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Physical measurements and nearshore nested hydrodynamic modeling for Lake Ontario nearshore nutrient study

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ABSTRACT

Application of a well-known hydrodynamic code for the Great Lakes was evaluated for its effectiveness, using a nested modeling approach, to examine nearshore physical processes in connection with the 2008 Lake Ontario Nearshore Nutrient Study (LONNS). The purpose of LONNS was to examine possible causes of nearshore eutrophication, and as a subset the goal of this study was to develop a framework for understanding the role of physical processes in nearshore eutrophication problems (e.g., benthic algae blooms). A relatively fine scale (200 m) nested model was interfaced with a coarser scale (2 km) whole-lake model to allow direct incorporation of processes acting on the whole-lake scale, while also providing spatial detail that better matched available data and the desired resolution for the nearshore. Both models were based on the Princeton Ocean Model. Measurements of temperatures and currents were obtained during 2008 in each of the three regions: Oak Orchard Creek, Rochester Embayment, and Sandy Creek (or Mexico Bay), representing three different regimes of human interaction with the nearshore. The model reproduced general temperatures and flow structures relatively well for the Oak Orchard and Rochester sites, but was less effective for Sandy Creek, where simulation results were possibly adversely affected by the relatively shallow conditions of this site. Results were generally better for summer and fall, while early spring comparisons appeared to be influenced by specified initial conditions, which were found to impact model results well past the one to two month period usually assumed for spin-up time.

Introduction

The first Great Lakes Water Quality Agreement (GLWQA), signed by the United States and Canada in 1972, was a response to a wave of scientific and public concern about pollution and significant water quality problems in Lake Erie (NGOs, 2007). The main goal of the GLWQA was to reduce eutrophication by decreasing phosphorus levels. Average open lake phosphorus concentrations in Lake Ontario were successfully reduced from a peak of about 25 μg/L in 1971 to below the target concentration of 10 μg/L by the mid 1980s. Offshore phosphorus levels have maintained a declining trend, and concentrations are now approximately 5–7 μg/L (EPA, Environmental Protection Agency, 2006). Despite this success, resurgence of the benthic filamentous algae *Cladophora glomerata*, which was widespread in shallower regions of the lakes in the 1960s and 1970s, and other nuisance algae problems indicate nutrient enrichment in nearshore areas (EPA, Environmental Protection Agency, 2006). Specific studies documenting *Cladophora* blooms and associated problems in Lakes Michigan, Erie and Ontario are referenced by Higgins et al. (2012), and sloughed *Cladophora* has led to frequent beach closings at two of our study areas—Oak Orchard and Rochester (see below). Anecdotally, *Cladophora* has also been tied to cooling water intake clogging at power plants along the southern shore of Lake Ontario.

A key component in setting target phosphorus loadings to achieve water quality objectives was the application of phosphorus mass balance models. These models ranged in complexity from primarily empirical loading relationships (e.g., Vollenweider, 1972) to more sophisticated process-based models (Thomann et al., 1975, 1976), or combinations of empirical and mechanistic approaches (e.g., Chapra, 1977, 1980). Models were generally applied with lake-wide or basin-wide resolution, and did not consider differences between nearshore and offshore locations. In order to examine in better detail water quality in nearshore areas, particularly in contrast with offshore waters, models are needed with appropriate spatial and process resolutions. Water quality models require advection and diffusion values, which are derived from a hydrodynamic model. A major challenge then is to provide the hydrodynamic forcing at a sufficiently fine scale in a nearshore area of interest, while incorporating whole-lake processes that may affect the nearshore, such as upwelling and downwelling, and at the same time avoiding excessive computational burden by having an overly fine scale for the whole lake.

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These requirements have led to the use of nested modeling, where a finer-scale grid for a region of interest is embedded within a coarser scale grid for the entire lake. For example, Murthy et al. (1986) applied a semi-empirical method to predict pollutant transport problems in the Pickering area along the northern shore of Lake Ontario. This same area is the site of a more mechanistic model application coupling a 2 km whole-lake grid with a 100 m finer grid, simulating both hydrodynamics and water quality, with an emphasis on nuisance algae (Leon et al., 2012). Shen et al. (1995) used several different resolutions to simulate pollutant dispersion from a small creek in the Toronto waterfront area under isothermal or stratified conditions, using an iterative scheme to match boundary conditions between the nearshore and whole-lake models. Hayashida et al. (2000) used a variable grid finite element approach to enable fine-scale analysis of flow patterns in the Niagara River outlet region, with grid dimensions varying from about 50 m to several kilometers. However, their model was vertically integrated, and therefore not able to simulate a full range of (three-dimensional) motions in the lake. More recently, Sheng and Rao (2006) applied a nested ocean circulation model to simulate circulation and temperatures in Georgian Bay, Lake Huron, reporting reasonable comparisons with observations.

The goal of the present work was to test the application of a well-known three-dimensional hydrodynamic code to the Great Lakes (the Princeton Ocean Model, or POM), using a nested model approach. This application is planned to serve as a basic component of a more comprehensive modeling framework to simulate nutrients, contaminants, sediment and lower food web dynamics to support management decision making for nearshore regions in Lake Ontario. It is similar to the approach used by Leon et al. (2012), except it uses a public domain model, to allow greater flexibility over a range of applications. The approach here is based on the nested modeling capability developed recently at the Great Lakes Environmental Research Laboratory (GLERL, D. Schwab, pers. comm.), and takes advantage of a field data set collected in 2008 as part of the Lake Ontario Nearshore Nutrient Study (LONNS), of which this study was a part (Higgins et al., 2012).

