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Numerical modeling of the morphodynamic response of a low-lying barrier island beach and foredune system inundated during Hurricane Ike using XBeach and CSHORE

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ABSTRACT

Follet's Island (FI) is a sediment-starved barrier island located on the Upper Texas Coast; a stretch of coastline along the Gulf of Mexico that experiences on average four hurricanes and four tropical storms per decade. During Hurricane Ike, water levels and wave heights at FI exceeded the 100-year and 40-year return values, respectively, leading to significant overtopping and morphology changes of this low-lying barrier island. The physical processes governing the real-time morphodynamic response of the beach and dune system during 96 h of hurricane impact were modeled using XBeach (2D) and CSHORE (1D). Hydrodynamic boundary conditions were obtained from ADCIRC/SWAN model runs validated with measured buoy and wave gauge data while LiDAR surveys provided pre- and post-storm measured topography.

XBeach displayed a decent model skill of 0.34 and provided numerical outputs of the entire 2D domain such as topography, suspended sediment load and bed load which was very useful in visualizing erosion and deposition patterns. CSHORE also displayed a decent model skill of 0.33 and was able to accurately predict the post-storm beach slope and shoreline, but was less effective at simulating the foredune morphology. Modeling results show that the complete morphodynamic response of FI to Hurricane Ike was governed by a sequence of impact regimes, including swash, collision, overwash, inundation, and storm surge ebb.

1. Background and motivation

In many places along the U.S. East and Gulf Coast, barrier islands are the first line of defense against extreme weather events threatening our coastlines. The morphological evolution of barrier islands depends on both long-term and short-term processes and is inherently linked to local sediment availability [19,43]. Many researchers have discussed long-term and short-term morphology changes of barrier islands with different focus areas (e.g. [27,34,42,11]), a detailed review of which is beyond the scope of this paper. Unfortunately, only limited data are available to quantify or predict the morphological evolution of barrier islands. The goal of this study is to better understand the dynamics of morphological changes in barrier island systems caused by extreme events since their compounding effects play a critical role in the long-term evolutionary trends of our coastlines and a better understanding of the governing processes will lead to improved coastal management strategies. As a case study, Follet's Island (FI), a sediment-starved barrier island along the Upper Texas Coast (UTC) is examined (Fig. 1).

The forcing conditions driving the morphodynamics of barrier islands during storms are characterized by four impact regimes as outlined by Sallenger [35]: swash, collision, overwash and inundation. During the swash regime, swash motions reach only as high as the dune toe, and sediment is pulled from the beach offshore. The collision regime is characterized by waves directly impacting and eroding the dune face. During the overwash regime, wave runup levels exceed the dune crest, allowing washover sediments to be deposited on the back side of the dune. Finally, during the inundation regime, the storm surge level exceeds the dune crest causing high velocity overwash flows and wave penetration to the back-bay.

Follet's island experienced all of these regimes during the passage of Hurricane Ike in 2008, including a prolonged collision regime due to a forerunner surge that preceded the storm surge [13]. Additionally, Follet's Island experienced significant morphological changes due to the ebbing storm surge after the hurricane made landfall. This additional morphodynamic forcing condition caused by gravity-driven flow from the bay to the ocean has been investigated by several researchers (e.g. [8,41,20,39,6]; and [36]). The significant gradient between bay and ocean water levels after passing of a storm can scour

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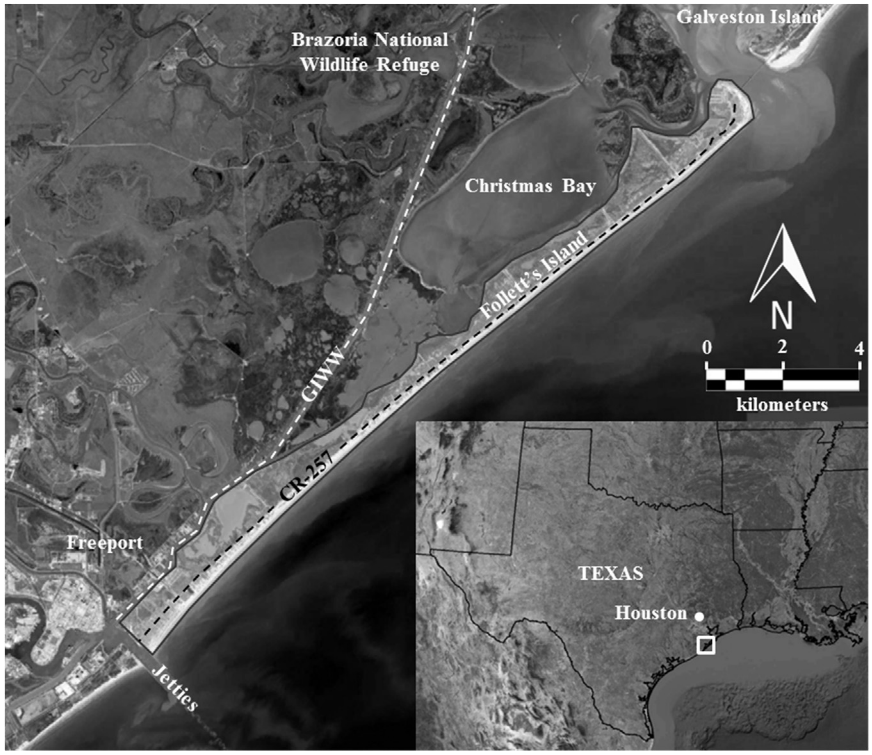

