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Evaluation of depth of closure using data from Duck, NC, USA

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Abstract

Using 12 years of frequent high precision profiles collected on a wave-dominated sandy oceanic beach to 8-m depth, the characteristics and interpretation of depth of closure — or the seaward limit of *significant* profile change — is critically examined. This includes evaluation of the predictive capability of d_l — the seaward boundary of the littoral zone — as originally defined by Hallermeier (1981) [Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. Coastal Eng. 4, 253–277.]. Depth of closure during major erosional events is usually produced by the seaward limit of offshore bar movement. Following the original recommendation of Hallermeier (1981), d_l based on 12 h exceeded wave height and a reference depth of mean low water provides a robust *limit* to the observations using a 6-cm change criterion. Empirically, the observed depth of closure is 69% of d_l, although the scatter is large. This scatter is partly controlled by pre-event profile shape, most particularly bar configuration. Depth of closure under accretional conditions can also be measured, but it is time-scale-dependent as accretion is a slow, steady process. d_l underpredicts closure for accretional situations. Time-interval (e.g., annual) depth of closure represents the integral effect of erosional and accretional events. An important observation of the data is that depth of closure increases with time scale. However, the full population of time-interval observations is not resolved at Duck due to the measurement limit (8-m depth). As time interval increases from 1 year to 8 years, less cases close. Most non-closing time-interval cases coincide with the periods influenced by the most energetic wave events. However, time-interval closures are generally deeper than the biggest event closure in the period, showing that it represents more than the largest event. The frequency distribution of the data suggests that most, if not all, of these missing data simply represent closures deeper than 8-m depth. Up to a 4-year time interval, $d_{l,t}$ appears to provide a reasonable *limit* to the quantified observations. It is an interesting result that d_l (an event-based approach) might provide a limit to closure over periods up to 4 years as these time-interval closures are generally larger than those produced by single storms. Therefore, the general applicability of this result for more complete data sets, or on rapidly evolving (i.e., eroding or accreting) coasts is uncertain. The present data also suggest that on swell-dominated coastlines where accretional processes are dominant, d_l may underpredict closure, suggesting an important limitation to this approach. But as sediment would be moving onshore, this may not be a practical problem. Therefore, within the limits of the data set, Hallermeier's (1981) approach is found to define robust estimates of depth of closure, particularly for individual erosional events. This useful result is expected to find widespread application in coastal geology and engineering. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: cross-shore; profile change; morphodynamics; shoreface; erosion; accretion

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1. Introduction

The seaward limit to *significant* sediment transport in sandy coastal regions is of fundamental importance to understanding cross-shore sediment budgets and modeling coastal evolution (e.g., Hands, 1983; Kraus and Harikai, 1983; Stive et al., 1990; Jiménez and Sánchez-Arcilla, 1993). This limit is expected to vary with environment (waves, tides, etc.) and time scale. In practical terms, a significant seaward limit can be defined by the *depth of closure* (henceforth D_c), beyond which repetitive beach–nearshore profiles show negligible vertical change. D_c is not an absolute boundary and more limited net sediment transport is expected to occur seaward of D_c. An analytical method to estimate D_c based on incident wave conditions has been proposed by Hallermeier (1977, 1978, 1981), but it remains relatively untested against high-quality field data.

The concept of D_c has attracted increasing attention as we improve our understanding of sediment transport and sediment budgets in the nearshore zone. This is particularly the case in the design of soft coastal engineering projects such as beach nourishment (e.g., Stive et al., 1991; Davison et al., 1992; Stauble et al., 1993). However, uncertainty about the magnitude and meaning of the D_c concept exists (Inman et al., 1993; Pilkey et al., 1993). We accept that the closure concept may not always be valid. For instance, the deep episodic loss of sand from the Texas coast described by Hayes (1967) following Hurricane Carla clearly violates closure as defined in this paper. However, it is important to define under what conditions closure works and under what conditions it might fail as a concept and why?

This paper examines D_c using a unique 12-year (July 1981 to July 1993) series of approximately biweekly, high-precision, beach–nearshore profile data to about 8 m depth. They were collected at the Field Research Facility of the U.S. Army Engineer Waterways Experiment Stations, located in Duck, NC, U.S.A. (Howd and Birkemeier, 1987; Lee and Birkemeier, 1993). In a companion paper, Lee et al. (1998)) conduct a combined analysis of Duck data from 1981 to 1991 which examines the bar migration and sediment budget, and its relationship to wave conditions. This work demonstrates that sand is usually conserved across the profiles with only abrupt, infrequent volumetric changes associated with groups of large storms. Therefore, the Duck data set is well-suited to study cross-shore exchanges of sand.

This study is motivated by three fundamental observations of these data.

(1) When pre- and post-storm survey data extended seaward of the maximum surf zone width of the storm, there is always a depth beyond which offshore bottom change is insignificant (Fig. 1a).

(2) When the mean annual variation in the 12-year data set is examined, depth variation declines away from the shore to a non-zero tail below 7 m depth (1b). A minimum at about 4 m depth clearly separates an active inshore zone (henceforth the *inner littoral zone*) from a less active offshore zone (henceforth the *outer littoral zone*).

(3) As the length of record increased, the observed depth variation across the entire profile increased (Fig. 1b). This is a result of the integral effects of accretional and erosional processes. Therefore, as time scale increases, D_c is generally expected to move further offshore.

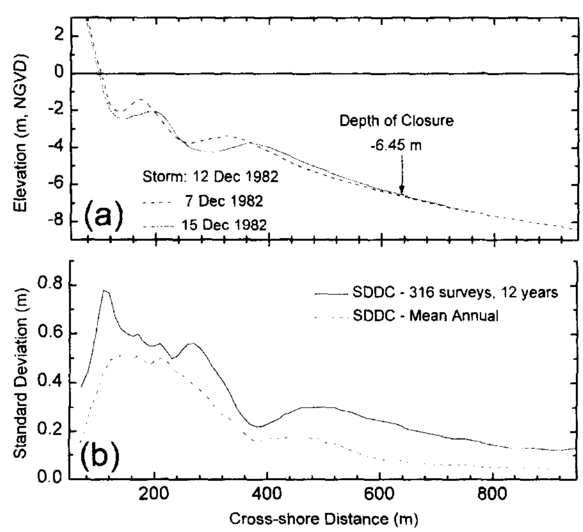

Fig. 1. Examples of depth of closure based on (a) comparison between two consecutive profiles, and (b) average annual and 12-year standard deviation of depth change (316 beach profiles) from 1981 to 1993.

This paper considers what controls the seaward limit of cross-shore sediment exchange on beaches by examining: (1) *event-dependent* depth of closure (henceforth E-D D_c), which represents the short-term profile response to a single erosional or accretional event derived from consecutive profiles (e.g., Fig. 1a); and (2) *time-interval* depth of closure (henceforth T-I D_c) which represents the integrated response of the profile to a number of erosional and accretional events over a longer time period. In this study, 1-year, 2-year, 4-year and 8-year periods are considered. The possible morphologic and sediment budget controls on D_c are considered, most particularly using the results of Lee et al. (1998)). This assessment includes an evaluation of the predictive capability of d_l (Hallermeier, 1978, 1981), and discussion of the utility and application of the D_c concept.

2. Previous studies

Hallermeier (1981) defined two cross-shore zones on wave-dominated sand beaches: the *littoral zone* which extends to "the seaward limit of intense bed activity caused by extreme near-breaking waves and breaker-related currents"; and the *shoal zone*, an area where "waves have neither strong nor negligible effects on the sand bed." The boundary between the shoal zone and the littoral zone is d_l, while the seaward limit of the shoal zone is d_i. Only d_l is evaluated in this paper.

As originally derived by Hallermeier (1977, 1978), the location of d_l can be described by a critical value of a sediment entrainment parameter (Φ_c) in the form of a Froude number:

$$\Phi_c = \frac{U_b^2}{\gamma' g d} = 0.03 \quad (1)$$

where: U_b = the maximum wave-induced horizontal velocity near the bed; g = the acceleration due to gravity; γ' = the ratio of the density difference between sediment and fluid, to the fluid density (γ' = 1.6 for quartz sand in seawater); d = the water depth.

The critical value (0.03) assumes that d_l generally lies seaward of the surf zone and implies that the peak near-bottom fluid kinetic energy per unit sediment grain volume is sufficient to raise an immersed grain a distance $0.015d$ above the bed. A comparison between measurements of the equilibrium depth of wave cut in a wave tank and Eq. (1) shows good agreement (Hallermeier, 1978). Hallermeier (1977) suggested an analytical approximation, using linear theory for shoaling waves, to predict an *annual* value of d_l on natural beaches. This can be generalized to a time-dependent form (e.g., Stive et al., 1992):

$$d_{l,t} = 2.28 H_{e,t} - 68.5 \left(\frac{H_{e,t}^2}{g T_{e,t}^2} \right) \quad (2)$$

where: $d_{l,t}$ = the D_c over t years; $H_{e,t}$ = the non-breaking significant wave height that is exceeded 12 h per t years, $(100/730t)\%$ of the time; $T_{e,t}$ = the associated wave period; g = the acceleration due to gravity.

To date, this is the only analytical method to estimate D_c. In this paper, for E-D D_c the t subscript will be dropped, while for T-I D_c, the above form will be used because it makes time scale explicit.

Following Eq. (2), d_l is primarily dependent on wave height with an adjustment for wave steepness. Hallermeier (1978) proposed using the 12-h exceeded wave height, which allowed sufficient duration for "moderate adjustment towards profile equilibrium." Eq. (2) is based on quartz sand with a median diameter between 0.16 and 0.42 mm (2.6 to 1.3 ϕ) (Hallermeier, 1978), which typifies conditions in the nearshore for most beaches. However, if the grain size exceeds 0.42 mm (1.3 ϕ), Eq. (2) may not be valid. Because tidal or wind-induced currents may increase wave-induced near-bed flow velocities (U_b in Eq. (1)), Hallermeier (1978) suggested using mean low water (MLW) as a reference water level to obtain a conservative D_c.

Hallermeier (1978) compared annual predictions from Eq. (2) to the observed annual D_c for three areas with different wave climates; the Gold Coast (Australia), Avondale (Florida), and Torrey Pines (California). The D_c was measured where the depth change of repetitive surveys declined below 30 cm (which was the operational accuracy of the data). The predicted D_c agreed with the observations to within 10%.

Birkemeier (1985) used the first 2 years of the Duck data set to evaluate Eq. (2). He reasoned that since any storm could be the annual event, an *event-dependent* d_l could be computed for each storm. Taking this approach, Birkemeier showed that the functional relationship proposed by Hallermeier appeared reasonable, but Eq. (2) over-predicted the observed D_c by about 25%.

The maximum exceeded wave height will increase with time scale and, based on Eq. (2), so should D_c. For instance, Stive et al. (1992) simulated the evolution of a beach fill using a cross-shore profile model and demonstrated that Eq. (2) provides reasonable predictions for the progressive offshore movement of the seaward limit of the beach fill over 10 years. Field data from the Great Lakes, over 5 to 10 years, and more speculatively over 125 years, also shows evidence of D_c increasing with time scale (Hands, 1977, 1983).

