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Storm-driven variability of the beach–nearshore profile at Duck, North Carolina, USA, 1981–1991

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Abstract

The US Army Corps of Engineers' Field Research Facility (FRF) at Duck, North Carolina, has collected approximately biweekly beach–nearshore profile data to 8-m depth and associated wave data since 1981. Sediment budget analysis was used to examine the medium-scale (years to a decade) variability of the beach–nearshore profile from 1981 to 1991. Significant changes occurred during four groups of energetic storm events during February/March of 1983, 1987, 1989 and December 1989. Each group was comprised of at least two storms within a period of less than 39 days both with $H_{mo} > 4$ m. During each storm group, offshore sediment movement caused a distinct outer bar to migrate offshore and grow in size resulting in an abrupt increase in the volume of sediment on the upper shoreface. The net profile changes were much larger than the changes due to single storms and the cumulative effect of the storms can be considered as one 'event'. During these events, the first storm appears to have a destabilizing effect on the profile which has insufficient time to recover before the second (and subsequent) storm(s). As a result, several storms in quick succession are able to have a large impact on the morphology. The intervening periods between the groups of storm events (termed fairweather conditions) lasted up to 4 years. They are characterized by slow, but steady sediment redistribution (averaging 33 m^3 m^{-1} $year^{-1}$) from the upper shoreface (> 5 m depth) toward the shore, while the total sediment volume was effectively constant. The onshore feed of sediment was not significantly affected by individual storms during the fairweather conditions. These two processes of (1) morphologic change during groups of storm events and (2) the steady onshore feed of sediments from the shoreface during fairweather conditions appear to play an important role on medium- and long-term profile evolution at least at Duck.

Keywords: storm event(s); profile change; sediment volume; shoreface; Duck, NC; erosion; accretion

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1. Introduction

It is well known that storms tend to move sand rapidly offshore, while under lower-energy conditions, sand moves onshore, causing gradual beach accretion (Komar, 1976). Over years to decades, the onshore–offshore exchange of sediments is not confined to the average surf zone, where most *beach profile* studies have occurred (e.g., Komar, 1976), but extends across the shoreface (Niedoroda et al., 1985; Wright et al., 1985a,b, 1991).

There is a hierarchy of scales between the hydrodynamic and morphodynamic processes. Short-term morphologic change is a response to the previous profile state and/or changing wave energy level (Wright and Short, 1984; Lippmann and Holman, 1990). Seasonal profile changes are induced by seasonal changes of wave climate (Shepard, 1950; Winant et al., 1975). Wright et al. (1985a) and Stive et al. (1990) suggest that the *beach–nearshore profile*, which extends to the shoreface, undergoes slow change over years to decades, superimposed on the short-term and seasonal changes. These larger-scale changes in time and space involve sediment transfer alongshore and across the shoreface.

This raises a fundamental question: is beach–nearshore profile response over years to decades simply the cumulative result of seasonal-scale processes or are longer-scale processes also at work? Of particular interest is the effect of a storm or a series of storms. While storms have long been recognized as a major modifying agent in terms of both morphology and sand volume (e.g., Dolan and Hayden, 1983; Birkemeier, 1985; Sallenger et al., 1985), the influence of storms on long-term profile evolution has not been well documented. In this paper, we will examine the medium-term (years to decade) profile variability using the beach–nearshore profile data collected between 1981 and 1991 at the Field Research Facility (FRF) of the US Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory (formerly the Coastal Engineering Research Center) (Fig. 1). We will use a sediment budget analysis and then examine the interaction between storms and profile morphology.

Using this extensive and unique beach–nearshore profile data set, Birkemeier (1985) and Larson and Kraus (1994) described temporal and spatial scales of beach profile change. They also examined the development and movement of the nearshore bars typically found on the profile. Using the same data set, Howd et al. (1993) and Lee et al. (1995) examined profile slope and its susceptibility to erosion. Using time-averaged video images of wave breaking at the FRF, Lippmann and Holman (1990) reported that the inner bar behaves in both an equilibrium and sequential manner, depending on the incident wave conditions and antecedent morphology. Lippmann et al. (1993) extended the study to the outer bar system and suggested that the outer bar system responds in an episodic, nonstationary manner to storms. Therefore, the focus of this paper will be the inter-annual profile change; volumetric changes during storms and groups of storms and the sediment transfer between the inshore and the upper shoreface during the intervening period.

2. Study area and data description

2.1. Study area

The Field Research Facility (Fig. 1) is described in detail by Birkemeier et al. (1985). The shoreline at the FRF is stable or slightly prograding, and backed by a well vegetated dune system. The subaerial beach and shallow nearshore to 2-m depth is primarily composed of a bimodal mixture of medium quartz sand and granules and small pebbles (mean sediment size $\sim$1 mm). The sediment size decreases offshore and becomes unimodal sand. On the upper shoreface, the sediment size varies from 0.12 to 0.20 mm (fine to very fine sand). The beach foreshore is steep (1 : 12), and beach cusps are generally present. The offshore bathymetry (>4 m depth) is relatively straight and simple. The bottom slope declines to 1 : 160 near the 8-m depth contour.

