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Evaluation of wave runup predictions from numerical and parametric models

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ABSTRACT

Wave runup during storms is a primary driver of coastal evolution, including shoreline and dune erosion and barrier island overwash. Runup and its components, setup and swash, can be predicted from a parameterized model that was developed by comparing runup observations to offshore wave height, wave period, and local beach slope. Because observations during extreme storms are often unavailable, a numerical model is used to simulate the storm-driven runup to compare to the parameterized model and then develop an approach to improve the accuracy of the parameterization. Numerically simulated and parameterized runup were compared to observations to evaluate model accuracies. The analysis demonstrated that setup was accurately predicted by both the parameterized model and numerical simulations. Infragravity swash heights were most accurately predicted by the parameterized model. The numerical model suffered from bias and gain errors that depended on whether a one-dimensional or two-dimensional spatial domain was used. Nonetheless, all of the predictions were significantly correlated to the observations, implying that the systematic errors can be corrected. The numerical simulations did not resolve the incident-band swash motions, as expected, and the parameterized model performed best at predicting incident-band swash heights. An assimilated prediction using a weighted average of the parameterized model and the numerical simulations resulted in a reduction in prediction error variance. Finally, the numerical simulations were extended to include storm conditions that have not been previously observed. These results indicated that the parameterized predictions of setup may need modification for extreme conditions; numerical simulations can be used to extend the validity of the parameterized predictions of infragravity swash; and numerical simulations systematically underpredict incident swash, which is relatively unimportant under extreme conditions.

1. Introduction

Hurricanes and other large storms can cause extensive changes to coastal topography, including shoreline erosion, destruction of protective dunes, creation of large overwash deposits, and opening of new inlets. These changes can have a profound impact on coastal environments and may increase coastal vulnerability to future storms. The type and magnitude of barrier island response to storms is dependent, in part, on the interactions between beach morphology and the oceanographic forces associated with waves and storm surge. The shoreline manifestation of these forces is wave runup, which can, in general, be estimated from knowledge of offshore wave height and period (or wave spectra) and nearshore topography, including the slope of the intermittently wet and dry foreshore (Bowen et al., 1968; Kobayashi et al., 1990; Reniers et al., 2002). Using data sets with numerous observations of offshore wave conditions and synchronous runup measurements, empirical parameterizations have been developed to predict the magnitude of runup and its components, setup and swash (Holman, 1986; Nielsen and Hanslow, 1991; Ruessink et al., 1998; Ruggiero et al., 2004; Stockdon et al., 2006). The Stockdon et al. (2006) parameterization (hereinafter referred to as S2006) in particular has been shown to support skillful predictions of coastal changes in the vicinity of hurricane landfall (Plant and Stockdon, 2012; Stockdon et al., 2007), despite not having been originally formulated using storm conditions. However, the accuracy of parameterized swash and setup during extreme storm conditions has not been examined. Evaluating the S2006 parameterization under extreme storm conditions, when observational data are typically unavailable, requires a new approach.

The S2006 parameterizations were determined by fitting a large number of observations to a statistical model based on observed offshore significant wave height (H), dominant wave period, and foreshore beach slope (β). The parameterizations are

$$\overline{\eta} = 0.35\,\beta\,\sqrt{HL}, \tag{1a}$$

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$$S_{in} = 0.75\,\beta\,\sqrt{HL}, \text{and} \tag{1b}$$

$$S_{ig} = 0.06\,\sqrt{HL}, \tag{1c}$$

where $\overline{\eta}$ is the wave setup, defined as the time-average of the non-tidal water level fluctuations at the shoreline. S_{in} and S_{ig} are the significant swash heights in the incident (frequency > 0.05 Hz) and infragravity bands (frequency < 0.05 Hz), respectively, defined as four times the standard deviation of the water levels within each frequency band. Wave length (L) is computed from local wave period. Local wave height is reverse shoaled to deep water to obtain an estimate of offshore wave height (H). The coefficients estimated as part of the parameterization development were based on observations from a restricted range of conditions (Stockdon and Holman, 2011). Specifically, the maximum offshore wave height was 4 m; therefore, the parameterization does not include extreme conditions associated with major storms or hurricanes when wave heights reach 7 m or more (Doran et al., 2013; Stockdon et al., 2012, 2013).

The importance of understanding and quantifying the accuracy of runup predictions under extreme conditions is twofold. First, the predictions of sediment transport in detailed numerical models and of morphologic change in statistical approaches are based on calibration. We want to know if these calibrations are correcting for underlying prediction errors in hydrodynamic processes. Second, the predictions of extreme water levels that include wave runup are required for more accurate assessments of coastal hazards (Stockdon et al., 2012). Wave-induced water levels can be a direct threat to people, infrastructure, and ecosystems; however they are not routinely included in the analysis of coastal hazards in, for instance, the weather forecasting community. Understanding the accuracy of runup predictions during extreme wave events will help to inform and improve assessments of potential hazards to people and wildlife that build communities (e.g., roads, houses, nests) in dynamic coastal environments that shift and change with each storm.

