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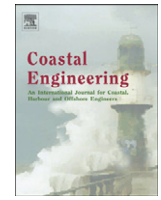

Offshore wind farm impacts on surface waves and circulation in Eastern Lake Ontario

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ABSTRACT

A coupled wave and hydrodynamic model was applied to the Kingston Basin of eastern Lake Ontario, a region with bathymetric variability due to channels and shoals, to assess the potential impacts on surface waves and wind-driven circulation of an offshore wind farm. The model was used to simulate a series of storm events with time-varying wind forcing and validated against wave, current and water level observations. The wind farm was simulated by adding semi-permeable structures in the surface wave model to represent the turbine monopiles, and by adding an energy loss term to the fluid momentum equations in the hydrodynamic model to represent the added drag of the monopiles on the flow. The results suggest that the wind farm would have a small influence on waves and circulation throughout the wind farm area, with spatial variability due to focussing of wave energy and re-direction of the flow. Overall, the results indicate that the wave height in coastal areas will be minimally affected with changes in significant wave height predicted to be <3%. Larger changes to the strength of circulation occur inside the wind farm region with localized changes in current magnitude of up to 8 cm s^{-1}. The results of this study may help to understand the impacts of future offshore wind farms and other offshore structures in the Great Lakes.

1. Introduction

Wind power, harnessed using a series of wind turbines mounted on monopiles, is becoming a reliable source of renewable energy in offshore areas around the world. Offshore wind farms have been built in the coastal ocean around Europe (e.g. Scroby Sands; CEFAS, 2006, Horn Rev and Nysted; Danish Energy Agency (DEA), 2006), but few wind farms have been constructed in freshwater systems and none exist in the Great Lakes of North America. One example of a small operational farm is in Lake Vanern in Sweden, although the scale of the lake (5655 km^2) and the farm (10 turbines) is small compared to the scale of a recent plan proposed for Lake Ontario (18,960 km^2, 130 turbines; Ortech Environmental, 2010), shown in Fig. 1. Scientific and technical issues associated with potential offshore wind farm development in North America have been studied (Baird, 2011; Manwell et al., 2007), highlighting the challenges (e.g., freshwater ice, social and ecological impacts, etc.) to consider before constructing wind farms in the Great Lakes.

The purpose of the present study is to investigate, using coupled numerical models, the near and far-field effects of an offshore wind farm on the waves and circulation in eastern Lake Ontario (Fig. 1a), known as the Kingston Basin (Fig. 1b). We define near-field as the area within the wind farm and 1 km outside the turbines and far-field as the area more than 1 km away from the turbines. The simulated wind farm is located in a 130 km^2 area with a mean water depth of 26 m, between Wolfe Island and Main Duck Island (Fig. 1b). The wind farm area is constrained by the USA/Canada border, the water depth (<30 m) and the distance from the coastline (>5 km). A model of Lake Ontario with a higher-resolution nested grid of Kingston Basin, described by McCombs et al. (in press), is used in this study to simulate the effects of a wind farm that is based on a proposed design by Ortech Environmental (2010). The modelling system uses a hydrodynamic model (Delft3D, Lesser et al., 2004), coupled to a surface wave model (SWAN, Booij et al., 1999) to predict the waves and circulation.

Various methods have been used to represent the impacts of offshore wind farms on waves in other studies. Ponce de Leon et al. (2011) used SWAN to simulate waves in an offshore wind farm consisting of 130 turbines on the Norwegian continental shelf. Since the monopile foundations considered in their study could not realistically be resolved, each monopile foundation was represented within the model domain as a dry point (i.e., land), reducing wave energy. They found that the simulated monopiles acted as obstacles blocking the propagation of wave energy and slightly altering the wave direction. Alari and Raudsepp (2012) also used SWAN to simulate changes in significant wave height due to offshore wind farms in the Baltic Sea. In their study, the wind farms were represented using five nested models, the finest having a resolution of 25 m. The cells closest to the locations of the 130 turbines were dry points. They concluded that changes to

