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Rapid wave modeling of severe historical extratropical cyclones off the Northeastern United States

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ABSTRACT

Storms play a significant role in coastal zone hydrodynamics, morphodynamics and flooding. The US Northeast is influenced by both extratropical (e.g. nor'easters) and tropical cyclones, which produce extreme winds, storm surges and waves, and as a result erosion and coastal damage. In this study, simulations of 100 of the most severe historical extratropical cyclones in this region were used to evaluate a new, rapid numerical wave model that is a candidate model for ensemble forecasting and hazard assessment. The main tool used was a coupled hydrodynamic-wave model, forced by wind and pressure from preexisting meteorological reanalysis datasets. The coupled models were the Stevens institute Estuarine and Coastal Ocean hydrodynamic Model (sECOM) and the Mellor et al. (2008) (hereafter MDO) wave model, and includes several important physical interactions (e.g. wave setup). Wave model results were compared to offshore buoy observational data from 1980 to 2012, and a sensitivity analysis was used to evaluate important model parameters. Results show that the wave model is very accurate for wave height (H_s), with an average *RMSE* of 0.92 m and *skill* ranging from 0.7 to 0.9. Results were less accurate for average wave period (T_{avg}), with an average *RMSE* of 1.97 s and *skill* ranging from 0.5 to 0.7. However, a comparison with a more widely used existing rapid wave model shows a substantial improvement over those T_{avg} results. Large waves approach the coast in Massachusetts Bay during extratropical cyclones, leading to important wave impacts including setup, and modeled storm surge is shown to have good accuracy and no bias at Boston. These results demonstrate the strengths and weaknesses of the model for rapid simulations of waves under history's most extreme extratropical cyclones, and the evaluation results and sensitivity analysis are used to suggest its appropriate uses and possible avenues of improvement.

1. Introduction

The processes of coastal hydrodynamics during severe storms include strong winds, storm surges, and wave-driven flooding, which can produce extensive erosion and catastrophic damage of coastlines (Butman et al., 1979; Chang, 2001). The US Northeast is severely affected by both extratropical (e.g. nor'easters) and tropical cyclones (e.g. hurricane), and therefore is vulnerable to coastal floods and waves (Colle et al., 2008; Herrington and Miller, 2010). Vulnerability to these storms and their effects on coastal beaches, buildings and infrastructure in the US Northeast has increased enormously in recent years, owing to the quick growth in coastal population and property (Keim et al., 2004).

The abovementioned cyclones (i.e., extratropical and tropical) differ in their timing, track, and impact on the nearshore region (Dolan and Davis, 1992). While tropical cyclones (TCs) typically can be more intense, extratropical cyclones (ETCs) are more frequent and have longer

Abbreviations: ADCIRC, ADvanced CIRCulation model; ETCs, Extratropical Cyclones; GLERL, Great Lakes Environmental Research Laboratory; HPC, High Performance Computing; NACCS, North Atlantic Coast Comprehensive Study; NOAA, National Oceanic and Atmospheric Administration; NDBC, National Data Buoy Center; OBC, Offshore Boundary Condition; OGCMs, Ocean General Circulation Models; OWI, OceanWeather Inc.; POM, Princeton Ocean Model; RMSE, Root Mean Square Error; sECOM, Stevens institute Estuarine & Coastal Ocean hydrodynamic Model; SFAS, Stevens Flood Advisory System; SNAP, Stevens Northwest Atlantic Predictions; SWL, Still Water Level; TCs, Tropical Cyclones; WIS, Wave Information Study.

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Nomenclature

C_p	phase velocity
D	water depth
H_s	significant wave height
k	wavenumber
N	number of observations
$\overline{O}_m$	experimental mean value
O_i	experimental values
P_i	predicted values
T_G, T_{avg}	GLERL and MDO average wave periods, respectively
ρ_0	reference density
σ	frequency
θ	wave direction
E_θ	directional spectrum of kinematic wave energy
E_T	total kinematic wave energy
γ	empirical breaker parameter

duration such that they can extend over multiple tidal cycles. ETCs are large, powerful systems and have an important, non-negligible influence on the seasonality and intensity of flood risk in the US Northeast (Orton et al., 2012, 2016). Because of their large wind fetch and waves, ETCs can drive coastal erosion of a similar or greater magnitude than TCs (Hondula and Dolan, 2010).

A useful tool for better understanding of coastal impacts of ETCs is numerical modeling. Generally, three main types of numerical models are employed for hydrodynamic simulations for extratropical storm events (Mellor, 2003; Xie et al., 2016): (i) ocean general circulation models (OGCMs) or tide-surge models (Bernier and Thompson, 2007) (ii), wind wave models (Panchang et al., 2008), and (iii) coupled wave models and ocean circulation models (Chen et al., 2013). While OGCMs are the most advanced tools existing for simulating the ocean motions, it is crucial to couple wave and ocean models for momentum exchange between surface waves and currents (Donelan et al., 2012). Three different generations of wave models have been used to simulate wave motions during storms (SWAMP, 1985; Booij et al., 1999): (i) first-generation models that do not consider nonlinear wave interactions, where processes of wave generation and dissipation are not properly represented (e.g., VENICE model (Cavaleri and Rizzoli, 1981), (ii) second-generation models that parameterized wave interactions (e.g., SAIL model (Greenwood et al., 1985)) and are usually supplemented with freely propagating swell, and (iii) third-generation models that include most of physical aspects of wave motions in 2D (e.g., SWAN model (Booij et al., 1999)).

