Abstract: Recent measurements of shoreline position reveal that coastlines move in a surprisingly alongshore-heterogeneous manner over temporal scales ranging from days to years. Along portions of the North Carolina Outer Banks, zones of accretion and erosion on the scale of hundreds of meters to several kilometers develop that migrate in the alongshore direction, resembling alongshore ‘sandwaves’ found along other coasts. A simple numerical model that treats alongshore sediment transport as a function of shoreline orientation develops similar correlated zones that migrate under the influence of waves that approach the shoreline at angles greater than the one that maximizes alongshore sediment transport. This simple model of shoreline change also captures many of the twenty-year patterns of erosion and accretion measured along the Outer Banks.

INTRODUCTION

Traditionally, researchers have assumed that alongshore sediment transport will diffuse, or smooth the plan-view shape of a sandy shoreline (Pelnard-Considere, 1956; Komar, 1998). However, recent research (Ashton et al., 2001; Murray, 2003) indicates that shorelines are unstable when the angle between the crests of approaching deep-water waves and the shoreline is greater than the one that maximizes alongshore sediment transport (‘high-angle waves’). If a shoreline is subjected to high angle waves, complicated accretion and erosion patterns should appear. Recent measurements along the North Carolina Outer Banks reveal that natural shorelines change in a surprisingly complex manner over many time scales, with correlated zones of accentuated erosion and accretion, sometimes called alongshore ‘hotspots’ (List and Farris, 1999; Tebbens et al., 2001). In this paper, we will examine whether connections exist between hotspots and alongshore sediment transport, treated as a simple function of the angle between deep water waves and the shoreline orientation.

SHORELINE MEASUREMENTS

SWASH (Surveying Wide-Area SHorelines), a shoreline measuring system developed by the U.S. Geologic Survey (USGS), utilizes Global Positioning System (GPS) positioning and a GPS-based attitude sensor mounted on an all-terrain vehicle (List and Farris, 1999). Shoreline position at mean high water level (MHW) is calculated using vehicle attitude and three-dimensional GPS location, assuming a constant foreshore slope (Figure 1). Position measurements, taken at 2 m intervals, are accurate to about 4 cm and measured beach slopes are accurate to approximately 0.4 degrees. At each measurement point, a shoreline position is calculated and 95% confidence limits are computed based upon both instrument limitations and possible deviation from the assumed constant foreshore slope.
Surveys extend from a point approximately 22 km north of the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) to the tip of Cape Hatteras, covering a distance of approximately 130 km (Figure 2). This continuous section of shoreline is broken by only Oregon Inlet. For simplicity, we have split the shoreline surveys into two segments, one from Duck to north of Oregon Inlet, the other from just south of Oregon Inlet to north of Cape Hatteras, referred to as the ‘Northern’ and ‘Southern’ sections, respectively. Measurements taken within the vicinity of Oregon Inlet and Cape Hatteras have not been used.

Surveys taken pre- and post-storms and at approximately monthly intervals document alongshore zones of accretion and erosion that can measure hundreds of meters to kilometers in length and persist from days to decades. Based on observations, we classify hotspots into three general categories:

1) *Short-Term Reversible Hotspots* consist of alongshore non-uniform patterns of storm erosion virtually erased by post-storm accretion (shown for the Outer Banks by List and Farris (1999)).

2) *Medium-term Hotspots* are spatially correlated zones of erosion and accretion that occur over hundreds of meters to a few kilometers and persist for months to years while often shifting in the alongshore direction. These are similar to ‘sandwaves’
documented along other coasts (Bruun, 1954; Stewart and Davidson-Arnott, 1988; Verhagen, 1989; Ruessink and Jeuken, 2002) that can be obvious visual features or more subtle zones revealed by measurements.

3) **Long-term Hotspots** appear as zones of erosion lasting for decades or longer that are often immediately adjacent to stable or accreting shorelines (Everts et al., 1983).

Our classification scheme is a simplification, as the shoreline generally changes over all surveyed spatial and temporal scales. For example, if short-term hotspots are not entirely erased, the residual could manifest as medium-term hotspots. And long-term hotspots will be measurable over the inter-annual scale of medium-term hotspots. However, the time periods of short-, medium-, and long-term hot spots correspond to meteorological time scales of individual storms, annual and interannual weather variations, and averaged wave climates, respectively. This paper will focus on medium- and long-term hotspot behavior occurring at scales larger than 100 m.

