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An Inter-Site Comparison of Net Offshore Bar Migration Characteristics and Environmental Conditions

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ABSTRACT

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In this paper we quantitatively identify behavioural characteristics of net offshore bar migration (NOM) and present the results of an inter-site comparison. The net offshore migration of sandbars on multi-bar coasts has been reported at sites on the Dutch coast, the eastern USA seaboard, and the New Zealand west coast. The NOM phenomenon is repetitive, with the life-cycle of each bar consisting of three stages: bar generation near the shore-line (stage 1), systematic offshore migration of the bar across the surf zone (stage 2), and finally bar disappearance in the outer surf zone (stage 3). The NOM sites are on multi-bar coasts with relatively short period waves and a narrow range of storm strength wind and wave conditions. They encompass a wide range of geometrical dimensions, physical boundary conditions and wind and wave approach angles relative to the shoreline. Parameters measuring migration width, duration, return period and rate of NOM are used to identify bar migrational characteristics for each stage. There is wide variation in the parameter values, both between the zones representing the NOM stages at each site, and between corresponding zones at different sites. NOM duration for stage 2 is identified as the system index parameter. An inter-site correlation analysis between NOM duration and key environmental parameters shows NOM activity to increase, *i.e.* NOM duration decreases, with increasing nearshore slope and decreasing wave height. NOM duration also decreases when the predominant wind direction tends towards a maximum of 40 to 45 degrees from the coastline. It is suggested that bar size and longshore currents influence NOM and possible mechanisms are discussed.

ADDITIONAL INDEX WORDS: *Multi-bar coast, surf zone, geomorphological scale, coastal orientation, nearshore slope, bar volume, longshore current.*

INTRODUCTION

Conceptual beach-change models have generally been based upon the morphological configurations and sequences which develop in response to varying inputs of wave energy. The most comprehensive of these models are three-dimensional, that is the models incorporate longshore variation in cross-shore (two-dimensional) profiles. Such three-dimensional modelling has focused on the most landward bar and on coasts with low tidal ranges, e.g. Davis and Fox (1972), Sonu (1973), Davis and Fox (1975), Fox and Davis (1976), Owens (1977), Chappell and Eliot (1979), Short (1979), Wright *et al.* (1979), Sasaki (1983), Nummedal *et al.* (1984), Wright and Short (1984), Shaw (1985), Sunamura (1988), and Lippmann and Holman (1990). Some beach-change modelling has been carried out on coasts with higher tidal ranges, *e.g.* King (1972), Jago and Hardisty (1984), and Masselink and Short (1993). While research into morphological models for the whole surf zone on multi-bar coasts has been less common, useful contributions have been made by authors such as Hom-ma and Sonu (1962), Goldsmith *et al.* (1982), Bowman and Goldsmith (1983), Aagaard (1990), Short (1992), and Short and Aagaard (1993).

Progress in developing conceptual beach-change models for multi-bar coasts has been thwarted by difficulties in collecting comprehensive morphological and process data. The difficulties involved in surf zone data collection were described by Holman and Sallenger (1986) Data-bases for the typically extensive surf zones of multi-bar coasts usually consist of either aerial photographs or relatively small areas of bathymetric map. In each case temporal limitations have occurred either because of low sampling rates or short project time-spans. Nevertheless, researchers have identified certain morphological configurations and sequences. In the few instances where temporally extensive data have been collected new morphological phenomena have been identified; of particular interest is a repeating (cyclic) offshore migration trend underlying sand-bar behaviour, *e.g.* Birkemeier (1984), de Vroeg (1988), Wijnberg (1995).

Researchers from the Netherlands (*e.g.* Ruessink and Kroon, 1994; Wijnberg 1995) have proposed a general three-stage conceptual model to describe the net offshore bar migration (NOM) cycle. The three stages of this 'Dutch model' are: bar generation near the shore-line; bar maturity and sys-

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tematic seaward migration across the inner nearshore; and finally bar dissipation (flattening out) and disappearance in the outer nearshore. Authors describing data sets from Wanganui on the New Zealand west coast (*e.g.* BAILEY and SHAND, 1996) and from Duck on the USA east coast (*e.g.* LIPPMANN *et al.*, 1993) have alluded to such a model. The sites where NOM has been reported are shown in Figure 1. Two examples of bar-crest time-series demonstrating NOM behaviour are given in Figures 2A and 2B. The full set of published bar-crest time-series from the sites in Figure 1 have been reproduced in SHAND and BAILEY (1999). Research at multi-bar sites on the Oregon coast (*e.g.* CHESSER, 1993) and along the Nile Delta (*e.g.* KHAFAGY *et al.*, 1992), suggests such a phenomenon may also occur at those locations. Smaller-scale detail and possible mechanisms underlying NOM behaviour have been identified from data sets which have higher sampling rates (*e.g.* LIPPMANN *et al.*, 1993).

While the Dutch model describes shore-normal change, three-dimensional morphological configurations also appear to influence the NOM cycle. KROON (1994) and RUESSINK and KROON (1994) have discussed the influence of longshore migrating bars. WIJNBERG (1995) and SHAND and BAILEY (1999) described longshore bar alignment switching. KROON (1994), BAILEY and SHAND (1996), and BAILEY and SHAND (1999) described bifurcation and double bar developments in the mid surf zone.

In a recent NOM review SHAND and BAILEY (in press) concluded that whilst the NOM cycle operates at a temporal scale of years and at a spatial scale of 100s to 1000s of metres the system is influenced by components operating at a range of scales. Episodes of offshore bar migration are driven by storm events, *i.e.* smaller-scale. The timing and nature of seaward bar crest migrations are influenced by small to moderate-scale antecedent morphology. The overall NOM characteristics are related to the large-scale physical boundary conditions such as cross-shore slope and coastal orientation.

The NOM review (SHAND and BAILEY, 1999) also found that while similar bar behavioural characteristics appeared to occur at all NOM sites, significant inter-site variation in NOM behaviour was also evident. These findings suggest that the three-stage Dutch model applies to other multi-bar coasts which experience NOM and that an inter-site quantitative analysis may provide further conceptual information on the morphodynamics of NOM systems. The purpose of this paper is firstly to study the larger scale NOM system by undertaking a quantitative assessment of the average cyclic morphological characteristics at each site using the published NOM data, and secondly to carry out an inter-site comparison between these NOM characteristics and the corresponding physical boundary and process conditions. The paper begins with a description of the environmental conditions at each site and the methods used to obtain comparable data.

STUDY SITES

The study sites are described in terms of a range of environmental parameters. These parameters are used in the inter-site analysis and their selection was based on likely associations with NOM characteristics suggested in previous reports. Because of the variation in data available from the different sites a number of specific definitions and assumptions were made to provide comparable statistics.

Cross-shore morphological zones were defined as follows. The foreshore/nearshore boundary is the location on the average (ground survey) profile, about spring low tide elevation, where there is a distinct change in slope. Data limitations required that the landward boundary of the foreshore be located at the mean sea level/average profile intersect. The nearshore/shoreface boundary is typically defined as the cross-shore location corresponding to the seaward limit of significant surf related effects on the seabed, i.e. the 'closeout depth' (HALLERMEIER, 1978; HALLERMEIER, 1981; BIRKEMEIER, 1985). The elevation variability within the profile bundles was found to converge where the standard deviation about the mean profile was approximately 0.2 metres. An illustration of these cross- shore boundaries for Wanganui (site) 2 is shown in Figure 3. Foreshore and nearshore limits for the Wanganui Rivermouth site (Wanganui 1) are based on values from the closest available profile bundle which was for a site located 200 metres to the northwest.

The physical parameters for inter-site comparison are shown in Table 1. These parameters consist of: the average slope ($\tan\beta$) of the mean sea-bed profile between the described boundaries; the nearshore width and the depth from MSL to the mean profile at the nearshore/shoreface boundary; the time-averaged number of bar-crests across each profile; and the median grain size (D50) from locations approximating the MHWL and the mid-nearshore. Representative sediment size values for these two locations are derived by spatial averaging in order to minimise size variation associated with the bar/trough morphology at the time of sampling.