Several researchers have investigated the ocean surface waves during the storms in the East Coast of US. Cardone et al. (1996) applied four spectral wave models (OWIIG, Resio2G, WAM4, and OWI3G) to the western North Atlantic basin using meteorological reanalysis data. They evaluated wave height and dominant wave period and suggested that further study is required to isolate the contribution of wind field errors, and model physics and numeric to the prediction of hydrodynamic characteristics under extreme storms. Xie et al. (2016) investigated the hydrodynamic response for ETC in the Gulf of Maine using SWAN and ADCIRC models. They postulated that the storm surges and waves simulations in the area are challenging because of the nonlinearity of surge-wave interactions, and the effects of wave action on coastal damage. Jensen et al. (2016) studied regional wave modeling and evaluation for the North Atlantic Coast Comprehensive Study (NACCS) using WAM model and concluded that WAM, generally, provided accurate wave estimations. Orton et al. (2012, 2016) conducted model validation, physical process experiments, and flood hazard assessment for historical and hypothetical tropical and extratropical storm tide events in the New York (NY) Bight region. The spatial structure, and directional spectrum of hurricane-induced ocean waves using a coupled atmosphere–wave–ocean model (UWIN-CM) and observations in the Northeastern Atlantic were examined by Chen and Curcic (2016). Their results showed that waves near landfall become more multifaceted than in the open ocean because of the variations in water depth and wind fields that are based on storm characteristics. Their results show that there remain many challenging aspects for simulating storms near landfall. Hitherto, none of the existing numerical models can accurately calculate all hydrodynamic characteristics during ETCs (Xie et al., 2016).

Wave modeling is a vital tool for operational flood forecasting systems such as Stevens Flood Advisory System (http://stevens.edu/SFAS). These systems provide information of meteorological and oceanographic conditions in real-time as well as in forecasts of up to several days. Probabilistic flood forecasting requires simulation of an ensemble of possible events, requiring hundreds of simulations per hour, and *rapid* hydrodynamic/wave modeling can be valuable if it is accurate. Even though third-generation wave models can simulate the detailed wave fields, simplified wave models exist like the Great Lakes Environmental Research Laboratory (GLERL) model and the MDO model, which are as a result less computationally expensive for wind wave predictions (Lin et al., 2002). As these models are currently either in use or candidate models for forecasting and hazard assessment, a comprehensive validation is warranted to quantify model accuracy.

In this study, the coupling between a well-established ocean model (sECOM) and rapid wave solvers for the US Northeast under ETCs is used and the wave model is validated. Then the validated wave model is applied to investigate how historical storms' waves have varied, back to the 1930s. A sensitivity analysis is also carried out to assess the effects of a few important model parameters on the model performance. In addition to a parametric model wave model (GLERL), that has been used in the New York Harbor Observing and Prediction System, NYHOPS, a new fast wave model (i.e., MDO) is evaluated. In comparison to the GLERL model, MDO includes more comprehensive spectral wave physics, swell propagation, and contains wave-induced radiation stress. The numerical results of sECOM and wave models are compared with the available field observations of National Data Buoy Center (NDBC) that were produced by National Oceanic and Atmospheric Administration (NOAA).

The model formulation and numerical scheme are briefly discussed in Section 2. Section 3 of the paper consists of a presentation and discussion of the numerical results, including model validation, sensitivity analysis and the demonstration of the model performance on the observational measurements for historical ETCs. Section 4 concludes the paper.

2. Model descriptions

In this study, we use a hydrodynamic model coupled with two different wave models that are described in Section 2.1. The hydrodynamic model is the three-dimensional Stevens Institute Estuarine and Coastal Ocean hydrodynamic Model (sECOM). The sECOM model (Blumberg et al., 1999; Blumberg and Georgas, 2008; Georgas, 2010) has been developed based on the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) and its version for shallow-water environment, ECOMSED model (Blumberg et al., 1999).

Here, the coupled model is applied on the Stevens Northwest Atlantic Predictions (SNAP) domain, on which it has recently been used and validated for hurricanes and ETCs with good accuracy (Georgas et al., 2016; Orton et al., 2016). SNAP covers the area from the Gulf of St. Lawrence to Cape Hatteras (about 1800 km alongshore) and about 1200 km offshore (Fig. 1). This domain is chosen to capture the large wind fetch from Mid-Atlantic Bight out to the Nova Scotia shelf during nor'easters. The size of all grid cells are constant, at 6 km by 4 km.

2.1. Wave models

Second and third-generation wave models consider more physical processes compared to first-generation wave models, and therefore these