**INSTABILITY IN SHORELINE SHAPE**

An alongshore current is driven by the alongshore-directed component of the radiation stress, which is constant as waves shoal and refract over shore-parallel contours (Longuet-Higgins, 1970; Longuet-Higgins, 1972). A common formula (Komar and Inman, 1970; Komar, 1971) for alongshore sediment transport ($Q_s$) multiplies the stress driving the alongshore current by the breaking wave velocity (taken to be proportional to the square root of the breaking wave height ($H_b$)), yielding:

$$Q_s = K H_b^{5/2} \cos(\phi_b - \theta) \sin(\phi_b - \theta)$$  \hspace{1cm} (1)

where $K$ is an empirical parameter, $\theta$ is the shoreline orientation, $\phi$ is the orientation of wave crests, and the subscript $b$ denotes breaking-wave quantities. Field measurements along the Florida coast using a sediment trap show a correlation between $Q_s$ and the functional part of (1) ($H_b^{5/2} \cos(\phi_b - \theta) \sin(\phi_b - \theta)$), with large site-specific variation in the empirical constant $K$ (Wang et al., 1998). Assuming shore-parallel depth contours, this relation can be recast as (using the approximation $\cos^{1/5}(\phi_b - \theta) \approx 1$):

$$Q_s = K' H_o^{12/5} \cos^{6/5}(\phi_o - \theta) \sin(\phi_o - \theta)$$  \hspace{1cm} (2)

where the subscript $o$ denotes deep-water values. Alongshore sediment transport is maximized for $(\phi_o - \theta)$ of approximately 43 degrees. Deigaard et al. (1988), using a process-based model with a detailed treatment of sediment transport, found a maximum in sediment transport for $(\phi_o - \theta)$ slightly greater than 45 degrees.

Assuming that the rate of sediment exchange between the nearshore and deeper water is negligible compared to the alongshore flux (so that nearshore sediment is conserved), when the angle between approaching wave crests and the shoreline is less than the maximizing angle, bumps on a straight shoreline will be diffused (Grijm, 1960; Pelnard-Considere, 1956; Komar,
However, when waves approach at an angle greater than the maximizing one, bumps on a straight shoreline will grow; the shoreline is unstable. (For additional discussion see Ashton (2001) and Murray (2003).)

As waves approach shore, their crests refract to become more shore-parallel, and ocean waves rarely break at angles greater than 45 degrees, the maximum for $Q$, in (1), holding $H_b$ constant. However, when deep-water waves approach the coast at greater relative angles, as $(\phi_b - \theta)$ increases, $H_b$ is reduced due to the stretching of the wave crests during refraction. For a given set of approaching waves, $H_b$ and $\phi_b$ vary together from one part of a shoreline to another. Therefore, for conceptual purposes, differences in alongshore sediment transport along a shoreline are better characterized using the deep-water wave angle and height, rather than the breaking values.

NUMERICAL MODEL

We have developed a simple numerical model to investigate the effects of the shoreline instability acting over an extended domain where waves approach the shoreline at different angles over time (Ashton et al., 2001). Similar in concept to other ‘one contour line’ numerical models (LeMehaute and Soldate, 1977; Ozasa and Brampton, 1980; Hanson and Kraus, 1989), our model discretizes sediment transport in the alongshore direction and assumes nearshore conservation of sediment. Our model, however, can handle an arbitrarily complex shoreline, and, more important for this investigation, uses a numerically stable solution during periods of high-angle wave approach. The model consists of a discretized plan-view domain where fractionally filled cells represent the shoreline position. Deep-water wave variables are refracted to a depth-limited breaking point assuming shore-parallel contours. Equation (1) determines sediment transport between adjacent shoreline cells (Ashton et al., 2001).

Every simulated day, a new wave approach angle is randomly selected from a probability distribution function (PDF). During a given simulation, wave heights and periods are held constant. Using monochromatic waves should not result in spurious effects because the model calculates only bulk sediment transport and assumes refraction over shore-parallel contours without computing convergence and divergence of wave crests. The input wave PDF represents long-term contributions to alongshore sediment transport. After a sufficient number of simulated days, the simulated net alongshore sediment transport will approach the value expected from the input wave climate.

