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Three-dimensional winter modeling and the effects of ice cover on hydrodynamics, thermal structure and water quality in Lake Erie

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ABSTRACT

A 3-dimensional numerical model of Lake Erie was set up for a winter season using a coupled hydrodynamic and water quality model (ELCOM-CAEDYM) and validated against observations. The model was successful in predicting average lake surface temperature (root mean square deviation, RMSD < 0.87 °C) when compared with the available observed temperature profile (RMSD < 0.78 °C). The ice cover hind cast favorably agrees with observations (ice coverage RMSD $= 3.1 \times 10^3$ km^2, ~10% of the lake surface, and thickness RMSD $=$ 2.1 cm). This study illustrates the importance of the inclusion of ice cover when simulating hydrodynamics and lake water quality. For example, the water level oscillations were significantly reduced under ice cover conditions. Although the model is not calibrated for water quality during winter conditions, the predicted variations in DO and Chl-a are qualitatively in agreement for all three basins of Lake Erie. Similar to recent field observations, our model results also suggest that despite low temperatures and low under-ice light availability, winter conditions can support high phytoplankton biomass in the central basin which is at least comparable to that typically observed in the summer. Our results also indicate that simulations without ice-cover during the winter results in higher phytoplankton biomass in the central basin compared to that in the scenario with ice. This suggests that changes in the extent of ice cover, its thickness and duration will influence winter productivity with the consequences for hypoxia to develop later in the season.

Introduction

The inclusion of ice cover is an essential part of hydrodynamic and biogeochemical modeling in mid and high latitude lakes. Ice cover inhibits direct wind stress on the surface and significantly modifies lake circulation. Vertical mixing under ice is primarily sustained by natural convection (Farmer, 1975). The ice and snow cover also isolate the water body from direct interaction with the atmosphere limiting the reception of solar radiation, heat, moisture and gas exchange. The ice cover has a significant effect on biological processes as it influences the productivity and composition of major taxonomic groups of phytoplankton (Semovski et al., 2000). Both the long duration and the sheltering of light by the ice cover are important conditions for the selection of certain phytoplankton species that are very efficient in light utilization that are well adapted to low temperatures and dim light environment (Lizotte et al., 1996). The stable inverse temperature stratification in an ice-covered lake allows phytoplankton to be contained in the relatively well-illuminated upper part of the water column, just below the ice sheet, where light is still sufficient for balanced or positive phytoplankton growth. In some cases, with the right conditions, phytoplankton may form blooms following seasonal increases in irradiance in late winter or early spring (Phillips and Fawley, 2002). There are a number of studies reporting observations of under-ice phytoplankton blooms in different lakes (Verduin, 1959; Vanderploeg et al., 1992; Lizotte et al., 1996; Arrigo et al., 2012), including Lake Erie (Chandler, 1942, 1944; McKay et al., 2011; Twiss et al., 2012).

Phytoplankton blooms and associated pulses in primary production have important implications for biogeochemical processes. They influence concentrations of the dissolved gases such as dissolved oxygen and carbon dioxide and have an effect on the lake carbon budget by exporting new organic matter to other trophic levels, including zooplankton and bacteria. The importance of pelagic production for the development of summer hypoxia has been hypothesized previously (Carrick et al., 2005; Lashaway and Carrick, 2010; Twiss et al., 2012). The sedimentation of the organic material from the under-ice phytoplankton bloom to the lake bottom and its further mineralization due to an increase in temperatures later in the season may lead to hypoxia and even anoxia. Under-ice phytoplankton blooms are important features in some known ice-covered mid and high latitude lakes (Chandler, 1942, 1944; Straškrábová et al., 2005; Tanabe et al., 2008; Twiss et al., 2012), but the mechanisms triggering such blooms are

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still not well understood as not all ice-covered lakes are known to develop under-ice phytoplankton blooms. The importance of winter blooms for lake ecology calls for a better understanding of the mechanisms involved in the development of such blooms (Wright, 1964). However, winter dynamics of physical, chemical and biological variables in mid and high latitude lakes is still the least studied and understood subject of limnology. The existing knowledge is inadequate, fragmented and limited to a few systems with very low sampling resolution, mainly due to logistical difficulties and safety concerns associated with conditions of winter sampling (Wright, 1964; Twiss et al., 2012). This limits the necessary knowledge to fully understand the effects of ice-cover on the biogeochemical processes in lakes. On the other hand, numerical models with an adequate representation of ice-cover, hydrodynamics and bio-chemical processes can be of great importance in providing researchers with more detailed understanding of the role of ice-cover on water quality; for example, winter dynamics of dissolved oxygen (DO) and phytoplankton biomass with chlorophyll-a (Chl-a) as its proxy. Therefore the current coupled hydrodynamic and ecosystem modeling of lakes and reservoirs requires accurate prediction of ice for long term simulations (White et al., 2012).

The Great Lakes have significant impact on the local weather and climate (Wang et al., 2010, 2012; Obolkin and Potemkin, 2006). For example, lakes that do not freeze during late autumn and early winter can generate large amounts of snowfall on their leeward coast (Scott and Huff, 1996; Liu and Moore, 2004). All the Great Lakes experience periods of partial ice cover, while Lake Ontario could be covered less than 24%, Lake Erie might reach 90% ice cover (Wang et al., 2010). Therefore, it is important to accurately model the effects of the ice cover on the numerical modeling of the Great Lakes (Oveisy et al., 2012), in particular Lake Erie.