Process characteristics are described using the parameters listed in Table 2. Wave data is based on deep water records. It is assumed that all wave recorders were established at depths sufficient to exclude the effects of sea-bed interactions, *i.e.* refraction/diffraction, friction and shoaling. The average condition is described using the mean daily significant wave height and the severe condition is parametised by the 1% wave height exceedence value. The mean daily significant wave period is used. For sites in The Netherlands, wind data from the centrally located Texel light-ship was used. The use of the Texel data is considered acceptable as WESTLAKE (1995, p35) reported that "It has been established that there exists a strong correlation between wind velocities measured at Ijmuiden (on the mid-Holland coast) and Terschelling. . ." Only storm-strength winds (taken as the upper 10% of wind speeds) are considered in this study as episodes of seaward migration appear to occur under high energy conditions (BIRKEMEIER, 1984; KROON, 1994; LIPPMANN *et al.*, 1993). The wind direction parameter (for the predominant storm winds) is measured relative to the coastline.

Physical boundary parameter values are presented in Table 1, and values for the process-variables are given in Table 2. While all nine sites are characterised by multiple bars and sea-wave environments, inter-site variability occurs for all parameters. Average bar numbers range between 1.4 at North Duck and 3.2 at Zandvoort. Nearshore widths range between 313 metres at South Duck and 1250 metres at Ter-

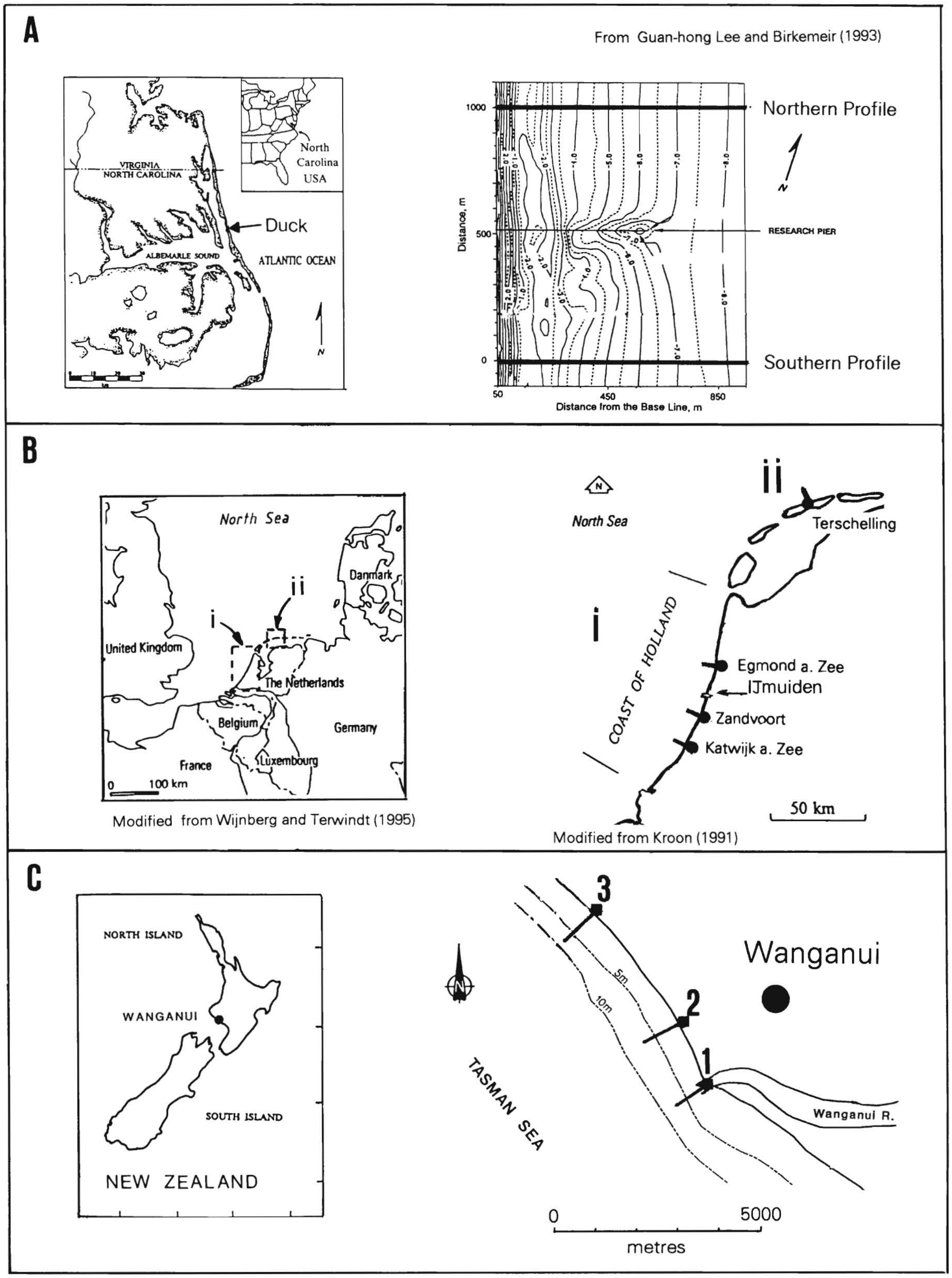

Figure 1. Location maps for the net offshore bar migration sites in North Carolina (Figure 1A), The Netherlands (Figure 1B) and New Zealand (Figure 1C). Survey transits are shown by the bold cross-shore lines.

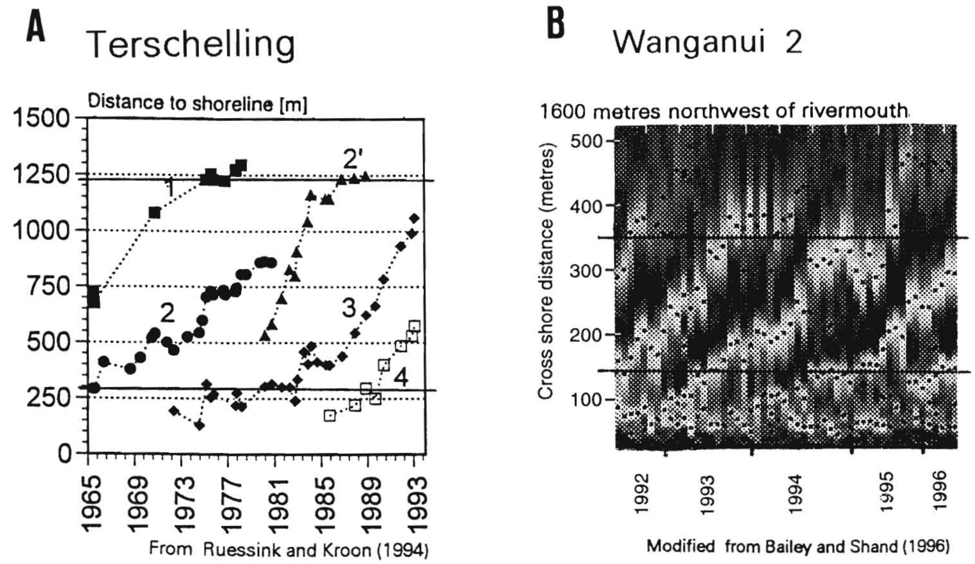

Figure 2. Examples of the net offshore migration of bar-crests for data acquired using different techniques. Figure 2A is from Terschelling in The Netherlands and uses echo-sounded data, Figure 2B is from site 2 on the Wanganui coast of New Zealand and uses rectified oblique photographic time-exposure images. The black dots in the 'time-stack' (Figure 2B) mark the location of relative intensity maxima which are used to locate the bar-crests. The underlying seaward trend in bar-crest movement is evident in both examples. The two bold horizontal lines in each figure divide the cross-shore into zones (see text) which represent the three NOM stages.

