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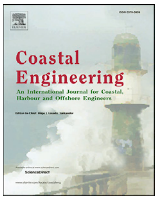

Assessing the impact of extreme storms on barrier beaches along the Atlantic coastline: Application to the southern Rhode Island coast

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ABSTRACT

In this work, we use the 2D model XBeach to dynamically simulate coastal erosion due to a synthetic 100-year storm impacting a typical North Atlantic barrier beach located in southern RI. This storm was extracted from the North Atlantic Coast Comprehensive Study (NACCS) database, based on results of an extreme value analysis of more than 1000 NACCS storms. XBeach parameters are first calibrated/validated by simulating Hurricane Irene (August 2011), for which both nearshore wave data and pre- and post-storm beach profiles were available in the study area. Comparing results to observations allowed calibration of the wave asymmetry and skewness parameter ($\gamma_{u_a} = 0.3$) in the model, resulting in a 6% mean relative error between the simulated and measured subaerial eroded volumes along 4 transects. In the 100-year storm XBeach simulations that include overwash, effects of land cover on beach erosion, in particular vegetation, are assessed by specifying a spatially varying bed friction function of high-resolution land cover. Results show that healthy back-dune vegetation is essential to prevent the dune crest from being fully eroded down to its toe level.

The predicted median 100-year eroded volume is 46 m^3/m for the entire barrier beach, in good agreement with FEMA's empirical value of 50 m^3/m at the two “official 1D transects” within the study area; mean post-storm reductions in dune crest elevations are in similar agreement. The model, however, predicts very large alongshore variations of these parameters, with eroded volumes over 1000 m^3/m where breaching and the opening of surge channels occurs. Overall, dune segmentation simulated in the model for the 100-year storm appears to be realistic and consistent with dune topography and land cover. XBeach thus provides an improved 2D methodology for assessing the impact of extreme storms on Atlantic barrier beaches, predicting changes in dune morphology, and quantifying the protective role of vegetation, and effects of land cover in general.

1. Introduction

Although there is significant uncertainty in assessing the coastal impact of future extreme storms, particularly in combination with Sea Level Rise (SLR) projections, there is a consensus in the coastal engineering community that inundation from large storms will increase over the next century along the U.S. Atlantic coast (Bender et al., 2010; Woodruff et al., 2013). In particular, in the Atlantic basin, models predict a doubling of the frequency of category 4 and 5 storms, with the largest increase occurring in the Western Atlantic, north of 20 degrees of latitude (Bender et al., 2010). In the U.S., these predictions have motivated regional and local efforts to reevaluate the extreme storm hazard [e.g., Jensen et al., 2016; Orton et al., 2016; Spaulding et al., 2017; Xian et al., 2015], to assess the resilience of coastal communities to extreme storms [e.g., Grilli et al., 2017b; Lin et al., 2012]. In this context, barrier beaches, with their persistent dune system, have been shown to offer critically important protection to many communities along the mid- and southern Atlantic states' coastline. In particular, the main parameters controlling the response of barrier beaches to extreme storms are the foredunes' sand reservoir and elevation relative to storm surge level [e.g., Houser et al., 2008; Morton and Sallenger, 2003; Sallenger, 2000]. Additionally, the back dune vegetation coverage is critical for limiting landward wave propagation [e.g., McKee Smith et al., 2016; Möller et al., 2014].

The Federal Emergency Management Agency's (FEMA) Flood Insurance Rate Maps (FIRMs) (FEMA, 2012) primarily serve to set property insurance rates and provide inundation limits with a 100-year return

