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Temporal and spatial scales of beach profile change, Duck, North Carolina

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Abstract

An 11-year time series of high-resolution beach profile surveys made on an Atlantic Ocean beach was analyzed for spatial and temporal characteristics of beach profile change. Approximately 300 profile surveys, most extending from the dune to 8-m depth, were available for the analysis on each of four cross-shore lines, together with electronically recorded and statistically processed wave time series from a nearshore gage located seaward of the survey site. The profile survey data set was analyzed for such quantities as depth change, frequency of depth change, general seasonal shape of the profile, seasonal depth change, and change in the profile produced by extreme storms. The morphodynamics of an inner and outer longshore bar were also examined, including depth to bar crest, bar height and length, and speed of bar movement onshore and offshore. Several properties of depth change were related to wave characteristics. Representative results were: average profile elevation change from +4 m to −4 m was symmetric about the mean sea-level shoreline; the average spring and autumn profile shapes were almost identical and occurred as transitional states between the summer and winter profile shapes; the depth of active profile movement (within survey accuracy of about 0.025 m) was 4 m for the summer and 6 m for the winter; and the 10-year frequencies of maximum absolute depth change in depths of 2, 4, 6, and 8 m were 1.64, 1.38, 0.22, and 0.12 m, respectively. A surprising result was that typical large storms transported sand into the nearshore from the seaward end of the profile (from a depth of about 6–8 m).

1. Introduction

This paper examines spatial variability in the beach profile on time scales ranging from those determining long-term characteristic shapes, such as the average, equilibrium, and seasonal shapes, through highly dynamic short-term changes in sand level brought about by storms. Early quantitative field and small-scale laboratory studies (e.g., Evans, 1940; Keulegan, 1945; King and Williams, 1949; Shepard, 1950; Short, 1975; Hands, 1976, 1980) examined the profile mainly as a 2-D (cross-shore) system and focussed on the morphology and movement of longshore bars, followed later by investigations of the equilibrium profile shape (e.g., Bruun, 1954; Dean, 1977; Wright et al., 1979; Dean et al., 1993).

Characteristic features, including seasonal changes in shape of the profile, have been examined

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quantitatively in a number of studies (e.g., the seminal study of Shepard, 1950; Inman and Rusnak, 1956; Nordstrom and Inman, 1975; Winant et al., 1975; Aubrey, 1979; Weishar and Wood, 1983; Aubrey and Ross, 1985). Shepard (1950) recorded seasonal changes in sand level of approximately 2 m in several surveys. Inman and Rusnak (1956) and Nordstrom and Inman (1975) performed a limited number of accurate measurements of both seasonal and extreme changes along profile lines on two southern California beaches using land-based surveying techniques nearshore and echo sounders and reference rods (long steel rods inserted into the sea bottom which were subsequently referenced to a datum by measurement tape) offshore. Inman and Rusnak (1956) found that the range of sand-level change at Scripps Beach, a wave-sheltered area, decreased with increasing depth, with inferred representative values of 0.6 m at 5.5-m depth, 0.09 m at 9.1 m depth, and 0.05 m at 15.9-m depth on the shelf neighboring Scripps Canyon. Nordstrom and Inman (1975) found representative sand level range values at a segment of Torrey Pines Beach of 1.25 m at 4.9-m depth, 0.46 m at 7.3-m depth, 0.18 m at 10.0-m depth, 0.06 m at 13.7-m depth, and no change at a depth of 19.8 m. Nordstrom and Inman (1975) also note that the range in sand level change for similar depths was greater at Torrey Pines Beach than at Scripps Beach and speculated that this result was due to the higher waves incident on Torrey Pines. DeWall and Christenson (1984) examined 33 data sets (1049 profiles) from eight sites covering the four coasts of the continental United States to develop methods for predicting nearshore profile change on unobstructed beaches. Most of the profile data were collected from piers and are believed to contain a small but probably non-negligible effect of scour at pier pilings or of sheltering by the piers. For significant extreme wave heights H_e (significant wave height expected to be exceeded 12 hours in a year) ranging from approximately 2.0 to 3.8 m, they found reasonable linear correlation with the maximum bottom change ΔD as $\Delta D = 1.15\ H_e - 1.25$ (m).

Laboratory investigations of profile change using large wave channels that eliminate scale effects have also been performed with monochromatic waves (e.g., Saville, 1957; Kajima et al., 1982; Kraus and Larson, 1988) and random waves (Kraus et al., 1992). Many of the analysis techniques employed in the present paper derive from those developed and tested by the authors in analyzing beach profile change generated in large wave tanks.

Quantitative study of 3-D nearshore morphology began early (Hom-ma and Sonu, 1962) and has continued (e.g., Sonu, 1973; Short, 1979; Birkemeier, 1984; Wright and Short, 1984; Sunamura, 1988; Lippman and Holman, 1990; Liang and Seymour, 1991). Larson and Kraus (1989) review the extensive literature of beach morphology studies with emphasis on quantitative approaches and results.

Progress in quantification of beach change is hindered by the difficulty in obtaining accurate data covering a range of wave conditions. Despite a considerable number of studies, little information is available on depth change along the profile and its time variation. In addition to being fundamental to understanding the morphodynamics of beaches, the spatial and temporal behavior of the beach profile has direct application in coastal engineering projects involving beach nourishment and in the siting of coastal structures.

An exceptional data set for quantitative study of the temporal and spatial characteristics of the nearshore beach profile is being collected at the Field Research Facility (FRF) operated by the Coastal Engineering Research Center of the U.S. Army Engineer Waterways Experiment Station. The FRF is located along an approximately 1-km long stretch of Atlantic Ocean barrier island beach in the village of Duck, North Carolina (Fig. 1). The FRF beach has been extensively studied both through short-term multi-institutional experiments typically lasting over one to two months (e.g., Mason et al., 1987) and through on-going, long-term data collection of waves, water elevation, and beach profile change. It is the latter data set that is analyzed in this paper, with emphasis on the 11-year long high-resolution beach profile survey data set.

In the following, beach morphology at the FRF is analyzed in a primarily 2-D approach that

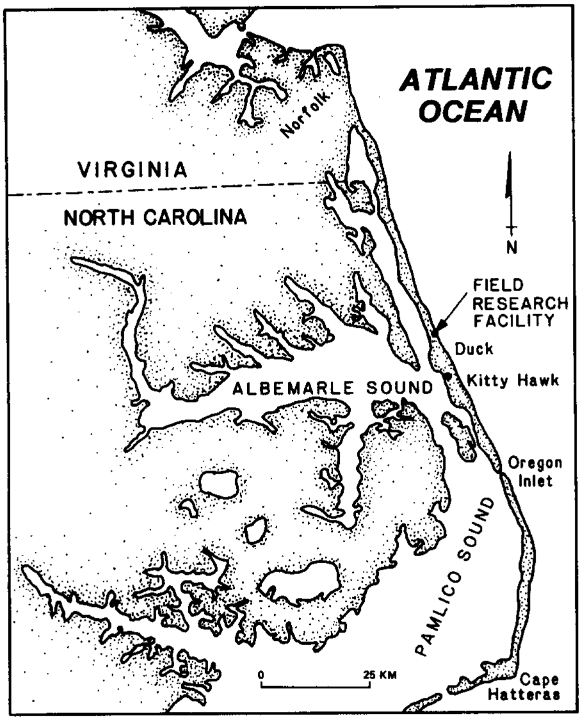

Fig. 1. Location map for the field research facility, Duck, North Carolina.

focusses on the beach profile. The procedure is quantitatively justified, and spatial scales are discussed. Average beach profile properties are then calculated for the period of record and for seasons, including bar geometry and average movement. Time-dependent analyses are performed to determine characteristic time and spatial scales of beach profile change, including frequency of sand-level (depth) change, seasonal profile development, and profile change produced by a single major storm. An effort is made to relate beach profile change to the wave climate characterized through simple statistical descriptors.

2. Data set employed

The FRF data set encompasses beach profile surveys with the associated wave and water level climate for a continuing measurement period starting in 1981. For the present analysis, data from the 11-year period 1981–1991 were available. This data set is similar to that studied previously by the authors (Larson and Kraus, 1992a,b), being extended for the present study by approximately 40 more recent profile surveys made in 1991 that included several strong winter storms.

The beach profile at the FRF is surveyed approximately every two weeks or more frequently along four shore-normal lines, with surveys extending from a base line located behind the foredunes seaward to a nominal water depth of about 9 m. High-density surveys on limited-area rectangular grids are also performed at the FRF during intensive, short-term field-data collection projects, but these measurements are not employed here other than those for the four target survey lines. The locations of the four survey lines (Lines 58, 62, 188 and 190) are shown in Fig. 2, together with the location of the FRF research pier. These survey lines were placed at the FRF property limits to minimize influence of the pier on wave and sediment-transport processes. The offshore depth contours at the lines are straight and parallel. All profile elevation data given in this paper are referenced to the U.S. 1929 National Geodetic Vertical Datum (NGVD) to which elevation is customarily referenced at the FRF, and cross-shore distance is referenced to the FRF baseline unless otherwise stated. The NGVD and Mean Sea Level (MSL)

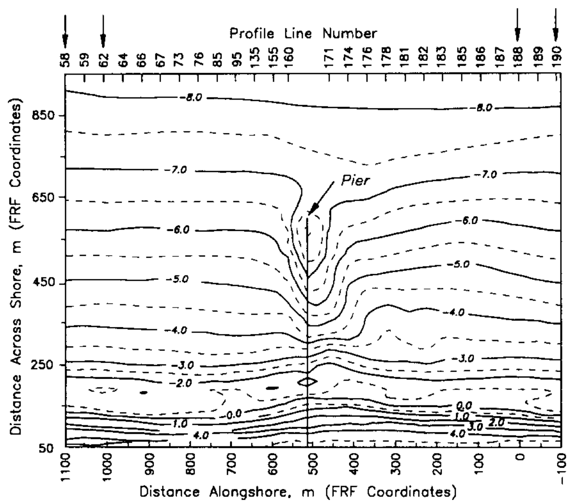

Fig. 2. Locations of survey lines relative to the FRF research pier and bathymetry on 9 September 1988 (depths in meters relative to NGVD) (after Leffler et al., 1990).

datum at the FRF are nearly the same, with the relation given by MSL = NGVD + 0.067 m.