schelling, while nearshore depths at the seaward limit range from 4.7 metres (South Duck) up to 8.0 metres (Terschelling). Nearshore slopes vary between .0041 (Terschelling) and .0098 (North Duck) and the steeper foreshore slopes range from .015 (Terschelling) up to .06 (North Duck). Nearshore sediment size (median) ranges between .16 mm (Wanganui 1, Zandvoort) and .21 mm (Egmond) while the foreshore sediments range from .21 mm (Zandvoort) up to .47 mm (Duck). Wave heights (upper 1%) varied between 3.05 metres at Duck and 4.3 metres at Terschelling, while wave periods ranged from 6 seconds for The Netherland sites to 7.8 seconds at Wanganui. Wind speeds (upper 10%) ranged between 12.3 m/s (Duck) and 14.8 m/s (Wanganui). In contrast to these relatively narrow ranges of severe wave height and storm wind speed, storm wind directions were highly variable and ranged from 17 degrees (to the coastline) at Terschelling to 82 degrees at Egmond. The energy values indicate that all sites are located in, or near to, the storm dominated environments identified by DAVIES (1980).

A variety of anthropogenic, geomorphological and geological conditions occur at the different study sites which may influence NOM characteristics; however, these typically larger-scale factors have not been included within the NOM/environmental parameter analysis. Both the Dutch and North Carolina regions may still be affected by submergence associated with glacio-isostasy, hydro-isostasy and possibly geoidal deformation (PELTIER, 1987). Tectonic deformation at Wanganui has resulted in seaward tilt across the coast (PILLANS, 1990). Both Terschelling and the Wanganui sites are situated on, or near, active ebb tide deltas (BURGESS, 1971; RUESSINK, 1998). At Wanganui, Duck and on the mid Holland coast, jetties have been constructed (BURGESS, 1971; MILLER *et al.*, 1983; WIGNBERG, 1995), and beach nourishment has occurred along the Holland coast (WIGNBERG, 1995). At the regional scale coastal stability studies indicate shoreline and/or shoreface erosion exists at all sites; however, at the local scale cross-shore and longshore variations in erosion and accretion often occur (DOLAN and HAYDEN, 1983; FENSTER and DOLAN, 1994; JOHNSTON, 1985; WIJNBERG, 1995).

DATA ACQUISITION METHODS

Details of the data collection systems used in this comparative study are summarised in Table 3. Field surveys for the Dutch data began in 1964 and have continued at yearly intervals using vertical aerial photogrammetry and echo-sounding (RUESSINK and KROON, 1994; WIJNBERG, 1995). Data collection at Duck began in 1981 and has continued at approximately fortnightly intervals using ground contact instruments (GUAN-HONG LEE and BIRKEMEIER, 1993). Wanganui Rivermouth data was collected at monthly intervals between August 1982 and May 1984 using echo-sounding (SHAND, 1990). Data collection on the Wanganui coast began in 1991 at two to four weekly intervals using levelling, echo-sounding, vertical aerial and oblique terrestrial photogrammetry (PATTERSON, 1991; BAILEY and SHAND, 1993; BAILEY and SHAND, 1996; BAILEY and SHAND, 1997). The nearshore photogrammetry at Wanganui (sites 2 and 3) used the breaking wave pattern at mean low water level to signal the seabed morphology. The associated data acquisition methods

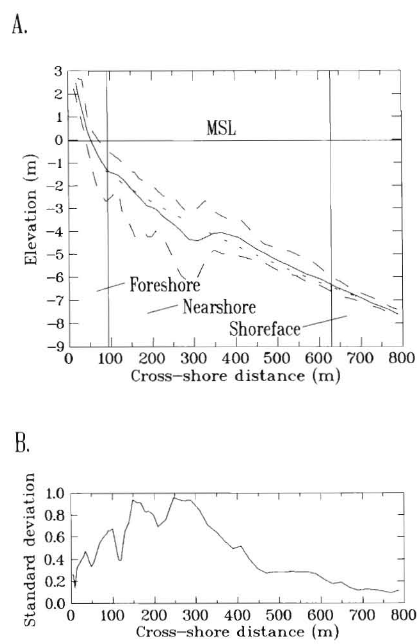

Figure 3. Ground (sea-bed) profile results for Wanganui site 2 (1600 metres from the rivermouth). The continuous curve in Figure 3A shows the mean (time-averaged) seabed elevation, the long dashed lines define the profile envelop and the short dashed line shows a power curve ($Elev = -.102Dist^{.658} + 0.612$) fitted to the mean nearshore profile. The power curve is used to detect time-averaged protuberances which represent modal bar-crest locations (see text). The foreshore and nearshore boundaries defined in the text are illustrated in Figure 3A. Cross-shore elevation variability is shown by the envelop limits in Figure 3A and alternatively by the standard deviations in Figure 3B.

have been described in LIPPMANN and HOLMAN (1989) and BAILEY and SHAND (1996).

In all NOM studies the bar-crests were detected using curve fitting techniques and the crest location was based on cross-shore distance from a benchmark situated landward of the beach-face. Bar-crest detection for the ground profile data, *i.e.* data obtained by survey instruments that sense the sea-bed such as echo-sounders, was based on the maximum positive residual from a smooth fitted curve as advocated by HOLMAN and BOWEN (1982). An example of a bar-crest time-series for echo-sounded data is shown in Figure 2A. Bar-crest detection for the intensity profile data, *i.e.* data obtained by detecting intensity variation associated with foam from broken waves, was based on locating the point on a fitted parabola with zero slope. Crest locations obtained by the two methods are similar (LIPPMANN and HOLMAN, 1989), but, as discussed below, not identical (see Figure 4). This is to be expected as intensity values are depth controlled whereas the ground profile crest locations are shape controlled. An example of a bar-crest time-series (time-stack) for intensity data is shown in Figure 2B.

To compare the NOM behaviour at the different study sites the Wanganui sea-surface intensity-based data was converted to equivalent ground (sea-bed) profile distances. This conversion, discussed in BAILEY and SHAND (1997), utilised intensity and ground survey data collected over the same time period at three cross-shore transits. Each set of data was time-averaged to minimise environmental errors and non-synchronised sampling errors. Protuberances representing modal bar positions on the averaged profiles were located using the bar-crest detection methods described earlier. Figure 3 shows an example of a power curve fitted to the Wanganui 2 mean profile. Figure 4 shows the protuberance detection curves for the intensity and ground survey data for data from the Wanganui 2 transit. The corresponding image and ground survey protuberance locations were differenced and related to depth. The best-fit correction function was:

$$C = -451D^{.133} + 500 \qquad \text{for } D > 1, D < 5$$

where: C = correction (m), and D = depth (m)) of ground profile protuberance below MSL. For protuberances located in shallow water landward corrections to intensity data are required, while for protuberances located in deeper water seaward corrections are required.

Errors associated with data suitable for time-series analysis are also summarised in Table 3. Elevation accuracy varies from ± 0.025 metres for levelling to ± 0.35 metres for echo-sounding. However, for oblique terrestrial photogram-

Table 1. *Morphological and sediment characteristics at the NOM sites.*

Site	Width (m) Nearshore	Depth (m) Nearshore Below MSL	Slope (tanβ) Nearshore	Slope (tanβ) Foreshore	Bar Number	Sediment Foreshore D50 (mm)	Sediment Nearshore D50 (mm)
Egmond	670	6.8	.0079	.020	2.2	0.32	0.21
Zandwoort	705	5.0	.0054		3.2	0.21	0.16
Katwijk	510	4.8	.0064		2.4	0.27	0.17
Terschelling	1250	8.0	.0041	.015	2.5	0.21	0.17
Duck South	313	4.7	.0096	.052	1.5	0.47	0.18
Duck North	460	6.0	.0098	.060	1.4	0.47	0.19
Wanganui 1	405	5.4	.0089	.031	2.2	0.40	0.16
Wanganui 2	536	6.3	.0092	.034	2.5	0.41	0.18
Wanganui 3	662	6.5	.0083	.029	2.7	0.23	0.20
Minimum	313	4.7	.0041	.015	1.4	0.21	0.16
Maximum	1250	8.0	.0098	.060	3.2	0.47	0.21

Sources: Burgess (1971), Larson and Kraus (1992), Short (1992), Stauble (1992), Gaun-hong Lee and Birkemeier (1993), Kroon (1994), Ruessink and Kroon (1994), Westlake (1995), plus Wanganui data collected and analysed by the authors.