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period, or a 1% annual probability of occurrence. In Rhode Island (RI) FEMA's methodology to develop the latest FIRMs is based on applying a one-dimensional (1D) phase-averaged nearshore wave model, in which storm waves are propagated over a static storm surge along selected cross-shore transects. In view of the increasing hazard from extreme storms, the accuracy and relevance of using a 1D methodology should be assessed, particularly in areas with complex coastlines and/or bathymetry where wave refraction can be important and focus (or defocus) wave energy on some sections of the coast. In earlier work (Grilli et al., 2017a, 2017b; Spaulding et al., 2017), this has led some of the authors to develop alternative flood maps for RI using the two-dimensional (2D) model STWAVE (Steady State Spectral Wave) (McKee Smith et al., 1999; Massey et al., 2011) to simulate wave propagation over a static water level combining storm surge and tide. To do so, the wave and storm surge characteristics of a local 100-year synthetic storm were extracted from results of the North Atlantic Coast Comprehensive Study (NACCS; Jensen et al., 2016; Nadal-Caraballo et al., 2015), in which the U.S. Army Corps of Engineers simulated over 1000 storms and saved time series of results at many offshore “save points”. In coastal areas with a protective barrier beach, storm impact was evaluated over a predefined empirical profile approximating the expected 100-year post-storm eroded beach/dune profile, based on historical data and field measurements (Oakley, 2016). Details of this earlier study, referred to as NAST (as it combined NACCS and STWAVE), can be found in (Grilli et al., 2017a, 2017b; Spaulding et al., 2017).

In FEMA's standard FIRM methodology along Atlantic open coasts, which are mostly made of sandy beaches, a predefined eroded beach/dune profile is assumed based on an empirical erosion protocol applied along 1D cross-shore transects, referred to as the “540-square-foot” protocol (Coulton et al., 2005). In this method, if the dune frontal sand reservoir, measured as the cross-shore area A_d above the 100-year Still Water ELevation (SWEL), is less than a critical value, $A_d \leq 540\ \mathrm{ft}^2$ (or a volume of 50 m^3/m of coast), material is removed from the dune above a theoretical line drawn landward at a 1:50 slope from the dune toe (junction between the relatively flat seaward region of the back-beach berm and the steeper slope of the dune's face). In contrast, if $A_d > 540\ \mathrm{ft}^2$, a dune retreat protocol is applied. The 100-year SWEL is equivalent to the open coast flood elevation, often referred to as Still Water Flood Level (SWFL), and includes the storm surge and the astronomical tide, but not the wave set-up or runup (Judge et al., 2003). The critical value of A_d, approximating the median area that would be eroded above SWFL during a typical 100-year event, was derived from an analysis of pre- and post-storm profiles for 38 erosional events on Atlantic, Gulf of Mexico, and Dutch coasts (Hallermeier and Rhodes, 1989; Dewberry and Davis, 1988), yielding, $A_d\,[\mathrm{m}^2] = 8T_r^{0.4}$ (with T_r the storm return period in years). While A_d has been widely used as an erosion indicator, in particular because it is part of FEMA's official protocol, other authors have proposed alternative simple dune vulnerability indicators, such as Kriebel et al. (1997) intensity index, which relates storm surge, wave height, and storm duration to the eroded volume, or Judge et al. (2003) resistance index, which includes dune geometry.

Short-term morphological changes of barrier beaches associated with historical storms have been extensively studied using conceptual erosion models [e.g., Rosati and Stone, 2009], statistical analyses [e.g., Houser et al., 2008; Morton and Sallenger, 2003], artificial neural network methods [e.g., Hashemi et al., 2010], empirical swash formulations combined with field erosion assessments [e.g., Wang et al., 2006], and, more recently, physics/process-based numerical models [e.g., Cañizares and Irish, 2008; de Vet and Lodewijk, 2015; Harter and Figlus, 2017; Luijendijk et al., 2017; Lindemer et al., 2010; McCall et al., 2010; de Santiago et al., 2017]. In this paper, we use XBeach (“eXtreme Beach behavior”), a 2D physics-based model (Roelvink et al., 2009, 2010), to dynamically simulate short-term dune erosion on the southern RI coast (Fig. 1), an environment representative of Atlantic barrier beaches. We model erosion due to a synthetic 100-year storm event set to occur in the very near future (i.e., for current climate conditions). In the study, we particularly illustrate the mitigating effects of dune vegetation on storm-induced erosion. [Note that long-term morphological changes caused by erosion resulting from SLR [e.g., Bilskie et al., 2014, 2016; Passeri et al., 2015, 2016; Vitousek et al., 2017] were independently addressed in (Grilli et al., 2017b) and are not considered in this study.]