Recently, Lake Erie has been the focus of many studies. Located in warmer weather conditions compared to the other Great Lakes, Lake Erie is surrounded by denser urban areas deriving in anthropogenic activities which adversely affect the water quality of the lake (Zhang et al., 2008). Rumer et al. (1981) developed an ice forecasting model for Lake Erie using Hibler's (1979) dynamic–thermodynamic sea-ice model. This model considers wind, currents, Coriolis force and internal ice stresses. It uses a simple circulation model by computing a steady-state current field using vertically-integrated equations of motion (Wake and Rumer, 1983). Hibler Yao et al. (2000) coupled Hibler (1979) the model with the three-dimensional (3D) Princeton Ocean Model (POM) and studied the seasonal variation of ice cover in Labrador Sea. Their model was driven by monthly atmospheric forcing in the Labrador Sea with relative success in simulating the seasonal variation of ice cover. Following similar studies that were conducted elsewhere, the extent and effect of ice cover on Lake Erie have been examined in recent studies. For example, Wang et al. (2010) simulated ice and water circulation in Lake Erie for the winter of 2003–2004 without including the ice-water stress coupling explicitly. Fujisaki et al (2012) extended that study by including the full ice-water stress coupling and basal melting which occurs due to a heat imbalance at the ice bottom. Dupont et al. (2012) developed Environment Canada's operational prediction model for the Great Lakes based on the three dimensional global ocean model Nucleus of European Model of the Ocean (NEMO). This model setup uses a sea-ice model which includes two layers of ice and one layer of snow. All these numerical models, however, remained limited to the hydrodynamic modeling realm and did not address the water quality processes in the lake. Recently, White et al. (2012) applied a 3D Regional Oceanic Modeling System, including ice dynamics, and studied the multiyear effect of ice cover on the long-term lake thermal structure and biology in Lake Superior. They concluded that the total annual gross primary productivity increases with the increase of mean annual temperature and decreases with the increase of mean winter ice-cover.

The Estuary Lake Coastal Ocean Model (ELCOM) coupled with the Computational Aquatic Ecosystem Dynamics Model (CAEDYM) for biogeochemical simulations has been used to assess the water quality in several lakes (Hillmer et al., 2008; Morillo et al., 2009). This model has also been successfully applied to Lake Erie for hydrodynamic and biochemical simulations (Leon et al., 2005, 2011; Bocaniov et al., 2014). These applications use a spatially constant sectional meteorological forcing, neglecting the importance of the spatial variability of winds on the circulation and thermodynamics of the lake (Huang et al., 2010). Despite intense calibrations conducted in the summer, none of the previous studies covered the winter season, mainly due to the lack of an ice component in earlier versions of ELCOM. Oveisy et al. (2012) introduced an ice module in ELCOM based on the solution of the steady-state heat conduction equation among the three layers of blue ice, white ice and snow cover with variable and process based ice and snow characteristics with no advection. The ice formation algorithm in ELCOM is targeted for rapidly variable weather in mid-latitude regions which included snowmelt due to rain, formation of snow-ice, variable snow density and conductivity, and ice and snow albedo. The model was validated against ice cover information in a large lake (Lake Ontario) and a small lake (Harmon Lake, BC, Canada). However, their verifications were limited due to the lack of significant ice cover in Lake Ontario. The ELCOM-CAEDYM model is being used for setting nutrient objectives in the portion of Canadian tributaries discharging to Lake Erie. These applications require multi-year simulations; therefore, this study is a first step in assessing ELCOM-CAEDYM performance in Lake Erie during a winter season. Here we set up the model with a spatially variable meteorological forcing generated from eight stations around Lake Erie and validate it against water temperature and ice-cover measurements. We further show the effect that ice cover can have on the physical and biochemical parameters such as DO and Chl-a.

Methods

Model setup

ELCOM solves hydrostatic Reynolds-averaged Navier–Stokes equations on a Cartesian Arakawa C-grid and uses the scalar transport equations to model mass, and temperature and salinity distributions in space and time (Hodges and Dallimore, 2006). The model uses a fixed, Z-coordinate finite difference mesh with a Euler–Lagrangian approach for momentum-advection. The model equations are solved on all wet cells and a turbulent kinetic energy based mixed-layer model is used for vertical turbulent mixing. Heat exchange through the water surface is governed by standard bulk transfer models (Hodges et al., 2000). The fundamental numerical semi-implicit scheme in ELCOM is adapted from the TRIM approach of Casulli and Cheng (1992) with some modifications for accuracy, scalar conservation, and reducing numerical diffusion (see Hodges and Dallimore, 2006 for details). Although the semi-implicit scheme in ELCOM may introduce numerical viscosity and result in dissipation of small scale eddies, the model is able to produce highly reliable vertical thermal stratification in the lake (Leon et al., 2011). The coupled mode with ELCOM and CAEDYM being run together, has been applied extensively to study lake processes and for biogeochemical and management studies in the Great Lakes (e.g. Rao et al., 2009; Leon et al, 2011; Bocaniov et al., 2014).

Lake Erie (42.17 N, 81.25 W) is the southernmost of the Great Lakes, with an area of approximately 2.6×10^4 km^2, consisting of three basins. The shallowest western basin (average depth ~9.0 m) is significantly under the influence of the inflow from the Detroit and the Maumee Rivers as the former is responsible for more than 92% of the total lake inflow (Bolsenga and Herdendorf, 1993; Schwab et al., 2009; Beletsky et al., 2012). ELCOM was set up to run from day 279 (October 5) in 2004 to day 109 (April 18) in 2005; this period was chosen due to the availability of field observations during this period, particularly at two locations from two thermistor strings located at T07 and T12 (Fig. 1). Data were recorded hourly, and they are accurate to the order of 0.1 °C. However, it was observed that the temperature reached zero at