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Modeling surface waves and wind-driven circulation in eastern Lake Ontario during winter storms

Matthew P. McCombs [a,*], Ryan P. Mulligan [a], Leon Boegman [a], Yerubandi R. Rao [b]

[a] Department of Civil Engineering, Queen's University, Kingston, ON K7L3N6, Canada
[b] National Water Research Institute, Environment Canada, Burlington, ON L7R4A6, Canada

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ABSTRACT

A spectral wave model coupled to a depth averaged hydrodynamic model was used to simulate the wave and flow conditions in the Kingston Basin of Lake Ontario during winter storm events. The simulations were verified using wave and current profiler data collected over the 2009–10 and 2011–12 winter periods. The model was forced with outputs from the Great Lakes Coastal Forecasting System (GLCFS) as open boundary conditions and winds from a local meteorological station. Wave simulations in the Kingston Basin were better represented using the GLCFS boundary forcing into a model domain of the Kingston Basin; whereas, a model domain that covered all of Lake Ontario yielded a better representation of flows with reasonable wave results. For five storm events that were simulated, approximately 80% of the wave energy outside the Kingston Basin entered the basin after crossing the Duck-Galloo Ridge. Flows throughout the basin showed a complex circulation pattern that is defined by both the forcing and the topographical features including islands, shoals and deep channels. The complex circulation within the basin is composed of several wind-driven gyres which are magnified during storm events. The impact of waves on the circulation patterns at the basin scale is negligible, since shoals are typically too deep (e.g. 20 m) relative to the wavelength and period (e.g. 7–10 s) to generate large-scale wave-driven flows. In general, the modeling system was successful in reproducing the waves and currents in eastern Lake Ontario and can be used for future engineering-type studies such as offshore wind farm impact assessment.

Introduction

Little is known about the winter circulation and wave climate in Lake Ontario because the development of ice cover necessitates the removal of mooring buoys and induces difficulties in computational modeling (e.g., Oveisy et al., 2012; Shore, 2009). Most previous work on the lake has focussed on the general ice-free seasonal circulation patterns (e.g. Huang et al., 2010; Simons, 1974). In the winter research on circulation, Pickett (1980) found that observed mean winter circulation patterns agreed with a steady-state, homogeneous model, driven with a wind from the direction of maximum response (from the west) and determined that circulation in the main basin of Lake Ontario is, on average, composed of clockwise flow in the north and counter clockwise flow in the south. Simons et al. (1985) found similar patterns using a high resolution array of current meters in the Mississauga Basin of the lake. Beletsky et al. (1999) used 30 years of current observations to improve the climatological circulation patterns and also found a two-gyre pattern in Lake Ontario during the winter season. Winter circulation was found to be almost entirely wind-driven with stronger currents than in the summer. Research on winter wind-wave processes remains non-existent. Boyce et al. (1989) determined that storm surges, in the ice-free seasons, rarely exceed 0.5 m in Lake Ontario and observed similar circulation patterns to other studies. Hamblin (1982) observed four modes of surface seiching, including the fundamental mode of 5.06 h related to the long axis of the lake. Flow distribution and circulation through the Kingston Basin have been described by Tsanis and Murthy (1990) and Tsanis et al. (1991), who studied mean summer currents in the Kingston Basin.

Year round waves and currents are modeled coarsely (5 km resolution) over all the Great Lakes by the Great Lakes Coastal Forecasting System (GLCFS) which is based on the finite difference Princeton Ocean Model (POM) and the Donelan wave model (Bedford and Schwab, 1991; Schwab et al., 1984). This modeling system provides hourly wave and current data for the Great Lakes but does not resolve the details of the Kingston Basin. Other recent research on the Kingston Basin (Paturi et al., 2012; Shore, 2009) has not modeled surface wave fields and/or been limited to summer circulation patterns. In the present study, we apply the Delft3D model coupled to SWAN with a finer resolution model grid to gain a better understanding of the winter wave and

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* Corresponding author.
E-mail address: matthew.p.mccombs@gmail.com (M.P. McCombs).

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circulation dynamics of the Kingston Basin due to its complex bathymetric features. We apply a high-resolution grid to the Kingston Basin and evaluate results with observed open boundary forcing from the lake and also from a coarse resolution lake-wide model. We focus on five specific storm events occurring over short time periods (5 to 8 days), which are important as they produce the largest current velocities, surface waves and storm surges.

Because most of the past modeling efforts in Lake Ontario have focused on summer circulation (e.g. Paturi et al., 2012; Tsanis et al., 1991), it is necessary to investigate the surface waves and winter circulation patterns in order to help understand the strongest annual events in the seasonal cycle. The model will be applied in future work to determine the impacts of an offshore wind farm on the hydrodynamics of the region.

Methods

Model description

Spectral wave models solve the action balance equation using source terms that account for wave generation by wind, non-linear wave interactions, and wave energy dissipation (wave breaking, whitecapping, and bottom friction) which evolve the shape of the wave spectrum. The Simulating Waves Nearshore (SWAN; Booij et al., 1999) numerical model is used in this study to simulate the wave field through Lake Ontario and the Kingston Basin. SWAN computes the evolution of random waves and accounts for refraction, as well as wave generation due to wind, dissipation and non-linear wave–wave interactions (Booij et al., 1999). The evolution of the wave field is described by the action balance equation (Eq. (1)), which equates the propagation of wave action density in each dimension balanced by local changes to the wave spectrum:

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}c_xN+\frac{\partial}{\partial y}c_yN+\frac{\partial}{\partial \sigma}c_\sigma N+\frac{\partial}{\partial \theta}c_\theta N=\frac{S_{tot}}{\sigma} \tag{1}$$

where t is time (s), c_x and c_y are wave celerities in the x and y directions (m s^{-1}), and c_θ and c_σ are rates of change of group velocity (speed at which wave action is transported), which describe the directional (θ) rate of turning and frequency (σ) shifting due to changes in currents and water depth. N is wave action density and S_{tot} are the energy density source terms which describe local changes to the wave spectrum. The energy density source terms include generation by wind, dissipation (whitecapping, bottom friction and depth-induced breaking) and non-linear interactions (triads and quadruplets).