Our model is simple, containing only some of the processes that affect coastal evolution. Also, the site-specific variability of the constant $K$ in (1) (Wang et al., 1998) and additional concerns raised by Thieler et al. (2000) bring into question the ability of an alongshore sediment transport model to predict exact rates of shoreline change, particularly our simplified, uncalibrated model. However, our model is useful if our goal is not to quantitatively predict rates of shoreline change, but to investigate the hypothesis that hotspot phenomena are connected to gradients in alongshore sediment transport due to alongshore variations in shoreline orientation.
WAVE CLIMATE ESTIMATES

The wave climate for the Outer Banks has been approximated using Wave Information Study (WIS) hindcast values for Station 55 (USACE, 2001). The approximate location of Station 55 is shown on the reference map (Figure 2). The relative contribution to alongshore sediment transport from deep water waves (approximated by $H_o^{5/2}$) is summed over the record period of 1976-1995 within 7.5 degree bins. Because we are interested in the contribution of incoming waves to alongshore sediment transport, summing $H_o^{5/2}$ values is more appropriate than summing wave height or wave energy density ($H^2$).

Although waves approach this shoreline at the FRF from all angles (Figure 3a), low-angle waves predominate, with a peak around zero degrees (normal incidence). The same climate compared to the regional orientation of the shoreline at Avon also shows that low-angle waves predominate here (Figure 3b), but the peak is closer to the angle that maximizes sediment transport, with a greater contribution from high-angle waves than at the FRF. Avon’s distribution of high-angle waves is also asymmetric, with a larger contribution approaching from a northerly direction (left facing offshore).

MEDIUM-TERM HOTSPOTS

To identify medium-term hotspots, we have analyzed the three-year data set of 36 approximately monthly surveys for the Northern Outer Banks section and 34 surveys of the Southern section taken between October 1999 and September 2002. Our approach is similar to that used by Ruessink et al. (2002) to investigate sandwaves along the Dutch coastline. Long-term net shoreline changes were first removed by computing a linear temporal trend of shoreline position over all of the surveys at each alongshore data point. The surveys were then

Figure 3. WIS Station 55 hindcasts of wave climates from 1976-1995, a. relative to the shoreline orientation at the FRF b. relative to the shoreline orientation at Avon. Negative wave angles approach from the left facing offshore.
broken into segments ten kilometers long to concentrate on shorelines of approximately similar orientation. For each approximately monthly survey, alongshore-homogeneous deviations were computed as the average along each 10 km segment of the distance between measured shoreline positions and the position predicted by the previously computed long-term temporal trend. After taking the measured shoreline positions, subtracting the temporal trend, and then subtracting the alongshore-averaged deviation from the temporal trend, the residual represents the shoreward or seaward displacement of the measured values from averaged values. More simply, we have computed how far shoreward or seaward each shoreline position is compared to an alongshore average.

Figure 4 shows time stacks of the results of this analysis. Along the Northern section, few organized patterns of erosion or accretion appear, and these zones are typically no larger than a few hundred meters, with no obvious migration in the alongshore direction (Figure 4a). In contrast, along the Southern section, where the waves tend to approach from greater angles, there are several noticeable correlated zones of accretion and erosion (Figure 4b). Some of these zones measure 2-3 km long and persist throughout the data record. Others are smaller and more transient. Most of the correlated zones tend to migrate to the south – in the direction of net alongshore sediment transport according to the WIS wave climate.

We have used the simple numerical model to determine how different wave climates could affect the development of hot spot behavior on an idealized sandy shoreline. The input wave climate PDF for the simulations approximates the WIS Station 55 wave climate by fitting a gaussian distribution function and a constant ‘background’ wave approach angle (Figure 5). By changing the location of the gaussian peak \((\phi_r - \theta_{\text{peak}})\), we can simulate shorelines with different orientations.

Simulations were performed for 20 km sections of an initially straight shoreline with white noise perturbations and alongshore-periodic boundary conditions. Figure 6 shows simulation results analyzed using the same method as above for different relative shoreline orientations (simulated by changing the location of the gaussian peak in Figure 5). Correlated zones of erosion and accretion develop for all of the simulations. The correlated zones in 6a, however, are artifacts of the binary plotting technique – the low-angle wave climate simply coalesces the initial white-noise perturbations and the deviations from a straight shoreline become small over time. In nature, other, smaller-scale processes will prevent a shoreline from becoming this smooth. As simulation wave climates include an increasing predominance of high-angle waves, correlated zones begin to migrate in the direction of net alongshore transport, with the migration rate increasing with increasing wave approach angles. For hotspots to migrate, simulations require an asymmetry in high-angle wave approach angle, not just an asymmetry in wave approach angle. In Figure 6c, where the wave climate is weighted slightly towards a
Figure 4. Time stacks of measured alongshore-heterogeneous shoreline behavior from SWASH surveys taken at approximately monthly intervals, binned every 200 m. Red pixels indicate measured shoreline locations shoreward of the temporal and spatial averages. Green pixels indicate measured shoreline locations seaward of the averages. Empty cells represent sections with insufficient data.
predominance of high-angle waves, the correlated zones merge over time, resulting in a net increase of sandwave wavelength. The wave climate for portions of the Southern Section (Figure 3b) resembles \((\phi - \theta)_{peak}\) of approximately 40 degrees, corresponding to the model results plotted in Figure 6b. In both cases (Figures 4b and 6b), our analysis shows kilometer-length migrating zones.

