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Shoreline Change as a Proxy for Subaerial Beach Volume Change

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ABSTRACT

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It is difficult and expensive to calculate changes in sediment volume for large sections of sandy beaches. Shoreline change could be a useful proxy for volume change because it can be collected quickly and relatively easily over long distances. In this paper, we summarize several studies that find a high correlation between shoreline change and subaerial volume change. We also examine three new data sets. On Cape Cod, Massachusetts, the correlation coefficients between the time series of shoreline change and subaerial volume change at two locations are 0.73 and 0.96. On Assateague Island, the correlation coefficient between along-coast variations in shoreline change and subaerial volume change is 0.71. On the Outer Banks of North Carolina, the average correlation coefficient between temporal variations in shoreline change and subaerial volume change is 0.84. For spatial variations, the average correlation coefficient is 0.88. It is therefore concluded that shoreline change is a useful proxy for subaerial volume change.

ADDITIONAL INDEX WORDS: *Beach erosion and accretion, beach profiles, shoreface, coastal change, shoreline position, profile change, Cape Cod, Outer Banks, Assateague Island.*

INTRODUCTION

Sandy coasts are dynamic environments that can change over all time and length scales because of a myriad of coastal processes. The ideal way to monitor these changes would be to calculate the entire volume of sand that is lost or gained. However, to accurately and thoroughly calculate the change in sediment volume, one would need to collect and process a vast amount of data over both time and space. Because this can be either technologically impossible or prohibitively expensive, a proxy is needed that can be measured rapidly and easily over long distances. Shoreline change has frequently been used as a proxy for the volume of sand that is lost and gained as sandy beaches erode and accrete.

To show why shoreline change might be a good proxy for volume change, we first need to define terms. The total volume of sand per meter shoreline stored under a cross-shore profile can be found by integrating under the profile down to the lowest elevation measured on the profile. Ideally the profile extends far enough landward into the dunes to be beyond sand movement and seaward out to the depth of closure—a theoretical limit offshore at which again there is no sand movement. Unfortunately, it can be difficult to collect enough data to calculate total volume accurately. Studies that are not investigating cross-shore sediment budgets often calculate subaerial volume. Subaerial volume does not have a standard definition. It is common to define the seaward extent of the subaerial beach where the foreshore intersects some set datum, such as mean high water (MHW; Figure 1). Data availability often determines the datum used. (With large wave run-up, it can be difficult to collect data at or below MHW.) The landward extent of subaerial beach is also variously defined, usually depending on data availability. Subaerial volume is integrated down to the datum used to determine its seaward extent.

Shoreline position is defined in several ways. One common type of shoreline is known as a datum-based shoreline, which is defined as the intersection of a specific elevation datum (*e.g.,* MHW) with the foreshore (Figure 1). Another common type of shoreline is known as a visually interpreted shoreline, in which a visually identifiable surrogate, such as the wet-dry line or the high-water line, is defined as the shoreline. In this study, we do not consider visually interpreted shorelines because they can move in response to changing wave conditions, even if no movement of sand results in volume change (RUGGIERO, KAMINSKY, and GELFENBAUM, 2003). For a datum-based shoreline to change position, some sand must move, at least at the elevation of the datum. However, the simple translation of one elevation on the profile does not contain information about sand movement across the entire profile. If one considers the possibility of cross-shore transport, in which sand is redistributed across the profile but not lost or gained, then the total volume change associated with a change in shoreline position is particularly uncertain.

With the simplifying assumption that the beach profile is in equilibrium (maintaining its shape as it moves landward

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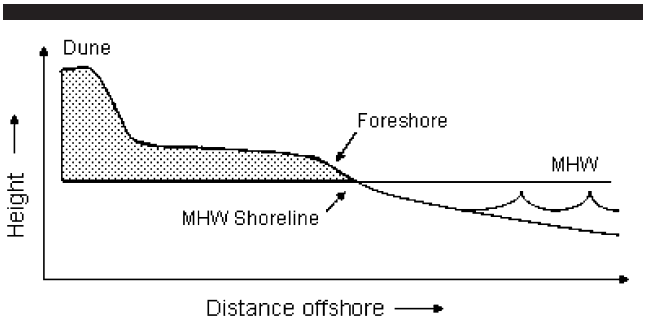

Figure 1. A schematic of a cross-shore profile. The horizontal line represents the height of mean high water (MHW). The shaded area represents subaerial volume per meter shoreline. The MHW shoreline is shown as the intersection of MHW with the foreshore.

or seaward), it has been shown that the change in total volume is simply equal to the height of the active profile times the horizontal movement of any elevation on the profile (*i.e.,* any datum-based shoreline; HANSON, 1989). Thus total volume change (per meter of shoreline) can be derived from MHW shoreline change as

$$\Delta V = H\Delta S,$$

where ΔV is total volume change, H is the height of the active profile, and ΔS is the change in the MHW shoreline position. It is common engineering practice when no volume data is available to estimate total volume change from shoreline change in this way (JARRETT, 1991).

Several previous studies have shown a strong similarity between alongshore variations in shoreline change and alongshore variations in total volume change (DEAN, LIOTTA, and SIMÓN, 1999; HARRIS, SAMUELSON, and DAMON, 2003). Both DEAN, LIOTTA, and SIMÓN (1999) and HARRIS, SAMUELSON, and DAMON (2003) consider decadal timescales, and indeed JARRETT (1991) suggests that this approximation works best over decadal and longer timescales because the equilibrium assumption is more likely to be valid over long timescales.

