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Modeling large-scale shoreline change caused by complex bathymetry in low-angle wave climates

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ABSTRACT

Coastlines where waves consistently approach at highly oblique angles experience anti-diffusional behavior, causing perturbations to grow seaward and form sand waves, capes, and spits. Coasts where waves approach at low offshore angles experience the opposite: perturbations diffuse and the coastline remains (or becomes) smooth. In this paper, by coupling a 2-D large-scale coastline evolution model to a spectral wave model, we show that anti-diffusional behavior is also possible in low-angle wave climates if the nearshore wave field is altered by complex bathymetry. In model simulations, low-angle waves refract over local shoals, creating a convergence in alongshore sediment flux behind the shoals that coalesces into small 'minor capes'. Depending on wave height and period, shoreline features take 80–400 years to reach an equilibrium cross-shore relief of 1–1.5 km over an alongshore distance of ~20 km. The modeled equilibrium time scale is consistent with analytically-determined characteristic shoreline diffusion time scales, and the modeled cross-shore relief and aspect ratio are similar to observed 'minor capes' along the U.S. Atlantic Coast where offshore bathymetric anomalies have previously been linked to shoreline change patterns. Better understanding of the links among nearshore bathymetry, wave transformation, and alongshore sediment transport is critical to understanding shoreline change patterns at the local level and how they fit into broader, regional-scale behavior.

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1. Introduction

On sedimentary coasts, large-scale (>1 km), long-term (>10^1 years) shoreline change is caused in large part by gradients in wave-driven alongshore sediment transport (Lazarus et al., 2011; van den Berg et al., 2012; Ashton et al., 2001). Sediment transport gradients are determined by the coastline's local orientation relative to incoming wave angles: where waves regularly approach the coast at high offshore wave angles (~>42° relative to the local shoreline angle), an instability arises that causes perturbations to grow seaward and form sand waves, capes, and spits (Ashton et al., 2001). Likewise, on coasts where waves approach at low deep-water wave angles, perturbations tend to diffuse, and the coastline remains (mostly) smooth. Considerable attention has been given to the high-angle instability as an elegant and widely applicable explanation of plan-view coastline shapes, and multiple models have recently been developed to explore it (Ashton et al., 2001; Falqués, 2003; Falqués and Calvete, 2005; Ashton and Murray, 2006a, 2006b; van den Berg et al., 2012; Kaergaard and Fredsoe, 2013a; Kaergaard and Fredsoe, 2013b; Kaergaard and Fredsoe, 2013c; Hurst et al., 2015). But, perplexing and subtle shoreline patterns also arise in low-angle wave climates (Fig. 1) and have received much less consideration (Lazarus and Murray, 2011). Examples include low-relief seaward-convex 'minor capes' (Riggs et al., 1995) in North Carolina, False Cape near Cape Canaveral, Florida, USA (Kline, 2013), and a local shoreline bulge on Fire Island, New York (Schwab et al., 2000, 2013; Fig. 1).

In addition to the high wave angle instability, coastline features can also be explained by the antecedent geologic framework that underlies the modern, active beach profile (Riggs et al., 1995; Schwab et al., 2000; Bender and Dean, 2004; Honeycutt and Krantz, 2003; McNinch, 2004; Browder and McNinch, 2006; Valvo et al., 2006; Mallinson et al., 2010; Denny et al., 2013; Lazarus and Murray, 2011; Thieler et al., 2014). Antecedent geology can affect shoreline change rates in several ways, including through the differential erosion of alongshore-varying lithology as the shoreface retreats landward, and the erosion of relict sediments that can supply sand to the active profile (Honeycutt and Krantz, 2003; Browder and McNinch, 2006; Lazarus and Murray, 2011). For example, Riggs et al. (1995) found that shoreline erosion rates in North Carolina, USA were the highest along shoreline segments underlain by relict drainage channels that provided little sediment to the active shoreface, and that subtle, kilometers-long shoreline undulations were correlated with structural highs in the geologic framework. Using a numerical model, Valvo et al. (2006) simulated the plan-view evolution of a sandy shoreline underlain by different lithologies and found, in support of Riggs et al. (1995) and others, that small shoreline

