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Application of SWAN+ADCIRC to tide-surge and wave simulation in Gulf of Maine during Patriot's Day storm

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Abstract

The southern coast of the Gulf of Maine in the United States is prone to flooding caused by nor'easters. A state-of-the-art fully-coupled model, the Simulating WAves Nearshore (SWAN) model with unstructured grids and the ADvanced CIRCulation (ADCIRC) model, was used to study the hydrodynamic response in the Gulf of Maine during the Patriot's Day storm of 2007, a notable example of nor'easters in this area. The model predictions agree well with the observed tide-surges and waves during this storm event. Waves and circulation in the Gulf of Maine were analyzed. The Georges Bank plays an important role in dissipating wave energy through the bottom friction when waves propagate over the bank from offshore to the inner gulf due to its shallow bathymetry. Wave energy dissipation results in decreasing significant wave height (SWH) in the cross-bank direction and wave radiation stress gradient, which in turn induces changes in currents. While the tidal currents are dominant over the Georges Bank and in the Bay of Fundy, the residual currents generated by the meteorological forcing and waves are significant over the Georges Bank and in the coastal area and can reach 0.3 m/s and 0.2 m/s, respectively. In the vicinity of the coast, the longshore current generated by the surface wind stress and wave radiation stress acting parallel to the coastline is inversely proportional to the water depth and will eventually be limited by the bottom friction. The storm surge level reaches 0.8 m along the western periphery of the Gulf of Maine while the wave set-up due to radiation stress variation reaches 0.2 m. Therefore, it is significant to coastal flooding.

Keywords: Nor'easter; SWAN; ADCIRC; Gulf of Maine; Patriot's Day storm; Tide-surge; Wave; Coastal flooding

1. Introduction

Coastal flooding along the southern coast surrounding the Gulf of Maine is mainly caused by the combination of elevated water levels and waves during nor'easters. Nor'easters, so named for the direction from which their winds blow over land, are the cyclonic storms battering the upper east coast of the United States from October through April (Davis and Dolan, 1993). In the past 30 years, more than 20 notable nor'easters swept through the Gulf of Maine and caused extensive infrastructural damage, beach erosion, and sometimes loss of lives (https://en.wikipedia.org/w/index.php?title=Nor%27easter&oldid=696766147).

The prediction of storm surges, waves, and coastal flooding in the area remains a challenging issue, which can be addressed from two aspects. First, the nonlinear interaction between tides, storm surges, and waves needs to be resolved with the presence of complex bathymetry and configuration of the coastline. Waves and currents interact with each other

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through the following physical mechanisms: (1) surface shear stress: the surface drag coefficient is modified with the presence of surface waves (Warner et al., 2008); (2) bottom stress: waves enhance the turbulent mixing, and, therefore, modify the bottom stress experienced by currents (Grant and Madsen, 1979; Zou, 2004); and (3) radiation stress, which represents the excessive momentum flux within the circulation due to the presence of waves (Longuet-Higgins and Stewart, 1964; Zou et al., 2006). It is well understood that waves contribute to the total water level by wave set-up through radiation stress (Longuet-Higgins and Stewart, 1962), while wave transformation and propagation are affected by the water depth and currents. Other interaction processes between waves and currents, including the surface wind stress and bottom friction, require further exploration. The other aspect is the role of wave action in contributing to coastal damage. Large battering waves can cause significant damage by means of wave run-up and overtopping/splash-over despite water levels below the flood stage.

Numerical studies of hydrodynamic processes in the Gulf of Maine during extratropical storm events fall into three categories: (1) wave models (Sucsy et al., 1993; Panchang et al., 2008), (2) tide-surge models (Bernier and Thompson, 2007), and (3) coupled circulation and wave models (Beardsley et al., 2013; Chen et al., 2013). Only recently, fully-coupled circulation and wave models have been used to assess the contribution of wave-current interaction to coastal flooding (Beardsley et al., 2013; Chen et al., 2013). While Beardsley et al. (2013) and Chen et al. (2013) mainly focused on model skill assessment, and the contribution of waves to circulation and surface elevation was not examined in detail.