Because of its established use over long timescales and because it is such a useful proxy, some studies have begun to use shoreline change as a measure of coastal change over shorter timescales. Unfortunately, the usefulness of shoreline change as a proxy for total volume change over long timescales does not necessarily mean that shoreline change will be a good proxy for total volume change over short timescales. Shorter timescales need to be addressed separately because expectation is lower for the equilibrium profile assumption to be valid. The classic understanding of a profile's response to changing wave conditions involves significant cross-shore movement of sand, between a "berm" and "bar" profiles (KOMAR, 1998). When the profile shape changes in this way, the total volume change could be minimal, even if erosion of the subaerial beach is substantial. Therefore, studies of coastal change that do not analyze sediment budgets often calculate subaerial beach volume change because, to a user of the beach, it is a better representation of the observed changes on the beach than total volume change.

In this paper, we will investigate whether shoreline change is a good proxy for subaerial volume change by analyzing shoreline change and subaerial volume change data collected at the same time to see whether they are well correlated. We begin by reviewing several previously published studies that give the correlation between shoreline change and subaerial volume change. This correlation, however, was not the main focus of these papers and was usually presented with little explanation or discussion. In addition, more measurements are needed to further verify the universality of the relationship. We therefore assembled three additional data sets that extend the observations both spatially and temporally. These new data sets allow for a more thorough analysis of how shoreline change and subaerial volume change covary over both time and space.

PREVIOUS OBSERVATIONS

In this section, data from five previously published studies are presented. In most of these studies, the correlation between subaerial volume change and shoreline change was calculated as an interesting sideline rather than as the main focus of the paper. In some papers, the details of the calculations are not given. As mentioned earlier, there is no standard datum to use when defining shoreline position and subaerial volume. However, our own tests show that the choice of datum does not significantly affect the results. Table 1 summarizes the studies presented in this section.

As part of a larger study to monitor coastal change, GORMAN, POPE, and PITCHFORD (1994) surveyed 20 km of Amelia Island off the Florida coast. They surveyed the beach twice: once during July 1988 and again during April/May 1992. They collected 17 profiles at approximately 0.9-km spacing. At each profile location, they calculated shoreline position and subaerial beach volume for each survey. They defined shoreline position as the high-water line and calculated beach volume from midtide (0 m National Geodetic Vertical Datum; the most seaward point with good data coverage) up to 4 m (little sand movement was measured landward of this point). Figure 2 shows both shoreline change rate and net volume change rate along the coast between the two surveys; they have a correlation coefficient (r) of 0.95.

LEE *et al.* (1995) analyzed 10.5 years of profile data collected at the Field Research Facility of the US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, located in Duck, North Carolina. These cross-shore profiles have been collected biweekly since 1981. LEE *et al.* (1995) used these data to test a conceptual model of how the beach profile responds to fair weather and stormy conditions. As a part of this study, they calculated shoreline position and volume change. They found a high correlation between shoreline position change and subaerial volume change (excluding the dunes), with $r = 0.90$.

DAIL, MERRIFIELD, and BEVIS (2000) used a GPS system to conduct three-dimensional beach surveys of Waimea Bay in Hawaii to observe the changes that occur on the subaerial beach in response to the high-energy winter waves. They collected data at 1–3-week intervals for 16 months. They used mean sea level for shoreline position and calculated subaerial beach volume with the use of all available grid points for

Table 1. *Summary of previously published results and results from this work.*

Author	State	Spatial Extent/ Resolution	Temporal Extent/ Resolution	Shoreline Datum	Landward Limit of Subaerial Volume	Seaward Limit of Subaerial Volume	Correlation Calculated Over Time or Space?	Correl. Coefficient (r)
Gorman *et al.* (1994)	Florida	20 km/0.9 km	4 y/4 y	High water	4 m	0 m (midtide)	Space	0.95
Lee *et al.* (1995)	North Carolina	Point	10.5 y/2 wk	NR	Toe of dune	NR	Time	0.90
Dail *et al.* (2000)	Hawaii	150 m/averaged	16 mo/1–3 wk	MSL	NR	NR	Time	0.98
Sallenger *et al.* (2002)	California	1.5 km/20 m	7 mo/7 mo	MHHW	NR	NR	Space	0.94
Dingler and Reiss (2002)	California	48 km/~5 km	15 y/~5 mo	MSL	NR	MSL	Time	0.72–0.96 mean = 0.88
This work	Massachusetts	Point	2, 3 y/~2 wk	MHW	Toe of dune	MHW	Time	0.73, 0.96
This work	Virginia	60 km/10 m	7 mo/7 mo	MHW	In dune	MHW	Space	0.71
This work	North Carolina	50 km/~1 km	3 y/~1 mo	MHW	In dune	MHW	Time	0.43–0.98 mean = 0.84
This work	North Carolina	50 km/~1 km	3 y/~1 mo	MHW	In dune	MHW	Space	0.78–0.95 mean = 0.88

NR = not reported, MSL = mean sea level, MHHW = mean higher high water.

which data existed for all 27 surveys. They averaged both shoreline position and beach volume over 150 m of the beach and found a correlation coefficient of 0.98 between changes over time of the spatially averaged shoreline position and subaerial beach volume.

