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Decoupling processes and scales of shoreline morphodynamics

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ABSTRACT

Behavior of coastal systems on time scales ranging from single storm events to years and decades is controlled by both small-scale sediment transport processes and large-scale geologic, oceanographic, and morphologic processes. Improved understanding of coastal behavior at multiple time scales is required for refining models that predict potential erosion hazards and for coastal management planning and decision-making. Here we investigate the primary controls on shoreline response along a geologically-variable barrier island on time scales resolving extreme storms and decadal variations over a period of nearly one century. An empirical orthogonal function analysis is applied to a time series of shoreline positions at Fire Island, NY to identify patterns of shoreline variance along the length of the island. We establish that there are separable patterns of shoreline behavior that represent response to oceanographic forcing as well as patterns that are not explained by this forcing. The dominant shoreline behavior occurs over large length scales in the form of alternating episodes of shoreline retreat and advance, presumably in response to storms cycles. Two secondary responses include long-term response that is correlated to known geologic variations of the island and the other reflects geomorphic patterns with medium length scale. Our study also includes the response to Hurricane Sandy and a period of post-storm recovery. It was expected that the impacts from Hurricane Sandy would disrupt long-term trends and spatial patterns. We found that the response to Sandy at Fire Island is not notable or distinguishable from several other large storms of the prior decade.

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1. Introduction

In the aftermath of extreme storm events there tends to be an increased societal focus on understanding the processes that control variations in coastal response, such as shoreline erosion and recovery. Such knowledge can be used for the development and refinement of models that predict future coastal behavior, and provides fundamental information needed to understand coastal vulnerability and resiliency. It is important to consider the relative roles of the various drivers of coastal change and the time scales of their influence when developing predictive models of coastal evolution in geologically and oceanographically complex coastal systems such as barrier islands.

Hydrodynamics are a primary driver of coastal change. Water levels and currents associated with waves, surge and tides interact with beach and bar morphology and associated sedimentary deposits to drive beach and shoreline response during single storm events and stormy periods (Lippmann and Holman, 1990; Plant et al., 1999; Sallenger, 2000; Stockdon et al., 2006; Wright and Short, 1984) and over longer timescales (e.g., Yates et al., 2009). The alongshore variability of wave energy reaching the coast can be influenced by the orientation of the coast, the bathymetry of the adjacent inner shelf and shoreface, and the morphology of the nearshore bar and surf zone. Morphodynamic response of a beach during storms is driven by hydrodynamic processes, but other factors, such as alongshore variations in beach and shoreface slope, island elevation, and sediment availability may also impact short-term beach response (Tătui et al., 2014; Wright and Short, 1984).

Longer-term behavior (years to decades) of the shoreline is the result of hydrodynamic and morphodynamic processes acting over multiple stormy and intervening calm periods during which the advanced or retreated state of the shoreline may be increasingly influenced by sediment supply and geology (Houser et al., 2008; Morton et al., 2007; Viles and Goudie, 2003; Woodroffe, 2003). Determining the relationship between shoreline processes and the response of the shoreline over a continuum of time scales requires data of sufficient temporal and spatial resolution and extent to resolve these scales (Stive et al., 2002).

Shoreline data capable of resolving storm events, annual and multidecadal response are uncommon, and as a result few studies have examined shoreline behavior over a broad range of time scales. And while oceanographic forcing parameters (e.g., offshore wave height and direction) can be evaluated over long time periods using data from wave buoys and tide gauges, or from modeled hindcast results (U.S. Army Corps of Engineers Wave Information Studies, for example). However, hydrodynamic processes alone are not sufficient to explain all

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shoreline variability over multiple time and space scales. Internal characteristics (e.g., framework geology and geomorphology) of barrier island systems exert control on both the long-term and/or short-term responses to the hydrodynamics.

Studies abound in the literature that describe the importance of framework geology on barrier island coastal evolution and response. The foundational studies of Belknap and Kraft (1985) and Riggs et al. (1995) related characteristics of the underlying stratigraphy of the inner continental shelf in North Carolina, including stratigraphic variations and sediment availability, to barrier island evolution over long temporal scales. Schwab et al. (2000, 2013) extended the North Carolina studies to examine the relationship between stratigraphic and lithologic variations in the pre-Holocene and Holocene deposits of the inner continental shelf off Fire Island, New York, and centennial scales of shoreline change. McNinch (2004), Miselis and McNinch (2006) and Schupp et al. (2006) built on the previous works but focused on smaller scales of framework geology and shoreline change. The studies examined the occurrence of paleochannels and deposits within the shoreface along a single barrier island and found a relationship between the patterns of decadal shoreline change and variable sediment availability, with shoreline erosion in areas dominated by paleochannels.

Hapke et al. (2010, 2011b) established the relationship between shoreline change on a variety of time scales (decades to century) and the modern morphology and framework geology of the inner shelf at Fire Island. Persistent shoreline undulations were shown to occur coincidently with the section of the island where a shoreface-attached ridge system extends into the very nearshore (~3–4 m water depth) and appears to influence hydrodynamic processes. Further, Lentz et al. (2013) spatially correlated decadal beach-dune morphology and response, including zones of persistent overwash, to variations in storm wave water levels that are related to bathymetric variations on the inner shelf. Thus, the framework geology, which controls the bathymetric variability is shown to be linked to island response on storm to decadal scales.