The FRF profile survey data for 1981 to 1984 have been tabulated by Howd and Birkemeier (1987a) and those for 1985 to 1991 were recently tabulated by Lee and Birkemeier (1993). For the present analysis, the profile data were made available to the authors on magnetic media directly from the FRF. Table 1 summarizes the data available for this study. Typically, between 20 and 50 distance-elevation pairs were recorded during each individual survey. The nominal horizontal spacing between survey points is 6 m, with regions of steep elevation change surveyed with smaller intervals. All surveys were made using the Coastal Research Amphibious Buggy (CRAB) (Birkemeier and Mason, 1984), which is an 11-m high, self-propelled platform mounted on three large-diameter wheels that can reach 8-m depth in up to 2-m high waves. Survey data are obtained with a total survey station by tracking prisms mounted on the CRAB. Horizontal and vertical accuracy of this system for profile surveying is estimated at 4 cm, and the CRAB is considered a hydrographic survey standard to which other systems are compared (Clausner et al., 1986). Systematic error or bias in elevation due to slight wheel penetration in the sea bottom tends to cancel in taking differences in profile elevation, leaving only small random error as the principal variability component of elevation.

The wave data used in this study were taken by a waverider buoy located in 18-m water depth directly seaward of the FRF research pier, as analyzed by the staff of the FRF. Wave height was obtained as energy-based significant wave height calculated as four times the standard deviation for a 20-min water level record. The wave period was determined as that corresponding to the peak in the energy spectrum. Wave height and period were typically recorded every 6 hr but more frequently during some parts of the observation period, for which hourly values were recorded.

Hourly values for the water level are available from a tide gage located at the end of the research pier at the approximate 4-m depth contour. The influence of water level was not included in this study because its typical period of variation was significantly shorter than the time between surveys, and the variation in most cases was almost symmetrical about the mean value and covered several tidal cycles. The average tidal range at Duck is about 1 m.

The mean significant wave height for the entire measurement series consisting of 32,027 individually recorded heights was 1.09 m (in 18-m water depth) and the mean peak spectral period was 8.4 s. The maximum significant wave height recorded during the 11-year measurement period was 6.8 m, which occurred during a storm in September 1985. At Duck the wave height exhibits clear seasonality, with lower waves occurring during the summer and higher waves in the winter, whereas the mean period remains fairly constant throughout the year. Table 2 summarizes the significant wave height and peak spectral period in 18-m water depth according to the defined 3-month seasons. The average yearly maximum wave height is highest in the winter and lowest in the summer, as expected, although this pattern is not observed in the overall largest wave heights recorded in the measurement series for each season, because hurricane and extratropical

Table 1
Summary of data for the four profile survey lines at the FRF

Line no.	No. of surveys	First survey	Last survey
58	306	810717	911218
62	340	810126	911218
188	297	810120	911218
190	265	810717	911218

Table 2
Wave climate statistics*, 1981–1991, Duck, North Carolina

Time period	Mean height (m)	Mean yearly maximum height (m)	Maximum height (m)	Mean period (s)
Winter (Jan–Mar)	1.28	3.4	4.8	8.4
Spring (Apr–Jun)	0.95	2.6	5.2	8.3
Summer (Jul–Sep)	0.88	2.2	6.8	8.5
Fall (Oct–Dec)	1.21	3.3	5.6	8.4
Year	1.09	2.9	6.8	8.4

*Wave statistics refer to the energy-based significant wave height and peak spectral period measured in 18-m water depth.

storms can arrive in September and continue through April. The largest average monthly wave height of 1.36 m occurred in March, and the lowest average monthly wave height of 0.63 m occurred in July. The maximum monthly wave height as an average for each month of the 11 years of record was 3.5 m and occurred in February, and the lowest average maximum wave height was 1.4 m, for July.

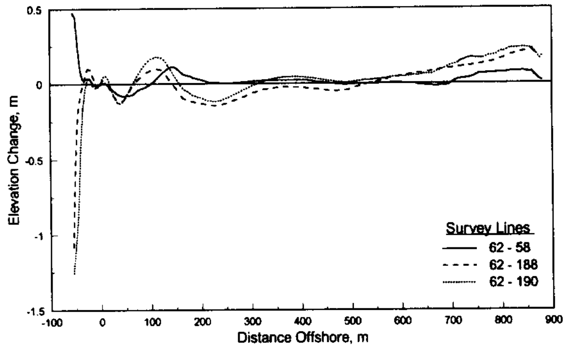

Fig. 3. Differences in average profile elevation with respect to Line 62.

3. Average (time-independent) profile properties

3.1. Longshore spatial variability

The average profile shape was computed for the four survey lines for all surveys in the period of record (1981–1991). Because individual survey points occur at varying distances from the baseline, interpolation (linear) was employed to obtain common points for averaging. The average profiles for the four survey lines have very similar shapes (see Fig. 6 for an example), with a steep foreshore joining to a gentle slope a short distance seaward of the shoreline. However, Lines 58 and 62, located north of the pier, have subaerial portions located somewhat more seaward of the FRF baseline in comparison with Lines 188 and 190 to the south (Larson and Kraus, 1992b). Because two longshore bars (inner and outer bars) are usually present in the nearshore at the FRF, the computed average profiles have two regions where the cross-shore beach gradient does not monotonically decrease. Larson (1991) showed that the modified equilibrium profile, an extension of the Dean (1977) equilibrium profile that includes fining of grain size offshore between two grain-size limits at the profile ends, well describes the long-term average profile shape at Duck. The long-term average profile at Duck and the equilibrium profile have effectively the same shape (Larson and Kraus, 1992a). Fig. 3 shows the difference between average profiles with reference to that of Line 62, for which the average profiles were aligned with respect to the mean shoreline position, horizontal coordinate 0. The aligned average profiles are virtually identical except at the dune. (The average profile shape for Line 62 is given in Fig. 6 for reference.)

The movement of specific depth contours was correlated between different pairs of survey lines for the 11-year record. Fig. 4 displays the correlation coefficient as a function of profile elevation for Line 62 in combination with the other three survey lines. Contour movement on neighboring Line 58 is well correlated with that on Line 62; however, at a water depth of 1–2 m, the correlation coefficient decreases markedly although still showing reasonably high correlation. In this depth region, the inner bar responds rapidly to changes in waves in combination with other hydrodynamic forcing, giving rise to local variations in bar location. During times when onshore transport prevails, crescentic bar formations develop with alongshore spatial periodicity (Lippman and Holman, 1990).

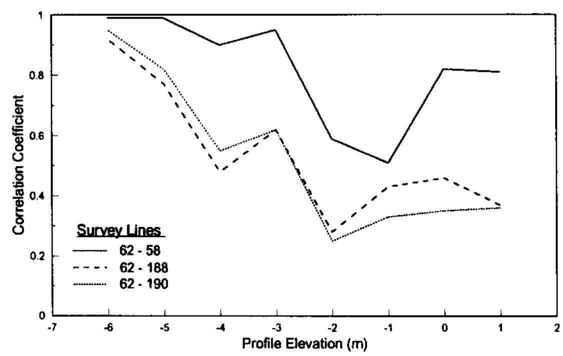

Fig. 4. Correlation coefficient for contour movement with respect to Line 62.

Correlation in contour movement between Line 62 and the survey lines south of the pier is lower, and high coefficient values occur only in water depths greater than 5 m. In the region of the inner bar there is almost no correlation between Line 62 and the southern lines. Correlation between Lines 188 and 190 (not shown) had coefficient values larger than between Lines 58 and 62, particularly in the region of the inner bar where the value never dropped below 0.7 (minimum occurred at the 2-m water depth). The correlation analysis has thus shown that at depths greater than 5 m, profile evolution at Duck is similar for a longshore length scale of about 1 km, whereas, in shallower water, the alongshore response of the profile is similar at a length scale one order of magnitude less. In the region of the inner bar, even neighboring profile survey lines show different responses.

To further investigate the similarity in response of the profile survey lines, empirical eigenfunctions were calculated for the period of record using principal component analysis (Winant et al., 1975; Aubrey, 1979). The analysis was based on the covariance matrix, for which the average beach profile at each survey line was subtracted prior to calculating the eigenvalues and eigenvectors. For all survey lines, the first three eigenvectors explained about 75% of the variation in the data, in agreement with Birkemeier (1984), who analyzed a shorter time series of profiles. Fig. 5 compares the first three eigenvectors for Lines 58 and 62. The almost identical eigenvectors for the two lines indicate a pronounced similarity in patterns for the exchange of material across the profile.