None of these studies examines high-quality field measurements of D_c versus Hallermeier's approach to closure determination. This paper examines Eq. (2) including the relevant parameters and its applicability for both short and long time scales, including both conditions of erosion and accretion.

3. Study area and data description

3.1. Study area

The Field Research Facility (FRF) is located on the Atlantic Ocean in Duck, NC (Fig. 2) (Birkemeier et al., 1985). Except in the area adjacent to the research pier, offshore contours are relatively straight and one or two nearshore bars are usually present (Fig. 1). The inner bar is highly dynamic and usually three-dimensional (Lippmann and Holman, 1990; Lippmann et al., 1993). The sub-aerial beach is steep (1 : 12) and often coarse-grained with a wide range of mean sizes (Fig. 3) (Meisburger and Judge, 1989). The bottom slope approaches 1 : 160 near the 8-m depth contour. In the outer littoral zone where D_c is most often observed the sediments are well-sorted fine and very fine sand (0.11 to 0.21 mm, or 3.2 to 2.3 ϕ) (Fig. 3). Seaward of 8 m depth, the grain size continues to decrease.

Tides are semi-diurnal with a mean range of approximately 1 m (spring tide range ~1.2 m). 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) with a mean peak spectral period of 8.3 ± 2.6 s (Leffler et al., 1993). Wave energy varies with storm occurrence: higher during the fall, winter and early spring months, and lower in the spring and summer months. Tropical storms and hurricanes can occur from July to October. A number of significant storms, mainly extratropical northeasters, occurred during the period of study. One category-3 hurricane (Gloria) passed close to the FRF in September 1985 producing the largest peak significant wave height of record (6.8 m), although the overall event was short-lived.

3.2. Profile, wave and water level data

The beach–nearshore profile data used in this study were collected along profile lines 58, 62, 188, and 190 (Fig. 2). All four profile lines are located over 500 m from the pier to minimize its influence (Miller et al., 1983). Horizontal distances are measured relative to a shore-parallel baseline behind the dune system. Elevation data are referenced to the 1929 National Geodetic Vertical Datum (NGVD) which is 8 cm below Mean Sea Level (MSL) and 42 cm above MLW. Surveys are typically collected every 2 weeks and after most storms, providing pre- and post-storm profiles which measure the integrated effect of storms, including any recovery. From 1981 to 1993 profile line 62 has 331 surveys, while 188 has 342 surveys.

Surveys of profile lines 62 and 188 extend up to 1000 m from the baseline to about the 8 m depth while profile lines 58 and 190 were generally surveyed only to 750 m. The lines were surveyed using the Coastal Research Amphibious Buggy or *CRAB*, a 10.5-m tall self-propelled three-wheeled vehicle. Position was determined using a circle of prisms mounted on the CRAB, which served as a target for a shore-based survey instrument. Lee and Birkemeier (1993) tabulated the profile data collected between 1981 and 1991, and discussed

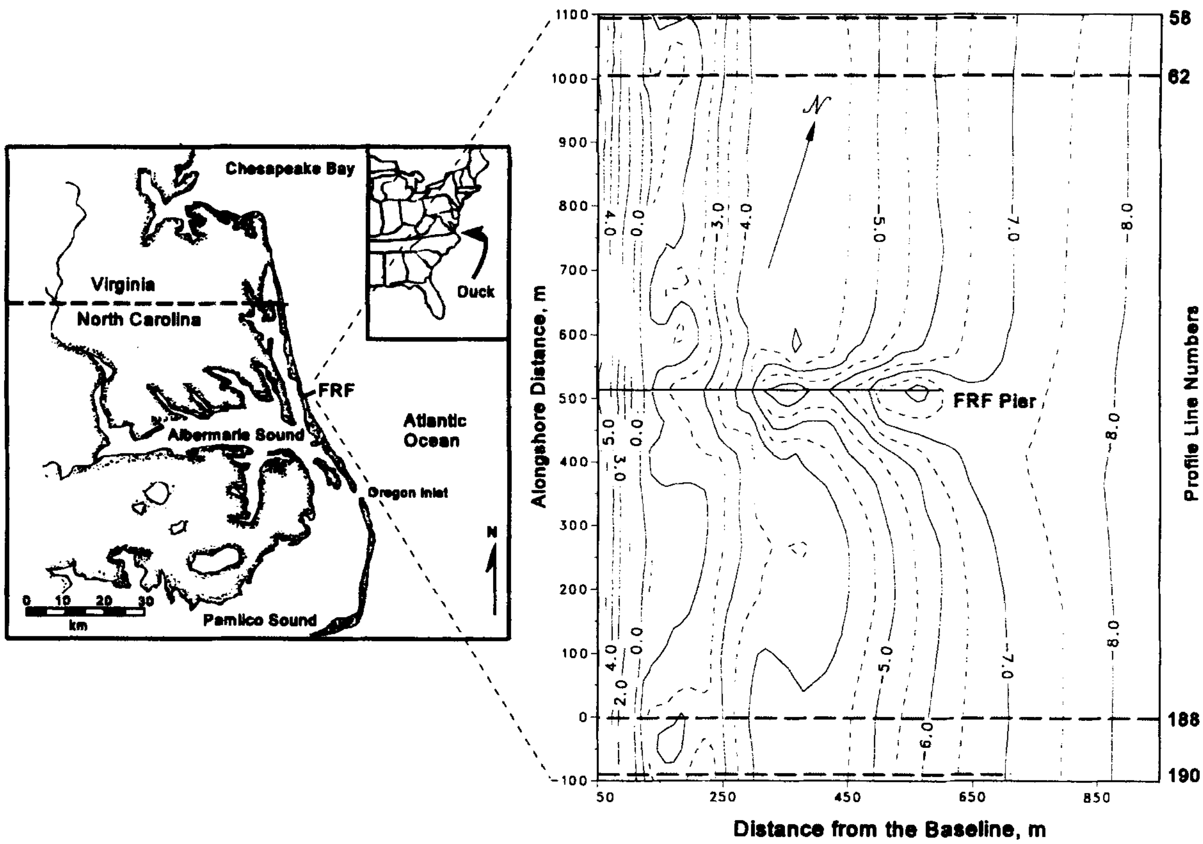

Fig. 2. Location of the Field Research Facility and bathymetric map of the study area showing locations of the four profile lines. Elevation is relative to NGVD.

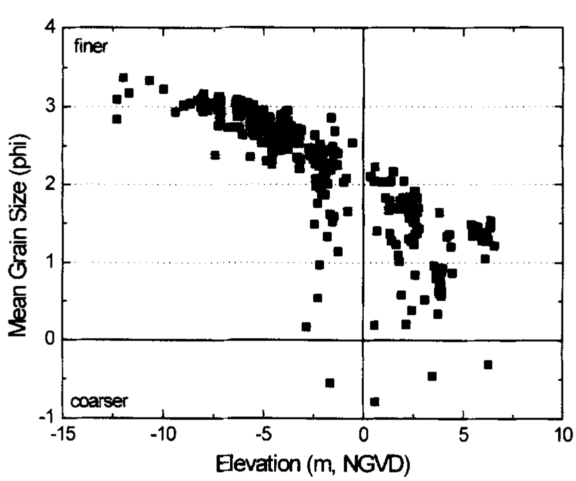

Fig. 3. Mean grain size versus depth at Duck. Data is derived from Stauble (1992), supplemented with 19 samples taken from −5 to −12 m NGVD during 1994.

survey methods and accuracy. Since the survey data were acquired with range-azimuth systems, vertical errors, though small, are greatest at the seaward extent of the survey. At a distance of about 1300 m from the instrument (about 8 m depth), the operational survey accuracy has a standard deviation of ±2.1 cm (1981–1990) and ±2.7 cm (1990–1993) (Lee and Birkemeier, 1993), while Larson and Kraus (1994) estimate an standard deviation of ±2.5 cm. This means that if we measure a 3-cm change and a 6-cm change, we are 66% and 95% confident that a real change has occurred, respectively. Birkemeier (1984), Howd and Birkemeier (1987), Larson and Kraus (1994) and Lee et al. (1995) reported some of the spatial and temporal characteristics of the same profiles. The profile and wave data from 1981 to 1991 are available online at: http://www.frf.usace.army.mil.

Wave height and period data were collected every 6 h, with hourly measurements during storms. Significant wave height was computed as the energy-based parameter (H_{mo}) defined as four times the standard deviation for a 34-min sea surface record sampled at 2 Hz. Wave period (T_p) is defined as the period associated with the peak in the energy spectrum. Leffler et al. (1993) provide details of the measurement instruments and the data analysis. The wave data used in this study were from gauges 620 and 630, which were waverider buoys located about 6 km seaward of the research pier in about 18 m depth.

The width of the surf zone was *visually* estimated from the deck of the research pier on a daily basis, giving a representative surf zone width, but not necessarily the maximum surf zone width that occurred. Surf zone widths exceeding 600 m (the length of the research pier) were less accurately estimated than smaller widths.

The water level data were measured by a National Oceanic and Atmospheric Administration (NOAA) tide station located at the seaward end of the research pier. The data were recorded instantaneously every 6 min. *Water level* represents the total water level including both tide and surge.

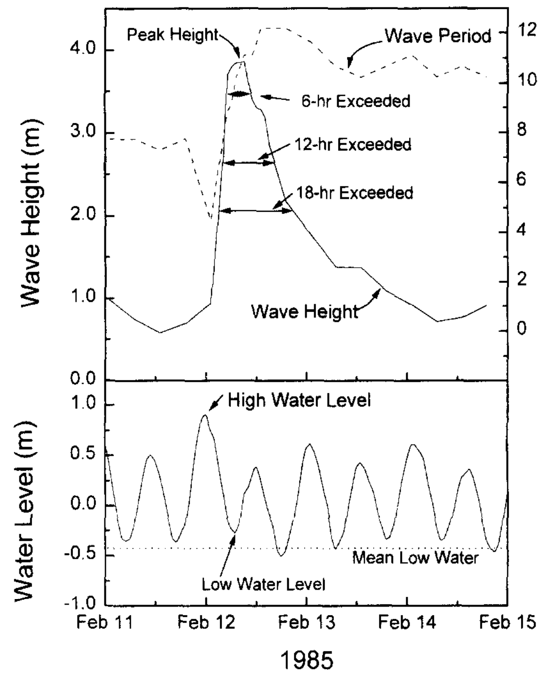

Fig. 4. An example of determining 12-h exceeded wave height and associated water levels. The series is 11 to 14 February 1985, inclusive.

4. Event-dependent depth of closure

The most appropriate values of three independent variables need to be considered when objectively assessing the validity and application of Eq. (2): (1) depth change criteria used to define observed D_c; (2) wave characteristics; and (3) reference water level. These parameters are now discussed in turn.