Table 2. *Energy characteristics at the net offshore bar migration sites.*

Site	Wave Recorder Depth (m)	Mean Wave Height (m)	Severe Wave Height (m)	Wave Period (seconds)	Spring Time Range (m)	Storm Wind Speed (m/s)	Wind/coast Angle (degrees)
Egmond	21	1.35	4.10	6.00	1.78	13.4	82
Zandwoort	21	1.35	4.10	6.00	1.84	13.4	67
Katwijk	21	1.35	4.10	6.00	1.86	13.4	58
Terschelling	15 & 26	1.35	4.30	6.00	2.50	13.4	17
Duck South	18	1.10	3.05	6.40	1.20	12.3	40
Duck North	18	1.10	3.05	6.40	1.20	12.3	40
Wanganui 1	30	1.20	3.20	7.80	2.36	14.8	43
Wanganui 2	30	1.20	3.20	7.80	2.36	14.8	37
Wanganui 3	30	1.20	3.20	7.80	2.36	14.8	20
Minimum	18	1.10	3.05	6.00	1.20	12.3	17
Maximum	30	1.35	4.30	7.80	2.50	14.8	82

Sources: Wieringa and Rijkoort (1985), Macky et al. (1988), Ministry of Transport (1989), Patterson (1991), Larson and Kraus (1992), Patterson (1992), Short (1992), Gaun-hong Lee and Birkemeier (1993), Hoekstra et al. (1994), Kroon (1994), Ruessink and Kroon (1994), Westlake (1995), Wijnberg (1995), also: Birkemeier (1997 pers. com.) for tidal information from Duck; Wanganui raw wind data were obtained from the National Institute of Water and Atmospheric Research (NZ).

metry the intensity variation only represents relative depth change. Cross-shore accuracy varies from c. ±1 metre for foreshore levelling to c. ±10 metres for nearshore echo-sounding and nearshore photogrammetry (as used at Wanganui 2 and 3, see Figure 1). In the photogrammetric situation the error increases with increased distance cross-shore; from ± 8.4m at 200m offshore to ± 12.9m at 500m offshore. It should also be noted that with aerial and terrestrial nearshore photogrammetry, accuracy relates to the position of sea-surface intensity maxima rather than to the location of morphological features on the seabed. If adjustments are made for environmentally associated errors when reducing echo- sounded data or when rectifying photographs then the errors decrease by approximately 40% and 55% respectively. As noted earlier, differences also occur between image-based data and ground survey data and these must be reconciled if a comparative analysis is made.

METHODS OF ANALYSIS

In order to quantitatively define inter-site bar migrational characteristics associated with each NOM stage, it was necessary to develop a method capable of dividing the foreshore/nearshore into three zones representing the three NOM stages. While a preferred method would have been to determine the actual stage boundaries by studying behavioural characteristics of each bar sequence as depicted on ground profiles, this was not possible as complete ground profile data were not available for all sites. A method was therefore required that could utilise both the bar-crest time-series and the time-averaged profile data which were available for all sites.

The method adopted here is based upon the indication in precious reports on NOM that preferential locations of bar residence may be associated with bar generation and bar degeneration (see KROON, 1994; RUESSINK and KROON, 1994; and WIJNBERG, 1995). Such a location of preferential residence would be expected to leave a stationarity signature in the form of an upwardly directed protuberance on the time-averaged profile. The protuberances would then identify 'equivalent' locations at each site which may separate out the three cross-shore NOM stages. To test this hypothesis the bar-crest locations for Wanganui 2, the Wanganui site with the longest record, were analysed.

Locations associated with bar generation, degeneration and the positions of maximum upward protuberance on the time-averaged profile for Wanganui 2 are shown in Figure 5. It is

Table 3. *Details of data collection systems at the different sites.*

Site	Record Years	Field Methods		Sampling Rate (/y)	Elevation Accuracy (m)	Cross-shore Accuracy (m)
Egmond	1964–90	nearshore:	echo-sounder	1	±0.25	±10
Zandvoort	1964–90	foreshore:	aerial photo	1	±0.10	±2.0
Katwijk	1964–90		theodolite	1	±0.01	±1.0
Terschelling	1965–93	nearshore:	echosounder	1	±0.20	±10
Duck north	1981–92	nearshore:	theodolite	24	±0.03	±1.5
Duck south	1981–92	foreshore:	theodolite	24	±0.03	±1.5
Wanganui 1	1981–84	nearshore:	echosounder	12	±0.25	±10
Wanganui 2/3	1991–96	nearshore:	aerial/terrestrial photography	12	relative	±11
	1991–93	nearshore:	echosounder	4	±0.30	±10
	1990–94	foreshore:	theodolite	4	±0.025	±2.5

Sources: Horikawa (1988), Shand (1990), Gaun-hong Lee and Birkemeier (1993), Shand (1995), Wijnberg (1995), Bailey and Shand (1996).

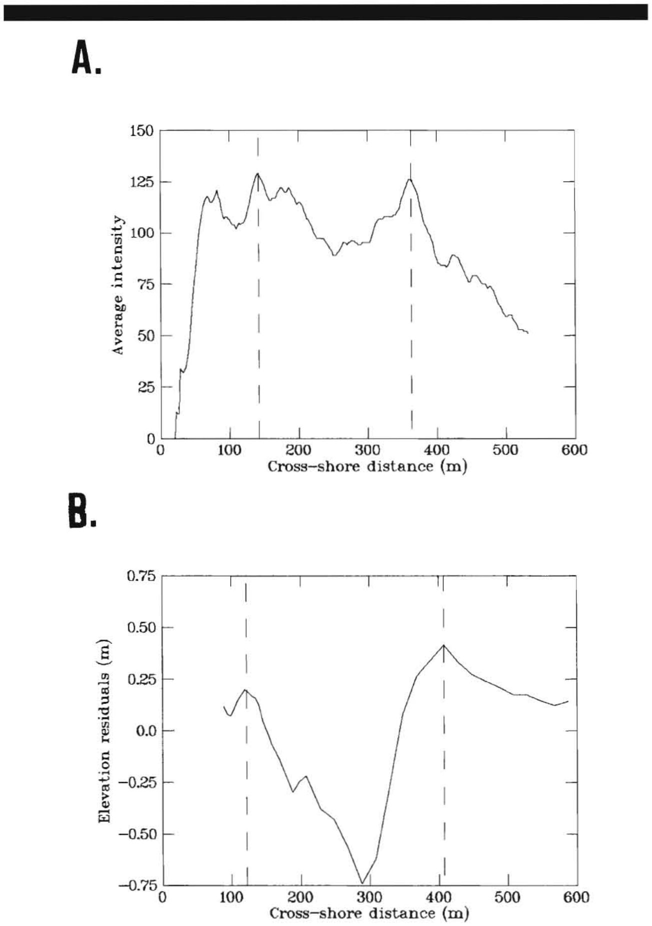

Figure 4. The difference between protuberance locations from time-averaged intensity data and time-averaged ground survey data sampled over the same period at Wanganui site 2 (the ground survey data are plotted in Figures 3A). Figure 4A shows the time-averaged intensity profile for monthly data sampled between 8.91 and 11.93. Figure 4B shows the residuals from the power curve fitted to time-averaged ground survey profiles. Vertical lines locate the corresponding maxima. The intensity maxima based on wave breaking displaces the protuberances, i.e. the modal bar-crest locations, seaward in the inner nearshore and landward further offshore.