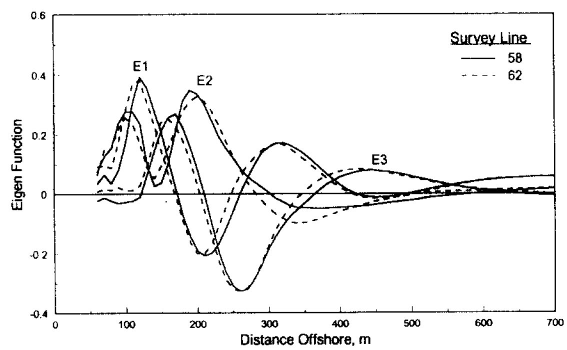

Fig. 5. First three eigenvectors for Lines 58 and 60.

The lower eigenvectors for Lines 188 and 190 display the same kind of similarity as for Lines 58 and 62, but the eigenvectors for the lines north and south of the pier differ, possibly due to wave shadowing by the pier on Lines 188 and 190 from the predominant incident waves, which arrive out of the north. Thus, in agreement with the result of the previously discussed correlation analysis, neighboring survey lines exhibit similar profile response to wave action, whereas lines north and south of the pier respond in a somewhat different manner.

As a third measure of quantifying spatial scale of profile response, the sum of absolute depth change across the profile was calculated for pairs of consecutive profile surveys on each line (depth change is discussed in detail below; only surveys extending beyond a water depth of 6 m were included in the present analysis). This sum represents a measure of the total profile change that occurred between two surveys, and a time series of such sums was obtained for each line. Correlation between the lines gave a coefficient value of 0.77 for Lines 58 and 62, and a value of 0.83 for Lines 188 and 190. Corresponding correlation values for lines north and south of the pier were around 0.6; thus, this measure confirms the observations from the earlier analysis.

Based on the above results, most of the following labor-intensive calculations were limited to Line 62. As found above, the long-term statistical properties of the beach, such as average profile shape, should be representative for a length scale of several kilometers, whereas quantities derived from individual profile surveys in general are valid over length scales of several hundred meters. For selected individual surveys, markedly different response could be found also for neighboring lines (compare Sallenger et al. 1985), but in a majority of the surveys similarity between neighboring lines was observed.

Fig. 6 displays the average profile calculated for Line 62 and envelopes of maximum and minimum elevation recorded in any survey, plotted with the median grain size as determined from surficial sediment samples. The elevation envelopes give an indication of relative profile variability during the

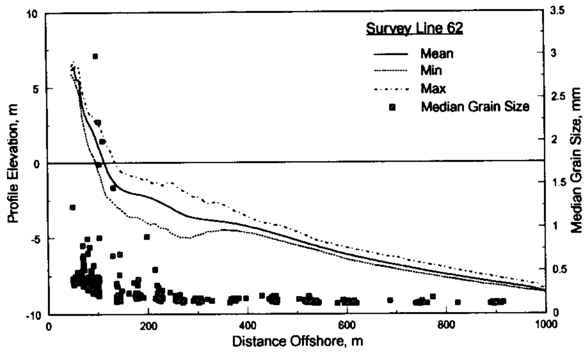

Fig. 6. Average profile elevation, maximum and minimum elevation envelopes, and median grain size across shore, Line 62.

measurement period, showing areas where maximum change in elevation occurred. Profile elevation variation (distance between minimum and maximum depth envelope) decreases significantly at a depth between 4 and 5 m, which approximately corresponds to the location of the break point for the higher waves during a severe storm. The profile envelope, although clear in showing extremes in elevation variability, reflects the influence of mainly unrelated single points along the profile; results of more robust methods for describing the variability that involve all the data points are given below. Coarser material is located close to the shoreline, and median grain size decreases with distance offshore and becomes approximately constant about 200 m from the shoreline, where it is slightly less than 0.2 mm.

In Fig. 6 it is seen that, seaward of the average 4-m depth, the deviation of the minimum depth envelope from the average depth is greater than the deviation of the maximum depth from the average. In contrast, landward of about the 4-m average depth the deviation of maximum depth is greater. As discussed below, large storms tend to raise the profile in the offshore and lower it in the nearshore, creating this asymmetry in profile envelope.

3.2. Cross-shore profile variability

To quantify variability in elevation along the profile, its standard deviation was computed at fixed locations using the entire data set (Kraus and Harikai, 1983; Birkemeier, 1984; Howd and Birkemeier, 1987a).

Fig. 7 shows the variation in standard deviation of elevation as a function of average elevation for the four survey lines. Depth variability decreases markedly at an average depth of about 4 m, as indicated by the steep gradient in standard deviation. Thus, most of the beach profile change occurs shoreward of the 4-m depth contour, although exchange of material occasionally does take place with the deeper portion of the profile, producing a small depth variation in this region.

Neighboring pairs of survey lines exhibit similar variation in standard deviation across the profile (Fig. 7), whereas the lines north and south of the FRF pier exhibit somewhat different characteristics seaward of the 4-m depth contour. Lines 188 and 190 have a peak in standard deviation at a depth of about 5 m, whereas a similar but smaller peak is found for Lines 58 and 62 at about 6-m depth. Similarity in profile variability between neighboring lines, particularly in deeper water, indicates that the overall profile response is well correlated for Lines 58–62 and Lines 188–190, respectively. As discussed below, the variation in depth in the outer part of the profile was produced by a few extreme storms that vertically displaced the entire profile in this region. After these storms, material returned slowly to the inshore portion of the profile, so that the seaward part of the profile deviated from the average shape for a considerable time in surveys made subsequent to the storm.

Figs. 6 and 7 indicate that, for most of the

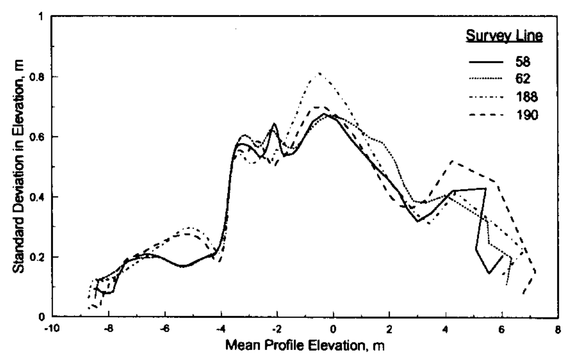

Fig. 7. Standard deviation in elevation as a function of average elevation, Lines 58, 62, 188, and 190.

11-year period of record, movement of sediment occurred mainly on the section of the profile located shoreward of the 4-m depth contour, and that sand transport in deeper water was considerably less. This type of observation has influenced engineers to define a depth of closure that represents a limiting depth for which cross-shore transport seaward of this depth can be considered negligible for applications such as structure siting and beach fill design.

As an alternative measure of variability along the profile, change at selected elevations was calculated from pairs of consecutively surveyed profiles and assigned to the respective average elevation for the pair. For depths greater than about 3 m and less than about 1 m, a unique contour location normally existed, but for the intermediate-depth range (1–3 m), where an inner bar was frequently present, contour location was often double-valued. In the case of double values, the most seaward contour location was selected for analysis because it is most exposed to the incident waves, and it should better indicate profile variability than the corresponding depth contour located inshore.

Although change in profile elevation was calculated, emphasis here is on elevation below NGVD or depth, and it is convenient to refer to depth change in much of the following. An early study of maximum change in bed level at the FRF (DeWall and Christenson, 1984) was performed by lead-line survey from the pier, and maximum depth change (sand level change) from surrounding ambient surface was found to be correlated with wave height. The present work employs high-resolution repetitive surveys on lines distant from the pier and automated analysis procedures to extend and refine the earlier study.

Change in depth between consecutive surveys was taken as a representative indicator of beach profile change (compare Inman and Rusnak, 1956). The average survey time interval for the most frequently surveyed Line 62 was 13 days, with a standard deviation of 7.5 days. However, depth change displayed no correlation with length of the survey interval, representing the integrated response of the profile to the wave climate existing between the two consecutive surveys. Due to the complexity of this response, as a first step elevation change was treated as a random variable, allowing its statistical properties to be determined based on the measurements. Such an analysis, which treats depth change as an independent series of events, neglects information contained in the time sequence of the recorded depth change, such as seasonality in profile response and more short-term cyclical accretionary and erosional sequences. The related variable of absolute depth change was found to be an informative descriptor, giving a unified measure of profile change at a certain elevation, for which not only the time sequence is neglected but also the direction of the elevation change.

Fig. 8 plots the average absolute elevation change across the profile for all survey lines. A striking feature of the absolute elevation change is its symmetry about a location slightly seaward of the NGVD shoreline, for all four lines, where the change is a maximum. The absolute depth change indicates profile variability across shore that is qualitatively similar to the standard deviation in depth (Fig. 7), but gives a clearer description in deeper water. After a major storm, when the offshore portion of the profile has been significantly displaced and recovery under smaller waves toward the equilibrium depth condition takes place slowly, a marked increase will appear in the standard deviation of depth that is not indicative of significant profile change. The almost constant average depth change in Fig. 8 in deeper water is mainly related to survey accuracy, where the small variability would produce an apparent persistent depth change. At the 8-m depth contour, the

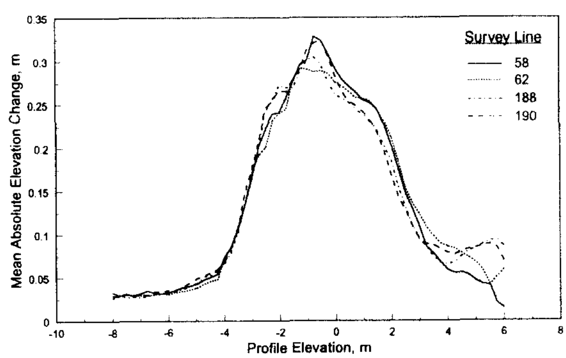

Fig. 8. Average absolute elevation change across shore, Lines 58, 62, 188, and 190.

standard deviation in absolute depth change was almost constant (0.025 m) for all survey lines, providing a good pragmatic estimate of the survey accuracy of the CRAB.