Hallermeier (1978) and Birkemeier (1985) both used the operational accuracy of their survey data to define a depth change criterion for the D_c. Given the high accuracy of the Duck data set (standard deviation <3 cm), it is possible to examine how D_c varies with depth change criteria (*criteria* hereafter): closure at 3 cm (based on the accuracy of the surveys), 6, 10 and 20 cm were evaluated.

Hallermeier (1977, 1981) suggested using Mean Low Water (MLW) as the reference water level for d_l. Logically, one would expect d_l to be associated with the lowest water levels during a given event, but field confirmation of this assumption is important, particularly for areas with large tides and/or large surges. Therefore, actual Low Water Level (LWL) during each event, actual High Water Level (HWL) during each event, and the fixed level of MLW were assessed. These reference water levels were associated with the highest and lowest water levels occurring during, or nearest the 12-h period of maximum wave height between two consecutive surveys (e.g., Fig. 4).

Four representations of significant wave height were assessed: peak (i.e., 1-h), 6-h, 12-h and 18-h exceeded wave height were assessed. From the wave record between surveys, the wave height parameters were graphically determined using the hourly wave data when available (e.g., Fig. 4). The associated wave period was determined directly, or by averaging wave periods over the 6, 12 and 18 h, respectively. For erosional cases, the changes could usually be related to a specific wave height peak occurring between surveys. The same parameters were also determined from the largest peak during the accretional cases; however, since accretional change is more gradual, these wave parameters may not have been the ones responsible for the accretional change.

It is well-known that the time scale of profile response to storm forcing is often longer than storm duration on natural beaches (e.g., Hands, 1983; Kriebel and Dean, 1985, 1993) and as a result, equilibrium conditions are rarely, if ever attained. However, d_l shows good agreement with near-equilibrium situations in wave tanks (Hallermeier, 1977, 1978). Therefore, in wave-dominated, event-dependent cases, d_l is best seen as an equilibrium limit (or potential D_c) and, within the limits of data accuracy, the following inequality is used to help assess the validity of different estimates of d_l:

$$d_l \geq \text{observed } D_c \tag{3}$$

This represents a change in the interpretation of d_l when compared to Hallermeier (1978, 1981) and Birkemeier (1985) who both used a best-fit approach when comparing predictions and field observations. In the field, Eq. (3) may be violated by non-wave-induced currents.

4.1. Depth of closure measurement

To measure D_c for each event, consecutive surveys were compared. Since we were concerned with cross-shore profile change, all surveyed profiles (usually four) were required to show a similar erosional or accretional sequence, and each observed D_c had to be within ± 0.75 m of the mean value, otherwise they were excluded from the analysis (Fig. 5). For the deepest observed D_c only profile lines 62 and 188 provide data. The observed D_c relative to NGVD was adjusted to other water levels as needed. The cross-shore distance from the shore to each D_c was also computed for all profile lines and averaged.

A subjective procedure based on bar movement between surveys (cf. Birkemeier, 1985) was used to classify each case as erosional, accretional, or

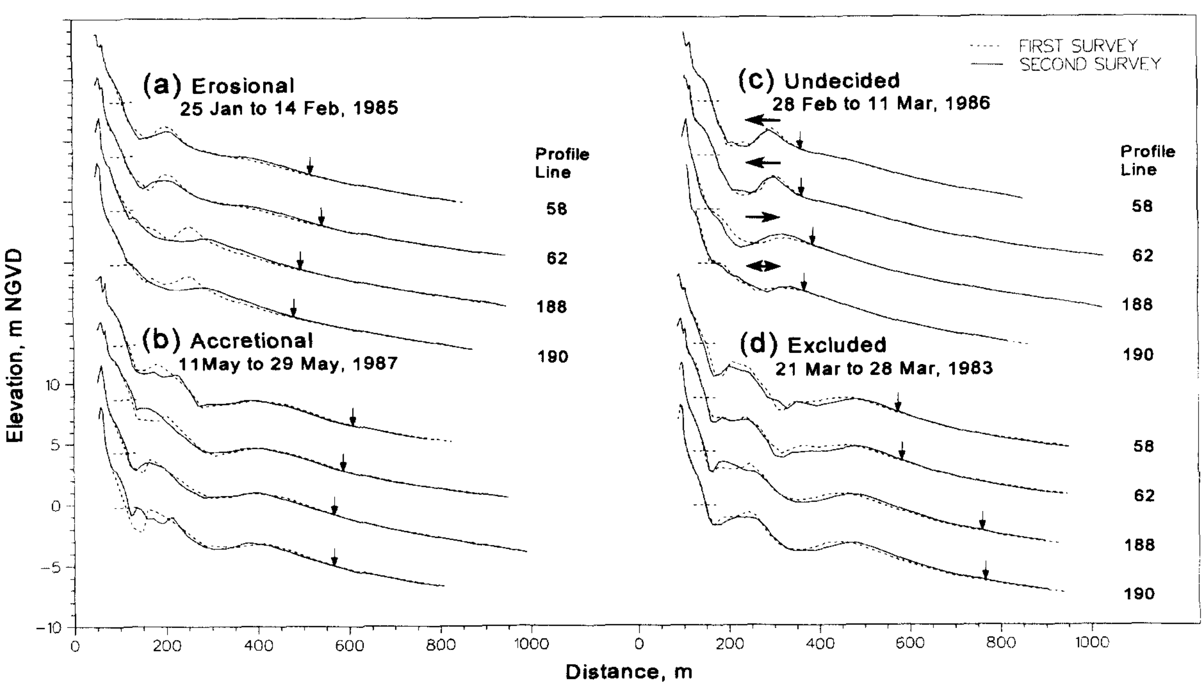

Fig. 5. Examples of profile change. The arrows indicate observed closure.

Table 1
The event-dependent erosional cases using a 6-cm criterion, including the observed depth of closure and predictions using Eq. (2) using peak significant wave height and 12-h exceeded significant wave height

Stm No.	Survey date		Wave peak	Observed D_c (6-cm criteria), m			Peak wave			12-h exceeded wave		
	begin	end		HWL	LWL	MLW	H, m	T, s	d_l, m	H, m	T, s	d_l, m
1	810804	810825	810820	5.68	4.49	3.82	3.7	9.1	7.3	3.1	10.0	6.3
2	810928	811016	811013	5.27	3.89	3.60	3.0	8.0	5.8	2.6	7.3	5.1
3	811016	811103	811101	5.09	4.26	4.02	2.7	12 2	5.8	2 6	9.9	5.4
4	811103	811116	811113	7.57	5.93	5.65	4.3	12.2	8.8	3.7	14.7	8.1
5	811207	820105	820101	5.77	4.69	4.65	3.4	9.5	6.8	2.1	9.6	4.4
6	820824	820901	820829	3.86	3.35	2.89	2.1	7.3	4.3	1.5	6.6	3.0
7	821015	821026	821025	6.62	5.98	4.92	5.4	13.7	11.2	4.8	11.3	9.7
8	821108	821206	821123	5.05	4.75	4.03	2.8	14.2	6.1	2.4	13.4	5.2
9	821207	821215	821212	7.52	6.57	5.87	4.2	9.5	8.2	3.7	10.5	7.6
10	830124	830209	830125	8.05	6.56	6.19	4.5	10.2	8.9	3.9	10.2	7.8
11	830209	830224	830214	6.84	5.59	5.37	5.0	11.1	9.9	3.9	11.3	8.0
12	830224	830321	830318	6.73	5.63	5.13	3.8	10.7	7.8	3.0	10.5	6.2
13	830808	830825	830813	5.14	4.21	3.64	2.1	6.9	4.1	1.7	7.1	3.4
14	830908	830918	830915	5.45	4.70	3.98	3.1	8.0	6.0	2.7	7.7	5.3
15	830918	831001	830929	5.37	4.58	3.86	4.5	9.9	8.8	3 5	11.0	7.3
16	831202	831227	831212	4.97	4.40	3.85	3.6	9.1	7.2	2.6	9.9	5.4
17	840210	840216	840214	5.10	3.64	3.85	3.3	11.1	6.9	2.2	10.4	4.7
18	840224	840308	840227	4.80	3.47	3.47	4.2	8.5	7.9	2.6	8.0	5.2
19	840403	840406	840405	4.90	3.80	3.68	1.9	11.1	4.1	1.7	11.0	3.7
20	840830	840906	840905	3.76	2.81	2.44	1.4	5.6	2.7	1.1	7.3	2.3
21	840906	840910	840908	4.04	2.99	2.91	1.7	8.8	3.5	1.5	7.1	3.1
22	840910	840921	840916	4.24	3.64	3.12	2.0	6.9	4.0	1.8	7.2	3.6
23	840921	841002	840929	5.38	4.31	3.69	2.9	10.2	6.1	2.4	7.8	4.8
24	841002	841015	841013	6.19	5.29	4.51	4.1	13.5	8.6	3.7	13.2	7.9
25	850102	850105	850103	4.61	3.81	3.29	3.3	8.0	6.3	2.8	8.1	5.6
26	850105	850124	850120	3.94	2.97	3.00	2.3	7.3	4.6	1.8	5.9	3.4
27	850124	850214	850212	5.85	5.15	5.03	3.9	11.6	8.1	2.8	11.9	5.9
28	850326	850423	850415	6.30	5.45	5.43	4.4	11.6	9.0	3.0	13.5	6.5
29	850724	850807	850802	4.79	3.62	3.40	2.5	7.8	5.0	2.1	8.0	4.3
30	850906	850915	850914	4.50	3.22	3.05	2.4	6.1	4.4	2.2	6.2	4.1
31	850925	851015	850927	5.24	4.54	3.87	6.8	16.0	14.2	3.5	16.3	7.7
32	851015	851106	851104	6.06	5.10	4.57	3.9	11.1	8.1	3.0	11.2	6.3
33	860416	860422	860418	6.25	5.68	5.08	3.5	8.0	6.6	3.1	9.6	6.3
34	860813	860818	860817	6.16	4.81	4.59	4.0	9.1	7.8	1.9	9.3	4.0
35	860902	860918	860917	4.57	3.28	3.26	1.8	8.4	3.6	1.7	6.1	3.4
36	861125	861204	861202	7.65	6.03	5.96	4.3	10.7	8.7	3.7	11.3	7.6
37	870123	870213	870126	6.61	5.76	5.34	3.7	9.9	7.4	2.8	10.7	5.9
38	870203	870219	870217	4.91	4.01	3.53	4.8	8.8	8.8	4.3	9.0	8.2
39	870302	870317	870309	*	*	*	4.9	11.1	9.7	4.6	11.1	9.2
40	870402	870430	870425	8.21	7.21	6.59	3.9	10.2	7.9	3.6	9.1	7.2
41	870731	870812	870811	4.72	3.28	3.21	1.4	5.5	2.7	1.3	5.6	2.6
42	870812	870901	870815	5.12	4.03	3.80	2.5	11.6	5.3	2.2	10.6	4.7
43	871113	871125	871121	3.98	3.12	3.06	2.2	6.7	4.2	1.8	7.2	3.6
44	871223	880104	871230	5.70	4.57	4.20	3.2	11.1	6.6	3.0	10.3	6.2
45	880112	880202	880114	4.49	4.04	3.61	3.1	8.0	6.0	2.4	6.8	4.5
46	880321	880415	880413	5.49	4.31	3.34	5.2	11.1	10.3	4.2	10.7	8.6
47	880602	880607	880603	4.96	3.63	3.07	2.6	6.9	4.9	2.3	7.2	4.5
48	880909	881011	881004	4.89	4.15	3.53	2.9	7.1	5.4	2.4	7.0	4.7
49	890221	890227	890224	9.55	8.44	7.80	4.6	10.7	9.2	4.2	11.1	8.6