Delft3D (Lesser et al., 2004) is a 3-dimensional (3D) hydrodynamic model that computes the results of the non-steady flow and transport equations that result from meteorological and wave forcing (Deltares, 2011). The wave forcing is predicted by SWAN and used as input to the hydrodynamic (Delft3D) model. The Fredsøe formulation was used to represent the stresses due to waves, using the default parameterization coefficients developed by Soulsby et al. (1993). The Chézy bottom roughness formula was applied using the default coefficient of 65.0 m$^{1/2}$ s^{-1}. The model was implemented as a 2-dimensional (2D) depth-averaged model. The 2D horizontal momentum equations derived from the Reynolds-averaged Navier–Stokes equations with a Boussinesq approximation and the depth averaged continuity equation are given by:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+\frac{\omega}{h}\frac{\partial U}{\partial \sigma}-fV= -\left(g\frac{\partial \zeta}{\partial x}+g\frac{h}{\rho_0}\int_{\sigma}^{0}\left(\frac{\partial \rho}{\partial x}+\frac{\partial \sigma'}{\partial x}\frac{\partial \rho}{\partial \sigma'}\right)\partial\sigma'\right)+\upsilon_H\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right)+M_x \tag{2}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+\frac{\omega}{h}\frac{\partial V}{\partial \sigma}-fU= -\left(g\frac{\partial \zeta}{\partial y}+g\frac{h}{\rho_0}\int_{\sigma}^{0}\left(\frac{\partial \rho}{\partial y}+\frac{\partial \sigma'}{\partial y}\frac{\partial \rho}{\partial \sigma'}\right)\partial\sigma'\right)+\upsilon_H\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)+M_y \tag{3}$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (hU)}{\partial x}+\frac{\partial (hV)}{\partial y}=0 \tag{4}$$

where U and V are the depth-averaged generalized Lagrangian mean velocity components (m s^{-1}) including waves (Stokes drift components). f is the Coriolis coefficient (s^{-1}), g is gravitational acceleration (m s^{-2}), h is water depth (m), υ_H is the horizontal eddy viscosity (m^2 s^{-1}), ρ is the fluid density (kg m^{-3}), ρ_0 is the reference density of water (kg m^{-3}), σ is the vertical topography following coordinate (m), ζ is the water surface elevation above reference datum (m) and ω is the vertical velocity component in the sigma coordinate system (s^{-1}). M_x and M_y represent contributions from external sources and sinks of momentum (m s^{-2}) and in this case represent the wave stress terms from SWAN. Wave breaking is modeled as a shear stress at the water surface (Stive and Wind, 1986; Svendsen, 1985) and is simplified using the expression derived by Dingemans et al. (1987).

Lake Ontario (Fig. 1a) is comprised of three basins. The Mississauga Basin is located to the west, the Rochester Basin to the east, and the Kingston Basin at the northeastern end of the lake. The Kingston Basin (Fig. 1b) contains complicated bathymetry including many islands and shoals protecting it from large waves produced in the main basin (Mississauga and Rochester Basins) of Lake Ontario. Two deep channels exist around these islands which affect wave and current propagation. The channel on the east side of Main Duck Island (Fig. 1b) is named the St. Lawrence Channel (56.2 m deep) and on the west side is the Simcoe Island Channel (41.2 m deep). The shoals and islands, which protect the Kingston Basin form Duck-Galloo Ridge, have an average depth of approximately 15 m.

Two domains were used and compared in this study, each using different boundary or input forcing. The Lake Ontario model-domain (LOM, Fig. 1a) used winds from the GLCFS in the main basin of Lake Ontario applied uniformly across the lake representing typical winter storm conditions (Pickett, 1980). A closed boundary was implemented at the St. Lawrence River as circulation exchange due to the outflow at this boundary is negligible within 10 km of the river (Prakash et al., 2007). The Kingston Basin model-domain (KBM) was used as both a stand-alone domain and a nested sub-domain of the LOM (Fig. 1b). The simulations were forced with wind and wave data from the GLCFS and hourly water level data from L1 (Oswego, NY) and L2 (Alexandria Bay, NY) and compared with wave observations within the Kingston Basin and along the Duck-Galloo Ridge. The wave parameters simulated by the GLCFS at site D (Fig. 2), the location of the Environment Canada Prince Edward Pt. buoy (not deployed in the winter months), were implemented along the southern boundary. This buoy is used to verify the GLCFS during the summer months, insuring an accurate forecast during the winter months for use in this study. Water level observations at the southern boundary (from L1 in Fig. 1a) and at the St. Lawrence River boundary (from L2 in Fig. 1a) were used to force the KBM hydrodynamic model (NOAA Tides and Currents, 2013).

Observations

Two sets of observations for waves and currents (outside and inside the Kingston Basin during winter periods in 2009–10 and in 2011–12) were used for model validation. The 2009–10 winter observations were collected using a Nortek AWAC (acoustic wave and current profiler, Fig. 1b, site A); which captured two significant storm events (Fig. 2,