The probability of exceedance for a specific absolute depth change at a certain depth was computed from the measured time series of depth changes and related to a return period as available in the 11-year record. Fig. 9 shows the frequency distribution curves of absolute depth change for four depths for the four survey lines, illustrating the return period for the exceedance of a specific absolute depth change. For example, for Line 62, at the average depth of 4 m, a depth change of 0.3 m is exceeded on the average once every year, whereas the same change occurs almost every month at the 2-m depth. Frequency distribution curves such as those presented in Fig. 9 define a depth of closure in a probabilistic context, with the closure depth given as a specified absolute depth change not exceeded more often than a selected return period. The depth change shown in Fig. 9 also indicates that the four profile lines respond similarly to wave action with reference to comparative depth change.

3.3. Bar properties

Larson and Kraus (1992a,b) performed an intensive analysis to quantify geometric and dynamic properties of natural longshore bars at the FRF. Longshore bars reduce erosive energy reaching the surf zone by breaking the incident

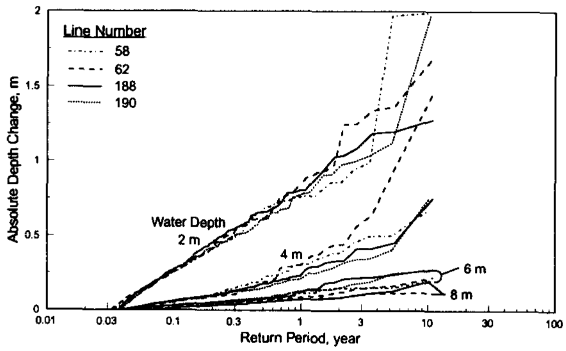

Fig. 9. Frequency distributions of absolute depth change at selected depths.

waves, and bars also function as a temporary storage location for sand in the offshore. Thus, these features are of importance in connection with beach profile change, as well as in surf zone hydrodynamic and sediment transport processes, and portions of the profile that experience the greatest cross-shore transport and depth change often coincide with the locations where longshore bars appear. Another motivation for investigating natural longshore bars is their similarity with nearshore berms created from dredged material, suggesting that rational criteria and procedures for designing nearshore berms may be derived by analyzing the behavior of natural bars (McLellan and Kraus, 1991; Larson and Kraus, 1992a).

In this study, bars were defined through intersections of the measured profile with the modified equilibrium profile (Larson, 1991) that was least-square fitted to the average profile, where areas along the subaqueous part of the profile located above the modified equilibrium profile constituted a bar (Larson and Kraus, 1992a,b). Because the four survey lines displayed similar overall long-term behavior, focus of the considerable analysis of bar properties was directed at Line 62, which contains the largest number of surveys (340). The following properties were calculated for every identified bar of each individual profile survey: depth to bar crest h_c; bar length L_b; bar height Z_m; bar volume V_b; location of bar mass center x_{cg}; and bar speed $\Delta x_{cg}/\Delta t$, where Δt is the time interval between profile surveys determining x_{cg}. Fig. 10 defines the various bar properties, where the inshore part of the modified equilibrium profile is shown together with a typical profile.

In most of the surveys, two bars can be identified

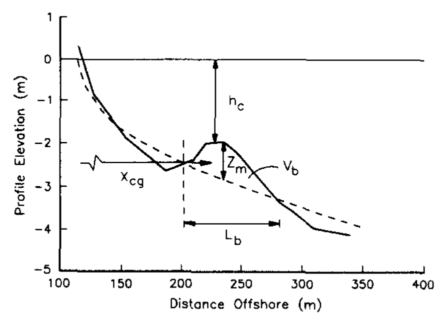

Fig. 10. Definition sketch of calculated bar properties.

along the profile, an inner bar and an outer bar (Howd and Birkemeier, 1987a). During extended periods of low waves, the outer bar disappears and only the inner bar persists. The center of mass of the outer bar was typically located about 300 m from the shoreline, whereas the location of the center of mass of the inner bar varied more, with a characteristic distance of 100 m from the shoreline. The outer bar experiences breaking waves only during major storms, in contrast to the inner bar that is exposed to wave breaking most of the year, resulting in greater variability in its position. Thus, the inner and outer bars display significantly different temporal behavior.

Tables 3 and 4 summarize calculated morphodynamic parameters for the inner and outer bars, respectively. The average depth to crest for the inner bar was 1.6 m, average maximum bar height 0.9 m, and average bar volume 45 m^3/m based on 230 profiles where an inner bar was identified. The average speed of the inner bar was 1.4 m/day for onshore movement and 2.6 m/day for offshore movement, with maximum calculated speeds of 8.7 and 18 m/day, respectively. The average depth to crest for the outer bar was 3.8 m, average maximum bar height 0.4 m, and average bar volume 45 m^3/m based on 221 profiles where an outer bar was present. Although the outer bar on the average had a volume similar to the inner bar, the maximum height was considerably less, giving a much more gentle bar shape. The average speed of the outer bar was 0.6 m/day for onshore movement and 1.1 m/day for offshore movement, with maximum speeds of 6.1 and 15.2 m/day, respectively. For storm-induced bar movement, these speeds tend to be underestimates because of the relatively long time interval between profile surveys. Birkemeier (1984), Sunamura and Takeda (1984), Sallenger et al. (1985) and Larson and Kraus (1992a,b) have discussed bar movement in the field, and Sunamura and Maruyama (1987) and Larson and Kraus (1989) have examined bar movement generated in large wave tanks, where survey frequency is greater. Bar speed and dimensions are comparable between large wave tanks and the field.

4. Time-dependent profile properties

Beach profile elevation varies at several temporal and spatial scales, and the variability in time and

Table 3
Statistics for inner bar properties

Property	Mean	Minimum	Maximum	Q_{25}*	Q_{75}*
Depth to crest (m)	1.6	0.6	2.5	1.3	1.9
Bar height (m)	0.9	0.2	1.7	0.7	1.1
Bar volume (m^3/m)	45	6	102	29	57
Bar length (m)	95	35	280	70	105
Bar mass center (m)	215	150	330	200	235

*The quantities Q_{25} and Q_{75} denote the limits for which 25 and 75% of the values are below, respectively.

Table 4
Statistics for outer bar properties

Property	Mean	Minimum	Maximum	Q_{25}*	Q_{75}*
Depth to crest (m)	3.8	1.3	5.1	3.4	4.1
Bar height (m)	0.4	0	1.4	0.27	0.6
Bar volume (m^3/m)	45	0	120	20	67
Bar length (m)	170	25	280	150	200
Bar mass center (m)	410	200	520	390	440

*The quantities Q_{25} and Q_{75} denote the limits for which 25 and 75% of the values are below, respectively.

space is interconnected in the sense that changes over longer time intervals tend to involve larger portions of the profile. As shown in several studies (e.g., Shepard, 1950; Winant et al., 1975; Aubrey, 1979; Aubrey and Ross, 1985), a prominent characteristic time scale of beach profile change is associated with seasonal exchange of material across the profile. During late spring and summer, material is mainly transported onshore by low-steepness waves to build the foreshore, simultaneously as nearshore bars are reduced in volume, whereas, during fall and winter, high-steepness waves erode the foreshore to build nearshore bars. Thus, material is shifted between the inner and outer portions of the profile, going through an annual cycle with a maximum amount of material located along the inner portion of the profile at the end of summer.

Another characteristic time scale for the beach profile is that of a single storm, which typically brings 1 to 3 days of severe wave action for the beach at Duck. A consecutive number of such high-wave, long-period events separated at relatively short intervals is responsible for the seasonal shift in material across the profile. A storm rapidly transports material seaward to an area of the profile where the action of waves and currents is not strong enough to sustain the transport, and the material is deposited, often in the form of a longshore bar. In this section we examine seasonal changes in the profile, storm-induced changes, and, finally, the relation between waves and profile change.

4.1. Seasonal variation in profile morphology

The profile survey data were analyzed for seasonal characteristics by dividing the year into four time periods encompassing the months of January–March (winter), April–June (spring), July–September (summer), and October–December (fall). The analysis was initially performed by month, but, to increase the number of surveys within each data subset, it was decided to proceed with the analysis for quarters of the year. Little additional information was gained on seasonal characteristics of the beach profile and some reliability was lost by decreasing the time interval of the analysis to a month.