Tides are semi-diurnal with a mean range of approximately 1 m (spring tide range $\sim$1.2 m). While storm surges are generated by coastal storms, they have not been of great significance:

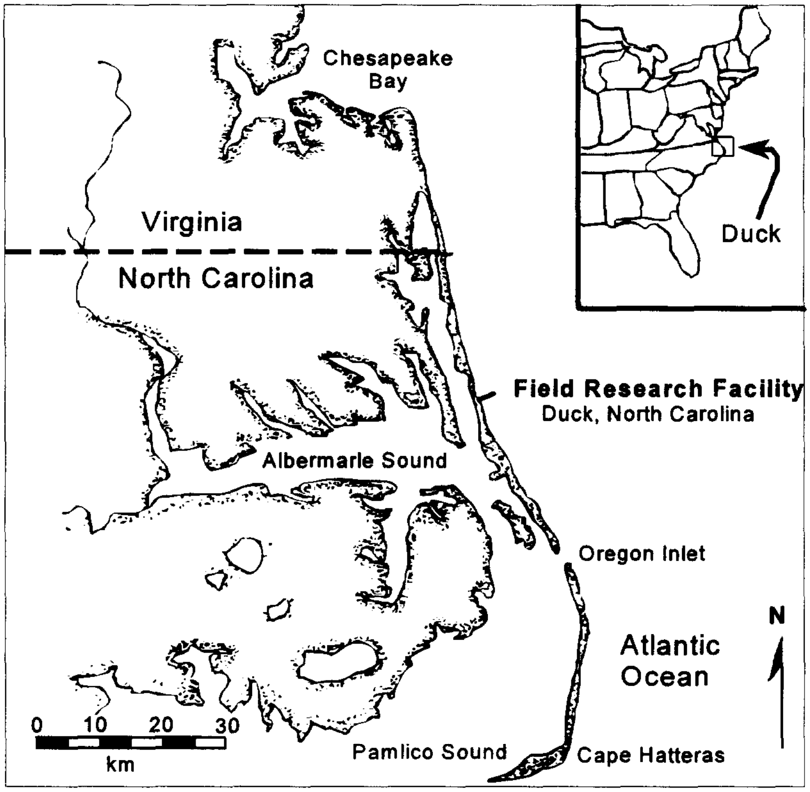

Fig. 1. Location of the Field Research Facility.

the highest water level measured in the data set is 1.7 m. Average annual significant wave height is 1.0 ± 0.6 m (1980–1991), having a mean peak spectral period of 8.3 ± 2.6 s (Leffler et al., 1993). Wave energy varies with season and is higher during the fall, winter and early spring months due to frequent extratropical storms and lower during the late spring and summer. Tropical storms and hurricanes may occur during the summer and fall season.

2.2. *Profile and wave data*

The profile data were collected along four profile lines (58, 62, 188, and 190) (Fig. 2) and cover 10.5 years from July 17, 1981 to December 19, 1991. Offshore distance is measured relative to a shore-parallel baseline located behind the dune system. Elevation is referenced to the 1929 National Geodetic Vertical Datum (NGVD). Howd and Birkemeier (1987) and Lee and Birkemeier (1993) tabulated the profile data and discussed survey methods, errors, and accuracy in detail.

The primary survey lines (62 and 188) are located about 500 m from the research pier to minimize the influence of localized scour near the pier (Miller et al., 1983) (Fig. 2). Shorter, adjacent profile lines (58 and 190) are designed to verify longshore similarity of profile lines 62 and 188, respectively. To standardize the profile data, (1) the dune portion of the profile and short profile surveys were excluded from this study; (2) the surveys had to reach -7.5 m for profile lines 62 and 188 and -6.5 m for profile lines 58 and 190. Table 1 summarizes the profile data before and after the removal of short profiles.

Wave height and period were collected every 6 h routinely and every hour when the wave height exceeded 2 m (e.g., Leffler et al., 1993). The wave data used in this study were collected by a waverider buoy located 6 km (18-m depth) offshore (gauges 620 and 630). When data were

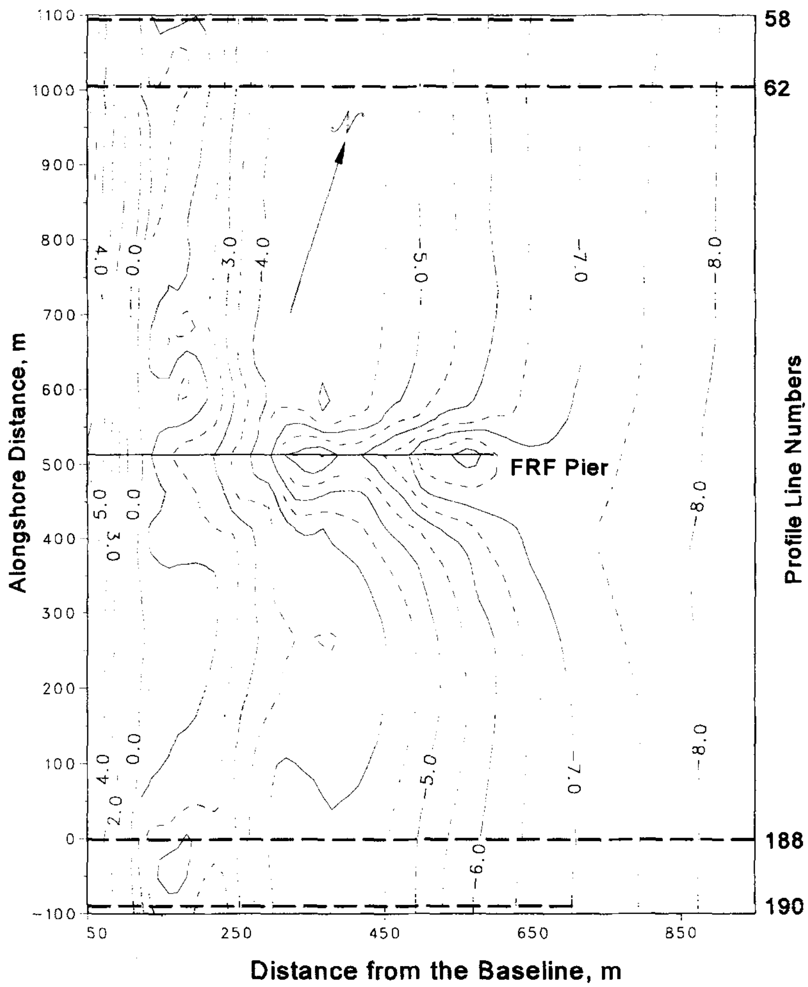

Fig. 2. Bathymetry map of the study area showing locations of the four profile lines (April 2, 1987).