SALLENGER *et al.* (2002) use lidar data from Montara State Beach in California to measure the beach's response to the energetic waves of an El Niño winter. They surveyed 1.5 km of the beach twice: September 1997 and April 1998. They derived shoreline position with the mean higher high water datum and calculated subaerial volume. The spatial variability in shoreline change was highly correlated with the spatial variability in subaerial volume change. From their data, we calculated a correlation coefficient of 0.94.

DINGLER and REISS (2002) collected profile data at nine different beaches extending over 48 km of Monterey Bay in California 34 times from 1983 to 1998. They calculated beach width at mean sea level and beach volume down to mean sea level. They normalized the data by subtracting the mean from each value and dividing the result by the standard deviation. The resulting normalized beach width can be treated as shoreline change and the normalized beach volume as volume change. The correlation between the time series of normalized beach volume and the time series of normalized beach width was calculated for each of the nine beaches. Their values of r ranged from 0.72 to 0.96, with an average of 0.88. They found the lowest correlation coefficients occurred on beaches with mobile cusps above mean sea level (thereby effecting volume but not width).

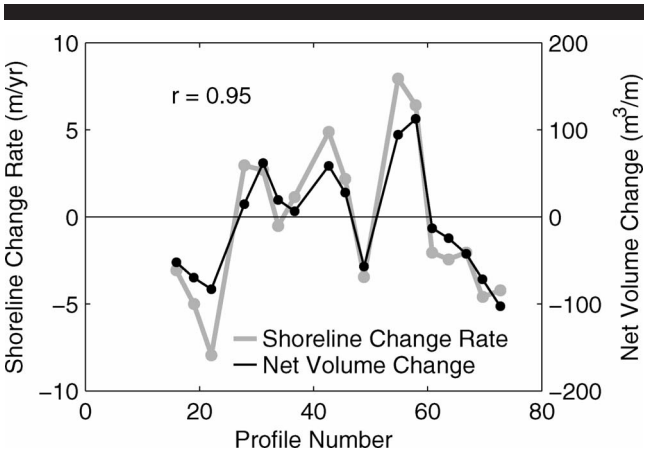

Figure 2. Shoreline change rate and subaerial volume change for Amelia Island, Florida, from July 1998 to May/June 1992. Data are from Gorman *et al.* (1994). Profiles are numbered from north to south.

DATA AND METHODS

We used data from three study areas within the United States: Cape Cod, Massachusetts; Assateague Island off the coast of Maryland and Virginia; and the Outer Banks of North Carolina. The beaches on Cape Cod and Assateague Island are virtually unaffected by coastal development or other human activities. In the Outer Banks, the impact is minimal from coastal development, although considerable dune building has been done. For each study area, we calculate subaerial beach volume per meter of shoreline, which we define as the area of sand under a cross-shore profile and above MHW. We use the intersection of the foreshore with MHW as the seaward limit of volume calculations in Assateague because it is the furthest seaward location with good data coverage. For consistency, we decided to use the same datum at the other two regions as well. The landward limit for volume calculation is different for each area and is given in the sections for each study area. We define shoreline position as the location of the MHW datum on the foreshore. Once we have derived shoreline position and subaerial volume, we calculate the change in these quantities over time from the first observation. These changes over time in shoreline position and subaerial volume are used to calculate all correlations.

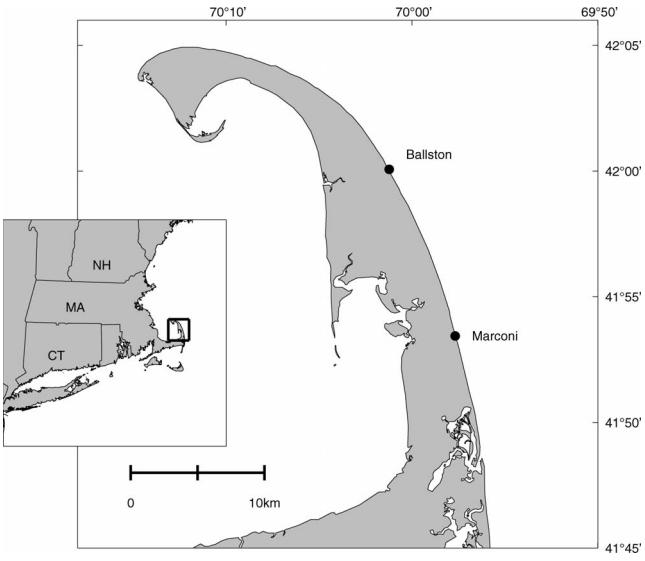

Figure 3. Location of Ballston and Marconi Beaches on Cape Cod, Massachusetts.

