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Improving understanding of near-term barrier island evolution through multi-decadal assessment of morphologic change

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ABSTRACT

Observed morphodynamic changes over multiple decades were coupled with storm-driven run-up characteristics at Fire Island, New York, to explore the influence of wave processes relative to the impacts of other coastal change drivers on the near-term evolution of the barrier island. Historical topography was generated from digital stereo-photogrammetry and compared with more recent lidar surveys to quantify near-term (decadal) morphodynamic changes to the beach and primary dune system between the years 1969, 1999, and 2009. Notably increased profile volumes were observed along the entirety of the island in 1999, and likely provide the eolian source for the steady dune crest progradation observed over the relatively quiescent decade that followed. Persistent patterns of erosion and accretion over 10-, 30-, and 40-year intervals are attributable to variations in island morphology, human activity, and variations in offshore bathymetry and island orientation that influence the wave energy reaching the coast. Areas of documented long-term historical inlet formation and extensive bayside marsh development show substantial landward translation of the dune–beach profile over the near-term period of this study. Correlations among areas predicted to overwash, observed elevation changes of the dune crestline, and observed instances of overwash in undeveloped segments of the barrier island verify that overwash locations can be accurately predicted in undeveloped segments of coast. In fact, an assessment of 2012 aerial imagery collected after Hurricane Sandy confirms that overwash occurred at the majority of near-term locations persistently predicted to overwash. In addition to the storm wave climate, factors related to variations within the geologic framework which in turn influence island orientation, offshore slope, and sediment supply impact island behavior on near-term timescales.

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1. Introduction

Natural and anthropogenically-induced drivers of change contribute to the long-term evolution of coastal environments over a range of timescales (Harris et al., 2005). Short-term (events, seasons, years) changes are commonly studied to evaluate their immediate impacts on coastal regions, whereas near-term (decades, half centuries) assessments can provide essential information on the morphodynamics of coastal evolution (Morton and Miller, 2005; Hapke et al., 2006; Backstrom et al., 2007; Hapke et al., 2010a). Once behaviors and trends are quantified, identifying the relative importance of drivers and controls responsible for change–storm events, human influences, sediment inputs, and geologic framework expressions–aids in anticipating future vulnerable areas and guiding decision-making in coastal regions. For example, the alongshore wave climate, particularly as driven by major storms, can shape the behavior and morphology of a dunes and beaches by focusing overwash through repeat events, thereby creating areas more vulnerable to dramatic change (Sallenger, 2000; Stockdon et al., 2007). Similarly, the geologic framework–the morphology, antecedent geology and underlying stratigraphy–of a coastal system has been linked to the presence of nearshore features and longer-term expressions of shoreline variations in a number of coastal regions (Schwab et al., 2000; McNinch, 2004; Harris et al., 2005; Browder and McNinch, 2006; Schupp et al., 2006; Houser et al., 2008; Hapke et al., 2010b; Houser, 2012). Anthropogenic modifications to dunes and beaches, such as beach replenishment, increase the elevation, grade, and width of a beach, though their impacts on morphologic behavior are often poorly understood (Thornton et al., 2006; Park et al., 2009). The primary objective of this paper is to explore the dominant controls of system-wide dune–beach morphologic changes on decadal timescales. To accomplish this goal, near-term morphologic changes are quantified and examined relative to several known drivers of coastal evolution and behavior, among them: the wave climate, the geologic framework, and ongoing replenishment activities.

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A paucity of detailed historical topographic datasets commonly prevents assessment of long-term morphologic change; therefore, historical coastal change is commonly assessed from shoreline datasets derived from maps, features extracted from aerial photos and widely-spaced beach profiles. However, historical surfaces can be generated with digital stereo-photogrammetry resulting in high-resolution three-dimensional (3D) datasets with continuous spatial coverage that can be directly compared with more recent (lidar) surfaces to gain a better understanding of 3D morphology change over decadal timescales (Judge and Overton, 2001; Hapke and Richmond, 2002; Hapke, 2005). The research presented here integrates photogrammetrically-derived historical topography and recent lidar datasets to examine morphologic change to the dune–beach system along the length Fire Island, New York. The topography is used to assess decadal-scale morphodynamics and changes on the barrier island from 1969 to 2009.

The 40-year span of topographic data presented in this study, which brackets a number of major storm events, has been coupled with 30 years of wave information to discern the influence of storm events, wave energy, and alongshore morphologic variation on the near-term evolution of a barrier island dune–beach system. Change is quantified specifically by: 1) determining subaerial volume changes through time; 2) measuring the alongshore changes, net movement, and correlations of features such as the dune crest position and elevation, shoreline position, width of the beach, and the subaerial cross-shore profile volume; and 3) evaluating these metrics in conjunction with parameterized wave run-up. The results are compared with existing theories on the influence of the geologic framework and anthropogenic modifications to gain greater insight into the near-term coastal behavior and response of barrier island systems.

2. Regional setting

Fire Island is centrally located in a barrier system that spans the south shore of the Long Island, New York (Fig. 1). The 50-km barrier island is oriented east-northeast, and the predominant southerly wave direction drives net longshore transport from the east to the west (Taney, 1961). Longshore transport is thought to be the dominant mechanism by which sediment moves into and through the system at Fire Island; there are no riverine sources, and limited understanding of cross shore transport volumes, timescales, and mechanisms exists (Schwab et al., 2000; Hapke et al., 2010b). Two engineered inlets bound the island and are maintained for navigation purposes: Moriches Inlet to the east, and Fire Island Inlet to the west (Fig. 1). Mean tidal range in the microtidal region is 1.3 m (NOAA, 2010).