Table 1
Summary of beach–nearshore profile data

Profile line	Before filtering		After filtering						
	No. of surveys	Depth criteria (m)	No. of surveys	Offshore distance (m)			Offshore depth (m)		
				ave.	max.	min.	ave.	max.	min.
58	260	−6.5	233	826	1199	660	−7.53	−9.75	−6.56
62	284	−7.5	234	954	1216	797	−8.24	−9.78	−7.50
188	294	−7.5	252	952	1102	798	−8.45	−9.30	−7.52
190	265	−6.5	252	816	1122	612	−7.60	−9.36	−6.51

unavailable from these gauges, a pressure sensor located in 8-m depth was substituted (gauge 111).

2.3. Profile variability

The profile configuration observed at the FRF varied from unbarred to triple-barred. A double-barred profile with a narrow, well-defined inner bar and a broad outer bar was most frequently observed (Howd and Birkemeier, 1987; Lee and Birkemeier, 1993). The bars are constantly moving, depending on wave conditions and previous profile geometry. In this paper, a bar is defined as an *inner*, *transitional* or *outer* bar based on the cross-shore distance to the crest, as indicated in Fig. 3. An important, but infrequent morphologic transition can occur due to big storm events. If the profile comprises a single inner bar, large storms may cause the bar to move offshore to a transitional position (Birkemeier, 1985; Lippmann et al., 1993). With further storms, the bar may move further offshore to form an outer bar, while a new inner bar will form. Under persistent lower-wave conditions, the outer bar migrates slowly onshore and declines in height, ultimately disappearing over several months to years. These changes are illustrated in Fig. 3.

The vertical range of the profile envelope of all surveys is greatest from the shoreline to about 300 m, where the inner bar is most active (Fig. 4). Further seaward, the profile envelope shows significant, but smaller variation (maximum range = 0.6 m at 800-m offshore). The mean profiles have a steep foreshore and a gentle offshore profile with no discernable difference.

The alongshore and cross-shore variability of the four profiles were studied by Larson and Kraus (1994). The profile variability increases as the alongshore distance between profile lines increases and the cross-shore distance from the shoreline decreases. Since neighboring pairs of profile lines (58–62 and 188–190) exhibited similar variation, the following analyses are limited to profile lines 62 and 188, unless stated otherwise.

3. Methodology

To gain insight into net profile change, a sediment budget analysis was performed. Three cross-

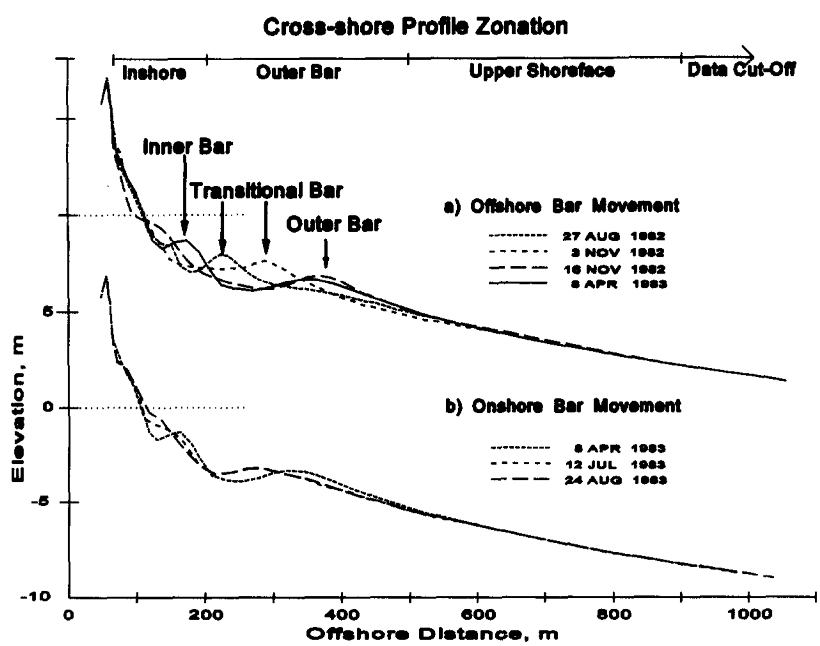

Fig. 3. Cross-shore profile zonation and bar movement sequence which occurred on profile line 188. Typical inner, transitional and outer bars are also shown.

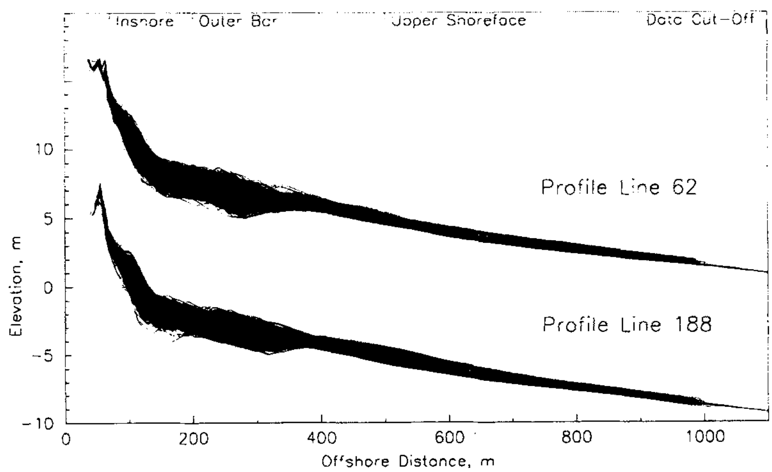

Fig. 4. Profile envelope of profile lines 62 and 188. Vertical change is greatest from the shoreline to about 300 m offshore where the bars are most active, and decrease offshore.

shore zones were defined as *inshore zone*, *outer bar*, and *upper shoreface*. After testing a range of possible cross-shore distances, cross-shore boundaries of 70, 200, 500 and 900 m, respectively, were selected (Fig. 3). The landward bound of the inshore zone was set at the base of the dune, while the seaward bound of the inshore zone was determined by the mean breaker distance, based on daily observations from 1984 to 1991. The outer bar/upper shoreface boundary was based on the simple, near-linear nature of the profile seaward of this point. This zone (500–900 m) is defined as the upper shoreface because it is seaward of the surf zone except during significant storms. The seaward end of the upper shoreface was set at 900 m, because most surveys reached this far. Sediment volume changes were calculated for the total profile (70 to 900 m), and for each zone by computing the change in cross-sectional area between successive surveys using the distance limits defined above and multiplying by a unit distance alongshore.

