Process signatures in regional patterns of shoreline change on annual to decadal time scales

Eli D. Lazarus[1] and A. Brad Murray[1]

[1]   Gradients in wave-driven alongshore sediment transport influence the morphologies of sediment-covered coastlines on a range of spatial and temporal scales, affecting accretion and erosion patterns relevant to human development. Recent theoretical findings predict that a correlation between shoreline change and shoreline curvature results from patterns of alongshore sediment flux; the sign (positive or negative) of that correlation depends on whether high- or low-angle waves dominated the wave climate. Using lidar surveys of the northern North Carolina coast from 1996–2005 to document shoreline change and quantify alongshore patterns of erosion and deposition, we isolate these signals diagnostic of alongshore-transport processes. Our analyses show a persistent, significant negative correlation between shoreline-position change and shoreline curvature consistent with a low-angle-dominated incident wave climate over the last decade. At large spatial scales, convex-seaward promontories have eroded landward, while concave-seaward bays have aggraded seaward, resulting in an apparent diffusion of alongshore morphological features. **Citation:** Lazarus, E. D., and A. B. Murray (2007), Process signatures in regional patterns of shoreline change on annual to decadal time scales, *Geophys. Res. Lett.*, *34*, L19402, doi:10.1029/2007GL031047.

1. Introduction

[2]   The relative strengths of the morphological processes that shape seaboard shorelines are typically difficult to quantify. In the last decade, the advance of remote-sensing technologies such as lidar (Light Detection and Ranging) has enabled large-scale, high-resolution, three-dimensional views of the littoral zone that offer a consistent means by which to analyze changes in shoreline morphology [*Irish and White*, 1998; *Irish and Lillycrop*, 1999; *List and Farris*, 1999; *Brock et al.*, 2002; *Stockdon et al.*, 2002; *Tebbens et al.*, 2002; *Woolard and Colby*, 2002; *White and Wang*, 2003; *Mitasova et al.*, 2005].

[3]   Changes in shoreline shape provide clues about the forces that cause them. Recent theoretical, modeling, and data-analysis work indicates that on sediment-covered coastlines, gradients in wave-driven alongshore sediment flux affect shoreline accretion and erosion patterns on a range of spatial ($10^0 - 10^3$ km) and temporal (month to 10^3 yr) scales, even on reasonably straight shorelines with subtle promontories and embayments [*Ashton and Murray*, 2006a; *Ashton and Murray*, 2006b; *Valvo et al.*, 2006]. Where shoreline curvature is convex seaward, such as at a promontory or plan-view bump, deep-water waves approaching shore from highly oblique angles ($>\sim45°$) set up a convergent flux in alongshore sediment transport that causes the bump to accrete and grow; when deep-water waves approach convex-seaward shoreline features from smaller angles ($<\sim45°$), they generate a divergent alongshore sediment-transport flux that causes promontories to erode [*Ashton et al.*, 2001; *Ashton et al.*, 2003; *Falqués*, 2003; *Ashton and Murray*, 2006a]. A wave climate dominated by high-angle waves is therefore an antidiffusive regime that tends to exaggerate plan-view shoreline features, while a low-angle or diffusive wave climate tends to smooth them out [*Ashton and Murray*, 2006a]. For a given time span, if gradients in alongshore transport cause shoreline change, a correlation between shoreline curvature and shoreline change should result, with a sign (positive or negative) that depends on whether high- or low-angle waves dominated the wave climate during that period.