Fig. 11 displays the main portion of the four average seasonal profiles derived from all surveyed profiles within the respective season, with the number of profiles within a season varying between 66 and 110. The summer average profile has a maximum amount of sand stored along the inshore and the greatest depth along the offshore end of the profile. In contrast, the inshore of the winter profile achieves maximum depth relative to other seasons, and a general decrease in depth occurs in the offshore as material is slowly transported from the inshore and deposited. The average spring and fall profiles almost coincide and represent transition states between bounding or extreme states of summer and winter average profiles. A pivot point where all seasonal average profiles intersect is located at a depth of about 2.6 m, in agreement with observations of Aubrey (1979) reported for Torrey Pines Beach in southern California and based on an empirical eigenfunction analysis. Another intersection between the summer and winter profile occurs at about 6-m depth (outside the range shown in Fig. 11), but the vertical difference in elevation between the different seasonal profiles is small in this region. Thus, the extreme storms that significantly displace the profile in deeper water produce a shift in the profile that persists for considerable time, influencing the average profile properties of consecutive seasons.

The standard deviation in profile elevation was calculated by season for fixed locations across

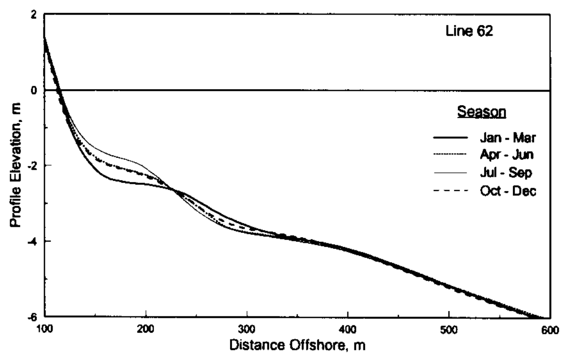

Fig. 11. Average seasonal profiles: Jan–Mar, Apr–Jun, Jul–Sep, and Oct–Dec, Line 62 (only portion with main change shown).

shore and plotted as a function of mean elevation (Fig. 12). Seaward of the 4-m depth contour, the standard deviation is similar for all seasons except summer, where less profile variability is observed immediately seaward of this contour. Further inshore, however, some seasonally characteristic differences appear. In spring, a marked peak in standard deviation is noted around the shoreline, caused by onshore transport in connection with the transition from winter to summer season. Similarly, in fall there are two clear peaks around the 3-m depth contour, indicating transition from summer to winter profile shape under higher waves.

Average absolute elevation change was calculated for each season. This measure better reflects profile movement in the offshore than standard deviation, because residual changes occurring after extreme events do not influence consecutive calculations of profile variability, as discussed in connection with Fig. 8. Fig. 13 shows the average absolute depth change computed for the winter and summer seasons, clearly showing the larger swings in profile depth that occur during winter. Around the vicinity of the shoreline, elevation change during the winter is typically almost twice as great as during the summer. The seaward limit of significant depth change differs markedly between seasons; in the summer this depth is about 4 m, whereas in the winter some movement is noted as deep as 6 m. Leveling out of the curves in the seaward portion of the profile is related to survey accuracy and is independent of season.

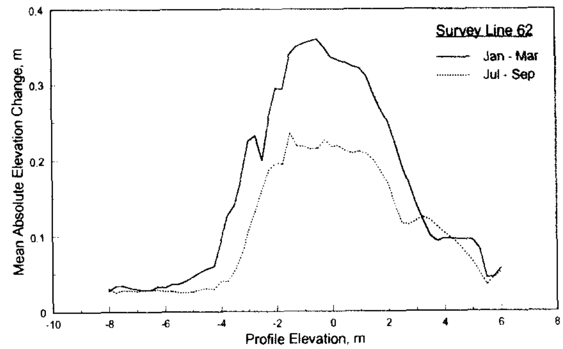

Fig. 13. Average absolute depth change with elevation, summer and winter, Line 62.

Calculated frequency distribution curves for absolute depth change also display a marked dependence on season, where the exceedance probability for a certain depth change is considerably higher during winter in comparison with summer. Fig. 14 shows frequency distribution curves for winter and summer for the 2- and 4-m depth contours. At the 4-m depth, an absolute depth change of 0.1 m was exceeded for 5% of the changes during the summer, whereas the same depth change was exceeded for 25% of the changes during the winter.

The larger depth-change values in the empirical frequency distribution curves are influenced by a limited number of major storms that occurred during the survey period. These storms may be associated with wave-generating conditions differing from typical meteorological conditions; thus, strictly speaking, depth-change values associated

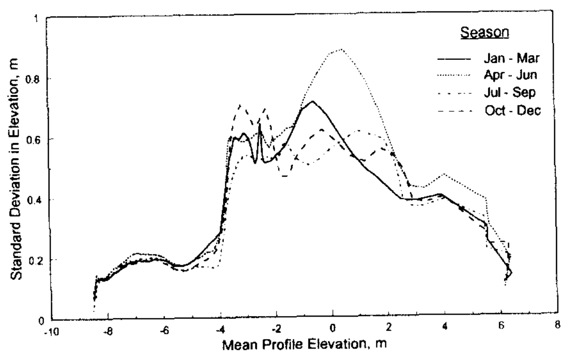

Fig. 12. Standard deviation in elevation as function of mean elevation for all seasons, Line 62.

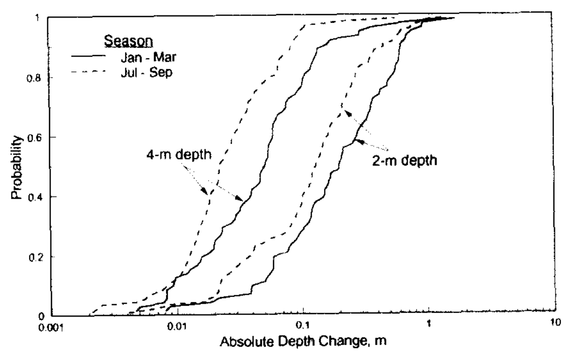

Fig. 14. Frequency distribution of absolute elevation change at 2- and 4-m depths, summer and winter, Line 62.

with extreme events may belong to a different population and should be analyzed separately. However, the number of such events is small, and the basis for obtaining reliable estimates of the return period for a specific depth change during extreme storms is insufficient. Therefore, all data are used in this analysis. The next section will discuss beach profile response to extreme storms to bring to light some characteristics of profile change that occur over time scales much shorter than a season.

4.2. *Profile variation during extreme storms*

Large storms produce major profile change on a time scale of hours during which material is transported offshore and deposited in deeper water where the profile does not otherwise experience significant depth change. Sallenger et al. (1985) tracked the response of the profile at Duck for several storms and observed the rapidity of its adjustment to the wave conditions, both during the erosional and the accretionary phases of a storm. The typical time period of 14 days between consecutive surveys in the present data base does not allow information to be derived on details of the profile response during a storm, but the data can be used to reveal the result of a storm. If we restrict consideration to profile change produced by the most extreme storms, the criticality of surveying immediately before and after a storm is reduced because the change induced by the storm will be considerably higher than that associated with much smaller waves occurring before and after the storm.

To examine extreme storm processes, the wave data were analyzed to identify large storms, defined as those for which the significant wave height exceeded 4 m. Eighteen storms satisfied this criterion, and the four that produced the most nearshore erosion (and had longer durations), were selected for detailed examination of short-term extreme profile change. The average absolute volume change across the profile was employed as a measure of profile change (Larson and Kraus, 1989), where only surveys extending beyond a depth of 6 m were included. This measure was calculated by integrating the absolute volume change between two consecutive surveys across shore and dividing by the length of the profile over which the change occurred.

The four storms producing the most profile response during the measurement period are summarized in Table 5, which gives the dates of the profile surveys before and after the storms, the wave and water level conditions during the storm, and overall measures of the profile change between defining surveys. It is noteworthy that three of the four largest storms occurred during 1989, and that two of the storms, those of February and March, were separated by only a few weeks. The mean spectral peak period of 20 s associated with the 1991 storm is much greater than those of the other storms. The 1991 storm was an unusually well-developed northeaster that caused considerable damage along the U.S. East Coast (Jensen and Garcia, 1993).

The largest profile change recorded in terms of absolute volume change during the measurement period was produced by the storm of March 1989. The profile surveys give a sum of absolute volume change across the profile of $\Delta V_{tot} = 320$ m^3/m, corresponding to an average cross-profile change of $\Delta V_{av} = 0.37$ m^3/m^2, where ΔV_{tot} has been divided by the length of the profile over which any change occurred. However, the most extreme storms induce change in the bottom topography at water depths beyond the normal maximum survey depth, implying that volume-change values presented in Table 5 somewhat underestimate the actual change. For comparison, the average cross-profile change for all pairs of consecutive profiles was 0.099 m^3/m^2 based on all surveys extending to water depth beyond 6 m (272 surveys).