The relationship between intensity, duration and frequency of storms was established using a partial-duration series of wave height. This technique is useful for estimating events of low recurrence interval from a short record (Dunne and Leopold, 1978). The partial-duration series consists of all events greater than some arbitrary base magnitude, usually the smallest of the annual-maximum series. The smallest maximum significant wave height in the annual-maximum series was 2.7 m, occurring on December 22, 1983.

The intensity of each storm was measured by the integration of wave power (P) over the duration of each storm following the Shore Protection Manual (US Army Corps of Engineers, 1984). A similar approach to measure storm intensity by wave power was introduced by Dolan and Davis (1992) using peak wave height squared multiplied by the storm duration. The storm duration was defined as the interval of time that the wave height exceeded 2 m. In addition to individual storms, the net effect of several storms over a short period (i.e., a group of storm events) may have important morphological impacts. To identify high-energy periods, cumulative storm wave energy was obtained using a 1 month window from the partial-duration storm series.

4. Results

In this section, we present the relationship between medium-term profile variability and storm intensity.

4.1. Wave conditions

Table 2 presents the partial-duration series of the 55 storms events, including maximum signifi-

Table 2
Duration and intensity of major storm events

Date	Gauge	H_{mo} (m)	Duration (h)	Integrated wave power (10^{10} J)	Event	Date	Gauge	H_{mo} (m)	Duration (h)	Integrated wave power (10^{10} J)	Event
81Oct12	620	3.0	116	2.39		87Jan26	630	3.7	48	1.42	
81Nov13	620	4.2	72	4.25	A	87Feb17	630	4.8	48	2.02	C
81Nov25	620	3.0	43	1.39		87Mar10	630	4.9	161	5.50	
82Jan01	620	3.3	18	0.45		87Apr26	630	3.9	37	2.32	
82Feb18	620	3.4	44	1.55		87Oct14	630	3.3	66	1.79	
82Oct25	620	5.0	48	2.64		87Dec29	630	3.2	25	0.84	
82Dec12	620	4.2	42	1.67		88Jan08	630	3.7	17	0.43	
83Jan28	620	4.5	44	1.82		88Jan14	630	3.1	19	0.37	
83Feb14	620	5.1	34	1.90	B	88Apr08	630	3.1	36	0.74	
83Mar18	620	3.8	43	1.49		88Apr13	630	5.2	53	2.73	
83Mar25	620	5.1	77	2.92		89Jan23	630	3.3	34	0.96	
83Mar31	620	3.1	16	0.37		89Feb18	630	3.3	53	1.01	
83Sep29	620	4.5	67	2.35		89Feb24	630	4.6	56	2.66	D
83Dec12	620	3.6	31	0.89		89Mar07	630	4.3	104	5.12	
83Dec22	620	2.7	36	0.59		89Sep23	630	3.3	52	1.14	
84Oct13	625	3.5	92	3.42	G	89Oct26	630	3.3	90	2.38	
85Feb12	630	3.9	24	0.87		89Dec09	111	4.2	59	2.34	E
85Mar23	630	3.3	24	0.57		89Dec13	111	2.9	15	0.35	
85Apr15	630	4.4	30	1.16		89Dec24	630	5.6	67	3.49	
85Sep27	630	6.8	21	2.02		90Oct26	630	4.7	49	1.75	
85Oct22	630	3.1	50	1.26		90Nov10	630	3.7	12	0.30	
86Mar21	630	3.5	32	0.55		90Nov18	630	2.8	44	0.60	
86Apr18	630	3.5	60	2.03		91Jan08	111	3.5	53	1.51	
86May10	630	3.4	54	1.84		91Apr20	630	3.5	26	0.66	
86Aug17	630	4.0	9	0.32		91Oct18	630	2.8	24	0.40	
86Oct11	630	3.5	54	1.46		91Oct31	630	5.9	98	6.32	F
86Dec02	630	4.3	56	2.65		91Nov09	630	4.9	65	2.91	
87Jan01	640	3.7	24	0.57							

Four groups of major storm events are shown as B, C, D and E. Storm events A, F and G are also shown for comparison (see text for more).

cant wave height, duration and intensity of each storm. Each storm event is plotted in terms of wave energy in Fig. 5a and cumulative storm wave energy using a 1 month window is shown in Fig. 5b. Six high-energy periods stand out in terms of cumulative wave energy, comprising four groups of storm shown as B, C, D and E (Table 2; Fig. 5) and two of the most energetic storms (A and F). All these events exceeded 4.25×10^{10}J in terms of cumulative wave energy. Four groups of storm events comprised two or more storms occurring over a relatively short period of 11 to 39 days and two of the storms in each group had a peak wave height exceeding 4 m with a duration of 34 h or more (Table 2).

Event F is the most energetic single storm (the 'Halloween storm') on October 31, 1991, near the end of the study period. Its wave energy (6.18×10^{10}J) is equivalent to four groups of storm events. However, it comprised unusual high-energy, long-period (up to 24 s) swell, rather than the more typical shorter-period (7 to 12 s) storm waves produced by northeasters which produce most of the high-energy events at Duck. Event A is the fourth largest storm in terms of cumulative wave energy, and occurred on November 13, 1983. Six events (A to F) are compared with the morphological response below.