[4]   The degree to which cross-shore or alongshore transport drives shoreline change likely depends on the time and spatial scales over which change is measured; signals indicative of alongshore transport are only apparent when they dominate the higher-frequency, more localized sediment cycling of cross-shore transport processes. On the storm time scale of days to weeks, sand stripped from the beach is deposited in offshore bars that migrate landward with post-storm fair-weather swells, causing little net change to shoreline features [*List and Farris*, 1999]. If the effects of alongshore sediment fluxes become evident, at what scales in shoreline patterns does this occur? Previous analyses of shoreline change along the North Carolina Outer Banks suggest that shoreline curvature need not be pronounced for corresponding gradients in alongshore sediment transport to be effective [*Ashton et al.*, 2003; *Valvo et al.*, 2006]. Here we directly test this prediction, calculating and comparing shoreline change and curvature using annual lidar surveys of a long, continuous stretch of barrier island on northern flank of Cape Hatteras, North Carolina (Figure 1).

2. Methods

[5]   We define areas convex (concave) seaward in plan view as having positive (negative) curvature. Shoreline position retreating landward is defined as negative change; where the shoreline aggrades seaward is positive change.

[6]   For our measurements we extracted shorelines from U.S. Geological Survey and U.S. Army Corps of Engineers lidar surveys of the northern North Carolina Outer Banks

[1]Division of Earth and Ocean Sciences, Nicholas School of the Environment and Earth Science, and Center for Nonlinear and Complex Systems, Duke University, Durham, North Carolina, USA.
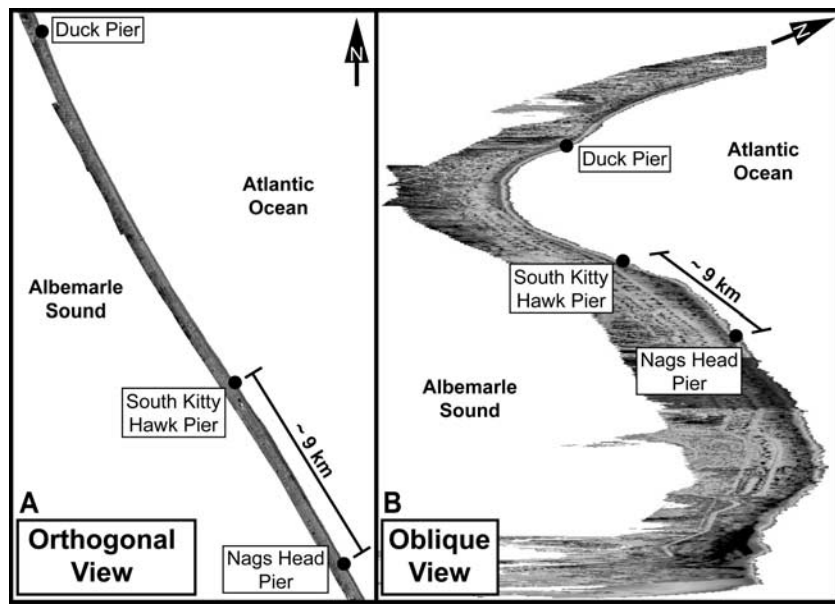
Figure 1. A lidar-derived DEM of the northern North Carolina Outer Banks, in (a) orthogonal and (b) oblique view. Note that even an apparently straight segment of shoreline (Figure 1a) has subtle curvature evident in Figure 1b.

