HEADLAND AND WAVE CLIMATE CONTROLS ON THE FORMATION AND SHAPING OF THE OUTER CAPE COD COASTLINE

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Abstract: Moving northwards, the coast of Cape Cod coast curves—shorelines that face the west transition to northward facing beaches. Similarly, erosion changes to accretion as sediment supplied from eroding bluffs deposits updrift. To better understand how alongshore sediment transport shapes this coast, we present two analyses of spit growth relevant to Cape Cod. First, we analyze wave-climate-derived metrics to check whether transport trends for the modern wave climate are consistent with a recently introduced conceptual model of spit growth. Second, to better understand the influence of high eroding bluffs on shoreline extension, we present modeling results that suggest the shoreline of an eroding headland is expected to continue to rotate over long periods of time. Most interestingly, model results also suggest that spit growth should be slower for larger bluffs. Although such large bluffs would seem to be capable of supplying large quantities of sediment, by locally slowing erosion, these bluffs actually reduce sediment supplied downdrift of the headland.

Introduction

The iconic ocean-facing Cape Cod shoreline, formed as bluffs of proglacial sediment erode and deposit a downdrift-extending spit system, has been the subject of geomorphologic interest since early investigations by W.M. Davis (1896). Here, we address two specific aspects of the growth of Cape Cod within a broader framework of spit formation and evolution. First, we analyze the wave climate moving along the curved Cape shoreline to test a conceptual model of spit growth that suggest passing the threshold of maximized alongshore sediment results in a transition to accretion and shoreline instability. We then present modeling results that investigate the effect of bluff height on shoreline extension from an eroding headland.

Controls on Spit Form

Recent research has identified key controls on spit form and evolution (Ashton *et al.*, 2016), whereby spit evolution can be best understood by tracking key geomorphic locations along the shoreline determined by the gradients in alongshore sediment transport. Leaving the eroding headland, a spit should transition from an erosional neck to the downdrift accretional hook (Fig. 1). The spit neck and hook are connected by a "fulcrum point" where alongshore sediment transport is maximized. The transition of the shoreline through a maximizing value of alongshore sediment transport is a necessary condition for alongshore-transport-driven accretion of the spit hook. Such a transition through a maximum flux orientation should be expected for all spits that are not heavily affected by tidally driven sediment transport. Moving through this fulcrum point, the wave climate is expected to transition from a stable, low-angle dominance to unstable, high-angle dominance (Ashton and Murray, 2006a, 2006b).

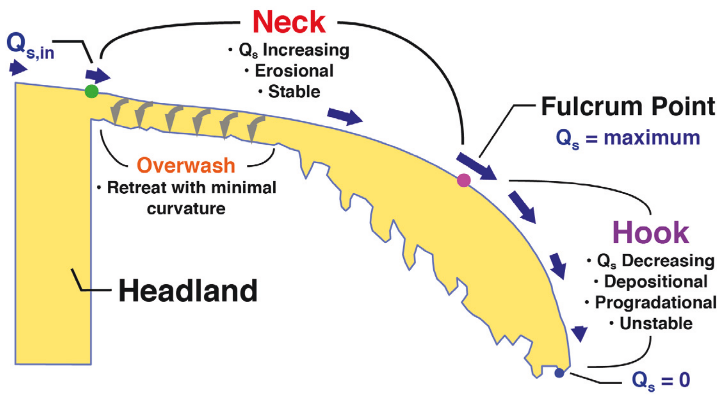

Fig. 1. Schematic of the morphodynamic components of a spit extending from a headland based upon alongshore sediment transport regimes and neck overwash. After Ashton *et al.* (2016).

Wave Climate Analysis

We perform a preliminary test of this hypothesis by analyzing modern wave climates along the Cape Cod coast using Wave Information Study (WIS) hindcast data (Jensen, 2010). By summing over the entire 32-year dataset, using the deep-water CERC formula (Ashton and Murray, 2006) we computed net alongshore sediment transport, the predicted gradient in transport, and the relative diffusivity (gamma) for different coastal orientations (Fig. 2), which allows us to predict the locations of erosion, accretion, nodal points, fulcrum points, and shoreline instability. Negative (left-moving standing on the shore) sediment transport is predicted to increase moving to the north (left). Towards the cape tip, alongshore transport is maximized, leading to predictions of accretion and shoreline instability (negative gamma). Comparing these with historic shoreline changes (Giese *et al.*, 2007, 2011), erosional and accretional trends are consistent as are predictions of the fulcrum point.

