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Integration of coastal inundation modeling from storm tides to individual waves

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ABSTRACT

Modeling of storm-induced coastal inundation has primarily focused on the surge generated by atmospheric pressure and surface winds with phase-averaged effects of the waves as setup. Through an interoperable model package, we investigate the role of phase-resolving wave processes in simulation of coastal flood hazards. A spectral ocean wave model describes generation and propagation of storm waves from deep to intermediate water, while a non-hydrostatic storm-tide model has the option to couple with a spectral coastal wave model for computation of phase-averaged processes in a near-shore region. The ocean wave and storm-tide models can alternatively provide the wave spectrum and the surface elevation as the boundary and initial conditions for a nested Boussinesq model. Additional surface-gradient terms in the Boussinesq equations maintain the quasi-steady, non-uniform storm tide for modeling of phase-resolving surf and swash-zone processes as well as combined tide, surge, and wave inundation. The two nesting schemes are demonstrated through a case study of Hurricane Iniki, which made landfall on the Hawaiian Island of Kauai in 1992. With input from a parametric hurricane model and global reanalysis and tidal datasets, the two approaches produce comparable significant wave heights and phase-averaged surface elevations in the surf zone. The nesting of the Boussinesq model provides a seamless approach to augment the inundation due to the individual waves in matching the recorded debris line along the coast.

1. Introduction

The implementation of circulation models for storm surge computation has greatly improved the capability to predict coastal inundation due to extratropical and tropical cyclones (Kowalik, 1984; Jelesnianski et al., 1992; Westerink et al., 1992). These models, which describe the current and surface elevation from atmospheric pressure and wind forcing, have extensive applications in engineering design, hazard assessment, and weather forecasting. Superposed on the storm surge are surface gravity waves that can reach 40 m height near the center of a tropical cyclone (Wang et al., 2005). Such energetic waves have significant implications for modeling of coastal flood hazards and assessment of infrastructure vulnerability. Acknowledgment of the influence of tropical cyclone waves has led to implementation of spectral wave models in storm surge computation (e.g., Ozer et al., 2000; Sheng et al., 2010; Dietrich et al., 2011). These phase-averaged models account for wave energy dissipation in the surf zone through parameterization of the processes (e.g., Booij et al., 1999). The resulting radiation stress provides additional forcing in the storm surge model to produce a further increase of the near-shore water level known as wave setup.

The impact of the individual waves can be more significant than their phase-averaged effects in areas with steep near-shore bathymetry. This can be illustrated by the landfall of Hurricane Iniki on the Hawaiian Island of Kauai in 1992. The tide gauge reading at the eye shows 1.64 m above the Mean Sea Level (MSL), but the floodwater reached the 9-m elevation contour in the general area (Chiu et al., 1995). Observations of the damage and debris suggest energetic storm waves propagate on an elevated water surface due to the storm tides, overtop the dune systems, and inundate large swaths of low-lying coastal land. Cheung et al. (2003, 2007) and Kennedy et al. (2012) provide a more realistic account of the flood event by simulating phase-resolving surf and swash-zone processes on a storm-tide level using a Boussinesq model. The initial water level is based on output from a circulation model and is applied uniformly within the computational domain. However,

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wind setup can substantially increase the water level across shallow fringing reefs (Demirbilek et al., 2007). Shallow lagoons and jagged shores produce localized increase of wind setup that might negate the use of a uniform water level to represent the coastal storm surge. The capability to appropriately account for the variation of storm surge across the surf zone and along the coast is important for tropical coastal environments.

The present paper describes the linkage of circulation, spectral wave, and Boussinesq models in nested computational schemes that include spatial variation of the surge in modeling of both phase-averaged and phase-resolving wave processes. In contrast to the earlier work of Cheung et al. (2003, 2007), the selected numerical models have been validated with laboratory and field measurements pertaining to tropical island environments characterized by steep insular slopes and shallow fringing reefs. Sections 2 and 3 describe the model components, environment datasets, and the nesting schemes. Important features not considered in the earlier work include the use of global reanalysis and tidal datasets to define the background tide, wind, and wave conditions; coupling between the circulation and spectral coastal wave models; and an adaptation of the Boussinesq model to compute wave transformation over a non-uniform still-water surface. Section 4 summarizes the data and impact of Hurricane Iniki, reconstruction of the surface wind field, and development of the nested computational grids for the case study. Section 5 describes implementation of the model system to reproduce the storm tides, waves, and inundation on the south shore of Kauai. The recorded water levels and debris lines from Chiu et al. (1995) allow validation of the proposed scheme for phase-resolving processes and demonstration of its versatilities in comparison to phase-averaged approaches. In Section 6, we provide a summary of the findings and their implications for coastal flood hazard mapping.

2. Model components

Storm-induced coastal inundation is attributed to combined effects of tides, surges, and waves over a broad range of spatial and temporal scales. These physical processes have little interaction in the open ocean, but are inherently connected near the shore. Fig. 1 illustrates the interaction of these processes through a hierarchy of variables. The MSL defines the water depth d and provides the reference for the phase-averaged surface elevation ζ, which increases toward the shore. Storm waves propagate on the elevated still-water surface defined by ζ with phase-resolving perturbations denoted by η. The scale difference allows the use of a nesting scheme to describe the physical processes and their coupling through a package of interoperable models. These include the circulation model NEOWAVE (Non-hydrostatic Evolution of Ocean Wave) of Yamazaki et al. (2009, 2011), the spectral wave models WAVEWATCH III of Tolman (2008) and SWAN (Simulation Wave Nearshore) of Booij et al. (1999), and the Boussinesq Ocean and Surf Zone (BOSZ) model of Roeber and Cheung (2012a). This section summarizes the model components as well as their adaptation to facilitate interoperability in the model package.