Fig. 1. Follet's island area map showing important economic assets such as the port of freeport, the Gulf Intracoastal Waterway (GIWW), and the CR-257 highway as well as ecological assets like Christmas Bay and the Brazoria National Wildlife Refuge.

previously deposited material and potentially affect the sediment budget of the beach-barrier-bay system due to this offshore sediment transport mechanism.

Storm surge at FI reached a peak storm elevation of 2.6 m NAVD88, which exceeded the 100-year high water level. This peak was preceded by a forerunner surge of about 1 m beginning approximately 18 h before landfall, after which the water level steadily rose to 2.2 m NAVD88 over the next 12 h. This flooded Christmas Bay and the back barrier region well before Ike made landfall. Waves offshore of FI exceeded 4.5 m significant wave height at 16 s peak period; roughly the 40-year wave conditions. After landfall, the water level quickly dropped to 2 m NAVD88 over the course of 12 h. The amount of inland flooding from the forerunner resulted in a strong ebb flow that scoured large channels in FI as the water dragged sediment back out to the gulf.

The UTC is characterized by a series of long, narrow barrier islands and barrier peninsulas comprised of fine sand, and a microtidal, wave-dominated hydrodynamic environment [22,25]. FI is one of the most vulnerable stretches of the UTC due to its lack of a major sediment source and high background erosion rates [28]. The island is approximately 25 km long, less than 500 m wide and 2.06 m in elevation (NAVD88), and contains a series of beach communities, including Treasure Island and Surfside. In addition, FI protects important economic and ecological assets like Christmas Bay, the Brazoria National Wildlife Refuge, the CR-257 Blue Water Highway, the Gulf Intracoastal Waterway (GIWW), and parts of the port of Freeport including the Naval Petroleum Reserve and an LNG de-liquification plant (Fig. 1).

In 1929, the Brazos River was rerouted 6.5 miles west of the Freeport jetties. The Brazos River was formerly a major sediment source for FI, and its rerouting in conjunction with damming upriver resulted in a sediment deficit on FI [22,26]. As a result, FI experiences high rates of background erosion due to cross- and alongshore transport, with shoreline retreat rates between −1.5 m/yr and −3.9 m/yr [28].

In this study we observe the impact of the hurricane on the subaerial morphology of FI comparing results from the coastal response numerical models, XBeach [31] and CSHORE [12,14]. While both numerical models utilize process-based techniques to compute short-term beach and dune morphology evolution, the two approaches differ greatly from each other. The motivation to compare results from these two inherently different model approaches to each other using a specific case study is manifold. Both numerical models have received funding for development through the U.S. Army Corps of Engineers MORPHOS project but to the authors' knowledge no direct comparison between them using field data has been published. Both models have become widely-used free-ware tools in academia, government agencies, and industry to assess storm impact on sandy coastline morphology. This comparative case study intends to highlight capabilities and shortcomings of both models using mostly default model parameters. Specifically, the trade-off between using a 2D model with greater spatial coverage and more resolved hydrodynamics but significantly higher computational cost versus a cross-shore depth-averaged probability-based model with only a fraction of the computational cost.

2. Numerical models

2.1. XBeach background

XBeach is a powerful numerical modeling tool developed for simulating the coastal response of sandy beach systems to time-varying storm conditions [30,31]. The model was built to simulate physical processes within different impact regimes of a storm as defined by Sallenger: (1) swash regime, (2) collision regime, (3) overwash regime, (4) inundation regime [35]. For resolving swash dynamics, the model incorporates a 2DH description of wave groups from the time-varying wave action balance. This wave-group forcing drives infragravity (IG) motions, including both longshore and cross-shore currents. In the collision regime, an avalanching model is used to transport sediment from the dune face (dry) to the swash zone (wet), incorporating the fact