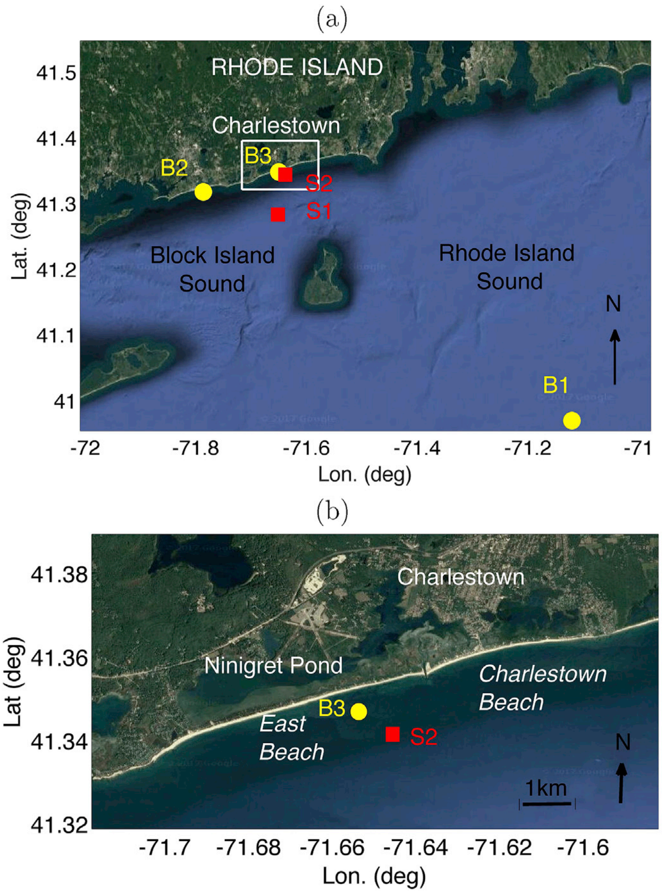

Fig. 1. (a) Footprint of study area (white box), with marked locations of wave buoys (Lon., Lat.): NOAA-44097 (−71.127, 40.999) (B1), Woods Hole (−71.79288, 41.31727) (Woods Hole Group, 2012) (B2 and (−71.65648, 41.34755) B3), and NACCS save points 9136 (S1) and 868 (S2) (Table 4); (b) close-up on study area showing the barrier beach system around Charlestown, RI. Satellite images are from Google Earth.

XBeach features a hydrodynamic model simulating mean currents in combination with a wave action conservation equation, and an embedded sediment transport and morphodynamic model, which describes storm-induced changes in bed level. It is beyond our scope to provide an exhaustive review of models used to simulate coupled nearshore hydrodynamics and sediment transport processes. A review of models prior to 2002 can be found in (Elfrink and Baldock, 2002); a review of more recent work, which led to the development of state-of-the-art physics/process-based models such as the 1D model CSHORE (Johnson et al., 2012; Figlus et al., 2012; Kobayashi, 2013) and XBeach (Roelvink et al., 2009), can be found in these references. In these models, in view of the complexity of processes involved (in particular nonlinearities and multiple time scales), sediment transport equations are typically simplified, including some empiricism, and time-averaged, consistent with the phase-averaged wave forcing. However, in more recent work, studies have moved towards developing sediment transport models coupled with phase resolving wave and hydrodynamic models, based on Boussinesq equations [e.g., Cobo et al., 2006; Kim, 2015; Long et al., 2008; Rahman and Keiko, 2012; Tehranirad, 2016].

An important feature of XBeach is its modeling of the long wave component of swash motions, the surf-beats, which are key hydrody-