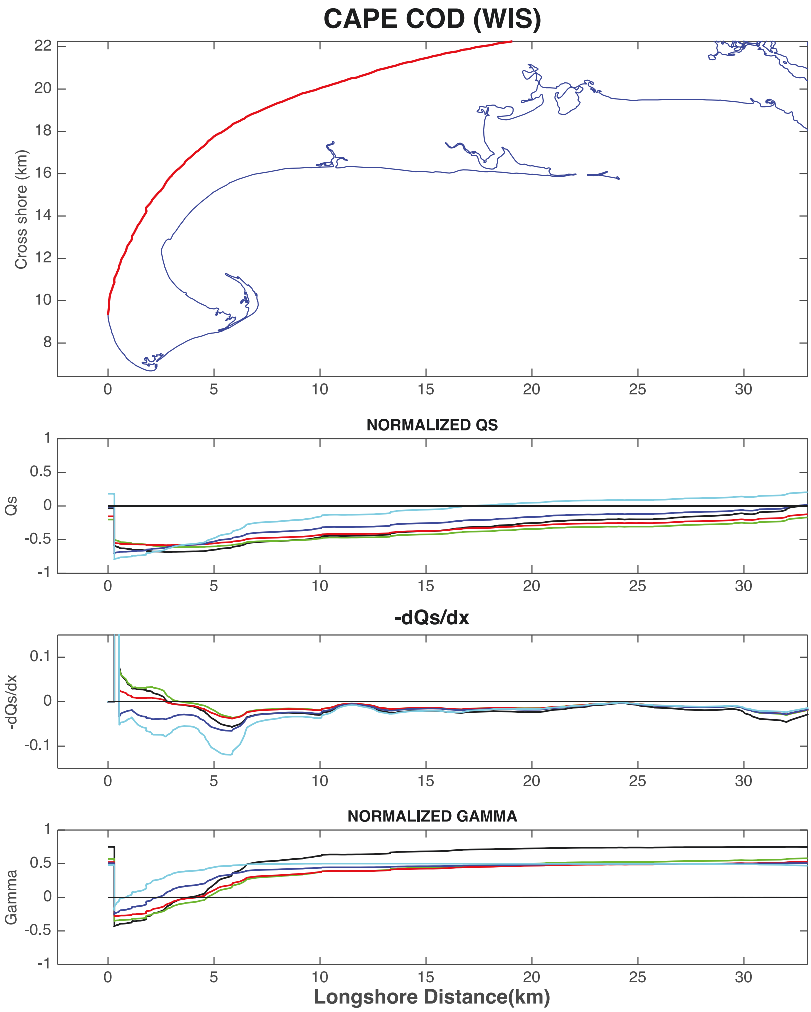

Fig. 2. Wave climate analysis for northern Cape Cod shoreline showing (rotated ~90 degrees counterclockwise), from top to bottom, shoreline location, normalized alongshore sediment transport (Qs), gradient in alongshore transport, and shoreline diffusivity (gamma) for various WIS stations along the coast.

Headland Effect on Spit Growth

To better understand the influence of sediment-supplying high bluffs on spit growth, we modify the Coastline Evolution Model (CEM) (Ashton *et al.*, 2001; Ashton and Murray, 2006a) used previously to model spit evolution (Ashton *et al.*, 2016) to include the influence of bluff height on shoreline recession due to local negative gradients in alongshore sediment transport. For a shoreface depth of 15 m, we vary bluff height from 1 to 40 m, finding surprisingly limited influence of bluff height on modeled spit shape and growth (Fig. 3). The predominant effect is slower recession of the headland shoreline as the spit extends. Looking more closely at the model results (Fig. 4), spits growing off of higher headlands grow in length slightly slower than counterparts with shorter bluffs. This can be attributed to the reduced sediment supply off of the headland ($Q_{s,in}$), which directly results from the slower rotation of the shoreline for taller headlands (Fig. 3; Fig. 4 bottom). Note that the model is run with a constant wave climate, yet the shoreline continues to rotate at the headland transition (Fig. 4 bottom), not reaching a steady state despite the growth of a large, several km-scale spit.