evident on Figure 5A that the vertical lines representing protuberance maxima do, for this site at least, separate the cross-shore into three zones which isolate the generating and degenerating bars from those undergoing systematic offshore migration. Note that the location of the protuberance maxima used to construct Figure 5A are slightly different to those indicated by the maxima on Figure 4; 119m c.f. 122m and 395m c.f. 408m. Figure 5B illustrates bar degeneration sequences in terms of elevation difference between the trough and adjacent seaward crest. In these examples it is evident that following the onset of bar degeneration a bar resides within a relatively narrow band of cross-shore distance (between c. 380 to 410 metres). The bar location histogram in Figure 5B illustrates how a frequency maximum accompanies, and thus signals, the onset of bar degeneration. Unfortunately, data were not available to determine how the inner maximum on time-averaged profiles relates to bar generation sequences.

The parameters used to define net offshore migrational behaviour in this paper are illustrated in Figure 6. A variety of parameters and terminology has been used by various authors to define and describe the NOM (DE VROEG, 1988; KROON and HOEKSTRA, 1993; KROON, 1994; RUESSINK and KROON, 1994; WIJNBERG, 1995). Three parameters are required to define a site's characteristic NOM cycle: the average cross-shore distance over which the bars migrate; the average duration of the bar migrations; and the average return period, that is the average time between migration cycles. These parameters will be used in the following inter-site comparative analysis. The average rate of offshore migration is also used. While rate is not an independent measure of NOM, the normalisation of migration distance with respect to time is useful when comparing sites and it has been widely used the other writers when describing sand-bar dynamics.

To determine the NOM parameter values for all three zones the identification of a landward boundary for zone 1, and a seaward boundary for zone 3 was required. Unfortunately the data needed to identify individual bar generation locations was only available for Wanganui site 2. In this case the foreshore/nearshore boundary was found to be landward of all bar generation locations and subsequent locations (see Figure 5A). This boundary was therefore used as the landward limit for zone 1 in the inter-site analysis. At each site, the seaward limit for zone 3 was taken as the average of the seaward excursion maxima for the bars. Figure 5B shows that while most of the bar degeneration at Wanganui occurred within a relatively narrow band of cross-shore distance, substantial seaward migration of the subdued bar could still occur prior to complete disappearance of the bar. This contrasts with some NOM sites such as at Duck where a landward trend appears to occur in bar migration during degeneration. Because of this directional variability during the degeneration stage, the average rate of NOM in zone 3 was determined by the slope of a linear regression line fitted to all bar location points following the onset of degeneration, *i.e.* once the bar had crossed the zone 2/3 boundary.

RESULTS

This section will describe the NOM parameters' values, identify an index parameter to represent the morphological system, and determine the associations between environmental variables and the index parameter for each site.

A wide variation in NOM parameter values are evident between the different field sites (see Figure 7). The Netherland sites tend to have NOMs with greater average migration widths, longer average durations, and lower average migration rates than the Wanganui and Duck sites. Terschelling is notable for its extensive width of zone 2, and narrowness of zone 3. Terschelling and Egmond have particularly long durations and return periods. Egmond has a very low NOM rate. The return periods for the Wanganui sites are notably lower than at the other sites.

The NOM parameter results in Figure 7 also show that a similar pattern of inter-zonal behaviour occurs at each site.

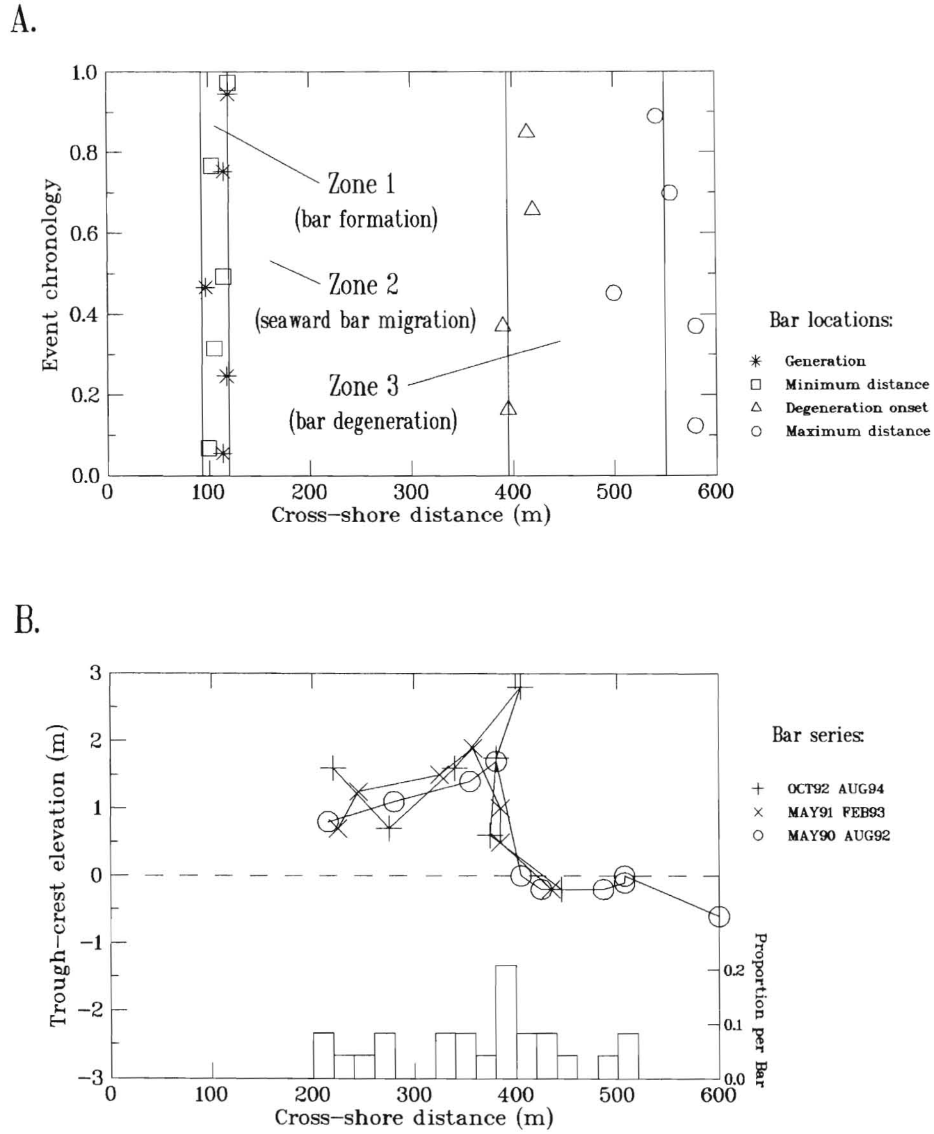

Figure 5. Figure 5A shows bar-crest generation and degeneration locations relative to the NOM zonal boundaries (see text) at Wanganui site 2. Bar-crest data in Figure 5A was taken from a data set sampled at monthly intervals between June 1990 to May 1996. While data was mainly collected using imaging techniques, all image-based data has been converted to equivalent ground profile distances (see text). The vertical lines marking the zone boundaries appear to separate bar-crest locations on the basis of NOM stage characteristics. Figure 5B shows bar-crest degeneration sequences and the corresponding frequency distribution for Wanganui site 2. The bar-crest time-series in Figure 5B were sampled at three monthly intervals between January 1990 and August 1994 using ground profiling techniques. Shape flattening of the bar (i.e. progressive degeneration) is defined by the elevation difference between the crest residual from a fitted power curve and the adjacent (landward) trough residual. Most degeneration occurs within a relatively narrow cross-shore zone and this results in the frequency maximum between 380 to 400m. Note that the degeneration time-series can still have seaward migration trends.