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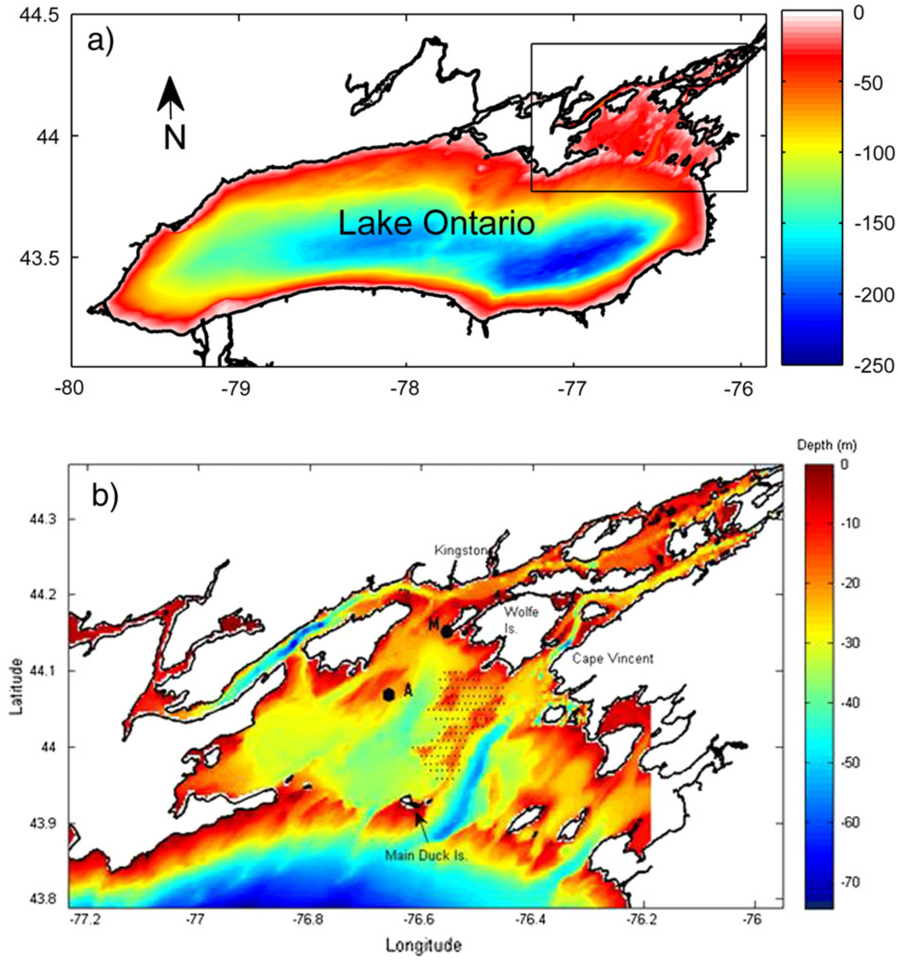

Fig. 1. Lake Ontario (inset, a) and northeastern Lake Ontario (Kingston Basin, b) with wind farm turbine locations shown on the 20–30 m deep shoal between Wolfe Island and Main Duck Island. Location A denotes the ADCP and M denotes the location of the meteorological station deployed during the 2011–12 winter months.

significant wave height were very marginal, <1% in the far-field. Other relevant studies (e.g. Cooper and Beiboer, 2002) also suggest that changes to the wave field due to offshore wind farms in various locations are small in the near-field and are unlikely to be significant in the far-field.

Changes to the strength and pattern of the circulation may also be impacted by offshore wind farms. Wind farm turbine piles may have effects on flows in the far-field, including flow separation and vortex shedding (Sumer and Fredsoe, 1997), and group-effects in the near-field (Sumer and Fredsoe, 2002). ETSU (2002) conducted a study using Delft3D to model 30 turbines in Liverpool Bay, UK, finding that circulation changes were small and that the greatest impacts would be seen in the near-field. Baird (2011) suggested that currents in the Great Lakes can be expected to change 2–4% in the near-field and <1% in the far-field based on a simple analysis of a synthesis of the global understanding of offshore wind farms (e.g. CEFAS, 2006; Cooper and Beiboer, 2002).

The remainder of the paper is structured as follows. In Section 2, the model is validated against observed wave, water level and current velocity data. The model application to the Kingston Basin is described and a transmission coefficient is used in SWAN to represent the sub-grid scale turbine piles. A quadratic friction term is then added to the Delft3D fluid momentum equations to predict the wind-farm impacts on the flow-field. In Section 3, the impacts of the validated models on the wave and flow fields are assessed for a winter storm event.

2. Model setup and validation

The SWAN spectral wave model was used to simulate the surface wave conditions within 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). Delft3D computes the results of the non-steady flow and transport equations that result from meteorological and wave forcing (Lesser et al., 2004). The wave forcing is predicted by SWAN and used as input to the momentum equations used in the hydrodynamic (Delft3D) model.

A two-dimensional spherical orthogonal grid was used for the domain which consisted of a coarse (1100 m × 790 m) resolution lake wide domain combined with a finer (380 m × 270 m) resolution domain of the Kingston Basin. The internal boundary uses domain decomposition, a 2-way nesting method for connecting the coarser grid (main basin of Lake Ontario) to the finer grid (Kingston Basin) where the computations on both domains are conducted simultaneously with an exchange of information between them. Simulations were set up with online coupling, meaning the SWAN model has a dynamic interaction with the hydrodynamic model (Lesser et al., 2004) at a specified time interval. The bathymetry of the lake was developed from two sources: Lake Ontario bathymetry was obtained from NOAA (2013) and the bathymetry of the headwaters of the St. Lawrence River was obtained from bathymetric soundings of Environment Canada as described in Paturi et al. (2012). The hydrodynamic simulations were run