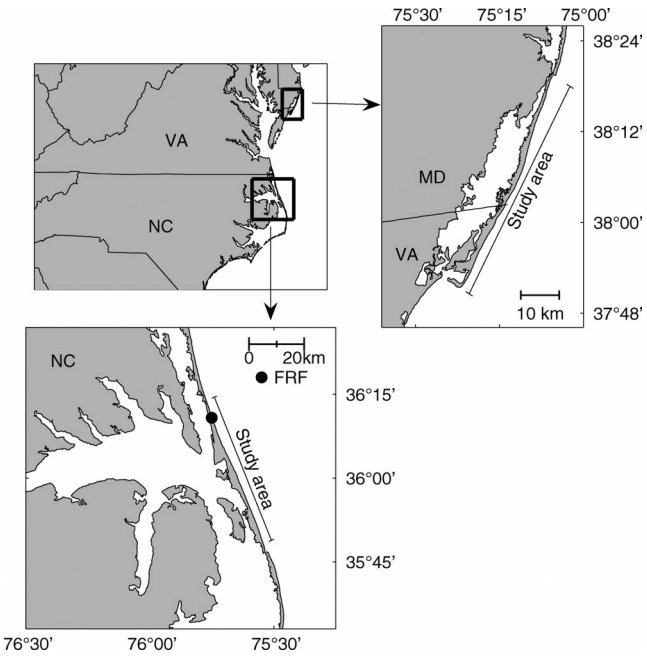

Figure 4. Location of lidar data on Assateague Island off the coast of Maryland and Virginia and profile data on the Outer Banks of North Carolina. The location of the Field Research Facility (FRF) of the Army Corps of Engineers is shown.

Cape Cod

A differential Global Positioning System was used to collect cross-shore profiles at two sites on Cape Cod: Marconi Beach and Ballston Beach (Figure 3). We collected data at Marconi Beach 36 times from February 2000 to February 2002 and at Ballston Beach 59 times from January 1999 to February 2002 with approximately biweekly sampling intervals. We calculated subaerial beach volume on each day from MHW on that day up to a set landward integration limit (X_{land}) that was near the base of the dune or bluff. This X_{land} was chosen to be a point as far landward as possible with good data coverage. The time series of shoreline change was compared with the time series of subaerial volume change at both locations.

Assateague

The second data set is lidar data from Assateague Island off the coast of Maryland and Virginia (Figure 4). Lidar data were collected with NASA's Airborne Topographic Mapper (Brock *et al.,* 2002) along almost 60 km of the beach on Assateague Island on 15 September 1998 and 3 April 1999. Cross-shore profiles were extracted from these data every 10 m along the coast (Stockdon *et al.,* 2002). To calculate subaerial volume, we used a landward integration limit (X_{land}) that was 50 m landward of the more erosional MHW shoreline position. Subaerial volume was calculated for both days from MHW (on that day) up to X_{land}. Although the same X_{land} was used for both days, each profile location along the coast has a different X_{land}. Because we use volume change instead of just volume, the changing integration limit between different profile locations should not significantly affect our results. Because this data set consists of only two surveys with extensive alongshore coverage, we analyzed how spatial variations in shoreline change correlate with spatial variations in subaerial volume change.

Outer Banks

The third data set is from the Outer Banks of North Carolina and was collected by the US Army Corps of Engineers. They surveyed 54 cross-shore profiles located along about 50 km of beach (Figure 4). These profiles were surveyed 48 times (approximately once a month, occasionally more frequently) from May 1974 through January 1977. Subaerial volume was calculated from the intersection of the profile with MHW up to the profile origin. Although it took up to 2 days to collect each set of profiles, we treat each survey as synoptic. Because this data set has both extensive spatial and temporal coverage, we were able to analyze how shoreline change and subaerial volume change covary over both time and space.

RESULTS

Cape Cod

The time series of shoreline change and subaerial volume change show remarkable similarities for both Marconi and Ballston Beaches (Figures 5A and 5B). The correlation coefficient (r) between the two time series is 0.73 for Marconi and 0.96 for Ballston (highly significant at the 95% level of confidence, as are all the correlation coefficients reported here). This good correlation can also be seen in a plot of volume change *vs.* shoreline change (Figures 6A and 6B). The Marconi data has two obvious outliers (where the shoreline change is large but the volume change is not) on 4 January 2001 and 30 March 2001. These two outliers occur because of welding swash bars, which have a large effect on shoreline

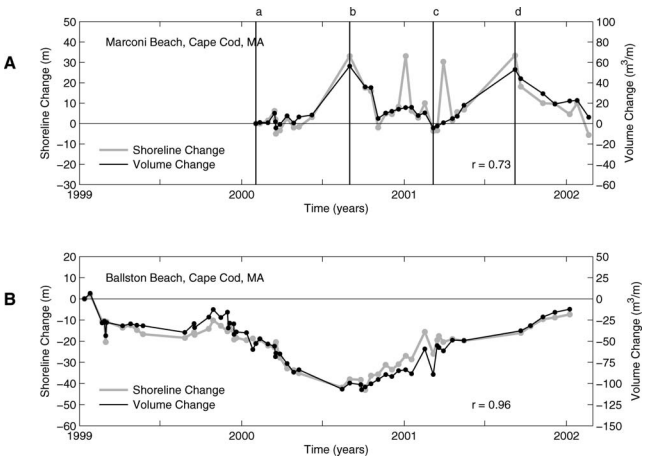

Figure 5. Time series of MHW shoreline change and subaerial volume change for (A) Marconi Beach and (B) Ballston Beach. Vertical lines in (A) refer to dates of profiles plotted in Figure 9.

position but not on beach volume. To illustrate this, Figure 7 shows the cross-shore profile on 30 March 2001 with 16 March 2001 as a reference (the profile on 4 January is similar to that on 30 March).