Table 1 (*continued*)
The event-dependent erosional cases using a 6-cm criterion, including the observed depth of closure and predictions using Eq. (2) using peak significant wave height and 12-h exceeded significant wave height

Stm No.	Survey date		Wave peak	Observed D_c (6-cm criteria), m			Peak wave			12-h exceeded wave		
	begin	end		HWL	LWL	MLW	H, m	T, s	d_l, m	H, m	T, s	d_l, m
50	890227	890312	890307	8.97	7.57	7.15	4.3	12.2	8.9	4.0	11.4	8.3
51	891117	891129	891123	4.94	4.12	3.60	2.6	6.7	4.9	1.6	7.1	3.4
52	891206	891212	891210	6.39	5.29	4.87	4.1	10.2	8.2	3.9	10.7	7.9
53	891221	891228	891224	*	*	*	5.6	11.1	11.0	4.4	12.1	9.1
54	900508	900524	900522	4.44	2.94	2.67	2.7	6.6	5.0	2.2	7.1	4.4
55	900820	900906	900904	4.89	3.56	3.39	2.0	8.3	4.2	1.7	8.3	3.6
56	900906	901030	901026	6.11	5.56	4.49	4.7	9.1	6.9	3.5	9.7	7.0
57	910111	910118	910112	4.20	3.26	3.00	2.8	8.8	5.8	2.4	8.9	4.9
58	910510	910524	910519	3.88	2.65	2.38	2.7	6.9	5.1	2.4	7.1	4.6
59	910823	910905	910901	3.83	2.87	2.27	2.7	7.5	5.3	2.2	7.7	4.4
60	911023	911103	911031	*	*	*	5.9	19.7	12.8	5.1	19.1	11.1
61	911103	911112	911109	6.49	5.81	4.87	4.9	11.1	9.7	4.2	10.9	8.5
62	911216	920106	920104	7.84	6.58	6.22	4.3	13.5	9.1	3.7	12.9	7.9
63	920227	920310	920307	3.62	2.57	2.68	2.4	9.5	5.1	1.6	9.7	3.4
64	920310	920325	920322	3.64	3.12	2.92	2.1	12.8	4.6	1.7	10.0	3.7
65	920820	920916	920915	3.97	2.90	2.79	1.5	8.9	3.2	1.2	8.1	2.5
66	920916	920929	920925	5.43	2.92	3.48	4.6	9.5	8.8	3.9	9.8	7.8
67	920929	921026	921005	5.18	4.85	3.68	4.6	9.5	8.8	3.8	9.5	7.5
68	921026	921218	921214	6.78	5.64	5.23	4.7	17.1	10.2	4.2	17.1	9.1
69	931004	930113	930110	4.98	3.30	3.23	3.9	11.6	8.1	3.7	11.6	7.7
70	930312	930315	930313	7.45	6.06	6.33	4.6	12.8	9.7	3.6	12.6	7.7
71	930315	930412	930406	6.03	4.37	4.19	4.2	9.9	8.3	3.5	10.8	7.2

'*' indicates closure not measured above 8 m depth.

undecided (Fig. 5). When the bar moved offshore and measurable deposition occurred seaward of the bar crest, the profile change was classified as *erosional*. An *accretional* change resulted in onshore movement of the bar crest with measurable onshore sediment movement. When it was unclear if the change was erosional or accretional, the case was labeled as *undecided* and it was not considered further.

The determination of D_c and the erosional and accretional sequence was automated using a computer algorithm. The algorithm ignored spurious variation in the data and located the most seaward D_c for each depth criterion associated with a zone of consistent vertical profile change. Because of the subjective nature of these parameters, the authors then independently reviewed the erosion/accretion assignment, which cases to include/exclude, and the D_c estimates.

4.2. Results

Of the 66 events where peak significant wave height exceeded 3 m, 37 (56%) were erosional (but 3 of these cases did not close within the surveyed profile), 9 were undecided, 2 were accretional and the balance were excluded for a range of reasons such as lapses in wave data, inconsistent longshore behavior, etc. Taking the data set as a whole, meaningful D_c were derived in 172 cases using the 6-cm criterion, 68 cases were erosional (Table 1), 74 accretional, and 30 cases undecided. Table 1 also includes the three erosional events which did not close within the surveyed profile. Most other cases were associated with low wave heights and variable profile behavior alongshore.

4.2.1. Erosive cases

The observed D_c vary from 2.7 m to 7.8 m below NGVD at a 6-cm criterion (Table 1). Twenty-

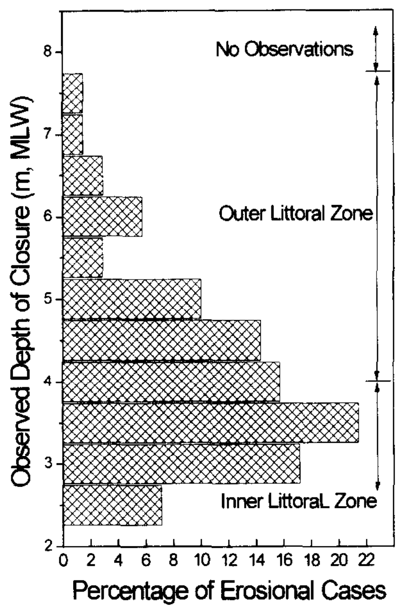

Fig. 6. The vertical distribution of the erosional event-dependent depth of closure cases and their relationship to the inner and outer littoral zones defined in Fig. 1b.

seven cases (or 36%) are within the inner littoral zone (Figs. 1b and 6) where most observed erosive D_c are closely associated with the seaward limit of the inner bar movement. Deeper closures are associated with movement of the outer bar. Hence, the intersection between successive profiles is usually distinctly lenticular, allowing unambiguous interpretation of D_c for the selected criteria. However, the deepest closure events involved more than simple bar movement and are discussed later.

To identify the best criteria for erosive conditions based on the field data, we compared the daily surf zone width measurements to the average distance from the shoreline to the observed D_c. This is based on the same logic as Hallermeier (1977, 1978) — the D_c is caused by extreme breaking and near-breaking waves and d_l should lie near the seaward edge of the surf zone. The best fit with breaker distance was found using the 3-cm and 6-cm criteria (Fig. 7). The 3-cm and 6-cm criteria give similar results in terms of D_c. As a 6-cm change corresponds to a conservative consideration of the survey data (>95% confidence that a real change has occurred), independent of location across the profile, a 6-cm criterion was selected as the best definition of D_c.

The two measured water levels, LWL and HWL, and the four wave height exceedance conditions were used in Eq. (2) and compared to the observations (Fig. 8). The limit requirement of Eq. (3) is not satisfied in any case when HWL is applied (Fig. 8a), and hence this water level is not considered further.

In terms of the four wave height exceedance conditions and LWL, peak significant wave height best obeys Eq. (3) (Fig. 8b). This suggests that under certain conditions, it is the significant wave height which controls the ultimate (or equilibrium) D_c. This is consistent with observations in physical models that the equilibrium depth of wave cut is sometimes established after only a small number of waves (R.J. Hallermeier, pers. commun., 1994). However, peak significant wave height is not a robust parameter and, on average, it overpredicts D_c by about 70%, the most extreme example being Hurricane Gloria (Fig. 8) for which the observed D_c was 4.7 m below LWL while Eq. (3) predicts 14.2 m. The 18-h exceeded wave height appears to underestimate the effect of short-duration storms and over 27% of cases violate Eq. (3). Although the 6-h exceeded height reduces overprediction, the 12-h exceeded wave height originally proposed by Hallermeier (1977) appears most reasonable, but with some limited violation of Eq. (3). No observation exceeds prediction by more than 0.5 m and scatter is reduced (Fig. 8). Hurricane Gloria ceases to be an outlier with a predicted D_c of 7.7 m.

All the overpredictions for 12-h exceeded wave height are associated with an observed $D_c < 5$ m below LWL. This corresponds to the zone influenced directly by the inner and outer bars. The inner bar often displays daily changes and three-dimensional morphology (e.g., Lippmann and Holman, 1990), while transverse bars further complicate the morphology (Konicki and Holman, 1996). Therefore, D_c in this zone is more controlled by bar geometry and movement than further offshore, and hence Eq. (2) may have less predictive capability.

Since the actual LWL may not be known, use of MLW as a reference level with peak and 12-h exceeded significant wave height gives similar

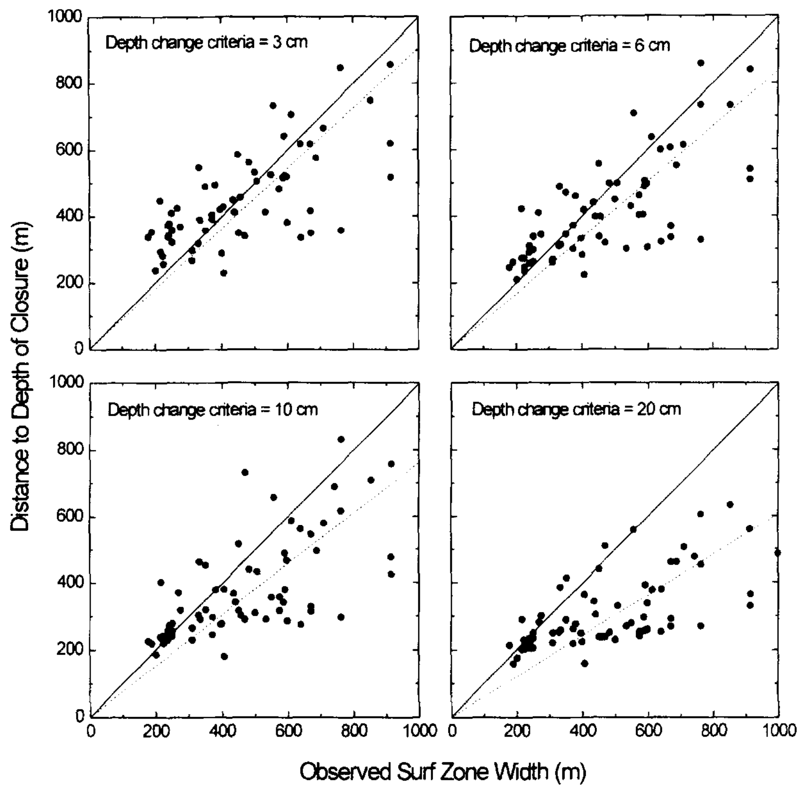

Fig. 7. Comparison of average distance from the shoreline to the erosional event-dependent depth of closure and the associated visually observed surf zone width for different criteria. Dashed line is the regression fit.

results (Figs. 8b and 9). For the rest of this paper wave conditions will be defined by 12-h statistics and the reference level will be MLW, unless otherwise stated.