The quantity ΔV_{av} represents the average elevation change between two consecutive surveys and could contain contributions from both cross-shore and longshore transport. During extreme storms, forcing conditions are typically uniform alongshore and over larger length scales than during ordinary wave conditions which tend to produce a bottom topography that is uniform alongshore, as documented at Duck by Lippman and Holman (1990). At the end of a storm, wave conditions become accretionary, because the wave height decreases while the wave period remains high,

Table 5
Parameters of four major storms at Duck, North Carolina, over 1981–1991

Date	H_{max} (m)	Dur_4 (h)	H_{s4} (m)	T_{p4} (s)	h_{max} (m)	$\Delta\lvert V_{tot}\rvert$ (m^3/m)	$\Delta\lvert V_{av}\rvert$ (m^3/m^2)	ΔV (m^3/m^2)
890221–890227	4.6	13	4.3	11.1	1.20	215	0.26	42
890227–890312	4.3	16	4.1	10.7	1.43	320	0.37	62
891221–891228	5.6	22	4.6	11.2	1.06	220	0.25	94
911023–911103	4.8	18	4.4	19.3	1.37	200	0.26	−68

H_{max} = maximum significant wave height; Dur_4 = duration the significant wave height exceeded 4 m; H_{s4} and T_{p4} = mean significant wave height and peak spectral period during the time period Dur_4, respectively; h_{max} = maximum water elevation above NGVD; $\Delta\lvert V_{tot}\rvert$ = sum of absolute volume change across the profile; $\Delta\lvert V_{av}\rvert$ = mean absolute volume change across the profile; and ΔV = net volume change across the profile.

promoting development of morphological features that display marked three-dimensionality alongshore such as crescentic bars. Thus, even though storms cause profile change that tends to be uniform alongshore, post-storm recovery would tend to produce different morphologic development at neighboring surveying lines, where the alongshore variation is governed by the characteristic length scale of the morphological features produced by the accretionary wave conditions.

The absolute volume change ΔV_{tot} listed in Table 5 was computed for the storms across the four survey lines to examine alongshore uniformity of the profile response. The average values of ΔV_{tot} for the four survey lines were, in chronological order of the four storms, 210, 250, 200, and 200 m^2/m. The deviation from the averages was at most 15% for an individual line, except for the March 1989 storm, which displayed considerably larger profile change north of the pier in comparison to the lines to the south, giving a deviation from the average of about 30%. For this storm, the pre-storm profile north and south of the pier had distinctly different shapes, with considerably more material stored above NGVD north of the pier. This material was moved offshore by the storm, and the post-storm profiles surveyed at March 12, 1989 are very similar for the four lines, only differing somewhat in the shape of the outer bar.

Fig. 15 illustrates the typical profile response at Duck to extreme storms. The surveys made before and after the storms in February and March 1989 are shown together with the calculated elevation

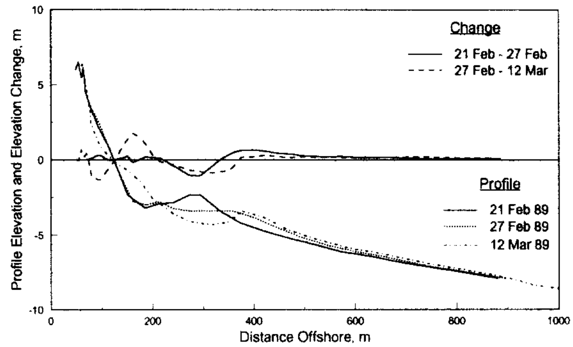

Fig. 15. Profiles surveyed at Line 62 before and after the storms in February and March 1989, together with the calculated elevation change between consecutively surveyed profiles.

change that occurred between the surveys (note that the first survey after the February 1989 storm also serves as the first survey prior to the March 1989 storm). The February storm moved the inner bar offshore, flattening it considerably, and vertically displaced the outer portion of the profile an almost constant amount of 0.1 m. The profile above NGVD experienced no change during the February storm, which is typical for the beach at Duck. The March storm, however, caused major erosion above NGVD and deposited more material on the outer portion of the profile, raising it another 0.15 m. During the February storm a water level of +1.0 m NGVD was exceeded about 6 hours, whereas this water level was exceeded approximately 19 hr for the March storm. The higher water level during the March storm allowed waves to attack the dune, causing erosion in this region not experienced during the February storm.

The maximum positive (accretion) and negative (erosion) elevation changes that occur during a storm are typically related to the formation and movement of bars and to erosion of the dune. Material eroded from the dune is often transferred past the shoreline and deposited just seaward of the shoreline. For example, a large amount of the material eroded above NGVD by the March storm was deposited in shallow water seaward of the shoreline, with a maximum elevation increase of 1.7 m (Fig. 15). Simultaneously, the elevation of the dune face decreased 1.4 m, and a pronounced trough was formed about 300 m from the FRF base line, at a depth of 4.2 m. Larson and Kraus (1991), using a dune erosion and profile numerical simulation model, show that the extent of seaward transport of material from the dune to beyond the shoreline depends on the duration of the storm.

Along the outer portion of the profile, from approximately 4.5-m depth (approximate seaward terminus of the outer bar) and seaward, an almost constant upward vertical displacement of between 0.10–0.15 m occurred for the extreme storms (Fig. 16). This upward vertical shift along the outer portion of the profile occurred in 15 of the 18 major storms; of the remaining three major storms, one had mixed onshore–offshore transport, and two storms produced erosion (March 1983 and October 1991) along the outer profile. The October 1991 storm stands unique in the 11-year measurement record and in general for the mid-Atlantic Ocean because of its unusually long

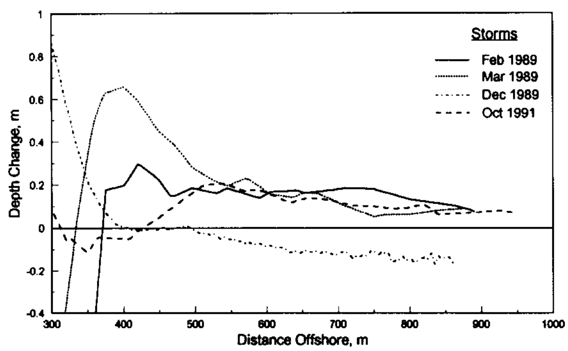

Fig. 16. Depth change along outer part of the profile for four major storms.

(20-s) wave period, which increased the depth about 0.13 m along the outer portion of the profile, in exceptional contrast to the other storms.

If it is assumed that profile change during the storms in Table 5 was primarily produced by cross-shore transport, i.e., gradients in longshore transport were relatively small, the equation of sand conservation may be integrated between two consecutive surveys to yield the cross-shore transport rate distribution. The integration was performed from the shoreward end of the profile, where no elevation change was observed, to the most seaward common survey point. The calculation gave the surprising result that for three of the four storms listed in Tables 5 (the exception being the very long-period October 1991 storm) and for 10 of the 18 major storms (those with wave height greater than 4 m), material moved *onshore* through the seaward end of the profile. The increase in net profile volume for the three major storms and decrease in net volume across the profile for the fourth (October 1991) storm are listed in the last column of Table 5. For the October 1991 storm, the cross-shore transport rate calculation indicated a loss of material through the seaward end of the profile.

4.3. Relation between waves and profile

The nearshore beach profile at Duck, directly exposed to the Atlantic Ocean, mainly responds to short-period waves, either directly through the wave orbital velocity and turbulence, or indirectly through cross-shore currents and long-period waves induced by the short-period waves. However, the resulting beach change is also controlled by water level, which, at the shore, partly depends on the wave height and period, as well as general characteristics of the beach such as profile shape and grain size distribution. The combined influence of these factors makes it difficult to derive simple relationships between beach change and the wave properties. For example, two storms with nearly the same wave conditions might produce different beach change, depending on the time history of the water level and the pre-storm profile shape, or even wind direction. The water level and profile shape determine the portion of the profile acted upon by the waves and the amount of material that needs to be moved for the profile to approach equilibrium with the prevailing wave conditions.

Larson and Kraus (1992a,b) derived relationships between longshore bar and wave properties for the beach at Duck and imposed thresholds for change to arrive at an acceptable level of significance in the calculation. Although the field data set from Duck is unparalleled with respect to high resolution in time and space of profile evolution, the average spacing in time for the most intensively surveyed line (Line 62) is 13 days. As observed by Sonu (1970), Birkemeier (1984) and Sallenger et al. (1985) in the field, and by Sunamura and Maruyama (1987) and Larson and Kraus (1989) through analysis of large wave tank data, the time scale of profile response associated with a storm is short for both the erosional phase and initial post-storm recovery, with significant changes occurring over a few hours. Thus, a specific survey in the present data set usually represents the integrated result of wave and water level conditions that prevailed since the previous profile survey, and characterization of the variable forcing by using a set of statistical parameters is difficult.

After applying a threshold on the change in bar volume and the location of the bar mass center, Larson and Kraus (1992a,b) related change in various bar properties to the wave conditions, although there was still considerable scatter in the data. The non-dimensionalized depth to bar crest and change in bar volume were both shown to be functions of the dimensionless fall speed parameter H/wT, where H and T are representative statistical wave height and period, respectively, and w is a representative fall speed of the sediment. Several simple criteria (Kraus et al., 1991) have been derived to determine onshore and offshore movement of the inner and outer bars (Larson and Kraus, 1992b). The criteria are expressed in terms of non-dimensional parameters characterizing wave and profile properties, such as dimensionless fall speed, wave steepness, and sediment Froude number, where the wave properties refer to deep-water conditions. The dividing line that best distinguished points corresponding to onshore and offshore bar movement was drawn by visual inspection for the parameter-pair combinations, and empirical coefficient values were established.

In the present study, we established the dependence of depth change at different depths in terms of the wave height, noting that the wave period varies little, on average, at Duck. The conditional probability of obtaining a specific absolute depth change was determined separately for waves that occurred between consecutive surveys with maximum significant wave heights H_{max} lying above or below 2 m. A maximum significant wave height of 2 m was selected to signify time intervals with and without notable storms (significant wave heights greater than 2 m occur about 10% of the time in the wave time series, corresponding to a return period of a little more than a month). Fig. 17 displays curves giving the probability that a specific absolute depth change at the 4- and 6-m water depths is not exceeded for the two conditions of H_{max} above or below 2 m.

