefly describes the field observations, model setup, and the quantitative definitions of epilimnion, thermocline, and hypolimnion. In the Results section the model is validated using the 2008 field data, and the results from the sensitivity tests of the thermal structure are presented in detail. The Discussion section compares some of our results with previous studies and discusses the benefits of three dimensional modeling compared with the one dimensional approach.

Methods

Field observations

Lake Erie has three major physiographic divisions: the western, central, and eastern basins. The western basin is the shallowest, with average and maximum depths of 7.4 m and 18.9 m. The central basin has average and maximum depths of 18.5 m and 25.6 m. It is separated from the western basin by a chain of islands and Point Pelee, and from the eastern basin by a relatively shallow sand and gravel bar between Erie and Long Point. The eastern basin is the deepest with a mean depth of 24.4 m and a 64.0 m maximum (Bolsenga and Herdendorf, 1993). Water level varies by about 0.5 m on seasonal time scales (Gronewold and Stow, 2013). The Detroit River provides about 90% of the inflow to Lake Erie at the western end of the western basin (Bolsenga and Herdendorf, 1993). This water then passes through the flat central basin, the bowl-shaped eastern basin, and is finally drained through the Niagara River at the eastern end of the lake. The residence time of Lake Erie is about 2.6 years (O'Sullivan and Reynolds, 2004).

In 2008 an intensive field investigation was carried out by Environment Canada's National Water Research Institute (NWRI), University of Waterloo, University of Guelph, and Queen's University to gather new information about the meteorology, water temperature, currents, dissolved oxygen, and nutrients in Lake Erie. For convenience purposes the seven mooring stations are renamed to Sta. W, Sta. C1–C5, and Sta. E (*see* Table 1). The five stations in the central basin (Sta. C1–C5) are ordered by the distance into the western basin. Three meteorological buoys were deployed at Port Colborne, Port Stanley and at Sta. C3 (Fig. 1), from which hourly data were recorded. This includes air temperature, wind, solar radiation, longwave radiation, and relative humidity. The time series of 3 hour averaged meteorological data at Sta. C3 are plotted in Fig. 2. Temperature logger chains with a 10 minute sampling interval were deployed at the seven mooring stations. The deployment details are listed in Table 1. In addition, the lake surface temperature averaged over the Great Lakes derived from satellite remote sensing is available for model validation from the Great Lake Environmental Research Laboratory (GLERL).

Inflows from eleven major tributaries to Lake Erie (Detroit, Raisin, Maumee, Sandusky, Vermilion, Rocky, Cuyahoga, Grand [Ohio], Cattaraugus, Buffalo and Grand [Ontario] rivers) were included in the study. These account for 97.5% of the total inflow (Bolsenga and Herdendorf, 1993). The remaining tributaries have negligible effects on the lake's physical dynamics and heat budget. The data on flow rates and water temperatures for the modeled tributaries were obtained from several data sets provided by the U.S. Geological Service, the U.S. Environmental Protection Agency database on water quality monitoring data, Water Survey of Canada from Environment Canada, and the Grand River Conservation Authority.

Model setup

Numerical simulations were conducted using the Estuary and Lake Computer Model (ELCOM). ELCOM is a numerical modeling tool that applies hydrodynamic and thermodynamic models to simulate the temporal behavior of stratified water bodies with environmental forcing (ELCOM User Manual, 2006). It is a nonlinear, three dimensional, hydrostatic, free surface, and *z*-level model. The hydrodynamic algorithms are based on the Tidal, Residual, Intertidal Mudflat (TRIM) model of Casulli and Cheng (1992) with modifications for accuracy, scalar conservation,

Table 1
Temperature logger 2008 deployment details provided by the National Water Research Institute (NWRI).

Station name	Name used in paper	Latitude °N, longitude °W	Depth (m)	Deployment time (GMT)	Sampling interval (min)	Depth of measurement (m)
357	W	41–49–59, 82–57–03	10.1	01 May–14 Oct	10	1, 3, 5, 7, 9
1227	C1	41–48–36, 82–30–09	11.5	03 Jun–15 Oct	10	1, 2, 3, 4, 6, 7, 8, 8.7, 9.2, 11
1228	C2	41–47–40, 82–21–13	14.5	04 Jun–15 Oct	10	1, 2, 3, 5, 6, 7, 8, 11.5, 12, 12.5, 13, 13.5
341	C3	41–47–40, 82–17–35	17.6	02 May–14 Oct	15	1, 2, 3.5, 4.5, 5.5, 6.5, 7.5, 8.5, 9.5, 12.75, 13.5, 14.5, 15, 15.5, 15.9, 16.5, 17
1231	C4	41–47–30, 82–11–38	19.8	03 Jun–15 Oct	10	1, 2, 3, 4, 5, 6, 7, 8, 10, 11.5, 12.5, 13, 14, 15, 15.5, 16, 16.5
84	C5	41–55–07, 81–38-46	23.6	29 Apr–16 Oct	10	1, 3, 5, 7, 9, 11, 13, 15, 16, 17, 18, 19, 20, 21, 22, 23
452	E	42–34–55, 79–55–23	53.5	29 Apr–16 Oct	10	1, 3, 5, 7, 9, 11, 13, 15, 16, 17, 18, 19, 20, 23, 26, 30, 35, 40, 45, 50