In general, the correlation between shoreline change and volume change is good. This good correlation is due in part to the invariance of the profile shape, as shown by plots of the profile envelopes (Figures 8A and 8B). Although berm height and beach slope are consistent overall, at times the profile does not maintain its shape (4 January 2001 and 30 March 2001, mentioned above, are two examples). Other examples can be seen in Figure 9, in which on 2 February 2000 and 7 March 2001 the beach is in a winter erosional state (or "bar profile"), whereas on 31 August 2000 and 7 September 2001 the beach is in a typical summer accretional state (or "berm profile"). Despite the definite change in profile shape, shoreline change is shown to be a good proxy for vol-

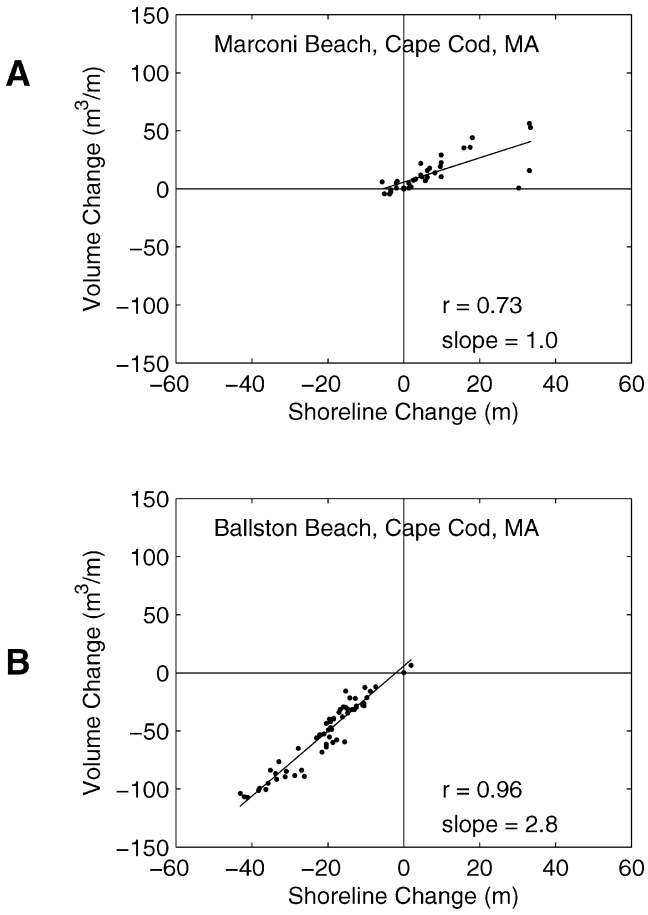

Figure 6. Subaerial volume change *vs.* shoreline change data from (A) Figure 5A, Marconi Beach, and (B) Figure 5B, Ballston Beach. Also shown is the best fit line through the data and its associated correlation coefficient and slope.

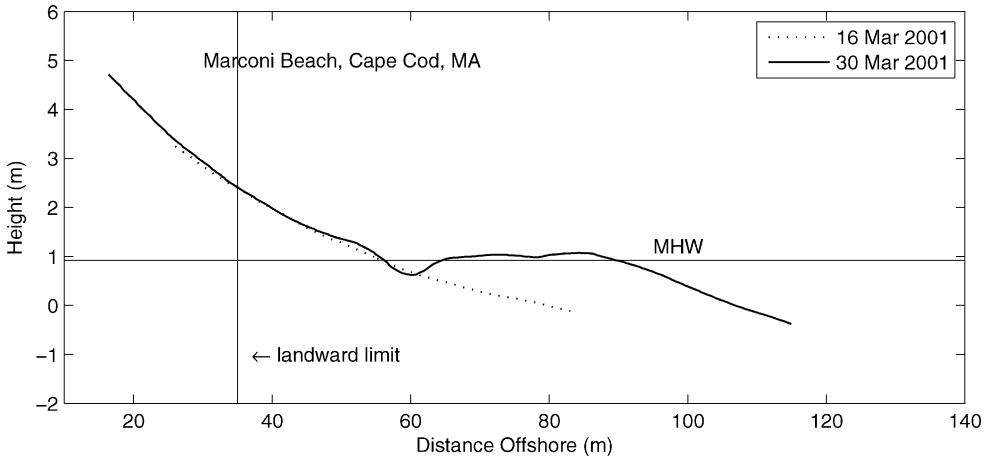

Figure 7. Cross-shore profiles at Marconi Beach on 16 March and 30 March 2001. On 30 March, a welding swash bar is evident.