Inter-zonal return periods are approximately constant at each site. However, significant inter-zonal variation occurs for duration, width and rate; higher values occur in zone 2 than in zones 1 and 3. While parameter values in zones 1 and 3 are similar, zone 3 values show greater variation than those in zone 1. Such zonal separation is further illustrated by the bivariate confidence ellipses in Figure 8.

Correlation analysis identified duration as the parameter most strongly associated with the other NOM parameters (see Figure 9). Duration was therefore selected as the index parameter to represent NOM behaviour in the analysis with environmental parameters. Only the zone 2 data were used for the inter-site analysis because zone 2 is the most spatially and temporally extensive zone and systematic offshore migration is the dominant type of bar behaviour.

A linear correlation analysis between (zone 2) duration and the physical boundary variables identified associations with a level of significance of 10% *i.e.* $p < .1$) in all cases except

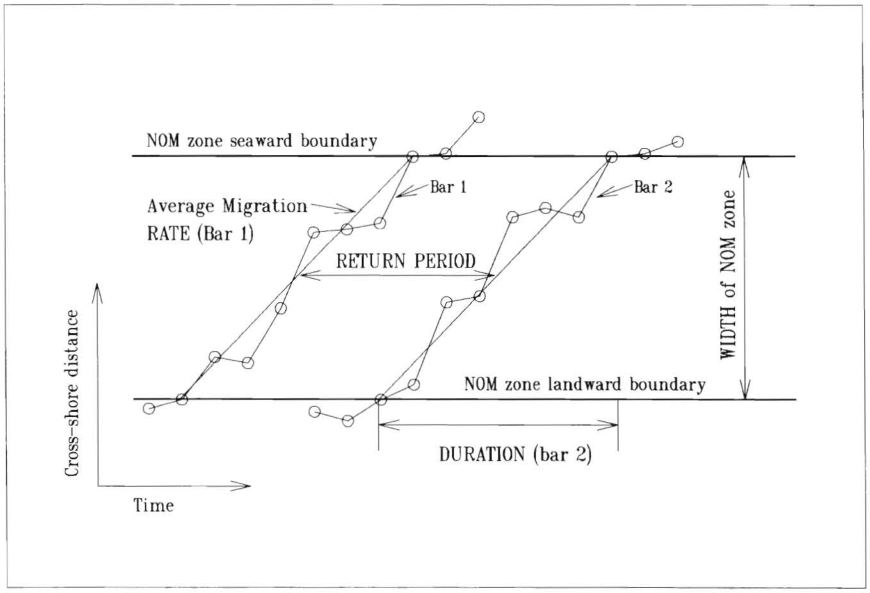

Figure 6. Diagrammatic representation of the parameters used to define net offshore bar migration.

bar number and nearshore sediment size (see Table 4A). Curvilinear regression models incorporating power functions appear to better fit the sediment/duration and slope/duration data (see Figure 10). Such nonlinear relationships may be appropriate given the typically nonlinear relationships between sediment size and cross-shore slope (see KOMAR, 1976a; HARDISTY, 1990; STAUBLE, 1993; HOEKSTRA *et al.*, 1994). Of particular interest is the apparent outlier status of Egmond which will be discussed later. The nearshore sediment size only began to show a visually identifiable association with duration when both the Egmond data and the Wanganui Rivermouth (W1) data were excluded (Figure 10C). Data from the latter site may have been contaminated by finer flood-borne river sediment prior to sampling.

The duration/process variable results should be interpreted with caution. Nonequivalency errors in the wave data, short record lengths, difficulties reconciling various statistics used in the different publications, and the relatively small inter-site ranges for many parameters may have resulted in errors that could affect the correlation strength.

The only process variables to show significant associations ($p < .1$) with duration are the mean and severe wave heights. However, the correlation coefficients in Table 4B are based on 9 independent samples while the wave data comes from only four recorders (see Table 2). To account for this lack of independence in the wave height data the NOM durations were averaged to provide only one value per wave height sample and the correlation analysis was then repeated. While the resulting associations with duration were weaker the severe wave height relationship remained significant.

No linear association is evident between duration and the wind parameters in Table 4B, however, a strong nonlinear relationship appears to exist with wind direction as is shown in Figure 11A. The wind direction variable was based on the angle between the shore-line and predominant (storm) wind approach and therefore incorporates the boundary condition of coastal orientation. Figure 11A shows that duration decreases from a high value at high angle (*i.e.* predominating wind tending shore-normal) to reach a minimum at approximately 45 degrees. Duration values increase again as the angle decreases toward zero (*i.e.* predominant wind tending shore-parallel). Repetition of the regression using a quadratic function improved the correlation coefficient from $r = .133$ (Table 4B) to $r = .846$. Residuals from the fitted parabolic curve shown in Figure 11A suggest that the actual relationship is asymmetrical with lower durations being maintained from c. 45 degrees toward c. 20 degrees before rapidly increasing.

DISCUSSION

The similar inter-zonal pattern in NOM parameter values evident at each site indicates that each NOM stage is subjected to different morphodynamics as would be expected by the Dutch model.

The wide inter-site variability in NOM parameter values, however, indicates that the actual morphodynamics are site specific. The high variability in bar behaviour for the degeneration zone is of particular significance in this regard. As the seaward zone is the first to interact with incoming wave energy its morphology is likely to be particularly responsive to the different environmental conditions characterising each study site. Recently RUESSINK (1998) has also speculated on the possibility of site specific NOM morphodynamics. Ruessink developed a conceptual model of NOM at Terschelling based on net suspended sediment transport paths; however, its applicability to other coastal sites with different process conditions and NOM characteristics appeared to be doubtful.