The most energetic storm outside events A to F, was a single storm on October 13, 1984 shown

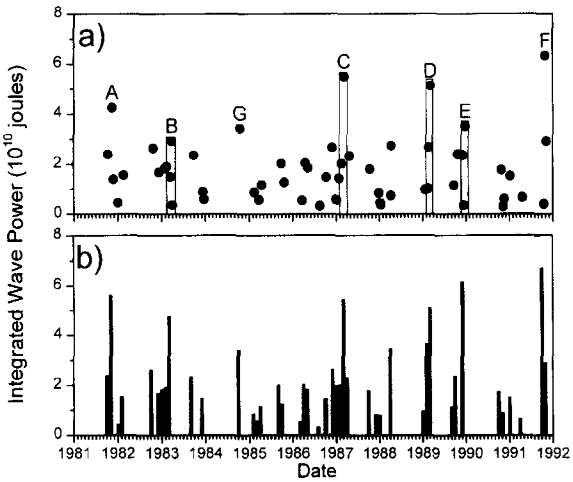

Fig. 5. (a) Wave power of individual storms during the study period. Groups of significant storm events are shown as B, C, D and E. Event F is the Halloween storm of 1991 and events A and G are significant single storms. (b) Cumulative storm wave energy using a 1 month window on the partial duration series (Table 2).

as G (Table 2; Fig. 5). In terms of cumulative wave power, this was the sixth largest single storm in the 10-year period (Table 2) and the wave power exceeded any of the storms in event B. However, in terms of peak wave height it was not unusual with 34 storms having an equal or greater peak height. It is labeled for later discussion.

4.2. Volume change

Cumulative sediment volume changes, relative to the initial survey of profile lines 62 and 188, for each cross-shore zone and bar crest movement are presented in Fig. 6. The total volume increased about 240 m^3/m (average for lines 62 and 188) over the 10.5 year period. Each cross-shore zone contributed to the total volume increase with most accumulation being in the inshore and upper shoreface zones. This indicates that the entire profile shifted seaward.

The increase in volume on the upper shoreface appears to be abrupt and rapid, rather than gradual. The trends of the upper shoreface volume change are similar on both profile lines. Four rapid volume increases on the upper shoreface occurred during February/March of 1983, 1987, 1989 and December 1989. These accretional events on the upper shoreface are concurrent with the four groups of storm events (B, C, D and E discussed above). We used the morphological response to refine the definition of storm groups discussed in the previous section and these are shown in Table 2 and Fig. 7. The early 1989 event was associated with overall profile accretion on both lines, and the 1987 and late 1989 events were associated with overall accretion on one line (profile lines 188 and 62, respectively). The abrupt nature of the change resulted from the offshore movement of the pre-existing transitional or outer bar to an outer bar position, combined with its substantial growth (Fig. 6).

During the groups of storm events, an existing transitional/outer bar migrated up to 100 m offshore with increasing bar height (height between bar crest and landward trough) (Fig. 7). The depth over the outer bar crest was usually constant at about 4 m (see fig. 23 in Larson and Kraus, 1992). Consequently, the offshore movement of the outer bar increased the volume on the seaward slope of the outer bar (which is defined as part of the upper shoreface) as shown at the top of Fig. 8. During the groups of storm events, the net volume on the inshore and outer bar zone decreases due mainly to deep trough development and partly due to beach erosion.

Between the groups of storm events (termed fairweather conditions), the total profile volume remained effectively constant and the upper shoreface slowly lost sediment at a near-constant rate (on average 33 $m^3\ m^{-1}\ year^{-1}$ for both profile lines 62 and 188; maximum 51 $m^3\ m^-1\ year^{-1}$; minimum 18 $m^3\ m^-1\ year^{-1}$). The volume change on the upper shoreface is related to the outer bar migrating onshore and diminishing in size as shown in the lower panel of Fig. 8. The onshore bar movement decreased the sediment volume on the upper shoreface and increased the volume in the inshore/outer bar zone (Fig. 8). While factors such as seasonal variation (Larson and Kraus, 1994) and three-dimensional morphology (Lippmann and Holman, 1990) introduce addi-

