Coastal Engineering 57 (2010) 985–995

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Numerical simulation of a low-lying barrier island's morphological response to Hurricane Katrina

C.A. Lindemer [a], N.G. Plant [b], J.A. Puleo [a,*], D.M. Thompson [b], T.V. Wamsley [c]

[a] Center for Applied Coastal Research, University of Delaware, United States
[b] U.S. Geological Survey, Saint Petersburg, FL, United States
[c] U.S. Army Corps of Engineers, Vicksburg, MS, United States

ARTICLE INFO

Article history:
Received 14 July 2009
Received in revised form 21 May 2010
Accepted 8 June 2010
Available online 14 July 2010

Keywords:
XBeach
Barrier Islands
Coastal processes
Hurricanes
Chandeleur Islands
Numerical modeling

ABSTRACT

Tropical cyclones that enter or form in the Gulf of Mexico generate storm surge and large waves that impact low-lying coastlines along the Gulf Coast. The Chandeleur Islands, located 161 km east of New Orleans, Louisiana, have endured numerous hurricanes that have passed nearby. Hurricane Katrina (landfall near Waveland MS, 29 Aug 2005) caused dramatic changes to the island elevation and shape. In this paper the predictability of hurricane-induced barrier island erosion and accretion is evaluated using a coupled hydrodynamic and morphodynamic model known as XBeach. Pre- and post-storm island topography was surveyed with an airborne lidar system. Numerical simulations utilized realistic surge and wave conditions determined from larger-scale hydrodynamic models. Simulations included model sensitivity tests with varying grid size and temporal resolutions. Model-predicted bathymetry/topography and post-storm survey data both showed similar patterns of island erosion, such as increased dissection by channels. However, the model under predicted the magnitude of erosion. Potential causes for under prediction include (1) errors in the initial conditions (the initial bathymetry/topography was measured three years prior to Katrina), (2) errors in the forcing conditions (a result of our omission of storms prior to Katrina and/or errors in Katrina storm conditions), and/or (3) physical processes that were omitted from the model (e.g., inclusion of sediment variations and bio-physical processes).

Published by Elsevier B.V.

1. Introduction

Low-lying barrier islands are susceptible to extreme damage during storm events due to large waves, storm surge and run up processes. Wave run up can scour the base of dunes leading to failure, while overwash can erode dune crests creating depositional fans on the landward side of the island (Sallenger, 2000; Stockdon et al., 2006). Inundation allows wind and wave-driven currents to alter erosion and deposition patterns over the entire island surface. A relationship has been determined between the relative height of the dune and storm-induced water levels to the vulnerability of beaches during storms such as hurricanes (Sallenger, 2000; Stockdon et al., 2006). Thus, low-lying coastlines, such as Louisiana, are at extreme risk during large storm events. The most catastrophic storm events are hurricanes that have increased in frequency since 1995, perhaps due to historical multi-decadal-scale cycles (Goldenberg et al., 2001). Morphological change caused by hurricanes accounts for up to 90% of shoreline retreat in Louisiana (Kahn, 1986), where foredune heights along the coastline are normally lower than 2 m (Stone et al., 1997).

One approach to predicting vulnerability is to perform numerical simulations for barrier island evolution. Several modeling approaches exist, including those that resolve geologic details of underlying sediment, but do not resolve individual storms (Cowell et al., 1995; Rosati et al., 2006; Stolper et al., 2005), to those that resolve the coupled interactions between topography, waves, currents, and sediment transport (Cañizares and Irish, 2008; Lesser et al., 2004; Roelvink et al., 2009; McCall et al., 2010). The detailed models can resolve variations in storm characteristics, be used to evaluate restoration scenarios and aide management decisions. In order for detailed models to be useful, it is important to demonstrate the realism of simulations of specific storm events. Simulations should correspond to sensible, if not quantitatively accurate, predictions of actual storm scenarios. Previous detailed models (Roelvink et al., 2009; Jiménez et al., 2006; McCall et al., 2010; van Thiel de Vries et al., 2008) have focused on barrier islands with relatively high dunes where storm-driven overwash is an important process. We are interested in extending detailed numerical predictions to relatively low-elevation barrier islands where inundation is a dominant process.

The Chandeleur Islands (Fig. 1, showing the northern portion of the islands), are part of the Breton National Wildlife Refuge, and are

* Corresponding author. Center for Applied Coastal Research, University of Delaware, Newark, DE 19716, United States. Tel.: +1 302 831 2440.
E-mail address: jpuleo@udel.edu (J.A. Puleo).

0378-3839/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.coastaleng.2010.06.004

located 161 km east of New Orleans, Louisiana. They form an 80 km long barrier island chain in the Gulf of Mexico and are oriented roughly north to south. The Chandeleurs are remnants of the St. Bernard Delta, formed by the Mississippi River. The islands are a significant feature in the gulf that may represent the fate of a dying barrier island; being one of the most rapidly receding island systems in the United States (Kahn, 1986). The topography in some areas is extremely low, with elevations in our focus region that were uniformly less than 2 m.

During the hurricane season of 2005, the islands were impacted by several hurricanes, most notably Hurricane Katrina. This hurricane is one of the costliest storms, in both fatalities and damage, to ever make landfall in the United States. It struck the Atlantic coast of Florida as Category 1 on the Saffir–Simpson Scale. It then crossed the Florida peninsula into the Gulf of Mexico and rapidly strengthened to Category 5, before making landfall as a Category 3 west of the Chandeleur Islands (Knabb et al., 2005). The high storm surge and strong waves resulted in island fragmentation with numerous breaches that exposed wetland once protected by beaches and dunes. Based on comparisons of lidar surveys, approximately 82% of the island area was lost between 2002, just after Hurricane Lili, and 2005, just after Hurricane Katrina (Sallenger et al., 2009).