One main result is perhaps counterintuitive—spits should grow slower from higher bluffs. Despite the ample sediment supply from large bluffs, shoreline orientation at the headland transition controls sediment supply from the eroding headland to the spit. The larger stockpile of sediment on the bluffs actually

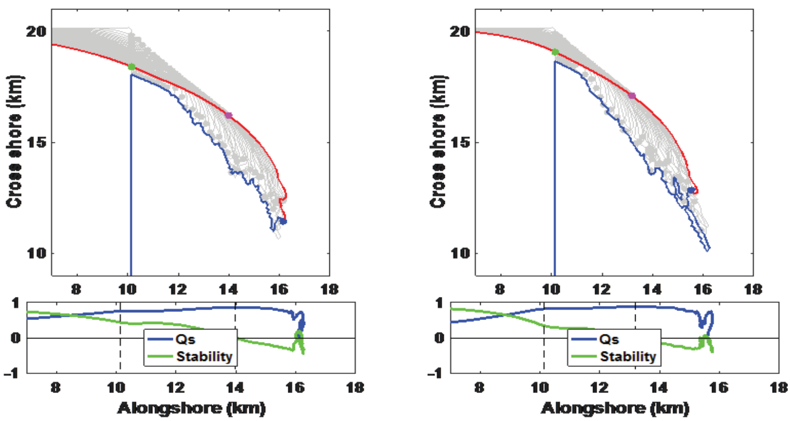

Fig. 3. CEM model results for spits extending off of headlands with different bluff heights with (left) a 1 m bluff and (right) a 40 m bluff. The shoreface depth is 15 m. Bottom panels show alongshore transport and normalized diffusivity (“stability”). For simulations, 60% of waves come from the left and 20% of the waves are from angles > 45 degrees with wave height of 1 m.

reduces the rate that the process of alongshore sediment transport rotates the coast, which is the primay control on the rate of sediment transport to the downdrift spit.

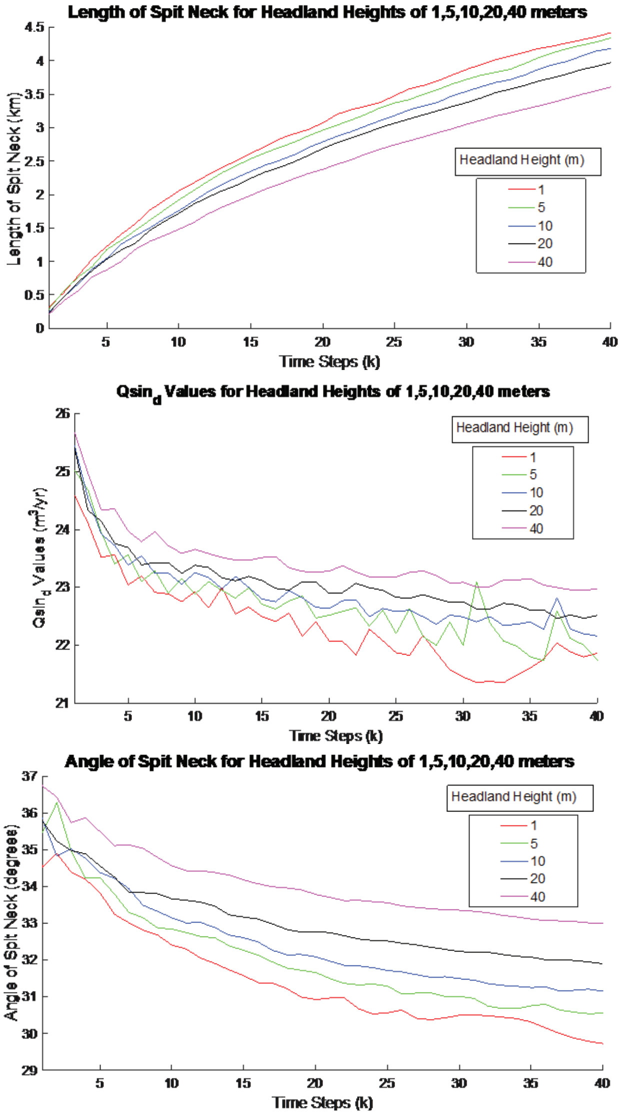

Fig. 4. Time evolution of spit variables from CEM model results (Fig. 3) for spits extending off of headlands with different bluff heights, showing (top) neck length, (middle) sediment flux from the headland to the spit, and (bottom) angle of the spit neck over simulation time. Model times steps are simulated days.

Discussion and Conclusions

These preliminary results offer new insights into the controls on the evolution of the Cape Cod shoreline. First, the modern shoreline orientation and wave climate are consistent with the conceptual model of spit growth presented by Ashton *et al.* (2016). Second, even as model experiments quantify the effect of bluff height (and therefore presumably composition) on the time evolution of headland-spit systems, they suggest that this geologic inheritance may not play a first-order role in spit growth as the orientation of the shoreline and the wave climate determines alongshore transport to the depositional downdrift region. Future efforts will more exactly compare wave climate predictions with measured historical rates of shoreline change as well as collected sedimentological and geophysical data that help constrain the growth and formation of the Cape Cod headland-spit system.

Acknowledgements

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