The underlying conceptual model guiding the LONNS is the nearshore shunt hypothesis (Hecky et al., 2004), which suggests nearshore nutrient sequestration and cycling as causes of nearshore eutrophication. These processes may be enhanced by nearshore circulation phenomena such as the thermal bar (Rodgers and Anderson, 1963; Rodgers, 1966, 1968; Rodgers and Sato, 1970) and upwelling and downwelling (Rao and Schwab, 2007). The spring thermal bar, for example, usually coincides with a period of relatively large runoffs and nutrient loadings due to urban, agricultural, and other sources. Cross-frontal exchange coefficients are reduced in the thermal bar region, with values typically an order of magnitude smaller than alongshore exchange coefficients (Gbah and Murthy, 1998). Rao et al. (2004) also suggested that mixing across the bar was reduced, at least when the bar was relatively close to shore. Upwelling and downwelling during stratified periods also play a significant role for nearshore biological and chemical processes, serving as major transport pathways moving material on- and off-shore (Rao and Schwab, 2007). All these processes alone, however, do not explain the present nearshore water quality conditions—the difference between current conditions and those with which the lake ecology evolved is the relatively recent introduction of invasive mussels. To investigate the cause of these problems, models are needed that can be used to interpret physical influences on biological and chemical processes on a finer spatial scale than is typical in whole-lake models.

The LONNS was initiated to investigate possible causes of observed water quality differences between nearshore and offshore waters in Lake Ontario, and to better understand reasons for the resurgence of *Cladophora* in the nearshore region. The field component of this study focused on three nearshore areas along the New York shoreline: (1) Oak Orchard Creek, (2) Rochester Embayment, and (3) Sandy Creek (also referred to as Mexico Bay) (Fig. 1). Sampling polygons with dimensions of approximately 5 km × 20 km were defined for each of these areas, and sampling cruises were conducted in late May to early June, early to mid-August, and late September to early October, to capture conditions representative of late spring, mid-summer, and early fall. The present study focuses on the physical

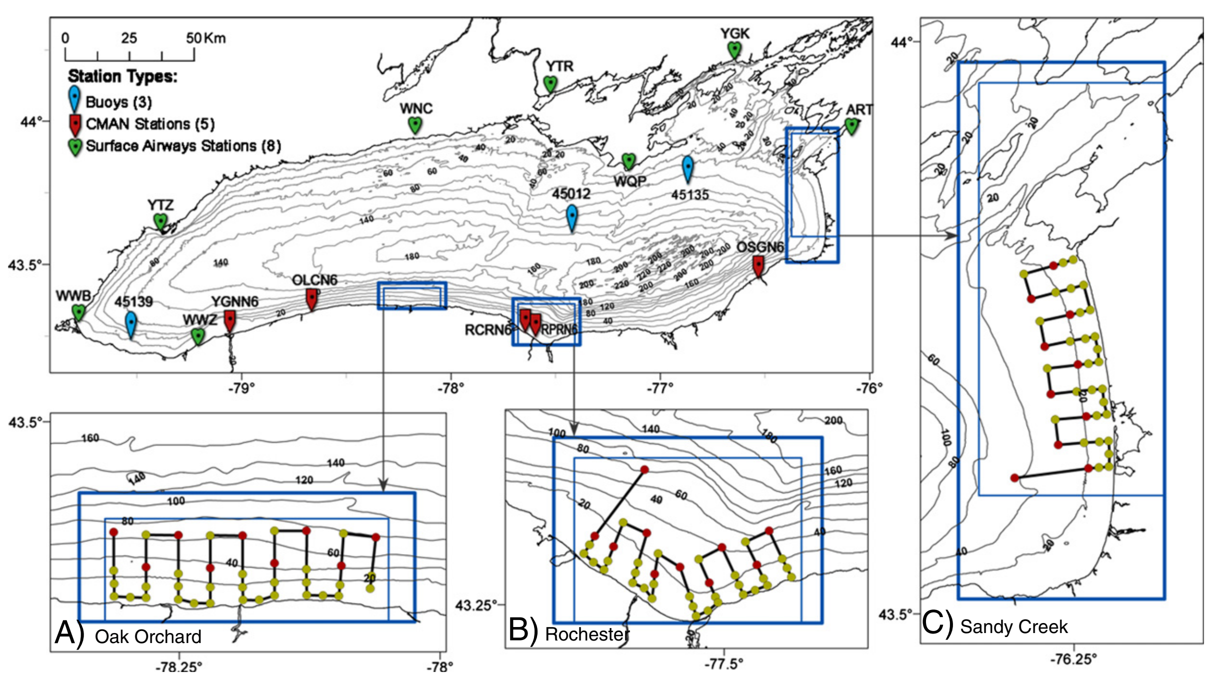

Fig. 1. The three study sites in Lake Ontario, showing meteorological stations in addition to sampling (inner boxes) and nested model (outer boxes) regions for (a) Oak Orchard, (b) Rochester, and (c) Sandy Creek. Also shown in the insets are cruise paths; filled circles along the paths indicate locations of water sampling stations, where near-surface water samples were taken to corroborate continuous sampling along the cruise paths. Open circles indicate intensive sampling locations for temperature profiles and ADP data.