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The influence of bed friction variability due to land cover on storm-driven barrier island morphodynamics

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ABSTRACT

Variations in bed friction due to land cover type have the potential to influence morphologic change during storm events; the importance of these variations can be studied through numerical simulation and experimentation at locations with sufficient observational data to initialize realistic scenarios, evaluate model accuracy and guide interpretations. Two-dimensional in the horizontal plane (2DH) morphodynamic (XBeach) simulations were conducted to assess morphodynamic sensitivity to spatially varying bed friction at Dauphin Island, AL using hurricanes Ivan (2004) and Katrina (2005) as experimental test cases. For each storm, three bed friction scenarios were simulated: (1) a constant Chezy coefficient across land and water, (2) a constant Chezy coefficient across land and depth-dependent Chezy coefficients across water, and (3) spatially varying Chezy coefficients across land based on land use/land cover (LULC) data and depth-dependent Chezy coefficients across water. Modeled post-storm bed elevations were compared qualitatively and quantitatively with post-storm lidar data. Results showed that implementing spatially varying bed friction influenced the ability of XBeach to accurately simulate morphologic change during both storms. Accounting for frictional effects due to large-scale variations in vegetation and development reduced cross-barrier sediment transport and captured overwash and breaching more accurately. Model output from the spatially varying friction scenarios was used to examine the need for an existing sediment transport limiter, the influence of pre-storm topography and the effects of water level gradients on storm-driven morphodynamics.

1. Introduction

Low-lying barrier islands are vulnerable to extreme morphologic change over short timescales as a result of storm events. Dune elevations regulate storm impacts (Sallenger, 2000; Stockdon et al., 2007; Long et al., 2014), which can be classified into four regimes: swash, collision, overwash and inundation (Sallenger, 2000). In the swash regime, water levels are confined to the foreshore, which causes minor sand erosion on the beach. In the collision regime, wave runup collides with the base of the dune, resulting in erosion of the dune face with sand transported offshore. As water levels continue to increase, wave runup can overtop the dune crest, causing erosion (typically a 30–85% reduction in elevation (Long et al., 2014)) with landward sand deposition. If water levels are high enough, the island will become inundated, which can induce water level gradients between the ocean and the bay that drive flow and sediment transport, and often result in breaches (Long et al., 2014; Sherwood et al., 2014; Harter and Figlus, 2017).

As coastal populations grow, predicting the response of coastlines is essential for guiding mitigation of future hazards. This requires a comprehensive understanding of the interactions between storms and coastal landscapes (Grzegorzewski et al., 2011). The process-based numerical model XBeach (Roelvink et al., 2009) is capable of predicting the morphologic response of barrier islands to specific storm events with high skill (Sherwood et al., 2014; Roelvink et al., 2009; McCall et al., 2010; Lindemer et al., 2010). Model performance depends on spatial and temporal model resolution (Lindemer et al., 2010), the accuracy of initial conditions (i.e., bathymetry/topography) (Lindemer et al., 2010), hydrodynamic forcing (Sherwood et al., 2014; Harter and Figlus, 2017; McCall et al., 2010), and the parameterization of physical processes (McCall et al., 2010; Elsayed and Oumeraci, 2017). McCall et al. (2010) determined that XBeach tends to overestimate erosion and overwash due to inaccurate calculations of sediment transport rates during sheet flow conditions. Therefore, a sheet flow sediment transport limiter was introduced to serve as a proxy for unknown factors that control resistance

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to erosion (McCall et al., 2010). Elsayed and Oumeraci (2017) further attributed the overestimation of erosion to the effect of wave nonlinearity on sediment transport as well as excess shear stress required to initiate sediment particle motion. The authors' explored how to better quantify the relationship between net flow due to wave skewness/asymmetry and beach slope, and account for grain stabilization. Lindemer et al. (2010) and Harter and Figlus (2017) acknowledged that the overestimation of overwash in their model simulations could be a result of not incorporating variable bed friction to capture the effects of vegetation or infrastructure; bed friction causes loss of fluid kinetic energy which slows surge propagation rates and attenuates overland surge amplitudes (Resio and Westerink, 2008; Garzon and Ferreira, 2016). In a preliminary study, De Vet et al. (2015) showed that applying a higher frictional coefficient to vegetated areas of a barrier island based on satellite imagery reduced the amount of dune erosion and overwash that XBeach predicted. However, there is a need for more thorough analysis to determine how to properly assign variable bed friction across topographic features on the scale of barrier islands in XBeach and confirm the model's ability to account for the effects of different land cover types (wetland, developed, forest, etc.) (Harter and Figlus, 2017).

This study primarily examines the influence of variable bed friction on morphologic change during two storm events using a 2DH (two-dimensional in the horizontal plane) XBeach model. Dauphin Island, AL was selected as the study area due to its variability in land cover and elevation, its substantial morphologic response during Hurricane Ivan in 2004 and Hurricane Katrina in 2005 (Morton, 2008), and the availability of data to initialize models and evaluate performance. To minimize error and isolate the effects of variable bed friction, the model was initialized using the best available lidar data and was forced with high-resolution wave and water level time-series that accurately describe storm characteristics. Three scenarios of bed friction were implemented to assess morphodynamic sensitivity during the two storms and the need for an existing sheet flow sediment transport limiter. Model accuracy was determined through a qualitative and quantitative comparison of observed and modeled bed level change and breach development for each scenario. The results from the sensitivity study were also used to evaluate the influence of errors in the pre-storm topography and the combined effects of variable bed friction and cross-island water level gradients on storm-driven morphodynamics.

2. Study domain

Dauphin Island, AL is a 25 km long, low-lying barrier island located between the Gulf of Mexico and the Mississippi Sound (Fig. 1). The wider eastern end of the island features higher dune elevations (2.5–3 m on average) and contains homes and infrastructure, including 2400 property owners and 1400 permanent residents (Five E's Unlimited, 2007). At the widest part of the eastern end, high dunes are backed by a maritime forest. The central and western segments of Dauphin Island are a narrow (minimum width of 169 m) Holocene sand spit backed by marshes (Morton, 2008). Dune elevations are generally less than 1.5 m, making this area susceptible to overwash during storm events. Historically, the middle of the island breached during tropical storm events dating back to 1851 and as recent as Hurricane Katrina (2005), which formed a breach approximately 2 km wide (Morton, 2008) (Fig. 6a).

3. Modeling approach

3.1. Model description

XBeach is a two-dimensional depth-averaged modeling software that resolves coupled short wave energy, flow and infragravity wave propagation, sediment transport and bed level change (Roelvink et al., 2009). The model code solves the nonlinear shallow water equations and incorporates time-varying wave action balance and roller energy balance. Sediment transport is calculated with a depth-averaged advection-diffusion equation (Galappatti and Vreugdenhil, 1985), in which an equilibrium sediment concentration determines increases or decreases in sediment concentration in the water column (Soulsby, 1997). The equilibrium sediment concentration is calculated with the Soulsby-van Rijn sediment transport formulation (Soulsby, 1997), which is not strictly valid for sheet flow conditions that may occur during the initial phases of dune overwash (Roelvink et al., 2009). Therefore, steady flow velocities are limited with an upper-bound Shields parameter (smax = 1.0) for the start of sheet flow (McCall et al., 2010).

XBeach incorporates bed friction associated with mean currents and long waves using the Ruessink et al. (2001) bed shear stress (τ_b) formulation:

Fig. 1. Study area; Dauphin Island, AL sits between the Mississippi Sound, Mobile Bay and the Gulf of Mexico.