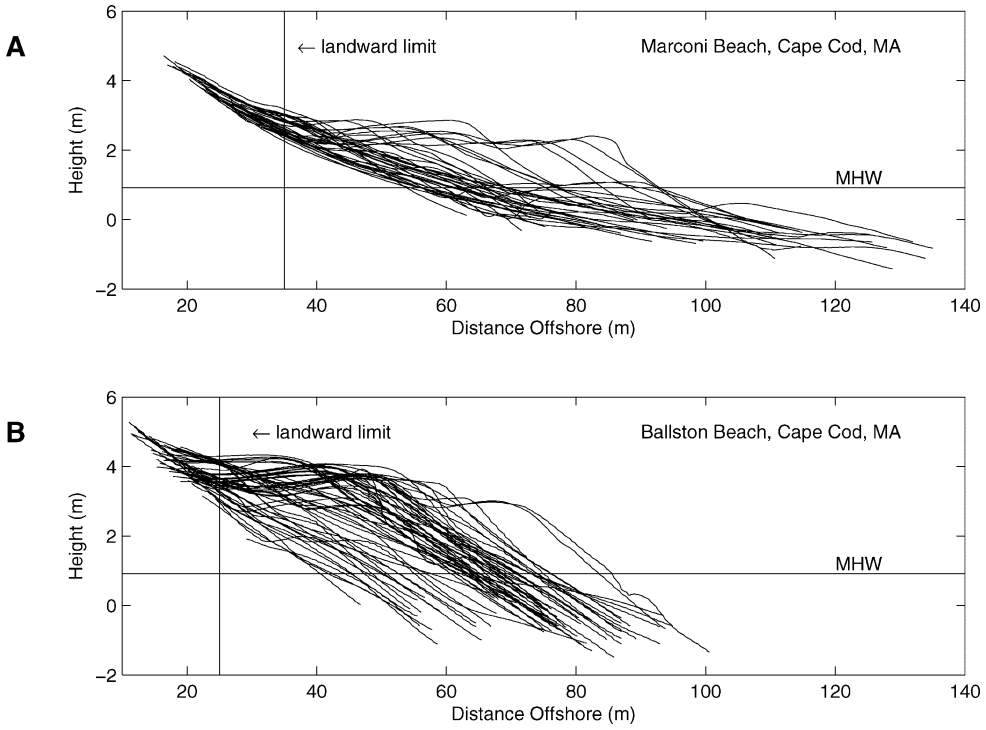

Figure 8. Envelope of profile variability for (A) Marconi Beach and (B) Ballston Beach.

ume change on these dates, as can be seen in Figure 5A (with dates of profiles shown in Figure 9 marked by vertical lines).

Assateague

The Assateague data extend over nearly 60 km of coast but on only two dates, thus, yielding information on how the volume/shoreline change relation varies through space rather than time as in the previous example. Figure 10 shows shoreline change and volume change as a function of distance along the coast. The two variables are fairly well correlated with an overall r of 0.71, with some parts of the coast appearing to have a better correlation than others. This correlation coefficient is lower than we have seen in other studies. A couple of factors might help explain this lower value. When calculating the correlation between the spatial variability of shoreline change and the spatial variability of volume change, any along-coast variations in profile shape will lessen the overall correlation. In addition, we are only considering two surveys, and between any two individual surveys, the profile shape might change considerably even though profile shape over time might be relatively constant (as was seen in the Cape Cod data). Despite the lower correlation, shoreline change is still a useful proxy for volume change, with 50% of the variability in volume change explained by the variability in shoreline change (as measured by r^2).

Outer Banks

The profile data from the Outer Banks of North Carolina include both spatial and temporal coverage; thus, we can look at the correlation of shoreline change with volume change over both time (similar to the Cape Cod data) and space (similar to the Assateague data). First we look at how well the temporal variability in shoreline change correlates with the temporal variability in volume change. Figure 11 is a plot of the correlation coefficient between the shoreline change time series and the volume change time series at each profile location. Some profiles have an excellent correlation (maximum $r = 0.98$), whereas for others, the correlation is much lower (minimum $r = 0.43$). Overall, shoreline change seems to be a good proxy for volume change because only a few locations have a correlation coefficient less than 0.7, and the average value is 0.84 (with a standard deviation of 0.12). The correlation coefficients for Cape Cod (0.73 and 0.96) are consistent with these values. The few locations with a poor correlation might be areas in which profile shape is more variable, possibly because of frequent welding swash bars or beach cusps. The correlation coefficient between all the shoreline change and volume change data (at all profile locations) is 0.88 (Figure 12). This is close to the average of the correlation coefficients calculated at each profile location, (0.84; Figure 11).

Next, we look at how well the spatial variability in shoreline change correlates with the spatial variability in volume change. For each survey date, we calculated shoreline change and volume change relative to the first date. Then, similar to the Assateague data, we calculated the correlation between the spatial variability in shoreline change and the spatial variability in volume change. However, for this data set, we have many more days of data and therefore many more cor-

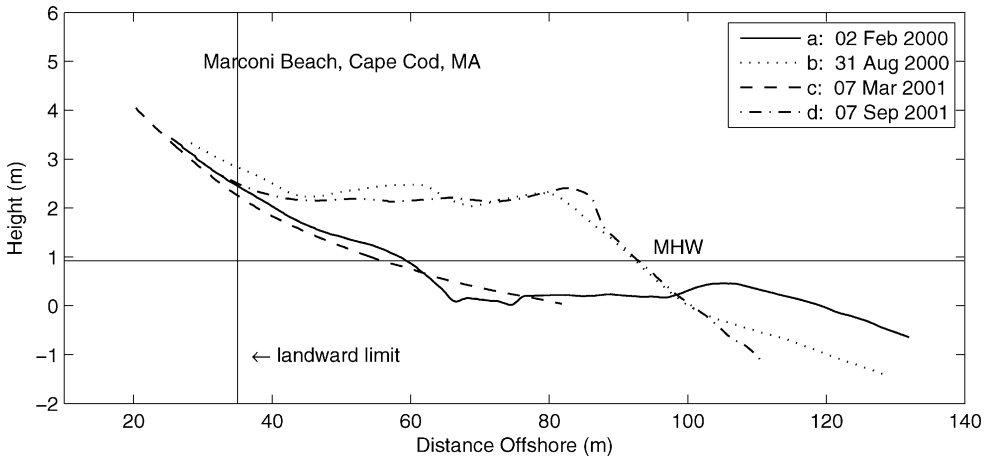

Figure 9. Cross-shore profiles at Marconi Beach on four dates. Letters associated with each date refer to vertical lines in Figure 5A.