2.1. Non-hydrostatic circulation model

NEOWAVE builds on the nonlinear shallow-water equations with a vertical velocity term to account for flows over steep slopes and weakly-dispersive waves (Yamazaki et al., 2009, 2011). It was originally developed for tsunami modeling and has been validated with current and surface elevation measurements from the 2011 Tohoku tsunami around the Hawaiian Islands (Cheung et al., 2013). We augment the governing equations to include the surface pressure p_a, the surface wind stress (τ_ξ, τ_ψ) from Garratt (1977), and the radiation stress $(S_{\xi\xi}, S_{\xi\psi}, S_{\psi\psi})$ from SWAN for storm surge and wave setup modeling. The boundary-value problem is defined by a spherical coordinates system (ξ, ψ, z), in which ξ is longitude, ψ is latitude, and z denotes normal distance from MSL. Let R, g, and ρ denote the earth radius, gravitational acceleration, and water density; and n the Manning coefficient accounting for bed roughness. The variation of the flow over time t follows the ξ, ψ, and z-momentum equations and the continuity equation as

$$\begin{aligned}
&\frac{\partial U}{\partial t} + \frac{U}{R\cos\psi}\frac{\partial U}{\partial \xi} + \frac{V}{R}\frac{\partial U}{\partial \psi} - \left(2\Omega + \frac{U}{R\cos\psi}\right)V\sin\psi \\
&\quad = -\frac{g}{R\cos\psi}\frac{\partial \zeta}{\partial \xi} + \frac{\tau_\xi}{\rho D} - \frac{1}{2}\frac{1}{R\rho\cos\psi}\frac{\partial q}{\partial \xi} - \frac{1}{2}\frac{q}{D\rho R\cos\psi}\frac{\partial(\zeta - d)}{\partial \xi} \\
&\qquad - n^2\frac{g}{D^{1/3}}\frac{U\sqrt{U^2+V^2}}{D} - \frac{1}{R\cos\psi}\frac{\partial}{\partial \xi}\left(\frac{p_a}{\rho}\right) \\
&\qquad - \frac{1}{D\rho}\left(-\frac{1}{R\cos\psi}\frac{\partial S_{\xi\xi}}{\partial \xi} - \frac{1}{R}\frac{\partial S_{\xi\psi}}{\partial \psi}\right)
\end{aligned} \tag{1}$$

$$\begin{aligned}
&\frac{\partial V}{\partial t} + \frac{U}{R\cos\psi}\frac{\partial V}{\partial \xi} + \frac{V}{R}\frac{\partial V}{\partial \psi} + \left(2\Omega + \frac{U}{R\cos\psi}\right)U\sin\psi \\
&\quad = -\frac{g}{R}\frac{\partial \zeta}{\partial \psi} + \frac{\tau_\psi}{\rho D} - \frac{1}{2}\frac{1}{\rho R}\frac{\partial q}{\partial \psi} - \frac{1}{2}\frac{q}{D\rho R}\frac{\partial(\zeta - d)}{\partial \psi} - n^2\frac{g}{D^{1/3}} \\
&\qquad \times \frac{V\sqrt{U^2+V^2}}{D} - \frac{1}{R}\frac{\partial}{\partial \psi}\left(\frac{p_a}{\rho}\right) \\
&\qquad + \frac{1}{D\rho}\left(-\frac{1}{R}\frac{\partial S_{\psi\psi}}{\partial \psi} - \frac{1}{R\cos\psi}\frac{\partial S_{\xi\psi}}{\partial \xi}\right)
\end{aligned} \tag{2}$$

$$\frac{\partial W}{\partial t} = \frac{q}{\rho D} \tag{3}$$

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R\cos\psi}\frac{\partial(UD)}{\partial \xi} + \frac{1}{R\cos\psi}\frac{\partial(V\cos\psi D)}{\partial \psi} = 0 \tag{4}$$

where (U, V, W) is the depth-averaged velocity, q is the non-hydrostatic pressure, and $D = d + \zeta$ is the flow depth defined in Fig. 1.

A semi-implicit, finite difference scheme integrates the continuity equation for ζ and the horizontal momentum equations for U

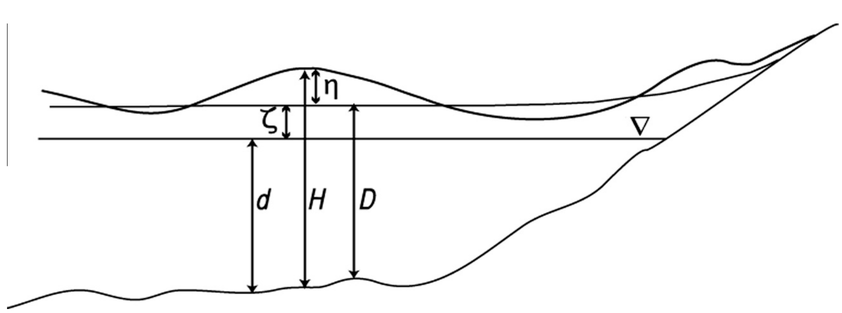

Fig. 1. Definition sketch of storm tide and wave inundation.