collected in 1996, 1997, 1998, 1999, and 2005. Lidar instruments are flown in a small plane at low altitude (~1500 m) and sweep a laser pulse over the land below; a receiver in the plane records the reflected laser return and processing software translates the returns into a high-resolution topographic map of the survey area. (An excellent lidar-sensor history and specifications summary is available through the NOAA Coastal Services Center, at www.csc.noaa.gov). Lidar is indispensable in low-lying topography such as coastal plains because the laser
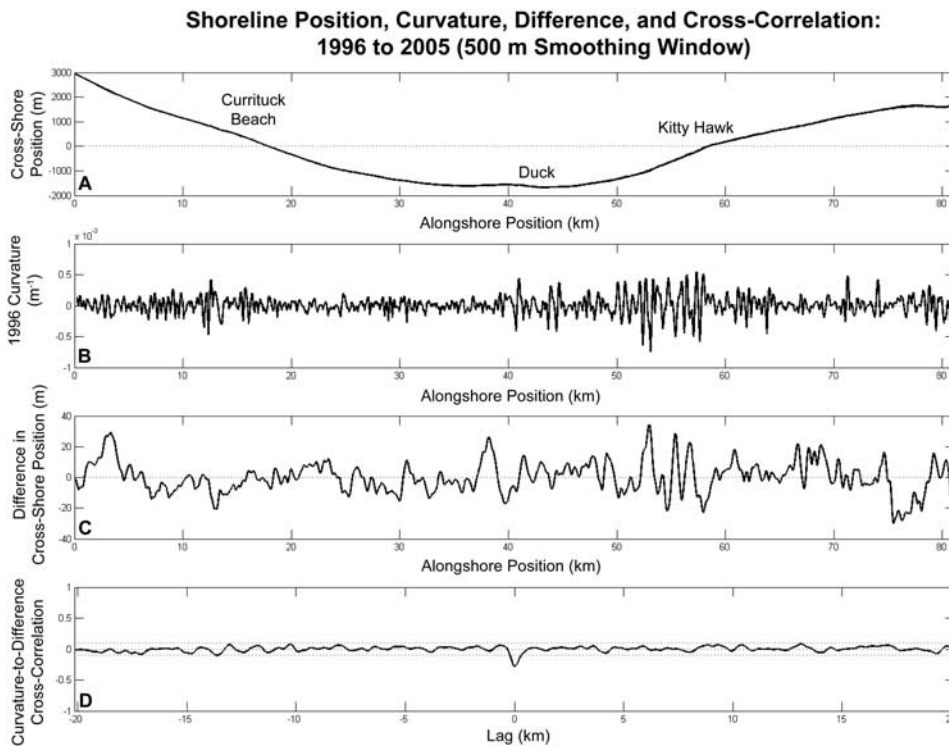
Figure 2. (a) Plots of shoreline position, labeled with general locations of Outer Banks towns, (b) 1996 shoreline curvature, (c) difference in shoreline position from 1996 to 2005, and (d) the cross-correlation between curvature and position difference, calculated for a 500 m smoothing window. In Figure 2d, the correlation peak at zero lag is outside the bounds of the 95% confidence interval, meaning the correlation between curvature and position change is robust.
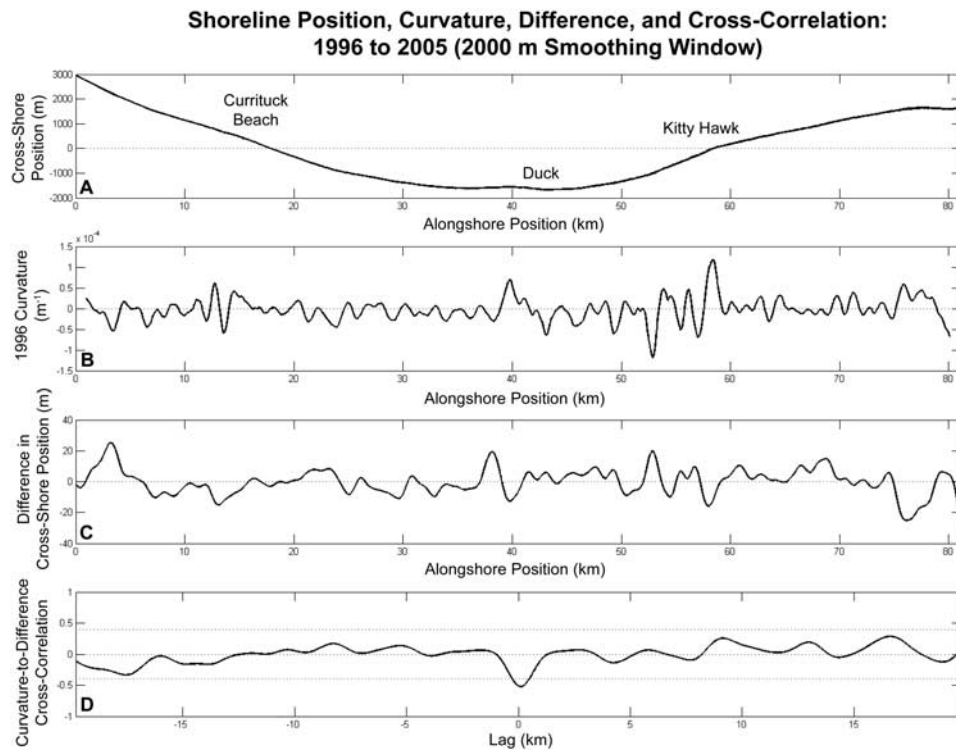
Figure 3. Plots same as in Figure 2, but calculated for a 2000 m smoothing window. Note that at this larger spatial scale for the 1996–2005 comparison, the correlation coefficient in Figure 3d is greater than in Figure 2d.