relation coefficients (Figure 13). These coefficients are less variable than the correlation coefficients calculated between the time series of shoreline change and volume change at each profile location (Figure 11). Here, the correlation coefficients vary between 0.78 and 0.95, with an average of 0.88 and a standard deviation of 0.04. Interestingly, the correlation coefficient (r) seems to become more stable and increase over time, suggesting that the problems associated with profile dissimilarities have less relative importance over longer time periods, as might be expected if the magnitude of change at each profile tends to increases with time.

These values of r are higher than for the Assateague data, which was evaluated in a similar fashion. However, the smallest r value for the North Carolina data (0.78) is not much larger than for the Assateague data (0.71), suggesting that the Assateague relation, measured only once, might represent an unusually low association. Alternatively, the alongshore variations in profile characteristics might be larger at Assateague.

DISCUSSION

We find that shoreline change and subaerial volume change are usually well correlated. A few areas have lower correlations (like Marconi on 4 January and 30 March 2001, and parts of Assateague; Figures 5 and 10). The profile data in these areas show that the profile shape changed over time (Figure 7). However, in most of the data profile, shape did not significantly change (Figure 8). In the introduction we stated that for a profile that retains its shape (stays in "equilibrium"), the theoretical relation between volume change (per meter of shoreline) and shoreline change can be given by

$$\Delta V = H\Delta S,$$

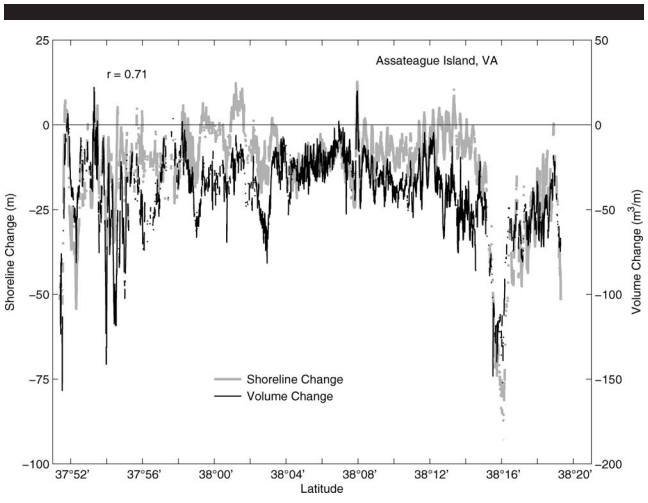

Figure 10. Along-coast subaerial volume change and MHW shoreline change from 15 September 1998 to 3 April 1999 for Assateague Island.

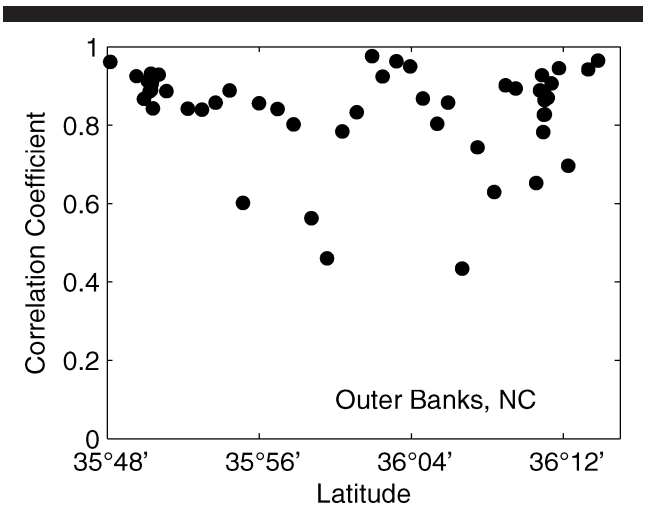

Figure 11. Correlation coefficients between shoreline change time series and subaerial volume change time series at each profile location on the Outer Banks of North Carolina.

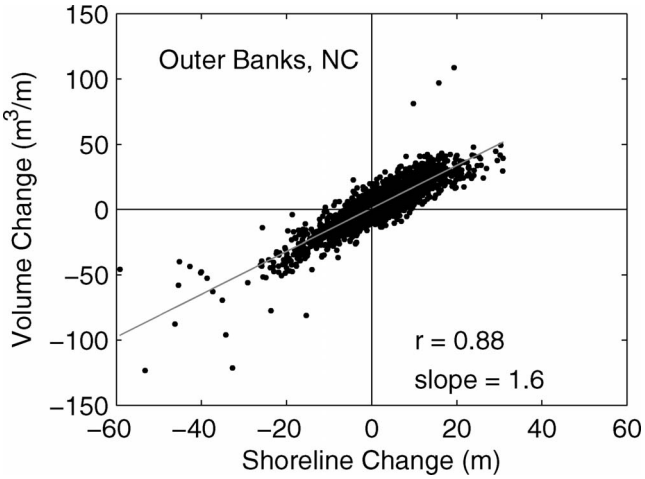

Figure 12. Subaerial volume change *vs.* shoreline change data from Figure 11. Also shown is the best fit line through the data with its associated correlation coefficient and slope. Data are from the Outer Banks of North Carolina.