The difference between d_l and the observed D_c (d_E) is of interest. Taking a best-fit approach (rather than following Eq. (3)), the following result was obtained (>95% confidence):

$$d_E = 0.69\, d_l \tag{4}$$

For E-D D_c, about 69% of the predicted change occurs on average in the Duck data set. However, there is some scatter around a straight line fit and Eq. (4) only explains about 50% of the variance.

To examine possible controls of the observed scatter, seven cases were selected where predictions using Eq. (2) are similar (7.5 to 8.0 m), but the observed values showed a range from 3.5 to 7.2 m (Fig. 9). The possible role of storm duration and wave energy were investigated, but these had poor discriminating ability (Fig. 10b). A more important factor appears to be pre-storm morphology. The shallowest D_c occurred when the pre-storm profile had a single inner bar (about 100 m offshore), while the deepest D_c occurred when the pre-storm profile had a single outer bar (about 300 m offshore) (Fig. 10a). Intermediate D_c were associated with a two-bar configuration. For the deepest observed cases, the D_c is produced by offshore movement of the outer bar. This analysis suggests that pre-storm morphology exerts some control on D_c, even in the outer littoral zone (Fig. 1b). As the profile at Duck changes from a one- to two-bar form and back again over periods of one to several years (Birkemeier, 1984; Lippmann et al., 1993), the likely erosional E-D D_c for a given wave condition is also varying. This interesting result requires further investigation.

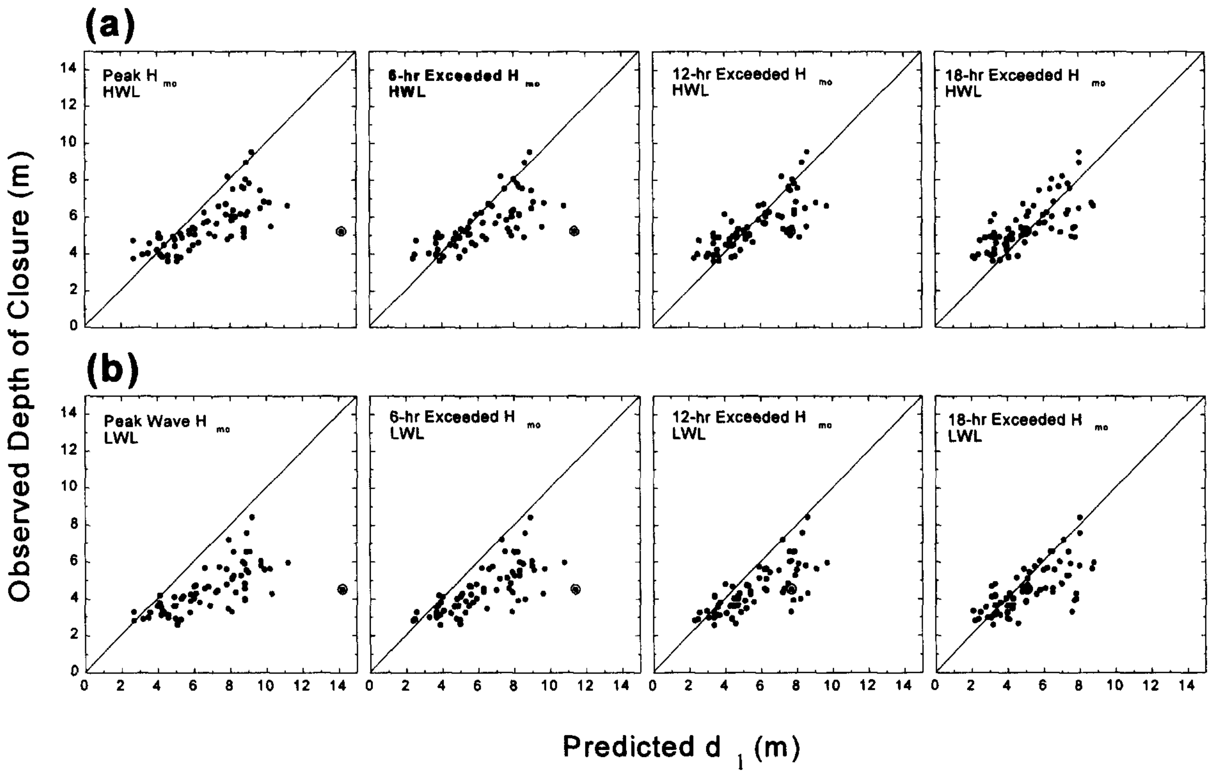

Fig. 8. Observed versus predicted erosional event-dependent depth of closure (using a 6-cm criterion) for four wave exceedance cases and two reference depths: (a) actual high water (*HWL*), and (b) actual low water (*LWL*). circled value indicates Hurricane Gloria.

Table 2
The deepest and non-closing erosional event-dependent depth of closure (D_c) cases using a 6-cm criterion, including a description of profile behavior

Date peak waves	Observed D_c (m, MLW)		d_l (m)		Profile behavior
	line 62	line 188	$H_{mo,peak}$	$H_{mo,12\ hr}$	
870309 [a]	* (>7.3)	* (>7.2)	9.5	7.9	Seaward profile translation, plus offshore bar migration
870425	6.7	7.2	7.9	7.2	
890224	7.4	8.2	9.2	8.6	
890307	7.5	6.8	8.9	8.3	
891224 [a]	* (>7.7)	7.3	11.1	9.1	
911031 [a]	* (>7.9)	* (>8.2)	12.8	11.1	Upper shoreface erosion

Non-closing cases are indicated as '*', together with the maximum survey depth.
[a] Case not used in Fig. 9.

Three events produced a D_c close to the survey range (>8 m depth), while three cases did not close (Table 2). These data are all consistent with Eqs. (2) and (3) as d_l is predicted to be deeper than the survey range, taking into account the offset for MLW. The March/April 1987, February/March 1989 and the December 1989 changes all coincided with energetic pairs of storms separated by 2 to 3 weeks and episodic net gains in beach volume combined with seaward translation of the profile

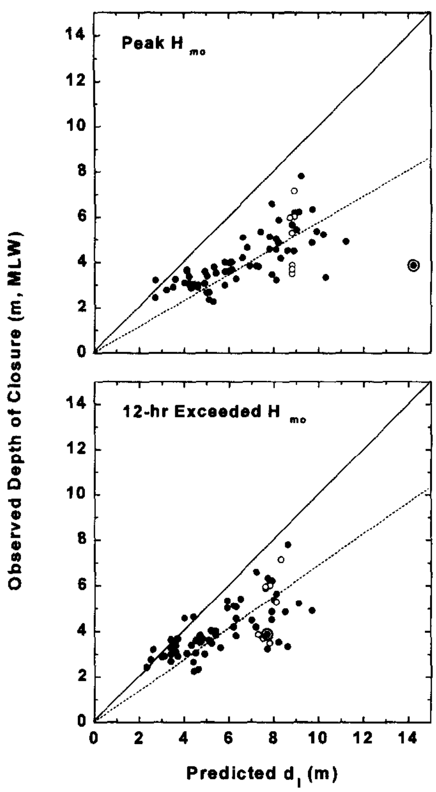

Fig. 9. Observed versus predicted erosional event-dependent depth of closure for (a) peak significant wave height and (b) 12-h exceeded significant wave height and a reference depth of mean low water (*MLW*). The circled value indicates Hurricane Gloria. The circles indicate the seven storms selected for further study (see Fig. 10). The dashed line shows the regression fit.

(Lee et al., 1995, 1998). The 'Halloween Storm' of October 1991, had uncharacteristically long wave periods (19.7 s) and is the most energetic wave event within the data set, producing a d_l of 11.1 m. It had an uncharacteristic behavior as it produced an average depth *increase* on the upper shoreface (0.13 m at 950 m offshore, or about 7.9 m below MLW). This was not related to offshore bar migration and suggests cross-shore loss of sand beyond the surveyed profile. In conclusion, the deepest closures and the non-closing cases are all related to the most energetic wave events, as well as profile translation (i.e., net volumetric gains or losses).

4.2.2. Accretional cases

The field characteristics of D_c under accretional conditions have not been examined prior to this paper. Hallermeier (1977) only associated the concept of D_c and d_l with erosive events — reflecting theoretical arguments behind the derivation of d_l. However, examining D_c under accretive conditions provides insight into the process of profile accretion and its similarities, or otherwise, with profile erosion.

Accretional D_c are more difficult to define than erosional D_c because of the geometric properties of the consecutive profiles. The profiles generally intersect at a more acute angle than erosional cases (Fig. 5). This makes the derived value of D_c more sensitive to the criteria utilized. Using a 6-cm criterion, the accretional D_c ranged from 2.1 to 5.2 m below MLW. In general, they were deeper than erosional D_c for equal wave heights, and the D_c usually occurred seaward of the surf zone (Fig. 11a) indicating that they were induced by shoaling rather than near-breaking waves. This behavior agrees with Hallermeier's (1981) shoal zone concept. Using 12-h exceeded waves, Eq. (2) tends to underpredict accretional D_c (Fig. 11b).

Because accretion is a more gradual process than erosion, the fixed change criteria used to define accretional closure will take time to occur, and the time interval necessary for 6-cm vertical change is expected to increase with depth. Therefore, accretional D_c are time-interval-dependent, even at time scales from a day upwards (cf. Hodder, 1995). To illustrate this point, Fig. 12 shows the progressive offshore movement of an accretional D_c on profile line 62 over a 6-month period in 1982 characterized by relatively calm wave conditions and the onshore movement and decline of the outer bar. As the time window expanded from 7 days to 6 months, so D_c increased from 3.3 m to 5.6 m below MLW: offshore movement was most rapid in the first 9 weeks. At the same time, sand was moving onshore as the outer bar declined, contributing to a positive sediment balance in the inner littoral zone (Lee et al., 1998). Therefore, under appropriate wave conditions and over long time periods, accretional closures deeper than those shown in Figs. 11 and 12 might be expected. The near-continuous nature of accretion must be considered when interpreting D_c under accretional and T-I conditions (see below).