equipment can measure ground elevations to within 15 cm [*Brock et al.*, 2002; *Woolard and Colby*, 2002; *Sallenger et al.*, 2003].

[7] From the lidar DEMs we selected the 1 m elevation contour, as opposed to the zero or regional tide-adjusted contour [*Weber et al.*, 2005; *Tebbens et al.*, 2002], to represent the shoreline, minimizing wave-crest interference. (The elevation data are registered to the 1988 North American Vertical Datum.) We also cropped our survey area to reasonably exclude beach-restoration and hard-structure emplacement at the northern extent near False Cape, Virginia, and tidal-inlet influences at Oregon Inlet, North Carolina, to the south [*Fenster and Dolan*, 1996]. We are thus able to focus our analyses on the morphological effects of wave forcing over 85 km of continuous coastline.

[8] Rendering the shoreline as an array of planar coordinates, we subtracted the linear trend of the shoreline's original spatial orientation so that the alongshore direction corresponds to the *x*-axis and cross-shore to *y* (Figures 2a and 3a). The shoreline data points are spaced 5 m apart, an interval dictated by the horizontal accuracy of the lidar instrument [*Brock et al.*, 2002; *Woolard and Colby*, 2002; J. Wozencraft, personal correspondence, 2006]. At such a small spacing, however, high-frequency undulations in shoreline position swamp more subtle, lower-frequency patterns. To isolate alongshore undulations up to the scale of several kilometers, we applied a series of sequentially larger smoothing windows that function as low-pass signal filters. In comparing shorelines from two different years, for

each window size we calculated the curvature of the shorelines, where curvature (κ) is defined as

$$\kappa = \frac{\dfrac{d^2y}{dx^2}}{\left[1 + \left(\dfrac{dy}{dx}\right)^2\right]^{\frac{3}{2}}}$$

and *x* and *y* are alongshore and cross-shore position in meters, respectively (Figures 2b and 3b). By linearly detrending each windowed shoreline segment before calculating κ, we reduce dy/dx to zero and thus simplify curvature to the second derivative of the shoreline. We then found the difference in shoreline position between the surveys by subtracting the earlier positions from the later (Figures 2c and 3c), and cross-correlated the change in shoreline position with the curvature results (Figures 2d and 3d), following the techniques and correlation functions described by *Emery and Thompson* [2004].