Wave runup processes are not easy to measure, particularly under extreme conditions. Powerful wave forces and significant beach change can damage observing equipment or introduce uncertainty in the underlying topographic elevations needed to understand the runup processes. One approach to circumventing observational challenges is to numerically simulate runup. This has been done using the XBeach model, which couples runup to sediment transport and dune erosion (Roelvink et al., 2009). The model does not resolve incident-frequency motions but directly computes setup and low-frequency wave motions which tend to dominate the runup processes during dissipative storm conditions (Roelvink et al., 2009; Ruggiero et al., 2004; Thornton and Guza, 1982). Model predictions have been compared to observed beach and dune changes to test the accuracy of the coupled runup and sediment transport formulations with skillful results (McCall et al., 2010; Roelvink et al., 2009; Splinter and Palmsten, 2012).

In order to use XBeach to simulate storm waves and runup for the purpose of extending runup parameterizations to more energetic wave conditions, the accuracy of the modeled runup must be evaluated. Here, we conduct a comparison and sensitivity study to assess the accuracy of XBeach runup predictions across a range of conditions that have corresponding runup measurements. The objective is to evaluate the model skill at predicting setup, incident swash, and infragravity swash. Then, using this information, we can test the application of the S2006 parameterizations to extreme conditions and compare them with numerical simulations. Finally, we present a methodology for improving statistical parameterizations based on assimilating model results and observations.

2. Methods

XBeach runup predictions were evaluated using data from the SandyDuck field experiment (Stockdon and Holman, 2011) at the U.S. Army Corps of Engineers Field Research Facility (FRF) located in Duck, NC, in October 1997. Runup data were collected over a 9-day period between October 16 and 24. These data have been presented elsewhere (e.g. Stockdon et al. (2006)), hence, we provide only a brief summary and then describe the XBeach model and runup extraction.

2.1. Observations

Daily beach surveys during the SandyDuck experiment provided the bathymetry for XBeach and foreshore beach slope in the S2006 parameterizations (Fig. 1). Wave height from the FRF Waverider buoy, located offshore in approximately 17 m water depth, was reverse shoaled to deep water and used as input in the parameterized model (Eqs. 1a, 1b, 1c). Wave spectra collected at the FRF 8-m array (Fig. 1) provided the offshore wave-boundary condition data for XBeach (Fig. 2). Waves measured from a cross-shore array of pressure sensors in 0–5 m water depth, between the shoreline and the 8-m array, (Raubenheimer et al., 2001) were used to evaluate XBeach simulated surf zone wave transformation. A tide gauge located at the end of the FRF pier was used for defining tide levels in XBeach (Fig. 2). Observed tide levels were removed from both the modeled and observed runup in order to focus on the wave driven processes.

Observed runup time series were extracted at six alongshore locations (Fig. 1) from video images (Fig. 3). This analysis produced 50 17-minute runup time series over the study period. Collection times are shown in Fig. 2. Each 17-minute time series was analyzed to extract setup and significant incident and infragravity swash. (See Stockdon et al. (2006) for more detail.)

2.2. Model simulations

Water levels at the shoreline were modeled using XBeach (v18), which solves coupled two-dimensional (2-d), depth-averaged equations for short-wave envelope propagation and flow for varying spectral wave and flow boundary conditions (Roelvink et al., 2009). The low-frequency wave motions interact and evolve to produce both low-frequency and, due to nonlinear behavior, some incident-frequency swash (Fig. 4b). Incident waves are dissipated due to breaking and are expected to vanish when the depth is zero. Sediment transport and morphology changes were not included in the simulations. In our case, the 2-d model spanned 380 m in the alongshore and about 800 m in the cross-shore (Fig. 1). The alongshore resolution was 10 m, and the cross-shore resolution varied from 0.5 m in the swash region to 8 m at the offshore boundary. Bathymetry was derived from daily survey data which were interpolated to the XBeach domain using a smoothing method that adapted to the grid resolution (Plant et al., 2002). Direction-frequency wave spectra from the 8-m array were applied to the offshore boundary of the model domain. Water levels from the tide gauge at the end of the FRF pier were applied uniformly to the offshore boundary. The lateral boundaries of the domain were treated as Neumann or no-gradient boundaries. All Xbeach parameters were set to default values except for the wave breaking parameter γ, which was set to 0.42. Details of model sensitivity to wave breaking parameters are described in Section 4.1.

The XBeach model can also be implemented in a horizontally one-dimensional (1-d) domain (i.e., along a single cross-shore transect) where alongshore uniformity is assumed. The 1-d approach has several advantages, including faster simulation times and reduction of required alongshore bathymetric detail. Because the alongshore components of bathymetry, wave groups, and swash are not fully resolved, it is expected that 1-d simulations will produce different swash levels than the 2-d simulations. When implemented in 1-d, separate XBeach domains were defined along each of the six video-based runup measurement lines, while using the same offshore wave and water level boundary conditions as in the 2-d simulations. The sensitivity of wave runup to the choice of dimensional space used in the model will be evaluated in later sections.