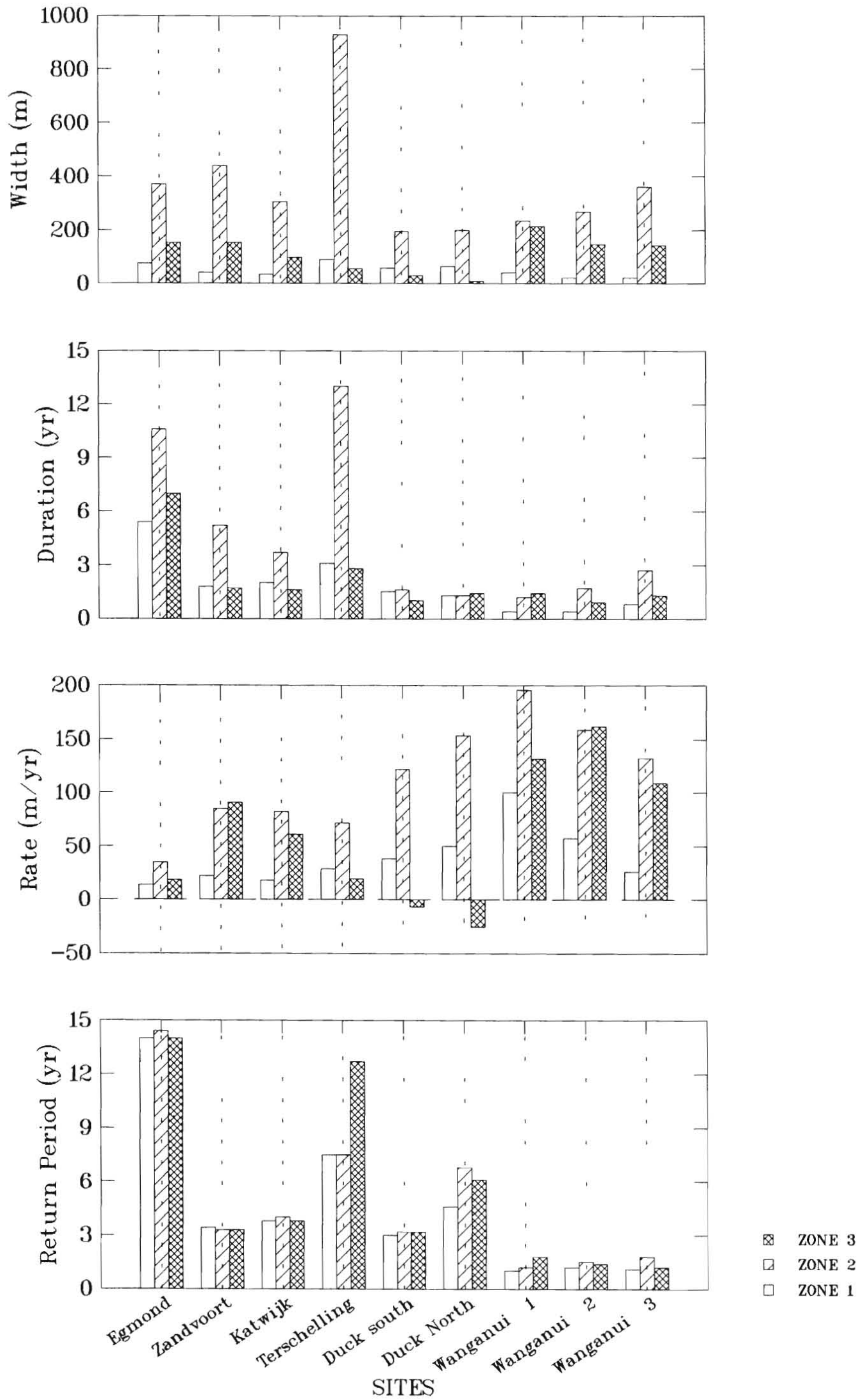

Figure 7. Graphs showing bar migration parameter values for the three zones at each site. With the exception of return period there is significant variation between the inter-zonal values at each site. Inter-site variation is also significant with The Netherlands sites tending to differ from the duck and Wanganui sites.

The different migrational trends that occur in zone 3, *i.e.* the degeneration zone, at the various sites (Figure 7) are consistent with the degeneration behaviours described by other researchers and summarised by SHAND and BAILEY (1999). This consistency further supports the zonation method of NOM stage separation developed for use in this study.

The Holland data subset (Egmond, Zandvoort and Katwijk) suggests oppositely directed NOM/slope relationships to

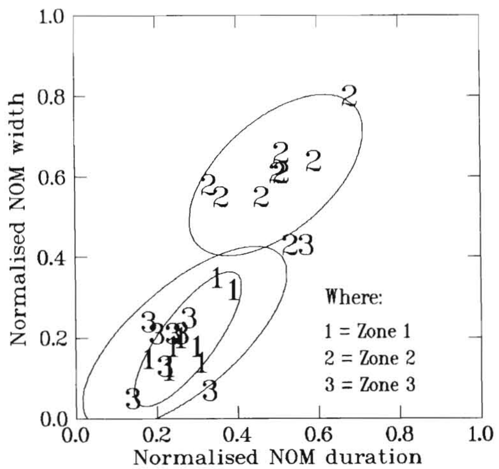

Figure 8. NOM width and NOM duration at each site plotted with gaussian bivariate confidence ellipses (99%). The values have been normalised by the total width and duration. The ellipses show that different NOM bar behaviour occurs in each zone. Zone 2 has higher magnitudes while zone 3 values have greater variability than zone 1 values.

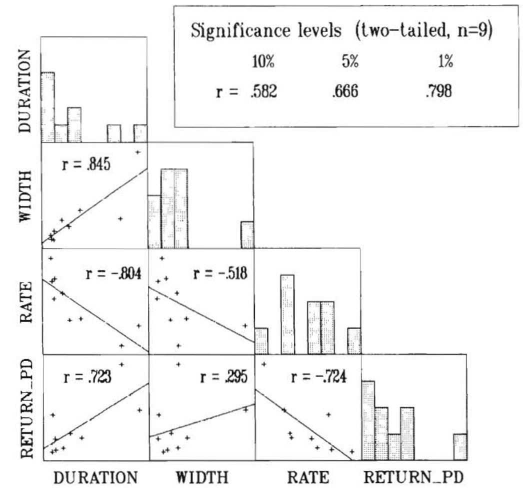

Figure 9. Correlation plots for NOM parameters showing fitted linear regression models, Pearson correlation coefficients and critical values for different levels of significance (two tailed for n = 9) are also shown.

those for the full data set (see Figure 10). KROON (1994) suggested possible NOM control mechanisms based on the negative NOM rate/slope relationship. However, the outlying status of the duration/slope data-point for Egmond appears to be the cause of this anomaly. WIJNBERG (1995) had noted that Egmond did not demonstrate the typical gradient/surf zone width/bar-number relationships observed on other coasts (KOMAR, 1976a) and which are also evident within the correlation matrix of Table 4A. In a study of large scale coastal behaviour along the Holland coast, WIJNBERG (1995) identified five differently behaving regions with Egmond and Zandvoort/Katwijk belonging to adjacent 'coastal cells'. While that investigation was unable to determine the controlling factors it was evident that the 2.5 kilometre long harbour moles at Ijmuiden (see Figure 1B) partitioned the cells and enhanced the differences in the adjacent bar systems.

Table 4. *Pearson correlation matrixes for NOM duration (zone 2) with morphological and sediment variables (Table 4A), and process variables (Table 4B).*

A.

	Duration (zone 2)	Sediment Foreshore	Sediment Nearshore	Slope Foreshore	Slope Nearshore	Depth Nearshore	Width Nearshore	Bar Number
Duration (zone 2)	1.000							
Sediment foreshore	−0.599	1.000						
Sediment nearshore	0.149	0.127	1.000					
Slope foreshore	0.653	0.680	0.000	1.000				
Slope nearshore	−0.739	0.862	0.397	0.620	1.000			
Depth nearshore	0.693	−0.325	0.385	−0.472	−0.322	1.000		
Width nearshore	0.854	−0.728	−0.049	−0.593	−0.823	0.789	1.000	
Bar number	0.302	−0.837	−0.295	−0.541	−0.658	0.134	0.487	1.000

B.

	Duration (zone 2)	Mean Wave Height	Severe Wave Height	Wave Period	Storm Wind Speed	Storm Wind Approach	Spring Tide Range
Duration (zone 2)	1.000						
Mean wave height	0.740	1.000					
Severe wave height	0.825	0.960	1.000				
Wave period	−0.576	−0.487	−0.691	1.000			
Storm wind speed	−0.129	0.154	−0.105	0.788	1.000		
Storm wind approach	0.133	0.423	0.395	−0.463	−0.226	1.000	
Spring tide range	0.287	0.424	0.248	0.496	0.860	−0.383	1.000

Critical values (two tailed) for 9 observations:	p = .1	.05	.01
	r = .582	.666	.798