The subaerial morphology of Fire Island is variable along coast. Generally, relatively narrow beaches and high dunes (some as tall as 11 m) characterize the central-eastern segment of the island, whereas wider beaches and lower dunes (averaging 4.5 m) are found to the west as observed in lidar from 1999 and 2009. Evidence of rapid spit growth to the west is observable in recurved dune ridges and in the historical shoreline record (Leatherman, 1985; Allen et al., 2002); from the time of construction of the Fire Island Lighthouse in 1830 to the emplacement of the inlet jetty at Democrat Point in 1942, the island grew more than 8 km westward (Kassner and Black, 1983; Psuty et al., 2005a) (Fig. 1). Some of the oldest and tallest dunes on the island, located between Sailor's Haven and Watch Hill, are thought to compose an ancestral barrier core (Leatherman, 1985; Leatherman and Allen, 1985; Psuty et al., 2005a, 2005b) (Fig. 1). Leatherman (1985) documented a number of historic inlets on the eastern reach of the island as evidenced by core logs, interruptions in the dune crest, and recurved dune ridges. The eastern reach of the island (roughly from Watch Hill to Moriches Inlet) exhibits more consistent landward migration patterns than the western reach with a wide flat back barrier marsh system; in fact there is no evidence of sustained breaches or inlet formation west of Watch Hill. Inlets carry sediment from the ocean to the back barrier to sustain the marsh system, and are thought to be more important than overwash in landward migration patterns at Fire Island (Leatherman, 1985, 1989).

In the late 1990s an extensive offshore mapping effort was conducted through a joint partnership between the U.S. Geological Survey and U.S. Army Corps of Engineers along the Long Island south shore inner-continental shelf (Schwab et al., 2000). The comprehensive data collection of single-channel bathymetry, sidescan sonar, and subbottom profiling shows a relatively thin veneer of modern sediment uncomformably overlying a Holocene marine transgressive (ravinement) surface along the inner shelf. In 2011, the U.S. Geological Survey conducted another geophysical survey over the inner continental shelf and lower shoreface of Fire Island, using higher resolution marine geophysical systems including interferometric swath-bathymetry and backscatter, and chirp seismic reflection profiles (Schwab et al., in press). These new bathymetry data are shown in Fig. 1. Preliminary analysis of these new data shows what was initially thought by Schwab et al. (2000) to be a submerged Cretaceous headland located offshore of Watch Hill, is in fact a lobe of Pleistocene outwash sediment (Schwab et al., in press). Erosion of this lobe of glaciofluvial sediment via oceanographic processes associated with Holocene marine transgression has supplied abundant well-sorted medium- to fine-grained sand to the inner-continental shelf downdrift to the west, which has been in turn reworked forming a series of shoreface-attached sand ridges west of Watch Hill (Schwab et al., 2000). Schwab et al. (2000) proposed that onshore flux of sediment from these ridges may be supplying the sediment volume required for maintenance of island stability west of Watch Hill and is a likely explanation for the observed historic spit growth west of Point O' Woods and related modern infilling of Fire Island Inlet. East of Watch Hill, the modern reworked sediment deposit is relatively thin or absent on the inner continental shelf and lower shoreface (Fig. 1). Here, the only sediment available to supply the island is from updrift erosion and the relatively coarse-grained, less mobile Pleistocene material offshore, thus the barrier island is migrating landward at a relatively rapid rate (Schwab et al., 2000).

Nearshore (2–12 m water depth) single beam bathymetry surveys in 2007 and 2009 show that the inner shelf ridges and axial troughs are connected to the shoreface on the seaward side of the nearshore bar (Hapke et al., 2010b). The ridges are composed of well-sorted medium to fine-grained sand similar to Fire Island beach sand (Williams and Meisburger, 1987; Williams and Morgan, 1993), and could be a source of sediment to the system not currently quantified in existing sediment budget estimates at Fire Island (Williams and Meisburger, 1987; Williams and Morgan, 1993; Schwab et al., 2000). In fact, all sediment budgets conducted for the south shore of Long Island barrier system to date estimate that an average of more sediment, approximately 200,000 m^3/yr, is leaving the system at Fire Island Inlet than is entering the system at Moriches Inlet (Taney, 1961; Kana, 1995; Rosati et al., 1999; Hapke et al., 2010b). The lack of landward migration along the western reach of the island supports the theory that alongshore contributions from the ridges may serve as a sediment source supplying the western reach with ample material to maintain position and balance the system losses at Fire Island Inlet (Williams and Meisburger, 1987; Williams and Morgan, 1993; Schwab et al., 2000; Hapke et al., 2010b).

2.1. Storm history

During the time span considered in this study, a number of extratropical storms (northeasters) and hurricanes made landfall at Fire Island, resulting in elevated wave heights and periods. The extratropical storms mostly occurred in the winter and early spring, between December and early March, with winds predominantly from the east and east southeast as observed from NOAA buoy data (-buoy #44025 shown in Fig. 1). Among these, three powerful northeasters made landfall on the south shore of Long Island between October 1991 and March 1993. The severity of the early 1990s' storms and their close temporal proximity resulted in extensive coastal flooding, overwash, and erosion along Fire