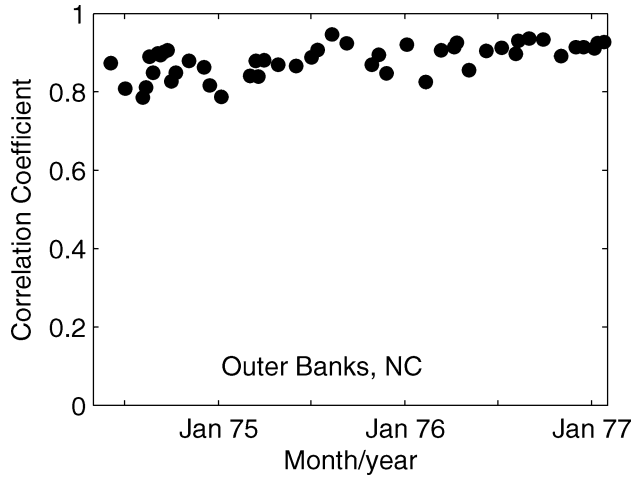

Figure 13. Correlation coefficients between along-coast variability in shoreline change and along-coast variability in subaerial volume change for each survey date for the Outer Banks of North Carolina.

where ΔV is subaerial volume change, H is the height of the active profile (relative to MHW), and ΔS is the change in MHW shoreline position. Therefore, in the linear regression of ΔV and ΔS, the slope of the regression is an estimate of the height of the active profile. We do not expect the regression slope to be a perfect measure of the height of the active profile, especially because we know the profile shape is not completely invariant. It is nevertheless interesting that Ballston has a higher berm crest and its regression has a steeper slope than Marconi. Visual estimates of the height of the active profile (relative to MHW) are roughly 1.5 m for Marconi and 2.5 m for Ballston (Figures 8A and 8B). These values are similar to the slopes of their linear regressions: Marconi = 1.0 m, Ballston = 2.8 m (Figures 6A and 6B). (The slope of the Marconi regression without the data on 4 January 2001 and 30 March 2001 is 1.6 m, with a correlation coefficient of 0.95.) It is interesting to note that the slope of the beach does not enter into the theoretical relationship between shoreline change and volume change (assuming an invariant profile) but might still have an effect because of the likelihood that the berm crest will be higher on a beach with a steeper foreshore slope because of higher wave run-up (HOLMAN, 1986).

Shoreline change data is used mainly in two ways. Some coastal change studies document shoreline change over time at one location. For example, one might be interested in whether the erosion at some important landmark or known hotspot is continuing or possibly increasing over time. Other studies investigate how shoreline change varies over space. For example, over a long stretch of beach, one might want to know which sections of the coast are more erosional than others. This study shows that shoreline change is a useful proxy for coastal change over both time and space.

Shoreline change is an imperfect proxy, however. Any significant variation in profile shape will reduce the correlation between shoreline change and volume change. These variations will be less important if the amount of change is large. The larger the volume change attributable to profile translation, the less important any volume changes will be because of variations in profile shape.

Profile shape can change in many ways. If extensive erosion or accretion significantly alters the amount of sand stored in the backshore, dunes, or both, then the shape of the profile in the backshore might change. Another process that can reduce the correlation might occur after significant erosional events when the beach recovers via a welding swash bar, as we saw in the Marconi data on 4 January 2001 and 30 March 2001. As noted by DINGLER and REISS (2002), mobile beach cusps above MHW can also reduce the correlation. The data presented here are on beaches not significantly affected by coastal development. The correlation could be less on developed beaches because human activities are likely to result in significant changes in profile form.

SUMMARY

This paper investigates the degree to which datum-based shoreline change might be a useful proxy for subaerial volume change. Several existing studies and three new data sets indicate that correlation is usually high between shoreline change and subaerial volume change, both spatially and temporally.

Along Cape Cod, the time series of shoreline change and subaerial volume change are highly correlated at both Marconi Beach and Ballston Beach (r = 0.73 and 0.96, respectively). These high correlations are primarily due to the relative invariance of the profile shape and show that shoreline change is a good proxy for subaerial volume change. On Assateague Island, the correlation coefficient between along-coast variations in shoreline change and subaerial volume change is 0.71. This implies that 50% of the variability in

volume change is explained by the variability in shoreline change, making it a useful, if imperfect, proxy.

Data consisting of 54 profiles, surveyed 48 times along the coast of the Outer Banks of North Carolina, were analyzed both spatially and temporally. First, we analyzed how well the temporal variability in shoreline change correlates with the temporal variability in volume change at each profile location. Although a couple of outlier correlation coefficients are low, the mean is high (0.84). We grouped the data by survey date and found the correlation between along-shore variations in shoreline change with along-shore variations in volume change for each date. No low outlier correlation values exist, and the mean is similarly high (0.88). These data further support our hypothesis that shoreline change is a useful proxy for subaerial volume change.

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