Fig. 2 shows satellite imagery of the evolution of the islands from 2001 to 2005, and the development of the islands from a continuous chain to a highly disconnected group. The islands during this time period were battered by hurricanes Lili (03 Oct 2002), Isidore (26 Sept 2002), Ivan (16 Sept 2004), Cindy (05 Jul 2005) and Katrina (29 Aug 2005). The storm tracks of these hurricanes are highlighted in Fig. 1. It is obvious that in several locations the islands completely disappeared (north section of islands) and sediment was washed away throughout the chain, leaving only marshland (Fig. 2).

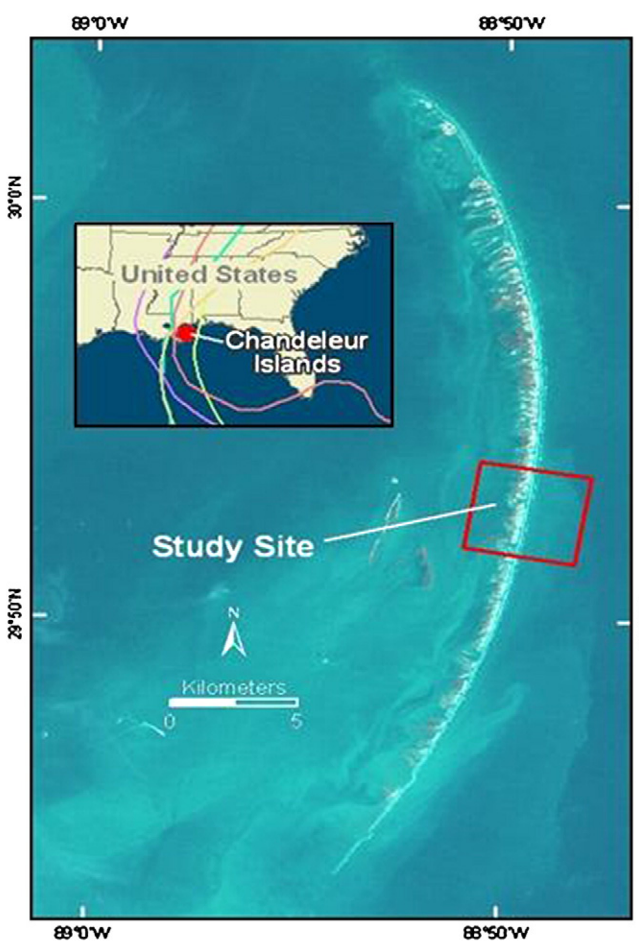

Fig. 1. Chandeleur Islands, study site highlighted in red box. Recent hurricane tracks are shown in the inset, with: purple — Lili (2002); aqua — Isadore (2002); green — Ivan (2004); beige — Cindy (2005); Pink—Katrina (2005). (Landsat satellite imagery, 2004).

A recently introduced numerical model, XBeach (eXtreme Beach behavior model), implements morphological modeling of dune erosion, overwash, inundation, and breaching (Roelvink et al., 2009). Roelvink et al. (2009) demonstrate that the model skillfully simulates storm hydrodynamics including short- and long-wave heights and associated currents as well as predicting sediment transport associated with dune erosion. In particular, they demonstrate that the model can recover observed variations in dune erosion associated with storms that struck Assateague Island on the U.S. east coast. The variations in erosion response depended on variations in the initial topography, that ranged from relatively high dunes (>4 m) to relatively low dunes (<2 m). These storm conditions were spatially homogeneous, with storm surge elevations close to 1 m and offshore wave heights of about 4 m such that dune overwash occurred where the dune height was less than about 2 m. This study indicated that variations in the storm conditions (i.e., surge height, wave height, and wave period) could also control the degree of dune erosion, primarily by increasing or decreasing the intensity of dune overwash.

In the case of low-lying islands, such as the Chandeleur Islands, inundation (i.e., submergence) occurs during major storms and this process can substantially alter island topography and planform areas (Fig. 2). Processes that are resolved by the XBeach model should be able to account for this island erosion scenario. We use XBeach to make detailed predictions of the response of a portion of the Chandeleur Islands to the sediment transport processes driven by Hurricane Katrina. Surge elevations at the island were predicted to be nearly 4 m and wave heights exceeded 5 m offshore (IPET, 2007). The following section describes the numerical model and the data sets that were used to initialize, force, and evaluate the model (Section 2). The model simulation results are presented (Section 3). Section 4 includes discussions of how subtle changes in the spatial (Section 4.1) and temporal resolution (Section 4.2) of the model impact the simulation results. We explore the impact of the omission of storms that occurred between the initial island survey in 2002 and Hurricane Katrina in 2005 (Section 4.3) and discuss the omission of geologic variation in sediment properties (Section 4.4). Conclusions are given in Section 5.

2. XBeach model

XBeach is a coupled hydrodynamic and morphodynamic model that can be used to test a range of morphological modeling concepts and resolve processes at relatively small spatial, O(1 m), and temporal, O(1 s), scales. It is capable of handling extreme conditions, including hurricanes. Processes that are resolved by the model include wave-averaged evolution of short waves, time-resolved evolution of long waves, wave-driven flows, sediment transport, and morphological change. For an in-depth description of XBeach, see Roelvink et al. (2009). For the purposes of this study, we require a morphological prediction that depends on hurricane-driven processes. Morphologic change is obtained from XBeach from the sediment mass conservation equation, wave- and flow-driven sediment transport parameterizations, wave energy conservation, and momentum conservation.

A key formulation in the morphological evolution problem includes a formal separation of the fast time scales associated with hydrodynamic processes and the relatively slow evolution of the