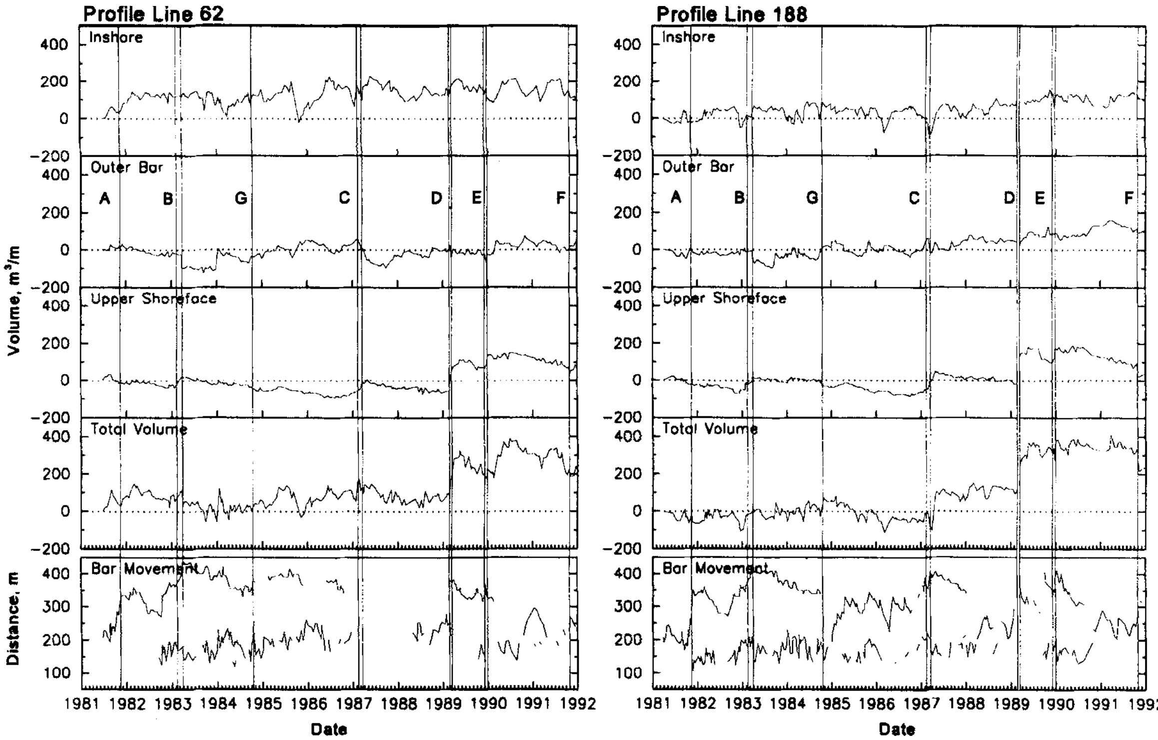

Fig. 6. Volume change and bar movement of profile lines 62 and 188. Four groups of storm events (B, C, D and E) and three significant single storms (A, F and G) are shown. Typical inner, transitional and outer bar positions, which are based on the cross-shore distance to the crest, are also shown (cf. Fig. 3).

tional variability, the volume change between the upper shoreface and the inshore/outer bar zone appears to be roughly balanced. This suggests that the upper shoreface slowly fed sediment onshore during the fairweather periods and that the system is near-closed in the cross-shore. This conclusion is also supported by the onshore movement of the outer bar during the fairweather periods (Fig. 6).

4.3. Comparison between profile changes and wave conditions

The change appears to be dominated by the formation, rapid offshore movement and growth, and subsequent slow onshore migration, decline and ultimate disappearance of the outer bar. The rapid offshore movement of the bar is driven by events B to E. In this section we compare this response with events A, F and G (Table 2; Fig. 7).

The Halloween storm (event F) caused a different morphologic response in that a single inner bar moved offshore to a transitional position, and an outer bar did not form. Further seaward, the upper shoreface was eroded and there was a net loss of sand seaward. As noted already, the Halloween storm was an unusual event with nearly shore-normal swell waves of up to 5.9 m in height with wave periods of up to 24 s (Davis and Dolan, 1992). During the peak of the storm, the entire surveyed profile was within the active surf zone. Therefore, a different response compared to the steeper, shorter-period storm waves of the storm groups might be expected. Unfortunately the magnitude and depth of the changes during the Halloween storm preclude a thorough analysis.

Event A had a large cumulative wave energy

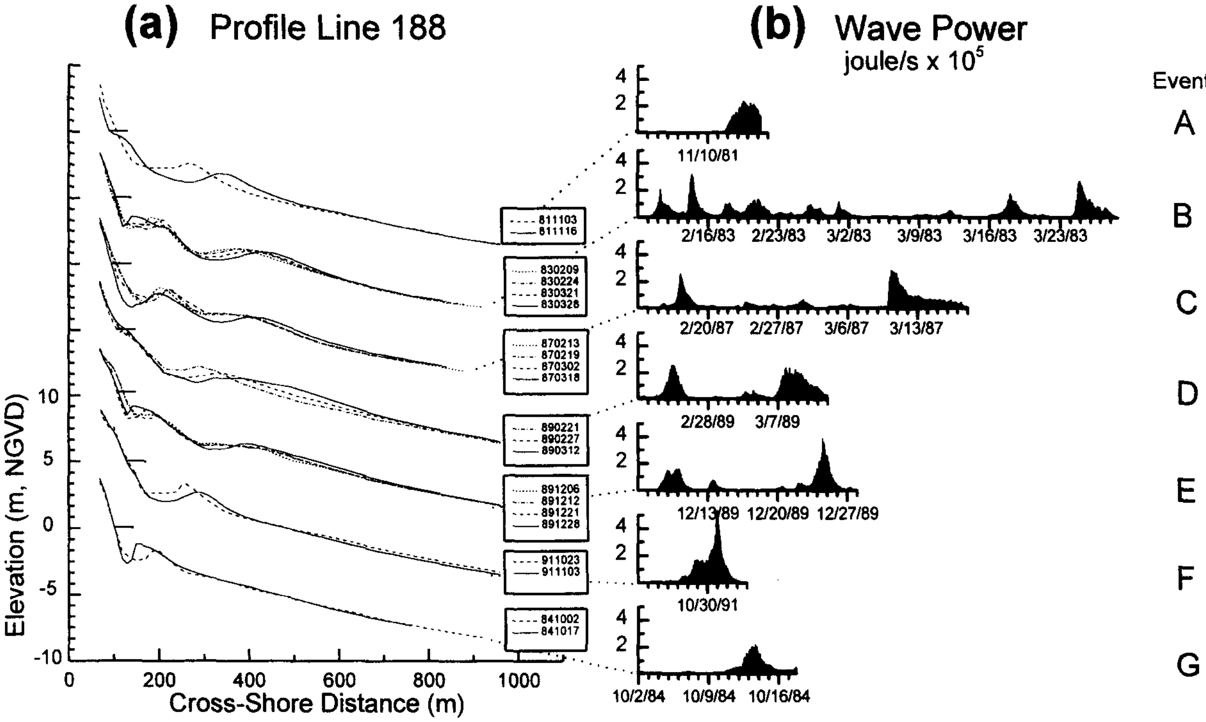

Fig. 7. (a) Sequence of change of profile line 188 during storm events. (b) Wave power during storm events.

exceeding 4.25×10^{10}J which is the fourth largest storm during the study period. However, the fundamental difference of morphologic response to this storm event from the four groups of storm events is that the starting morphology comprised a single inner bar with no transitional/outer bar. Therefore, while event A produced large morphological changes, including the formation of a transitional bar, there were no significant changes on the upper shoreface (Fig. 7) and the observed depth of closure was only 5.65 m below mean low water (Nicholls et al., 1998).