The empirical distribution function associated with waves of $H_{max} > 2$ m gives a considerably larger probability for a specific absolute depth change in 4-m water depth compared to the distribution function for waves with $H_{max} < 2$ m. This was found to be the case over the entire range of depth changes available in the measurements. However, at the 6-m depth the difference is small between the distribution functions associated with H_{max} above and below 2 m, except for larger depth changes. Depth change caused by $H_{max} > 2$ m implies a markedly larger exceedance probability

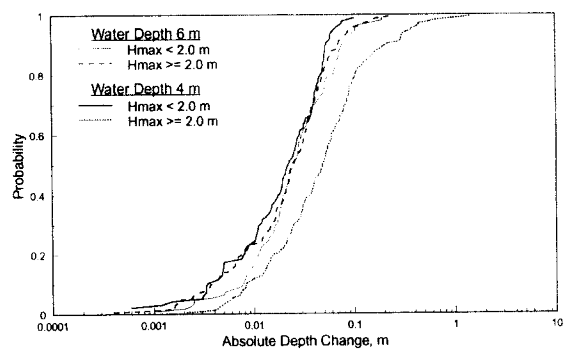

Fig. 17. Probability that a specific absolute depth change is not exceeded at water depths of 4 and 6 m based on the condition that the associated maximum significant wave height between surveys is above and below 2 m.

for changes to be greater than 5 cm, indicating that many time intervals with $H_{max} > 2$ m do not induce significant bottom change at 6-m water depth. In contrast, at the 4-m depth all time intervals with $H_{max} > 2$ m contain significant depth changes that are distinctly greater than those that occur during time periods with $H_{max} < 2$ m.

In order to characterize the waves, a distribution function for the height was derived based on the time series of wave measurements. As previously discussed, the measurements consisted of energy-based significant wave height typically recorded every 6 hours, and no information was available on individual wave heights. Thus, to obtain a distribution function for the wave height, some assumptions were needed to convert from a time series of significant wave height to statistics related to individual waves. If it is assumed that the properties of the random sea vary slowly in time, the variation in the sea surface elevation is approximately Gaussian during each wave recording, and the wave height follows a Rayleigh distribution. Thus, to derive an overall distribution function for individual waves a Rayleigh distribution was assumed to be valid for each record, and all the resulting Rayleigh distributions were averaged with equal weight to yield the overall distribution. The root-mean-square wave height H_{rms} for each Rayleigh distribution was obtained by multiplying the significant wave height by 0.706. This treatment neglects sequential information in the data, such as seasonality or correlation between successive wave heights; however, the purpose here is to obtain an overall statistical characterization of the wave conditions, and the results are considered to be an adequate first approximation.

Breaking waves have a pronounced influence on the profile development because the generated turbulence mobilizes sediment and promotes transport of sediment to a much greater degree than non-breaking waves. The ratio of broken waves was calculated at different water depths, including shoaling but neglecting refraction, based on the overall distribution function by truncating this function at a wave height of 0.78 times the local water depth. Fig. 18 plots the ratio of broken waves as a function of water depth together with the average absolute depth change across shore

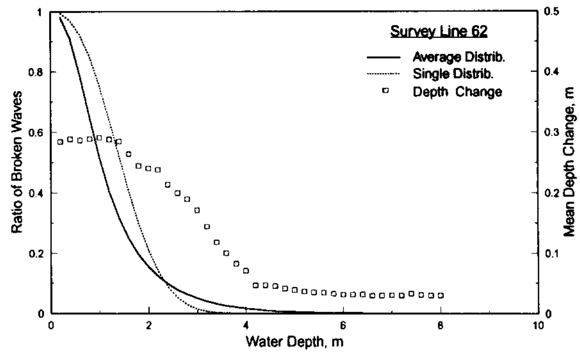

Fig. 18. Ratio of broken waves as a function of water depth calculated from a single Rayleigh distribution and as the average of the sum of individual Rayleigh distributions, together with the average absolute depth change across the profile at survey Line 62.

for Line 62. The ratio of broken waves is also shown as computed with a single Rayleigh distribution assumed to be valid for the entire wave measurement series ($H_{rms} = 0.91$ m). The figure clearly shows that using a single Rayleigh distribution underestimates the ratio of broken waves in deeper water as compared to the sum of individual Rayleigh distributions.

The correlation between the ratio of broken waves and the average absolute depth change at points across shore was 0.78 (this value is numerically the same as but not directly related to the breaking wave height to water depth ratio discussed above). Broken waves should act on the profile for a considerable distance shoreward of the incipient break point because organized wave energy is dissipated through turbulent motion over the breaker travel distance. Thus, in order to evaluate a possible shift in influence by broken waves on profile depth change, a cross-correlation analysis was performed between the absolute depth change and ratio of broken waves for different spatial lags implemented in terms of water depth. The results indicated that the ratio of broken waves was as well or somewhat better correlated with depth change in more shallow water (shoreward locations) as compared to correlation results with no spatial lag, and markedly lower correlations were found for spatial lags that implied larger depths (seaward location). The correlation dropped off six times more steeply in the seaward direction as compared to the shoreward direction, and for a spatial lag corresponding to 1.5-m water depth in the shoreward direction the correlation coefficient remained above 0.70.

The fairly high correlation between the ratio of broken waves and depth change prompted closer study of how these variables are related. A relative measure was employed by dividing the depth change by the local water depth. Fig. 19 displays the relative depth change as a function of the ratio of broken waves. Along the outer part of the profile, where the ratio of broken waves is low and the water depth increases gradually, the limit of survey accuracy produces a constant relative depth change. Further inshore, for a ratio of about 0.001, the relative depth change begins increasing, being approximately linear in the log–log plot up to a ratio of 0.01. Shoreward of the location where 1% of the waves break, the relative depth change is again close to linear, but with a greater slope than at seaward locations. At the break point between the two approximately linear segments with different slopes, both the relative depth change and the ratio of broken waves are approximately 1%. This point corresponds to about 4.5-m water depth, the seaward terminus of the outer bar.

5. Summary and conclusions

Analysis of an 11-year time series of high-resolution profile surveys made on a relatively straight mid-Atlantic sandy beach has greatly expanded quantitative understanding of the temporal and spatial changes in the beach profile. In the following, we summarize major results and conclusions of this study.

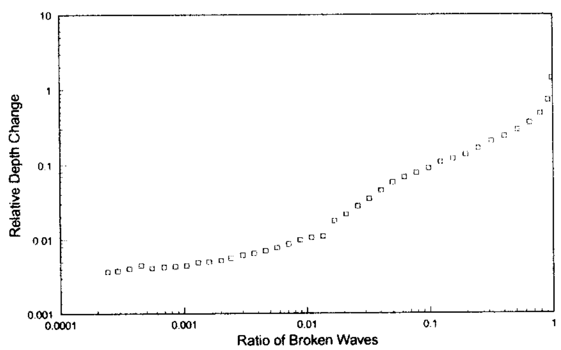

Fig. 19. Average absolute depth change normalized with the local water depth (relative depth change) as a function of the ratio of broken waves.

(1) Long-term average profile shape is the same for longshore distances on the order of a kilometer (Fig. 3), and the average seasonal profile shape consists of two extreme states, summer and winter, through which the spring and autumn shapes are almost identical as transition states between the two extremes (Fig. 11).

(2) Movement of depth contours is well correlated over longshore distances on the order of a kilometer for depths exceeding about 4 m, and is also well correlated to depths of about 2 m for longshore distances on the order of 100 m (Fig. 4). Correlation in contour movement between profiles spaced 100 m apart decreases greatly at the highly mobile inner bar located in about 2-m water depth.

(3) The envelope of maximum depth excursion (Fig. 6) is not quite symmetric about the average, but shows a tendency for greater depth increase in the nearshore (between about 2- and 4.5-m depths) and a greater increase from the 4.4-m depth to the limit of surveys, about 8 m. The asymmetry is attributed to the tendency for major storms to transport sand onto the profile from deeper water, and for breaking waves to scour the trough landward of the inner bar, which can rarely achieve an equilibrium bar crest depth owing to changing wave conditions.

(4) The seaward limit of significant depth change is about 4 m in the summer and 6 m in the winter (Fig. 13), and mean absolute elevation change is approximately symmetric about the shoreline (Fig. 8) between elevations of ± 4 m.

(5) Frequency or return-period diagrams were developed for the period of record, 11 years (Fig. 9). The frequency of depth change was consistent among the four survey lines and showed systematic increases in absolute change in depth with decrease in water depth. In 11 years, the maximum change in depth between two consecutive profile surveys was about 2 m, which occurred in the vicinity of the inner bar in 2-m water depth. In water deeper than 4 m, it is rare for the profile to undergo depth change greater than 0.5 m. This information was also expressed as a probability of

occurrence of absolute depth change (Figs. 14 and 17), which is more intuitively understood for seasonal depth change.

(6) The relative depth change (absolute depth change divided by the local depth) increased with the ratio of broken waves (increase in frequency of wave breaking).

(7) At Duck, major storms can move sand onto the profile from the seaward side from at least the 8-m depth, thereby increasing sand volume on the total profile from the dune to 8-m depth.