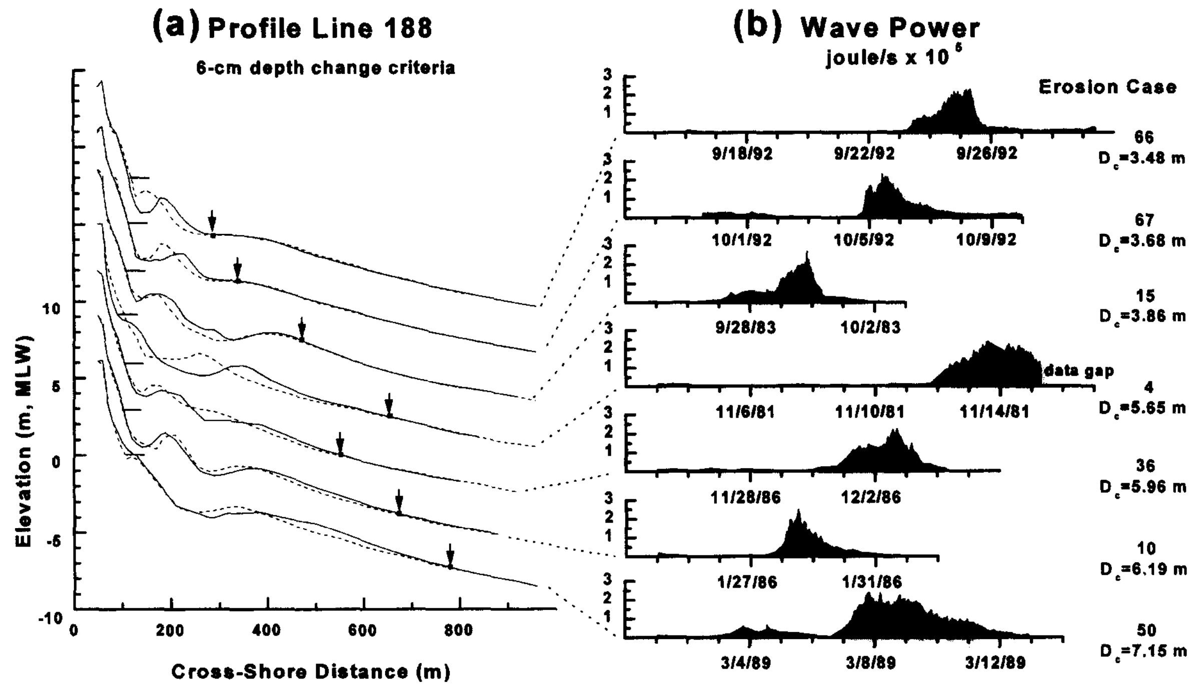

Fig. 10. Wave power (J/s) and profile changes for the seven storms indicated in Fig. 9. Case numbers are from Table 1. Cases are plotted in order of increasing observed depth of closure.

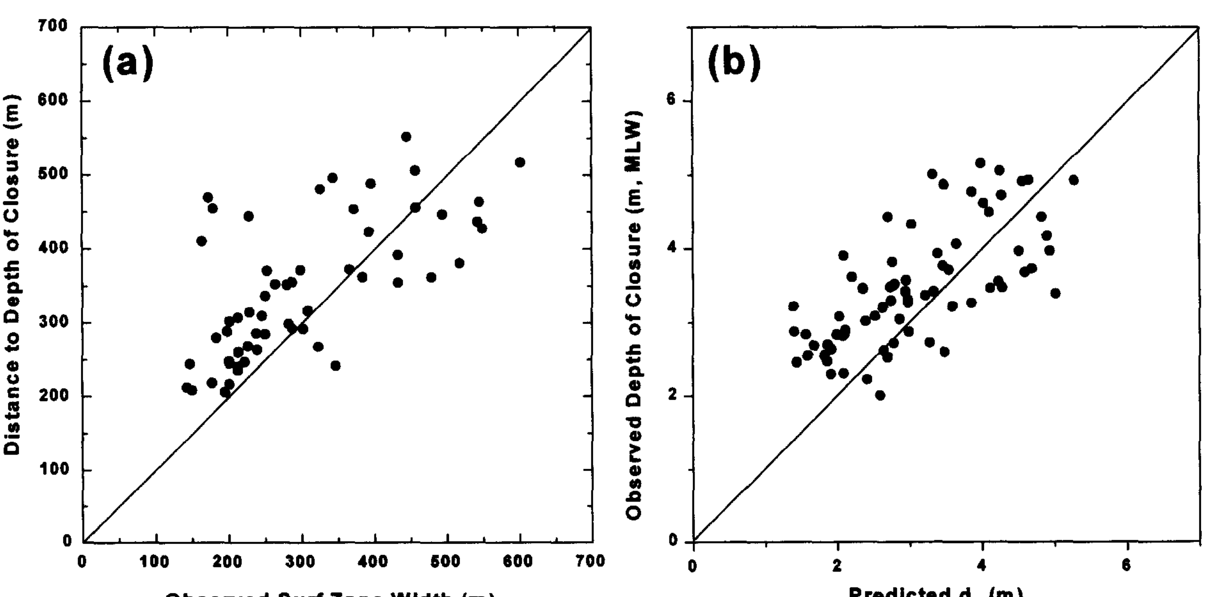

Fig. 11. (a) Comparison of average distance from the shoreline to the depth of closure (6-cm criterion) and the maximum visually observed surf zone width under accretionary conditions. (b) Observed versus predicted accretional closures using a 12-h exceeded wave height.

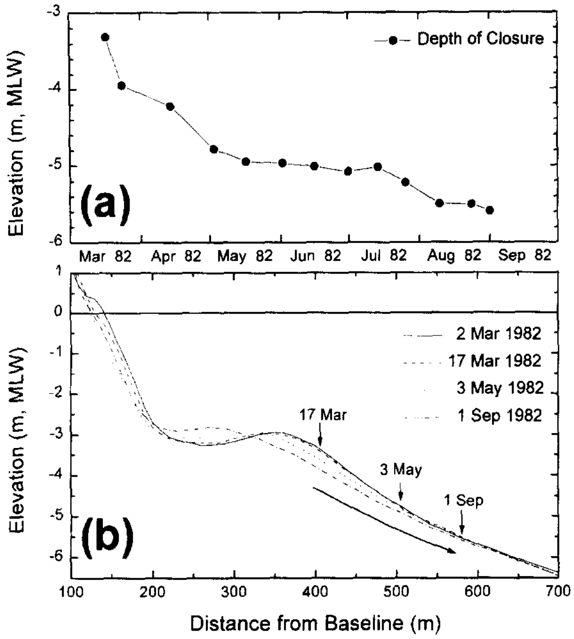

Fig. 12. Profile line 62. (a) Evolution of depth of closure due to accretional processes with an expanding time window up to 6 months (2 March 1982 to 1 September 1982) due to onshore migration of the outer bar. (b) Selected profiles in the period. Arrows indicate closure.

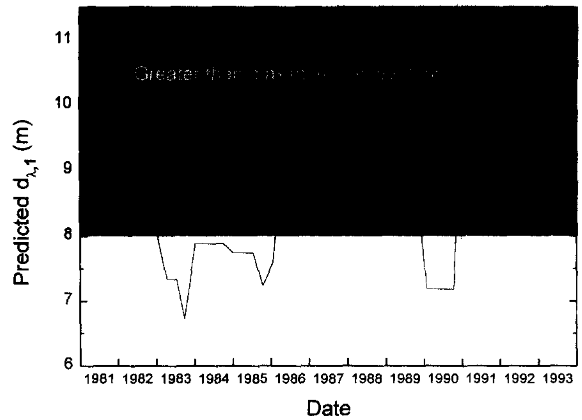

Fig. 13. Predicted time-interval closures — $d_{l,1}$ versus time showing those periods when closure would be expected to be observed.

5. Time-interval depth of closure

In the preceding section, Hallermeier's approach was validated on an event basis for erosional conditions. However, accretional D_c was shown to be time-scale-dependent. These observations have important implications for the interpretation and prediction of D_c over longer time intervals. Although Hallermeier (1981) defined d_l in terms of an annual time scale, it is simply determined by the highest wave event in any time period, as Eq. (2) considers no other effects. However, over time *real* profiles represent an integrated response to varying wave conditions, including the balance of erosional and accretional processes and any long-term trends (net erosion or accretion). A fundamental hypothesis is that time-interval (T-I) D_c will generally increase with time scale, as suggested by Eq. (2).

In this section, we examine D_c over varying time intervals as would be measured by infrequent cross-shore surveys, including: (1) the characteristics of T-I D_c; and (2) the validity of Eq. (2) in a time-interval context. These goals are complicated by the fact that over the 12 years of record, in addition to erosional and recovery processes, the profiles at Duck have experienced several episodes of significant net accretion with a total vertical change of over 40 cm at the seaward limit of measurements (e.g., Lee et al., 1995, 1998). Therefore, closure at a 6-cm criterion is not resolved whenever the time period being considered included either deep erosional or accretional events (>8 m depths). Gaps in the data are predicted by Eq. (2) (e.g., Fig. 13), and as with erosional events, the non-closing T-I D_c cases do not disprove closure — closure may occur seaward of 8 m depths. The competing hypotheses of no closure versus deep closure can be investigated by comparing the distribution of $d_{l,t}$ and observed T-I D_c, as discussed below. However, because these missing cases truncate the observations, we can only begin to examine the properties of T-I D_c.

5.1. Method

When considering the best methodology, it is important to note that D_c over annual or longer periods usually occurs near the seaward limit of the profiles where survey errors are of most concern and where the changes are smallest and often closer to the resolution of the survey data. Beneath

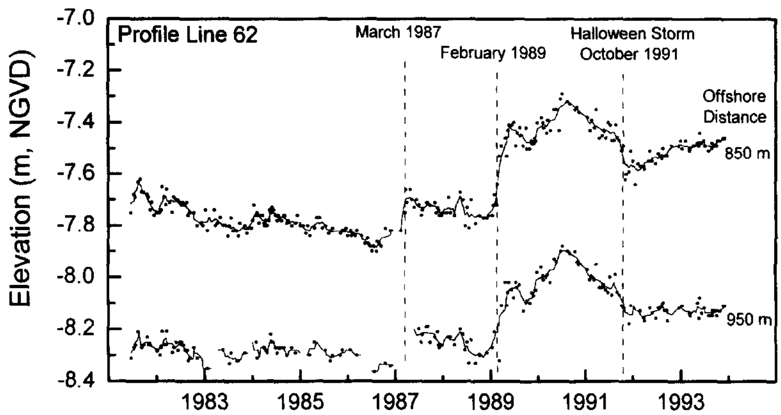

Fig. 14. Actual and smoothed time series of depth data (5-point running mean) from profile line 62 at 850 and 950 m seaward of the baseline. Dashed lines indicate the March 1987, February 1989 and Halloween (October 1991) storms.

5 m depth, it is known that apart from abrupt increases or decreases in sediment volume under certain combinations of storm conditions and bar configuration, changes are reasonably slow and steady, and there is little evidence of seasonal variability (Lee et al., 1995, 1998). Therefore, smoothing the time series of elevation for specified offshore distances with a 5-point running mean reduces survey errors (noise) without obscuring small, but real profile changes. Such smoothed data were used for all analysis (e.g., Fig. 14).