The integrated wave power of event G is comparable to individual storms within events C, D and E and greater than the intensity of any single storm in event B. However, no outer bar formation or sediment accumulation on the upper shoreface occurred (Fig. 7). This suggests that there is a wave energy (or related) threshold required for significant outer bar and upper shoreface changes to occur (Fig. 5). While this threshold may be exceeded during a single event, these data indicate that this threshold may be exceeded by two or more storms occurring over such a short period of time that they exert a cumulative impact. Further, it should be noted that no transitional/outer bar was present at the beginning of events A and G (Fig. 7) and this initial morphology may also influence the profile response.

5. Discussion

The beach–nearshore profile at the FRF has advanced seaward since 1981, gaining sand into the system. These gains are related to profile changes induced by several groups of storms. The constituent storms in a group usually had a peak significant wave height of ≥ 4 m and occurred in close succession — two or more storms over a period less than 39 days. During the groups of storm events the upper shoreface gained sediment,

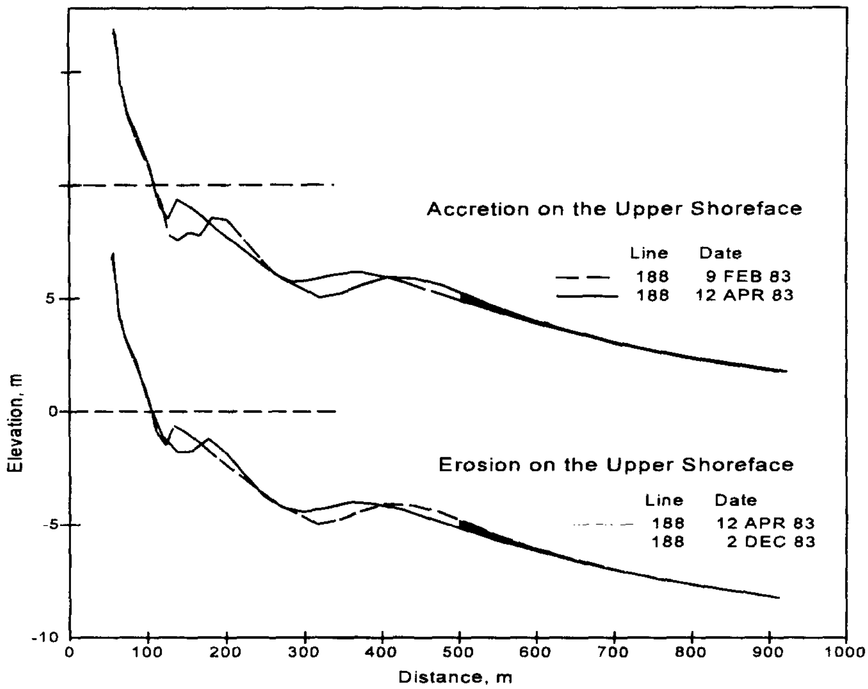

Fig. 8. Profile change and subsequent volume change on the upper shoreface due to the outer bar movement during and after event A.

while the inshore zone experienced erosion. The gain in sediment on the upper shoreface appears to represent offshore sediment transport from the inshore zone in events B and E, linked to the formation of the outer bar. Similar processes must have occurred in events C and D, but the overall gain indicates additional onshore or longshore movement of sediment into the system. During these big events, the upper shoreface temporarily becomes occupied by the surf zone and there is a large capacity for sediment transport. In the intervening periods, shoaling waves are responsible for the observed slow onshore transport.

The possible role of the shoreface in the coastal sediment budget is indicated by a number of studies. During a storm, wind-driven downwelling and upwelling flows are dominant on the shoreface (Niedoroda and Swift, 1991; Wright et al., 1991). Niedoroda et al. (1984) discussed the hysteresis during a northeaster off Long Island, New York. During the storm growth and peak with onshore component of wind and wave, the near-bottom current is directed offshore due to downwelling on the shoreface. However, as the storm wanes and the surf zone retreats landward, the current direction is reversed to onshore, inducing a bedload convergence on the upper shoreface.

Because the survey data examined here neither extend sufficiently offshore, nor do they resolve transport direction, we are able only to resolve the net change, not the source of sediment gain during events C, D and E (see also Nicholls et al., 1998). Event D is of most interest as accretion occurred on both profile lines which are 1000 m apart on opposite sides of the FRF pier (Fig. 2). One interpretation of this observation is that some of the sediment which deposits on the upper shoreface may come from offshore (see Larson and Kraus, 1994) for volume calculation of individual storms). An alternative interpretation is gain due to longshore transport. For instance, the March 7, 1989 storm within event D was characterized by intense and persistent alongshore winds (northeaster) and thus strong alongshore currents and downwelling in the nearshore zone. This resulted in significant erosion north of the FRF although well outside the survey frontage. At the same time, the extreme wave height (>4 m) produced a wide surf zone extending seaward of the survey measurements. Daily video images compiled by R.A. Holman during and after event D show longshore movement of a significant lobe of sediment moving toward the FRF pier (Fig. 2) and passing through profile line 62 (Holman, 1996). Although the relative contribution of cross-shore versus longshore sediment transport gradient cannot be assessed with this data set, profile changes induced by longshore sediment transport during extreme storms may be significant. Therefore, there is a need to improve our understanding of onshore versus longshore feed during large storms and groups of storms.