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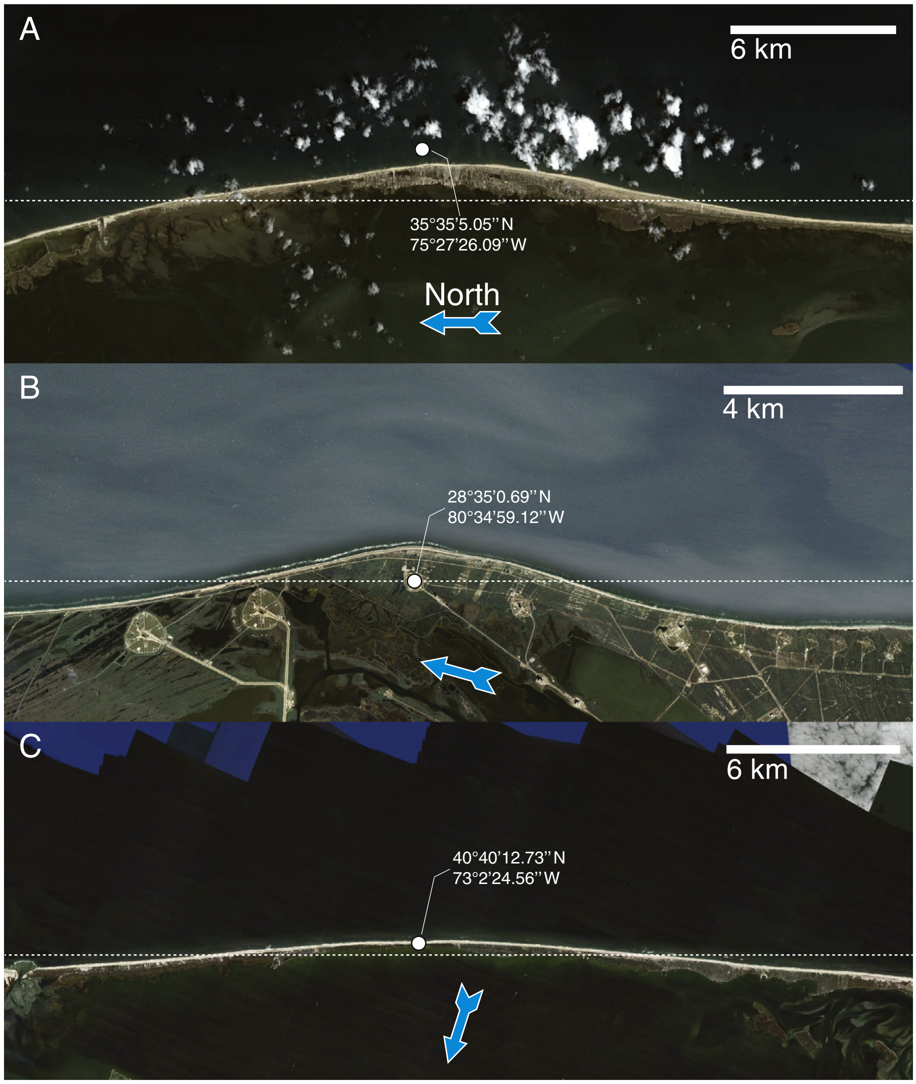

Fig. 1. Examples of 'minor capes'. A: Rodanthe area, Outer Banks, North Carolina; B: False Cape, near Cape Canaveral, Florida; and C: Fire Island, New York. The dashed line is a reference line used to visually compare these examples with model results in subsequent figures. Photos from Google Earth.

undulations (<100 m in total cross-shore relief or amplitude) can be maintained in steady-state by variations in antecedent lithologic strength and composition. Sand-poor, softer lithologies erode rapidly and form recessed bays, whereas sand-rich, harder lithologies erode slowly and form small promontories.

Antecedent geology can also help create complex nearshore shoals or submarine headlands. Such bathymetric anomalies can alter the alongshore distribution of wave energy and induce gradients in alongshore sediment transport, even in the absence of high-angle waves. At smaller alongshore scales, McNinch (2004), Schupp et al. (2006), and Browder and McNinch (2006) observed spatial correlations between erosional hot spots and subaqueous shore-oblique sand bars, hypothesizing that local wave field modification over the complex bathymetry is responsible for local erosion. Similarly Riggs et al. (1995) qualitatively linked wave energy redistribution over nearshore shoals to shoreline change patterns in North Carolina. Bender and Dean (2004) developed an analytical model that examined how wave shoaling and refraction over nearshore shoals and dredge borrow pits influenced shoreline change over short time scales (days). They found that bathymetric anomalies altered incoming wave directions and set up gradients in alongshore sediment transport such that the shoreline tended to recede behind borrow pits and accrete behind and near shoals. Aforementioned numerical modeling by Valvo et al. (2006) over longer time scales (>10^1 years) treated wave transformation in a basic way and could not account for complex bathymetry or wave energy convergence and divergence. All examples in Fig. 1 have prominent nearshore shoals that have been qualitatively linked to nearshore wave transformation and large-scale shoreline change (Riggs et al., 1995; Kline, 2013; Schwab et al., 2000; Schwab et al., 2013; Smith et al., 2008), but only one study by Idier et al. (2011) has quantitatively considered the two-way interactions between wave transformation over complex bathymetry and shoreline change. That study (Idier et al., 2011) modeled the coupling between wave transformation and shoreline change and suggested a plausible mechanism by which low-angle waves locally refracted by nearshore shoals can cause shoreline undulations (megacusps) over time scales of days to weeks and alongshore scales of 10^2–10^3 m.

In this paper, we explore how complex nearshore bathymetry can affect large-scale (>1 km) shoreline change in low-angle wave climates over 10^1–10^2 year time scales. We use a modified form of the Coastline Evolution Model (CEM; Ashton et al., 2001; Ashton and Murray, 2006a, 2006b) that simulates shoreline change caused by gradients in alongshore sediment transport. For simplicity and efficiency, the original CEM shoals and refracts waves in the most basic way using linear wave theory and Snell's Law. The model assumes that bathymetric contours are shore-parallel and extend seaward only to a given shoreface