The method employed is similar to the E-D D_c, and compares pairs of smoothed profiles, cross-checked with unsmoothed data as appropriate. However, only two lines (62, 188) were considered, and a slightly longer data set (July 1981 to October 1993) was used. The annual D_c was measured using two surveys separated by about 12 months. Starting at the seaward limit, the profiles were compared until a consistent change above 6 cm was identified, and hence closure was defined. Isolated changes above 6 cm, but below 10 cm at the seaward limits of the profiles occasionally occurred, but appeared to be due to survey errors rather than real change. Therefore, these points were generally ignored. All closure measurements are adjusted to MLW. Annual D_c was determined from July 1981 to October 1993 with a 3-month sliding window (July 1981 to July 1982, October 1981 to October 1982, etc.), providing 46 observations of annual D_c. Two-year, 4-year and 8-year D_c using the same criterion were similarly determined for the same period providing 42, 34 and 18 observations, respectively. Unlike the E-D cases, no alongshore averaging was used. This maximizes data availability, but tends to increase the scatter of the data.

To obtain the wave variables, 12-h exceeded wave height and associated wave period were determined for each time interval. Note that the wave height and period used here are the same as for the greatest E-D D_c for each time interval.

5.2. Results

The geometric properties of consecutive T-I profiles are quite variable, sometimes being similar to erosional and sometimes being similar to accretional E-D cases. Further many cases do not close within the surveyed profile. Table 3 shows the 6-cm criterion T-I D_c results. About 65% of the cases close over 1 year, about 60% close over 2 years, about 44% close over 4 years and only 3% (1 case) close over 8 years (Fig. 15). The non-closing cases nearly all coincide with periods embracing one or more of the major events listed in Table 2. The cumulative effect of the groups of storms in February/March 1987 and 1989 were long-lived as shown in the time series of depth change (Fig. 14). The storms of 9 March 1987 and the 24 February 1989 produced the biggest changes with a mean decrease in depth of 0.12 and 0.19 m at 950 m

Table 3
Observed and predicted (using 12-h exceeded wave height) time-interval depth of closure for 1-, 2-, 4- and 8-year moving windows

Starting year		1-year			2-year			4-year			8-year		
		line 62	line 188	$d_{l,1}$	line 62	line 188	$d_{l,2}$	line 62	line 188	$d_{l,4}$	line 62	line 188	$d_{l,8}$
1981	Jul	6.8	7.4	8.1	7.5	7.3	9.0	7.5	7.2	9.0	*	*	_9.1_
	Oct	6.8	7.2	8.1	7.6	7.2	9.0	7.6	7.2	9.0	*	*	_9.1_
1982	Jan	7.2	7.3	9.0	6.6	5.8	9.0	7.5	7.1	9.0	*	*	_9.1_
	Apr	7.7	6.1	9.0	7.6	6.1	9.0	7.8	7.1	9.0	*	*	_9.1_
	Jul	7.6	6.0	9.0	3.9	6.2	9.0	*	7.1	9.0	*	*	_9.1_
	Oct	5.9	6.0	9.0	4.0	7.8	9.0	7.5	*	9.0	*	*	_9.1_
1983	Jan	5.2	7.8	8.0	6.1	7.8	8.0	7.0	6.7	8.0	*	*	_9.1_
	Apr	6.1	7.0	7.3	6.4	6.1	7.9	*	7.3	9.1	*	*	_9.1_
	Jul	6.0	7.3	7.3	6.2	6.2	7.9	8.0	7.3	9.1	*	*	_9.1_
	Oct	6.1	5.9	6.7	6.4	6.5	7.9	*	7.4	9.1	*	*	_9.1_
1984	Jan	6.2	6.3	7.9	7.2	7.0	7.9	5.9	7.4	9.1	*	_8.0_	_11.1_
	Apr	5.8	6.4	7.9	7.3	*	7.9	_5.7_	_6.7_	_9.1_	*	*	_11.1_
	Jul	5.9	6.9	7.9	*	*	7.9	_5.9_	_6.6_	_9.1_	*	*	_11.1_
	Oct	6.6	8.1	7.9	7.4	*	7.9	_5.2_	_6.8_	_9.1_	*	*	_11.1_
1985	Jan	5.3	*	7.7	6.8	7.4	7.7	_4.8_	*	_9.1_	*	*	_11.1_
	Apr	7.3	*	7.7	_7.6_	_5.9_	_9.1_	_8.0_	*	_9.1_	*	*	_11.1_
	Jul	7.6	*	7.7	*	_7.3_	_9.1_	*	*	_9.1_	*	*	_11.1_
	Oct	7.0	6.8	7.2	*	_7.6_	_9.1_	*	*	_9.1_	*	*	_11.1_
1986	Jan	5.2	5.6	7.6	_7.8_	_7.7_	_9.1_	*	*	_9.1_			
	Apr	*	_7.7_	_9.1_	_7.8_	_7.6_	_9.1_	*	*	_9.1_			
	Jul	*	*	_9.1_	*	_8.0_	_9.1_	*	*	_9.1_			
	Oct	*	*	_9.1_	_7.5_	_7.7_	_9.1_	*	*	_9.1_			
1987	Jan	*	*	_9.1_	*	_7.4_	_9.1_	*	*	_9.1_			
	Apr	5.9	6.6	8.6	*	*	_8.6_	*	*	_9.1_			
	Jul	5.9	5.6	8.6	*	*	_8.6_	*	*	_9.1_			
	Oct	5.9	5.5	8.6	*	*	_8.6_	*	*	_9.1_			
1988	Jan	5.6	5.8	8.6	*	*	_9.1_	*	*	_11.1_			
	Apr	*	*	8.6	*	*	_9.1_	_7.9_	*	_11.1_			
	Jul	*	*	8.6	*	*	_9.1_	*	*	_11.1_			
	Oct	*	*	8.6	*	*	_9.1_	*	*	_11.1_			
1989	Jan	*	*	9.1	*	*	_9.1_	*	*	_11.1_			
	Apr	*	*	9.1	7.3	_5.8_	_9.1_	_6.5_	_7.2_	_11.1_			
	Jul	*	*	9.1	_5.0_	_6.9_	_9.1_	*	_8.2_	_11.1_			
	Oct	*	*	9.1	_4.9_	_5.9_	_9.1_	_6.7_	_7.3_	_11.1_			
1990	Jan	5.0	6.3	7.2	*	*	_11.1_						
	Apr	5.6	7.2	7.2	*	*	_11.1_						
	Jul	*	*	7.2	*	*	_11.1_						
	Oct	*	7.5	7.2	*	_7.7_	_11.1_						
1991	Jan	*	*	_11.1_	*	_7.5_	_11.1_						
	Apr	*	*	_11.1_	*	_7.2_	_11.1_						
	Jul	*	_7.4_	_11.1_	*	_7.2_	_11.1_						
	Oct	_5.9_	_7.2_	_11.1_	_6.3_	_6.8_	_11.1_						
1992	Jan	7.5	5.5	9.1									
	Apr	7.1	4.8	9.1									
	Jul	6.5	4.8	9.1									
	Oct	5.9	3.9	9.1									

Depths are in m relative to MLW; '*' indicates closure exceeded the largest measured depth (about 8 m). Individual non-closing cases which may violate Eq. (3) are shown in bold. Time groups which are influenced by the storms in Table 2 are in italics.

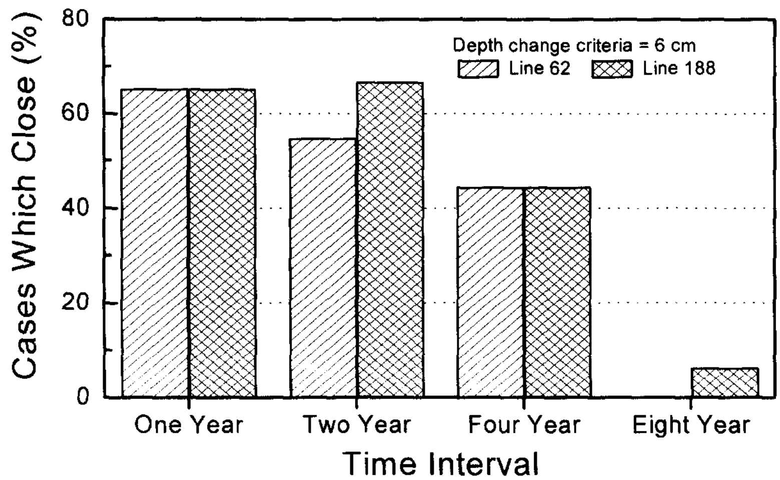

Fig. 15. Percentage of time-interval closures (6-cm criterion) at less than 8 m depth for profile lines 62 and 188, as a function of time interval.

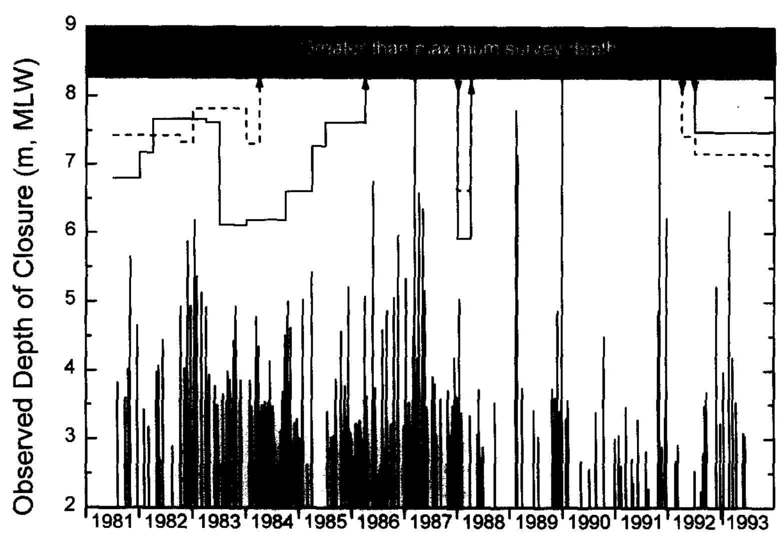

Fig. 16. Time series of observed annual depth of closure on profile lines 62 and 188 (shown as continuous lines), together with the observed time-interval erosional, accretional and undecided event-dependent depth of closures (shown as undistinguished bars). The observed annual depth of closure represents the maximum value in any time window.

offshore, respectively, corresponding to depths exceeding 7.8 m below MLW. Therefore, there is some relationship between E-D D_c and T-I D_c.