During intervening fairweather periods, the slope of the upper shoreface gradually decreased (see fig. 8 in Lee et al., 1995) and the volume also declined at a near-constant rate (on average 33 m^3 m^{-1} $year^{-1}$). While short-term fluctuations occurred, the rate of volume decline remained nearly constant despite a number of storms and the decline and ultimate disappearance of the outer bar. This indicates that the upper shoreface (>5 m depth) was steadily feeding sand onshore for periods of up to 4 years. This agrees with the findings that sediment flux during fairweather and swell conditions is primarily onshore due to wave orbital asymmetry and mean bottom flow (Wright et al., 1991), although it is surprising that large individual storms such as events A and G did not disrupt the steady nature of the onshore feed.

The most important observation of this work is the role of storm groups in controlling profile evolution at Duck. While the definition of the storm groups might seem arbitrary, this result is robust no matter how one looks at the data. The reason for this control is not entirely clear, but it seems that two conditions need to be satisfied for upper shoreface accretion: the pre-event profile must include a transitional/outer bar, and there must be a large and intense input of wave energy. Further the wave energy can be provided by more than one event if the events occur in rapid succession. Each of the storm groups B to E include at least two or more big events (H_{mo}>4 m) within a time period of 11 to 39 days and the cumulative wave power exceeded 6.18×10^{10}J. Storm durations and magnitudes vary among the storms and groups of storms so detailed comparisons are difficult. However, there are eleven other storms with peak wave height greater than 4 m, but with shorter duration and lower wave power which do not have the same morphologic effect (Table 2; Figs. 5 and 6). The importance of pre-storm morphology on the response to storms has been noted in a study of depth of closure at Duck (Nicholls et al., 1998). While wave conditions define the potential closure, it is only realized if the pre-storm morphology includes an outer bar due to morphological lags.

One possible explanation for why the storm groups have such a significant impact is that the first storm destabilizes the profile by resuspending and transporting sediment across the profile. Newly deposited sediment in the bars and on the shoreface is loosely packed and easily eroded. With the second storm arriving soon, the profile is easily changed and the two storms might be treated as a single long-duration event. Over time, the oscillatory action of the fairweather waves will recompact the sediment making it more difficult to erode. Further work to better understand these controls is required, but this work at least suggests that storm chronology is important to profile evolution at medium time scales (cf. Southgate, 1995).

A number of time scales are apparent in the 10.5 year study period. In addition to the seasonal cycles, the transitional bar formed on five occasions. The outer bar formed on three occasions, while the upper shoreface showed vertical accretion on four occasions. Lastly, the overall profile gained sediment on one occasion. The important point is that the medium-scale profile change was induced by processes that are longer than the seasonal cycle. Furthermore, four groups of storm events and subsequent fairweather conditions caused most of the total volume change. Therefore, medium-term profile evolution appears to be dependent on the intensity and return period of the significant storm groups in conjunction with profile conditions. Note that Thom and Hall

(1991) observed a similar morphologic behavior from Australia, in which their accretion-dominated and erosion-dominated periods are similar to storm and fairweather conditions in this study.

In summary, two different sequences of profile evolution are observed at Duck. During the four groups of storm events, the surf zone extends across the upper shoreface and an existing outer bar grows in size and moves offshore moving sediment to the upper shoreface as shown in Fig. 8. Subsequently, the outer bar moves slowly onshore and bar height also progressively decreases during fairweather conditions. The surf zone is usually near the inner bar during fairweather conditions, and sediment is slowly, but steadily transported landward on the upper shoreface, as already described. This fills the landward slope of the outer bar and contributes to both smoothing and landward movement of the outer bar combined with a decline in its size. Barusseau et al. (1994) observed similar processes on Mediterranean beaches in the Gulf of Lions. If this process continues over several months to several years, the outer bar eventually disappears. After the outer bar disappears, onshore movement of sand continues, but the inner bar shows greater offshore movement due to single storms (Lippmann et al., 1993) and major single storms may develop a transitional bar (Fig. 3). However, based on 10 years of data, the onshore feed from the upper shoreface continues until an appropriate morphology coincides with a group of storm events.

6. Conclusions

Our most important result is that given appropriate sequences, groups of storms can act as large individual 'events'. The impact of these events on morphologic changes is much larger than that of an individual storm. A 4-m wave event has a high recurrence interval at Duck (21 such events in 10.5 years in Table 2), but when combined with several other events the cumulative impact is large and inferred to be similar to a low-occurrence single storm event. In between the groups of storms there is a relatively large and steady onshore feed of sand from the upper shoreface of about 33 m^3 m^{-1} $year^{-1}$. These results provide further evidence that the simple model of storm-induced (e.g., storm/swell) profile change, drawn from observations in the average surf zone, is inadequate for describing medium-scale coastal behavior. They are expected to have important implications to medium- and long-term modeling of profile evolution and they raise several fundamental questions about medium-term beach–nearshore processes. In particular, the sediment source between the cross-shore and longshore must be determined to accurately understand medium-term coastal behavior.

The beach–nearshore profile data collected at the FRF are unique in terms of their survey interval, length, accuracy, and cross-shore extent. Continuing collection of the profile data at the FRF will provide more accurate insight into medium- to long-term coastal behavior. Occasional extension of the cross-shore profiles to greater depths (10+ m) and occasional surveys of a greater longshore length (10 km) would be particularly useful (see also Nicholls et al., 1998).

Different wave climates and resulting processes may induce different morphologic responses. Therefore, beach–nearshore profile observations from a range of other environments are needed to improve our understanding of medium- to long-term coastal behavior. Further, the relative importance of longshore versus cross-shore transport during groups of storm events remains uncertain. Understanding the contribution of onshore versus longshore feed during large storms is an important topic for further research. Collectively, these new results will allow a better understanding of medium- to long-scale sediment movement and profile change in the nearshore zone.

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