In this study, a state-of-the-art fully-coupled model, the Simulating Waves Nearshore (SWAN) model with unstructured grids and the ADvanced CIRCulation (ADCIRC) model, was used to investigate tide-surges and waves in the Gulf of Maine during the Patriot's Day storm. The paper is organized as follows: Section 2 briefly introduces the Gulf of Maine. In the third section, the Patriot's Day storm is described. A brief introduction of the numerical models, the ADCIRC and SWAN models, is presented in section 4. The following two sections describe model setup, results, and discussion. Finally, conclusions are provided.

2. Gulf of Maine

The Gulf of Maine (Fig. 1) is a mid-latitude marginal sea located on the North American continental shelf. It is bounded by the New England coastlines of the United States and Atlantic Canada. The seaward flank of the Gulf of Maine is the Georges Bank, a shallow submarine bank that separates the Gulf of Maine from the Northwest Atlantic Ocean, with a minimum water depth of less than 20 m. The geometry of the Gulf of Maine is characterized by several deep basins and shallow submarine banks. It also has the world's largest tidal range in the Bay of Fundy, the northern part of the Gulf of Maine.

3. Patriot's Day storm

The Patriot's Day storm severely impacted the northeastern United States from April 15 to 18, 2007. The surface low pressure system that triggered the development of the nor'easter originated in the southwestern United States. It intensified into a major storm as rapid cyclogenesis occurred well off the Mid-Atlantic Seaboard. A vigorous upper level low briefly retrograded the storm on a dangerous path towards the coastline, eventually allowing the system to become quasi-stationary near New York City on Monday morning, April 16. The lowest central barometric pressure recorded was 968 hPa, with an intensity similar to a moderate category II hurricane. The storm produced intense winds in the Gulf of Maine, with its peak wind gust above 70 m/s (Marrone, 2008).

The storm generated a pronounced storm surge and large wave acting along the western periphery of the Gulf of Maine. The recorded storm tide corresponded to a 10-year return period event in Portland, Maine. The storm tide peaked at Fort Point, New Hampshire, with a return period exceeding 50 years. The highest waves recorded by nearshore buoys were approximately 9 m (Marrone, 2008; Douglas and Fairbank, 2010). The combination of high astronomical tides, storm surges, and large battering waves resulted in significant coastal flooding and severe erosion along the vulnerable sandy coastline from southern Maine through Cape Cod, Massachusetts.

4. Methods

4.1. ADCIRC model

The ADCIRC model, developed by Luettich et al. (1992) and Westerink et al. (1994), was used to simulate the response of water levels and currents to the Patriot's Day storm in the Gulf of Maine. The two-dimensional (2D) depth-integrated version, often referred to as ADCIRC-2DDI, was used in this study. It basically solves generalized wave continuity equations on an unstructured triangular mesh with a continuous Galerkin finite element method. By using an unstructured triangular mesh, the model is capable of resolving complex geometry and bathymetry. The governing equations in spherical coordinates are as follows:

$$\frac{\partial \zeta}{\partial t}+\frac{1}{R\cos\phi}\left[\frac{\partial(UH)}{\partial\lambda}+\frac{\partial(VH\cos\phi)}{\partial\phi}\right]=0 \tag{1}$$

$$\frac{\partial U}{\partial t}+\frac{1}{R\cos\phi}U\frac{\partial U}{\partial\lambda}+\frac{V}{R}\frac{\partial U}{\partial\phi}-\left(\frac{\tan\phi}{R}U+f\right)V= -\frac{1}{R\cos\phi}\frac{\partial}{\partial\lambda}\left[\frac{p_{\mathrm{s}}}{\rho_0}+g(\zeta-\alpha\eta)\right]+\frac{\nu_{\mathrm{T}}}{H}\frac{\partial}{\partial\lambda}\left[\frac{\partial(UH)}{\partial\lambda}+\frac{\partial(VH)}{\partial\phi}\right]+ \frac{\tau_{\mathrm{s}\lambda}}{\rho_0 H}-\tau_* U \tag{2}$$