3. Results

[9] We find a persistent, robust negative correlation between shoreline curvature and shoreline-position change for 1–10 yr time scales and spatial scales from 100–3000 m. The negative correlation suggests that areas of positive curvature (convex-seaward promontories) tend to exhibit negative change in shoreline position (erosion landward)
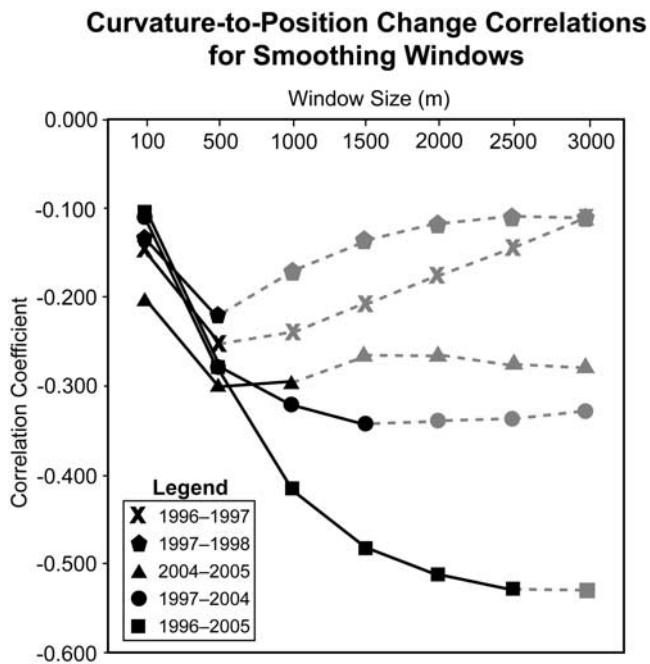
Figure 4. Plot showing curvature-to-position-change correlation coefficients versus window size for a range of year-to-year comparisons. At annual scales, correlation magnitudes reach a maximum around 500 m; at near-decadal extents, the coefficients reach a maximum between 1000–3000 m. The correlation between curvature and shoreline-position change may be a signal of alongshore sediment-transport processes; stronger correlations at decadal and kilometer scales suggests that alongshore rather than cross-shore processes tend to dominate shoreline change over longer time intervals and larger spatial extents. Where lines are gray, correlation does not exceed the 95% confidence interval.

and vice versa. The result points to an overall diffusive smoothing of shoreline features.

[10] Figure 4 shows that correlations are strongest over long time intervals and at large spatial ranges, on the order of kilometers for the decadal extent of the data. For annual time intervals the correlation reaches a maximum at smaller smoothing-window sizes (∼500 m); for longer time intervals (8–9 yr) the correlation reaches a maximum at larger smoothing windows (1000–3000 m). As the size of the smoothing window increases, the number of independent data points in the series decreases; the number of independent data points is so small beyond the correlation-coefficient maximum that the subsequent correlation coefficients at zero lag do not exceed the 95% confidence interval. (The confidence interval we employ is the extent to which we can reject the null hypothesis that there is no relationship between shoreline curvature and shoreline-position change.)

[11] As the smoothing window increases, undulations with an increasing alongshore wavelength are identified (e.g., Figure 2b compared to Figure 3b), and the amplitude of those undulations remains approximately constant throughout the range of smoothing windows. This analysis confirms that the alongshore features in our study area do not exhibit a dominant spatial wavelength, a finding

consistent with previous wavelet analysis of shoreline change in the same region [*Tebbens and Nelson*, 2000; *Tebbens et al.*, 2002].

4. Discussion

[12] As a signature of alongshore sediment-transport processes, the correlation we find between curvature and shoreline-position change, though significant at annual and sub-kilometer scales, is strongest at decadal and kilometer scales, suggesting that alongshore transport processes tend to dominate shoreline change over long time intervals and large spatial extents while cross-shore or nearshore processes presumably dictate morphologic variation on shorter and smaller scales.

[13] The spatio-temporal relationship evident in the negative correlation is also consistent with the analytically predicted time scale for diffusion, in which time is proportional to the square of the length scale [*Peldnare-Consideré*, 1956; *Ashton and Murray*, 2006a]. With the negative correlations over annual time intervals strongest at spatial scales inside a kilometer and over decadal intervals at 2–3 km, the smaller alongshore features exhibit change on shorter time scales than do the larger features.