(8) The time scale of change in the inner bar, frequently exposed to breaking waves, is much shorter than for the outer bar (Birkemeier, 1984), and the horizontal motion is more rapid and change in depth greater.

(9) As data collection continues, the frequency and probabilistic approaches for expressing depth change will become more and more useful.

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References

Aubrey, D.G., 1979. Seasonal patterns of onshore/offshore sediment movement. J. Geophys. Res., 84: 6347–6354.

Aubrey, D.G. and Ross, R.M., 1985. The quantitative description of beach cycles. Mar. Geol., 69: 155–170.

Birkemeier, W.A., 1984. Time scales of nearshore profile change. Proc. 19th Coastal Eng. Conf., ASCE, New York, pp. 1507–1521.

Birkemeier, W.A. and Mason, C., 1984. The CRAB: a unique nearshore research vehicle. J. Surv. Eng., 110(1): 1–7.

Bruun, P., 1954. Coast erosion and the development of beach profiles. Tech. Memo., 44, Beach Erosion Board, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.

Clausner, J.E., Birkemeier, W.A. and Clark, G.R., 1986. Field comparison of four nearshore survey systems. Misc. Pap. CERC-86-6, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.

Dean, R.G., 1977. Equilibrium beach profiles: U.S. Atlantic and the Gulf Coasts. Ocean Eng. Rep., 12, Dep. Civ. Eng., Univ. Delaware, Newark, DE.

Dean, R.G., Healy, T.R. and Dommerholt, A.P., 1993. A "blind-folded" test of equilibrium beach profile concepts with New Zealand data. Mar. Geol., 109: 253–266.

DeWall, A.E. and Christenson, J.A., 1984. Guidelines for predicting maximum nearshore sand level changes on unobstructed beaches. Misc. Pap. CERC-84-4, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.

Evans, O.F., 1940. The low and ball of the eastern shore of Lake Michigan. J. Geol., (48)5: 476–511.

Hands, E.B., 1976. Observations of barred coastal profiles under the influence of rising water levels, Eastern Lake Michigan, 1967–71. Tech. Rep. 76-1, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Center, Vicksburg, MS.

Hands, E.B., 1980. Prediction of shore retreat and nearshore profile adjustments to rising water levels of the Great Lakes. Tech. Pap., 80-7, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.

Hom-ma, M. and Sonu, C.J., 1962. Rhythmic pattern of longshore bars related with sediment characteristics. Proc. 8th Coastal Eng. Conf., ASCE, New York, pp. 248–278.

Howd, P.A. and Birkemeier, W.A., 1987a. Beach and nearshore survey data: 1981–1984. CERC, Field Research Facility. Tech. Rep. CERC-87-9, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.

Howd, P.A. and Birkemeier, W.A., 1987b. Storm-induced morphology changes during DUCK85. Proc. Coastal Sediments '87, ASCE, New York, pp. 834–847.

Inman, D.L. and Rusnak, G.A., 1956. Changes in sand level on the beach and shelf at La Jolla, California. Tech. Mem., 82, U.S. Army, Corps of Engineers, Beach Erosion Board (available at U.S. Army Eng. Waterways Expt. Stn., Vicksburg, MS).

Jensen, R.E. and Garcia, A.W., 1993. Wind, wave, and water

level assessment for the January 4, 1992 storm at Ocean City, Maryland. Shore Beach, 61(1): 13-22.
Kajima, R., Shimuzu, T., Maruyama, K. and Saito, S., 1982. Experiments on beach profile change with a large wave flume. Proc. 18th Coastal Eng. Conf., ASCE, New York, pp. 1385-1404.
Keulegan, G.H., 1945. An experimental study of submarine sand bars, Tech. Rep., 3, Beach Erosion Board, U.S. Army, Corps of Engineers (available from U.S. Army Eng. Waterways Expt. Stn., Vicksburg, MS.)
King, C.A.M. and Williams, W.W., 1949. The formation and movement of sand bars by wave action, Geol. J., 113: 70-85.
Kraus, N.C. and Harikai, S., 1983. Numerical model of the shoreline change at Oarai Beach. Coastal Eng., 7(1): 1-28.
Kraus, N.C. and Larson, M., 1988. Beach profile change measured in the tank for large waves, 1956-1957 and 1962. Tech. Rep. CERC-88-6, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Center, Vicksburg, MS.
Kraus, N.C., Larson, M. and Kriebel, D.L., 1991. Evaluation of beach erosion and accretion predictors. Proc. Coastal Sediments '91, ASCE, New York, pp. 572-587.
Kraus, N.C., Smith, J.M. and Sollitt, C.K., 1992. SUPERTANK Laboratory Data Collection Project. Proc. 23rd Coastal Eng. Conf., ASCE, New York, pp. 2191-2204.
Larson, M., 1991. Equilibrium profile of a beach with varying grain size. Proc. Coastal Sediments '91, ASCE, New York, pp. 905-919.
Larson, M. and Kraus, N.C., 1989. SBEACH: numerical model for simulating storm-induced beach change, Report 1: empirical foundation and model development. Tech. Rep. CERC-89-9, U.S. Army Eng., Waterways Expt. Stn., Coastal Eng. Res. Center, Vicksburg, MS.
Larson, M. and Kraus, N.C., 1991. Mathematical modeling of the fate of beach fill. In: J. van de Graaff, H.D. Niemeyer and J. van Overeem (Editors), Artificial Beach Nourishments. Coastal Eng. 16: 83-114.
Larson, M. and Kraus, N.C., 1992a. Dynamics of longshore bars. Proc. 23rd Coastal Eng. Conf., ASCE, New York, pp. 2219-2232.
Larson, M. and Kraus, N.C., 1992b. Analysis of cross-shore movement of natural longshore bars and material placed to create longshore bars. Tech. Rep. DRP-92-5, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.
Lee, G. and Birkemeier, W.G., 1993. Beach and nearshore survey data: 1985-1991, CERC, Field Research Facility. Tech. Rep. CERC-93-3, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.
Leffler, M.W., Hathaway, K.K., Scarborough, B.L., Baron, C.F. and Miller, H.C., 1990. Annual data summary for 1988 CERC Field Research Facility. Tech. Rep. CERC-90-13, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.
Liang, G. and Seymour, R.J., 1991. Complex principal component analysis of wave-like sand motions. Proc. Coastal Sediments '91, ASCE, New York, pp. 2175-2186.
Lippman, T.C. and Holman, R.A., 1990. The spatial and temporal variability of sand bar morphology. J. Geophys. Res., 95(C7): 11,575-11,590.
Mason, C., Birkemeier, W.A. and Howd, P.A., 1987. Overview of the DUCK85 nearshore processes experiment. Proc. Coastal Sediments '87, ASCE, New York, pp. 818-833.
McLellan, T.N. and Kraus, N.C., 1991. Design guidance for nearshore berm construction. Proc. Coastal Sediments '91, ASCE, New York, pp. 2000-2011.
Nordstrom, C.E. and Inman, D.L., 1975. Sand level changes on Torrey Pines Beach, California. Misc. Pap., 11-75, U.S. Army Eng. Waterways Expt. Stn., Coastal Eng. Res. Ctr., Vicksburg, MS.
Sallenger, A.S., Holman, R.A. and Birkemeier, W.A., 1985. Storm-induced response of a nearshore bar system. Mar. Geol., 64: 237-257.
Saville, T., 1957. Scale effects in two dimensional beach studies. Trans. 7th General Meet., IAHR, 1, pp. A3-1-A3-10.
Shepard, F.P., 1950. Longshore-bars and longshore-troughs. Tech. Mem., 15, Beach Erosion Board, U.S. Army, Corps of Engineers (available from U.S. Army Eng. Waterways Expt. Stn., Vicksburg, MS).
Short, A.D., 1975. Offshore bars along the Alaskan arctic coast. J. Geol., 83: 209-221.
Short, A.D., 1979. Three-dimensional beach stage model. J. Geol., 87: 553-571.
Sonu, C.J., 1970. Beach changes by extraordinary waves caused by Hurricane Camille. Coastal Studies Inst., Tech. Rep. 77, Louisiana State Univ., Baton Rouge, LA, pp. 33-45.
Sonu, C.J., 1973. Three-dimensional beach changes. J. Geol., 81: 42-64.
Sunamura, T., 1988. Beach morphologies and their change. In: K. Horikawa (Editor), Nearshore Dynamics and Coastal Processes. Univ. Tokyo Press, Tokyo, Chpt. II-2, pp. 136-152.
Sunamura, T. and Maruyama, K., 1987. Wave-induced geomorphic response of eroding beaches—with special reference to seaward migrating bars. Proc. Coastal Sediments '87, ASCE, New York, pp. 884-900.
Sunamura, T. and Takeda, I., 1984. Landward migration of inner bars. Mar. Geol., 60: 63-78.
Weishar, L.L. and Wood, S.L., 1983. An evaluation of offshore and beach changes on a tideless coast. J. Sediment. Petrol., 53(3): 847-858.
Winant, C.D., Inman, D.L. and Nordstrom, C.E., 1975. Descriptions of seasonal beach changes using empirical eigenfunctions. J. Geophys. Res., 80: 1979-1986.
Wright, L.D. and Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Mar. Geol., 56: 93-118.
Wright, L.D., Chappell, J., Thom, B.G., Bradshaw, M.P. and Cowell, P., 1979. Morphodynamics of reflective and dissipative beach and inshore systems: Southern Australia. Mar. Geol., 32: 105-140.