The above introduction is by no means a complete overview of the research that has established linkage between framework geology and coastal response. Such an effort is outside the scope of this paper. However, the examples and references therein provide the foundational knowledge that framework geology has an important and demonstrable influence on rates and trends of shoreline change on a variety of time scales. A question that remains is what is the relative importance of storm processes versus geological control on storm response and multi-decadal evolution of barrier islands?

In this paper, we utilize a statistical approach to examine spatial and temporal variations in the morphologic evolution and response of the shoreline at Fire Island, NY, and relate the behaviors to the influences of geology and storm processes. In addition, we take advantage of an enhanced temporal resolution of our shoreline data to capture the short-term response of a recent extreme storm event.

We hypothesize that there are separable patterns in shoreline response that can be utilized to examine the role of oceanographic forcing of storms of varying sizes versus geologic control. There may be feedback between the different components that alter how the system responds if there are large shifts in morphology or geology. For instance, large storms could change the distribution of sediment supply and alter subsequent patterns of short-term and long-term response. Hurricane Sandy (landfall on Oct. 29, 2012, near Atlantic City, NJ) is an event that we investigate to explore whether extreme storms alter the stability of the island, altering the relationship between geology and long and short time-scale behavior.

Fire Island is an ideal locale for examining this relationship due to the complex, but well-documented framework geology, distribution of sand deposits on the inner shelf, and variable bathymetry and island topography (Hapke et al., 2011b; Leatherman, 1985; Lentz and Hapke, 2011; Lentz et al., 2013; Schwab et al., 2000, 2013, 2014). We utilize an extensive database of shoreline positions that extends over a time period of 81 years to examine the morphodynamics of the shoreline over multiple time scales and assess the dominant controls on the spatial variations and temporal trends. The variance in the time series is analyzed using empirical orthogonal functions (EOF) to statistically evaluate temporal trends and spatial patterns that dominate the shoreline behavior. This approach allows us to decompose the complex time series to isolate the relative importance of the factors controlling shoreline behavior and the scales over which they have influence. We then describe the different modes, attribute them to oceanographic, geologic, or feedback processes, and identify what processes control shoreline variability at different spatial and temporal scales.

2. Oceanographic and geologic setting

Fire Island is part of the barrier island system that flanks the south shore of Long Island, New York (Fig. 1). The island is oriented east-northeast and extends for 50-km from Fire Island Inlet in the west to Moriches Inlet in the east. Both inlets are stabilized with jetties and periodically dredged to maintain navigation channels. The Fire Island coastal system is wave-dominated, microtidal, with a tidal range of 1.3 m (NOAA, 2014). Sediment transported along the shore of Fire Island is primarily from east to west, driven by the predominant wave approach out of the southeast (Leatherman, 1985). The ocean coastline of Fire Island is modified by storms and subsequent recovery. The most common severe storms are extratropical (nor'easter) systems that occur seasonally, typically from November through April. Nor'easters tend to have durations extending over multiple tidal cycles, generally 2–5 days. In contrast, hurricanes directly impact Fire Island less frequently and in general are faster moving systems, with impacts occurring over one or two tidal cycles, typically lasting <24 h (Birchler et al., 2015). Historic storms of note can be identified from reports of widespread erosion, overwash, breaching, and infrastructure damage along this coastline. Examples of such storms include the 1938 Hurricane, the 1962 Ash Wednesday storm, a series of powerful nor'easters in 1991, 1992 and 1993, and Hurricane Sandy in 2012. Significant wave heights during Hurricane Sandy reached the highest levels on record, 9.6 m (from NDBC wave buoy #44025) (Hapke et al., 2013).

Distinct variations in the morphology of the inner continental shelf and modern sediment distribution patterns offshore of Fire Island (Schwab et al., 2013, 2014) allow the system to be divided into three distinct geologic zones. Remnants of a Pleistocene glaciofluvial outwash lobe define a submerged headland offshore of central Fire Island (Fig. 1). The zone is more gently sloping than the adjacent areas and contains thicker deposits of sediments. To the east of the submerged headland, relatively older Pleistocene outwash is exposed over much of the inner continental shelf; little modern sediment exists in this zone (Schwab et al., 2000, 2013, 2014). The morphology of the inner continental shelf offshore of western Fire Island is dominated by a field of shoreface-attached sand ridges that migrate in a westerly direction (Duane et al., 1972; Schwab et al., 2013, 2014).

The morphologic behavior and storm response of the island is relatively well documented and both shoreline and profile morphodynamics have been related to the regional variations in inner shelf geology (Hapke et al., 2013; Leatherman, 1985; Lentz and Hapke, 2011; Lentz et al., 2013; Schwab et al., 2013). The historical record of shoreline change along Fire Island can be separated into three zones which correspond to the three geologic zones identified on the inner continental shelf. Schwab et al. (2013) noted that the rates of change are highly variable along the coast with erosion along the eastern segment of the island (-0.72 ± 0.18 m/year), modest shoreline accretion in the central segment of the island (0.38 ± 0.07 m/year) and mixed erosion and accretion along the western segment (-0.12 ± 0.14). In this paper we refer to the different zones as the western, central and eastern geologic zones (WGZ, CGZ, and EGZ).