Fig. 16 shows a time series of observed annual T-I D_c versus the observed erosional, accretional and undecided E-D D_c discussed in the previous section. This allows further assessment of the relative importance of individual 'events' versus the cumulative effect of events, including accretional processes. While the largest events are associated with the non-closing cases (Tables 2 and 3), it is apparent that the annual D_c is nearly always larger than E-D D_c when both are resolved. In addition to erosional events, there are several periods of up to 4 years duration when changes below 5 m depth were dominated by the slow, steady onshore movement of sand (Lee et al., 1998) and the annual D_c continued to evolve (e.g.,

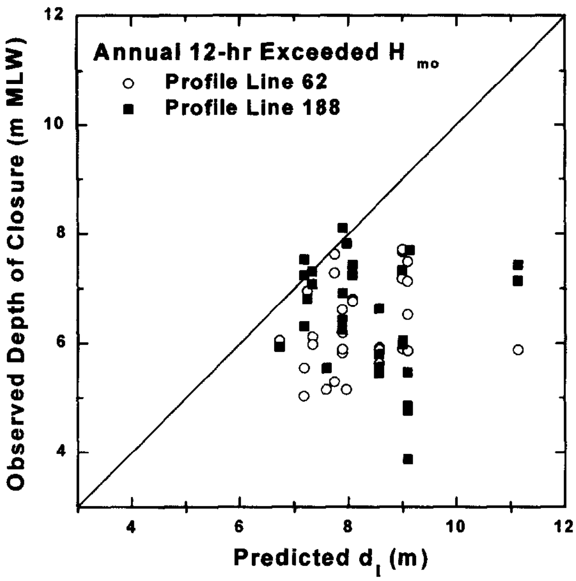

Fig. 17. Predicted versus observed annual depth of closure. Note that observations are truncated at about 8 m below MLW due to measurement limitations.

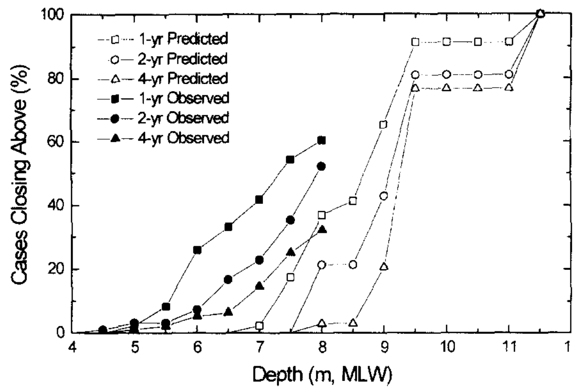

Fig. 18. Frequency distribution of predicted and observed time-interval cases for 1-year, 2-year and 4-year intervals.

from January 1985 to January 1986 annual D_c on both profile lines increased by more than 1 m (Fig. 16). This shows that annual D_c (and by implication any T-I D_c) represents an integration of accretional and erosional processes rather than being simply the signature of the largest erosional event over the time period.

The observed annual D_c versus $d_{l,1}$ are shown in Fig. 17. The predictions are generally larger than the observations, obeying Eq. (3). Ten non-closing cases (six annual cases and four 2-year cases) appear to violate Eq. (3) (shown in bold in Table 3). The relevant observations are missing so the magnitude of underprediction is unknown and they are not shown in Fig. 17. These ten non-closing cases are all associated with periods dominated by accretion, as discussed above. Therefore, all the non-closing cases are either associated with major wave events ($d_l > 8$ m), or accretional conditions.

An alternative way of looking at the data, which better represents the missing observations in the data set, is to consider the vertical distribution of observed D_c and $d_{l,t}$ for different time intervals (Fig. 18). The observed vertical distributions move to greater depths as time interval increases. Therefore, T-I D_c shows the behavior predicted by Eq. (2) — increasing D_c with increasing time. Importantly, the observed 1-year, 2-year and 4-year frequency distributions are all 1 to 2 m shallower than the appropriate frequency distribution derived from Eq. (2), so on average they are obeying Eq. (3). Further, the observed distributions are consistent with the hypothesis that the missing observations are closures >8 m depth. Simple linear extrapolation of the distribution of the annual observations to 100% closure suggests a maximum annual D_c at Duck of about 10 m below MLW.

In conclusion, the data provide some support for the validity of Eq. (2) as a limit for T-I cases, at least up to a time interval of 4 years. However, in periods when accretion dominates, this may not be the case as indicated in the earlier analysis of accretional closures.

6. Discussion

This study has utilized a unique high-resolution data set from a microtidal, wave-dominated coastal site to examine the characteristics and prediction of closure. Most importantly, the results show that closure exists at Duck for a range of conditions from short-term erosion and accretion to longer intervals such as 1 or 2 years. The results also raise important questions.

6.1. Erosional event-dependent depth of closure and d_l

Eq. (2) provides a limit for E-D erosional cases that close within the region surveyed, and correctly predicts the three cases which do not close. Some of the scatter shown by the observations below the predicted limit can be related to the pre-storm profile morphology. Therefore, in principle we could predict the maximum possible D_c for any individual storm. The appropriate input to Eq. (2) requires some consideration. Using peak significant wave height and MLW provides conservative estimates of erosional E-D D_c, but with significant potential for overprediction. Substituting 12-h exceeded wave height reduces this overprediction, but with some limited violation of Eq. (3). Knowing the limit also allows selection of alternative approaches such as an empirical best fit (e.g., Birkemeier, 1985).

6.2. Accretional depth of closure

Accretional D_c are always time-scale-dependent resulting from slow steady onshore transport which can take significant periods to cause a 6-cm vertical change. Given extended periods dominated by accretion, the analysis of the Duck data by Lee et al. (1995, 1998) suggests that onshore transport would produce a deep closure. At the same time, onshore transport and accretion would occur in the inner littoral zone. Importantly, Eq. (2) would significantly underpredict closure for such conditions. This has important implications for time-interval D_c below and more generally, implies that Eq. (2) might not work well for beaches which are swell-dominated.

6.3. Time-interval depth of closure, $d_{l,t}$ and time scale

Using the same input parameters as for E-D cases, Eq. (2) appears to provide a reasonable limit to the available observations up to a time interval of at least 4 years, with least certainty in periods when accretion dominates. This raises a fundamental question as to how Eq. (2) (an event-dependent approach) provides a limit to time-interval closure (the sum of a number of erosional and accretional events). One possible interpretation is a near-balance of erosional and accretional processes at Duck (while the profile at Duck has accreted, over the period of surveys the gross change[1] in the outer littoral zone is more than 15 times the net change). This suggests that sites which show strong accretional or erosional trends, may show different T-I D_c characteristics than Duck. The non-closing cases are also largely consistent with Eq. (2) in that they are predicted to be deeper than the surveys. Further investigation of T-I D_c is needed, including looking at other time windows.

Four groups of storms had profound effects on the profile evolution at Duck: February/March 1983, 1997 and 1989, respectively, and December 1989 (Lee et al., 1998). These storm groups comprise at least two storms with $H_{mo} > 4$ m within 2 to 6 weeks. The resulting abrupt profile translations at Duck, most particularly the largest profile translation in February/March 1989, all had a significant long-lasting influence on the Duck profiles. The last three storm groups were associated with closures which were not measured (Table 2). This shows that storm sequence profoundly influences the evolution of T-I D_c (cf. Lee et al., 1998) and there is a need to continue and expand morphological and process measurements seaward of 8 m depths at Duck. While profile changes seaward of 8 m depth are not measured, there is a 40-cm net vertical change over 13 years at 8 m below NGVD, which suggests significant changes occurred below 8 m depth.

In addition to the balance of erosional and accretional processes, as time scale increases, so onshore/offshore sediment exchange with the shoreface is expected to become more important in terms of the cross-shore beach–nearshore sediment budget (Wright et al., 1985, 1991; Stive and DeVriend, 1995). Collectively, this suggests that D_c will ultimately be governed by factors other than the biggest wave event and Eq. (2) will cease to be valid at some longer time scale. Therefore, while we might use Eq. (2) to predict closure for

[1]Gross change is a measure of cross-shore sediment rearrangement.

a 100-year erosional event, we would not expect it to work over a 100-year period.

6.4. Application to other sites and future work

The results presented here demonstrate the utility of the depth of closure concept and Eq. (2) at Duck. This result is expected to have general application at other microtidal, wave-dominated sandy beaches which occur widely around the world's coasts. However, several factors should be considered in application and future research.

(1) Non-wave-induced currents. As Pilkey et al. (1993) noted, Eq. (2) only considers sediment transport by wave-induced currents. Eq. (2) would be expected to underpredict D_c in areas with strong mean currents, such as in the vicinity of inlets. In mesotidal and macrotidal settings, closure is expected to have different characteristics.

(2) Profile characteristics and sediment budgets. The profile at Duck is relatively stable with a slight advancing trend. As already discussed, evolving profiles may influence D_c. Variability in the relative importance of erosional and accretional beach processes must also be considered.

(3) Geological factors such as shoreface composition (cf. Riggs et al., 1995) or shelf width. For instance, the wide shelf off Duck (ca. 100 km) may encourage sand retention at the coast as compared to a more narrow or steeper shelf situation. However, such geological controls are probably most important at longer time scales than the Duck data set considered here.

Exploring these questions requires continued research. Extension of the Duck surveys to greater depths would provide better data for larger events. This needs to be augmented by long-term studies at a range of other types of coastal location, including long time scales (> 10 years). Predictions using Eq. (2) should be utilized in the design of such studies, conditioned by the above discussion of its limitations, particularly as time scale increases.

Resolving medium- to long-term changes using profile change alone may be difficult. As the cross-shore zone of interest expands to include the entire shoreface, small vertical changes over large cross-shore lengths represent large fluxes of sediment, but they may be below the vertical profile resolution. The cross-shore distribution of sediment size also needs to be considered as this can be used to define likely limits of cross-shore exchange and hence define useful cross-shore boundaries (Hallermeier, 1981). Therefore, it seems likely that geometric studies of profile change such as this one will need to be combined with other techniques to fully understand sediment movement in these regions, and its influence on the coastal sediment budget (e.g., Wright et al., 1991, 1994).

7. Conclusions

Using a 12-year high-precision data set, depth of closure has been shown to exist in both event-dependent and time-interval cases at Duck, up to the limits of the data. An important result is that nothing in the data set invalidates using Eq. (2) to predict a *limit* to depth of closure for both erosional event-dependent cases and time-interval cases: even the cases where no closure was observed are correctly identified. The scatter of the observed erosional event-dependent depth of closures landward of the predicted limit is partly controlled by pre-storm morphology, even on the deeper part of the profile (4 m to 8 m depths). Time-interval depth of closure typically increases with time scale. This has important implications for the study of beach–nearshore profiles and coastal sediment budgets and all estimates of depth of closure should be associated with an explicit time scale. Profile translation (net volumetric gain or loss) also appears important, but cannot be fully examined with these data. Most non-closing cases are associated with profile translation. The major caution concerning Eq. (2) is that time-integrated closure in accretion-dominated situations may be underpredicted, but this is accompanied by a positive sediment budget in the beach–inshore region. This limitation may be more important on swell-dominated coasts.

Therefore, within the limits of the data set, the approach of Hallermeier (1978, 1981) is found to provide robust estimates of depth of closure, particularly for individual erosional events. However, the physical limits of the surveys limit our ability to examine fully the evolution of depth of closure over the 12 years of record. Analysis of long-term, high-precision beach–nearshore observations from a range of settings would be useful. Suitable observational programs are already in progress in many parts of the world. Maximum benefits of these efforts will be derived if these observations embrace the likely depth of closure over one or more decades. Working estimates of the likely closure for survey design purposes can be derived from Eq. (2).

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