**LONG-TERM HOTSPOTS**

In 1980, the National Oceanic and Atmospheric Association/National Ocean Service (NOAA/NOS) measured the location of the Northern section of the Outer Banks shoreline using aerial photography (Everts et al., 1983). Figure 7 shows shoreline change from 1980 to approximately 2000, computed by subtracting the 1980 Shoreline from the average 1999-2001 SWASH shoreline. Several zones of long-term erosion are adjacent to regions of long-term accretion. Two prominent erosion and accretion couplets also appear to coincide with ‘kinks’ in the measured shoreline orientation.

We have performed numerical simulations based upon the northern Outer Banks shoreline and wave climates. Again, because our numerical model is not designed for exact predictions, we have used the model to compute relative rates of shoreline change. Initial conditions represent the 1980 shoreline, cells are 100 m wide, and constant flux lateral boundary conditions were applied. Using an extremely small sediment transport rate constant \(K\), simulations were run for 1,000 wave approach angles randomly selected from the WIS Station 55 wave climate PDF, oriented to the survey reference line. To scale the shoreline changes in the model run to the observed changes, we multiply the simulated changes by the ratio of the

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**Figure 5.** WIS wave climate relative to the FRF shoreline orientation along with Gaussian approximation. The location of the Gaussian peak can be changed to simulate shorelines of different orientations.
maximum measured shoreline erosion rate to the maximum simulated erosion rate.

Figure 8 shows measured values and the normalized simulated values. Several of the prominent erosion/accretion couplets are captured, both their locations and relative magnitudes. The match is not as good further along the reference line, towards Oregon Inlet. Possibly inlet processes that are affecting net sediment transport rates are not captured by the model’s constant flux boundary conditions.

The wave climate for this portion of the outer banks is dominated by low angle waves approaching from the east-northeast (Figure 3a). Because the 1976-1995 wave climate is dominated by low-angle waves, our simulations of alongshore sediment transport acting alone can only result in a smoothing of existing shoreline bumps. Although the model and the recent
wave climate cannot explain the existing large-scale changes in shoreline orientation, they can help explain why the existing shoreline behaves as it does.

**DISCUSSION AND CONCLUSIONS**

In nature, many complications and processes not included in the numerical model affect shoreline behavior, including variations in shoreface lithology, off-shore bathymetry that concentrates wave energy, the configuration of alongshore bars, and variations in cross-shore sediment transport. In fact, despite the predominantly low-angle wave climate, the northern Outer Banks shoreline contains subtle undulations occurring over many scales, verifying that controls or processes other than gradients in alongshore sediment flux due to differences in shoreline orientation affect coastline shape. However, the evidence that some hotspots migrate, occur in different locations at different times, and can range across many scales suggests that neither stationary geologic control nor refraction patterns caused by stationary shelf bathymetry can fully explain all hotspot phenomena.
To investigate connections between hotspots and alongshore sediment transport, we have used a numerical model that focuses only on alongshore sediment transport caused by wave breaking. While the simplicity of our model would be weakness in a model designed to simulate natural behavior in as much detail as possible, this simplicity makes the connections between measured behavior and modeled processes more obvious (Murray, 2003). Simulations of idealized shorelines develop migrating zones of accretion and erosion, or sandwaves, under the influence of high-angle waves. These zones are similar to the measured migrating zones our analysis has identified along the Southern Outer Banks. Simulations using the measured location of the Northern Outer Banks shoreline show that the relative rate of long-term erosion and accretion at several hotspots match those predicted by the shoreline configuration and the recent wave climate. Using the simplified model and detailed shoreline measurements, we have preliminarily identified links between erosional hotspots and alongshore sediment transport (considered a function of the shoreline orientation), providing a possible explanation for observed Large Scale Coastal Behavior (LSCB) occurring over a range of scales.

Figure 8. Plots of measured shoreline change from 1980 to 1999-2001 and simulated relative rate of shoreline change.
ACKNOWLEDGEMENTS
The Andrew W. Mellon foundation and the USGS supported this research.

REFERENCES