[14] A negative correlation between shoreline curvature and shoreline-position change for the barrier-island coast between False Cape, Virginia, and Nags Head, North Carolina, dovetails with recent wave-hindcasting analysis for the northern Outer Banks documenting a predominantly a low-angle incident wave climate over the last two decades, and with the argument that the shadowing effects of large-scale capes, such as those of the Carolinas, tend to create and maintain low-angle wave climates on their flanks [*Ashton and Murray*, 2006b]. Cape tips, which extend tens of kilometers offshore, shelter cape flanks from some of the antidiffusive influence of high-angle waves; along the flanks, steady forcing from a low-angle-dominated wave climate (over long enough time scales) will cause alongshore perturbations at all wavelengths to diffuse. The resulting process signal therefore should be the same at all spatial scales, as long as cape tips are not included. The negative correlation also supports numerical-modeling results suggesting that shoreline change over 20 years consists largely of shoreline-shape diffusion [*Ashton et al.*, 2003].

[15] Though the correlation coefficients are small, a simple comparison experiment reinforces their validity. A complicating factor in comparing curvature and position change is that a bounded, noisy system produces an inherent negative correlation. Consider a set of randomized points sequestered between an upper and lower bound: if allowed to migrate over some time interval, points already situated near the margins cannot cross the boundary and therefore have a high probability of moving toward the interior of the envelope. The points nearest the bounds create areas of high curvature, so their probabilistic migration away from the boundaries reduces curvature and sets up a negative correlation between curvature and position change comparable to diffusion. Isolating signals diagnostic of alongshore transport processes thus requires differentiating those signals from a correlation attributable to noise. We generated two randomized datasets and processed them

with the same steps and algorithms applied to the lidar-derived shorelines. An unsmoothed randomized bounded dataset has a correlation coefficient of 0.5; with any smoothing, the correlation drops to zero.

[16] A bounded system, if an inappropriate analogy for a true shoreline, is at least a stringent null hypothesis. More complicating is that alongshore translation of features with a well-defined wavelength does give a negative correlation between curvature and shoreline change: Correlation magnitude increases as translation approaches half a wavelength, producing a maximum correlation at zero-lag in a cross-correlation analysis (as we observe at scales within 2 km), making process signals difficult to differentiate.

[17] The diffusive influence of a low-angle wave climate for at least two decades begs the question why any bumps in the shoreline still persist (Figure 1). Their sustained existence outstrips an argument for simple diffusion, but may stem from heterogeneities in underlying shoreface lithology [*Riggs et al.*, 1995, 1996; *Cleary et al.*, 1999; *McNinch et al.*, 2001; *Honeycutt and Krantz*, 2003; *McNinch*, 2004]. Integrated alongshore sediment-transport and geologic framework modeling by *Valvo et al.* [2006] offers evidence for the adjustment and persistence of lithology-related alongshore promontories and embayments in low-angle wave climate regimes, and predicts that correlations between curvature and shoreline-position change can switch from negative to positive on decadal time scales as the net diffusivity of the wave climate fluctuates about a mean. Given a steady wave climate and homogeneous shoreface substrate, our results would have predictive application for long-term shoreline change. However, variability in annual- to decadal-scale North Atlantic climate, in concert with lithological heterogeneity, confuses predictions of future shoreline position.

[18] Coastal change is one of the few circumstances in which geologic and political timelines intersect, and with mounting evidence for potential changes in storm frequency and severity in the future, ocean-side communities are facing increasingly difficult management dilemmas [e.g., *Slott et al.*, 2006]. Investigation of shoreline evolution and eventual predictive capacity is therefore of immediate importance to land managers at all governmental levels making decisions about coastal public domain, beach restoration, and erosion response.

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E. D. Lazarus and A. B. Murray, Division of Earth and Ocean Sciences, Nicholas School of the Environment and Earth Science, and Center for Nonlinear and Complex Systems, Duke University, Box 90229, Durham, NC 27708-0227, USA. (edl6@duke.edu)