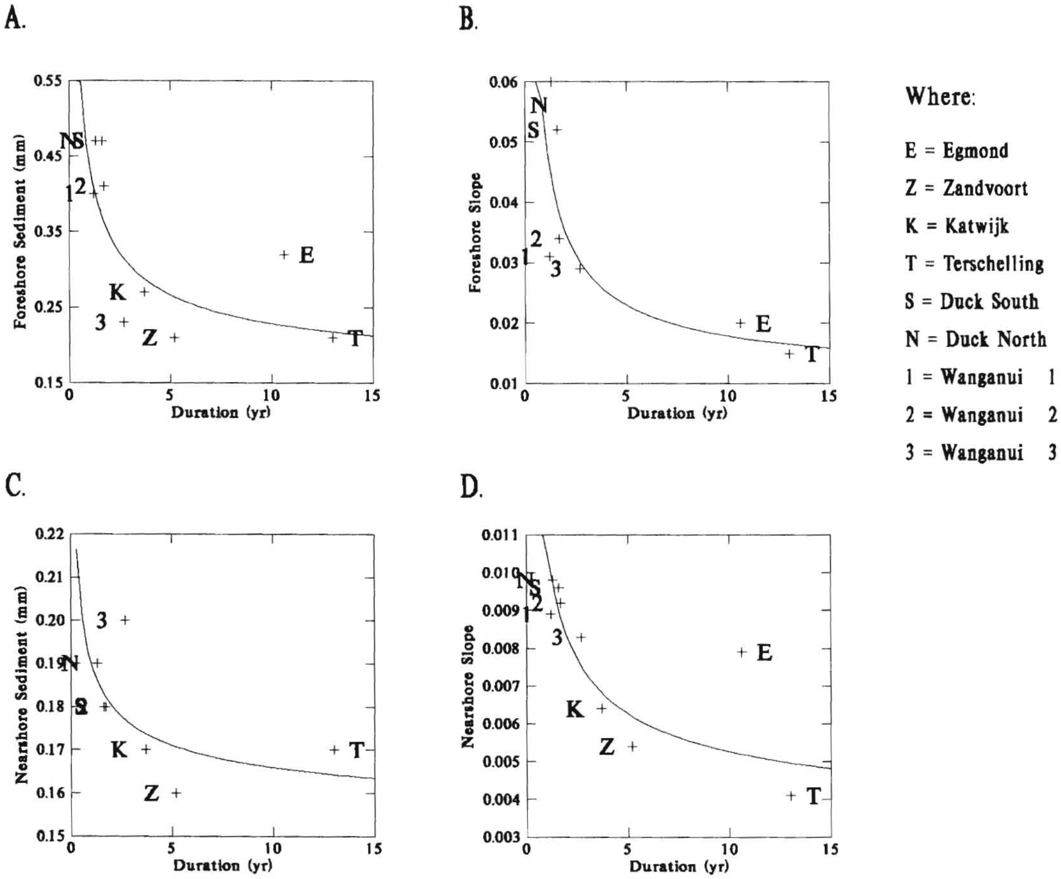

Figure 10. Plots showing nonlinear associations for NOM duration with sediment and slope. Power curves are fitted to the full data set in Figures 10A, B and D but Egmond and Wanganui site 1 are excluded in Figure 10C. These curves indicate that an underlying negative nonlinear association exists. The outling nature of the Egmond data is illustrated.

The results suggest that cross-shore slope has a strong influence upon bar migrational behaviour during NOM stage 2. Nearshore slope probably has greater causal association with NOM than foreshore slope given its closer proximity to NOM activity.

A possible explanation for the nearshore slope/NOM duration association is suggested by the cross-shore width, depth, and wave height relationships. By definition, cross-shore slope equals the depth to width ratio, *i.e.* $\tan\beta$. The correlation coefficients in Table 4A suggest that at the NOM sites the nearshore widths have greater influence over nearshore slope than does the depth at the seaward nearshore boundary; so lower slopes should correspond to wider and somewhat deeper nearshores. In a study of multi-barred coasts in the Great Lakes and Gulf of St Lawrence, DAVIDSON-ARNOTT (1988) found cross-shore width and outer bar depth were positively correlated with wave height (using fetch as an analogue). A similar result occurs for the global NOM sites in this study; the nearshore width/severe wave height correlation coefficient = .692. Davidson-Arnott explained this association by the increasing breaking depth achieved by the highest waves. Davidson-Arnott also found wave height to be related to bar height, although no causal mechanism was identified. From studies involving the analysis of bar size on multi-bar coasts (see LARSEN and KRAUS, 1992; and RUESSINK and KROON, 1994) it is evident that bar height is proportional to bar volume. As higher waves are also associated with longer NOM duration it can be hypothesised that differences in NOM activity may result from the different time taken for bars of different size to translate offshore under storm conditions. This is because larger bars take longer than smaller bars to migrate across the surf zone owing to the higher volumes of sediment to be transported. The relationship between seaward bar movement and storm events is well documented and supported by sediment transport theory (OSBORNE and GREENWOOD, 1992; ROELVINK and STIVE, 1989). This mechanism involves the suspension of sediment by broken waves and subsequent transport under seaward directed mean flows (*e.g.* GREENWOOD *et al.*, 1991; LARSEN and KRAUS, 1989).

To test this hypothesis that bar volume controls NOM duration, the sizes of bars at the study sites were compared with the corresponding NOM duration parameters. Bar volumes were based on the area enclosed by the positive residuals

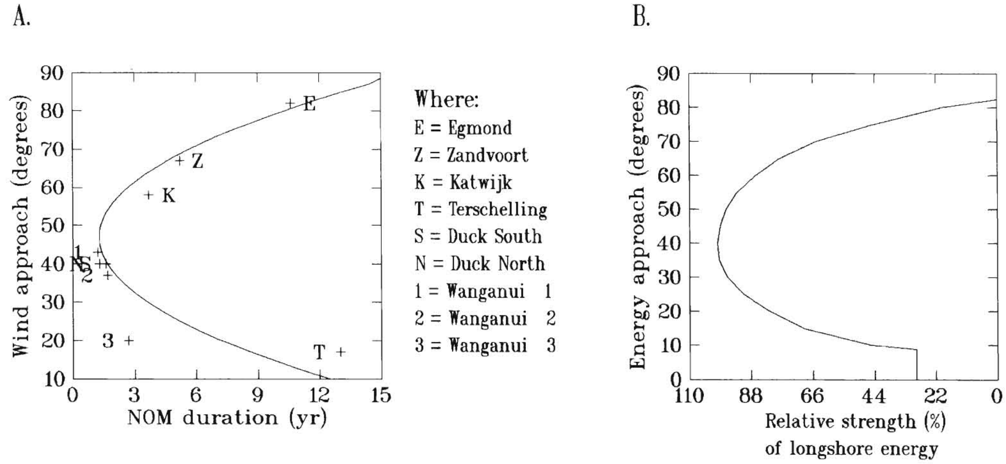

Figure 11. Nonlinear relationships between the angle of wind approach relative to the shoreline with NOM duration (Figure 11A), and the angle of wind/wave approach with the relative strength of the longshore energy component (Figure 11B). Low angle asymmetry in the duration/wind approach data (Figure 11A) is demonstrated by the deviations from the fitted parabola. The combined influence of both wind and wave energy have been incorporated in Figure 11B by adapting the method used by Whitford and Thornton (1993) to the average environmental conditions at the NOM sites. The 'relative strength of the longshore energy' in Figure 11B refers to the ratio of each angle's longshore energy value to the maximum value. The similarity between Figures 11A and 11B suggests that longshore currents may be significant in NOM morphodynamics.

(used to locate the bar crest) and the average profile curve, per metre longshore. Where possible, the volumes were derived for bars just prior to the onset of degeneration. This condition was imposed as bar size tends to increase across the nearshore until degeneration begins (LARSEN and KRAUS, 1992; KROON, 1994; RUESSINK and KROON, 1994). However, neither equivalent nor complete bar volume data was acquired for all study sites so the results shown in Table 5 are only approximate. Nevertheless, they do support the proposition that the sites with highest durations have larger bars and those with the lowest durations have the smallest bars.

Nearshore slope may also have some influence NOM activity by gravitationally induced downslope transport. However, while such effects have been included as part of the bed-load and suspended load contributions in energetics-based cross-shore sediment transport models (BOWEN, 1980; BAILARD, 1981), subsequent studies (STIVE, 1986; THORNTON *et al.*, 1996; and GALLAGHER *et al.*, 1998) suggest that the gravity driven transport is of relatively minor importance. The influence of coastal orientation on NOM may be via longshore currents. Strong local winds with an oblique orientation to the shoreline generate longshore currents via the longshore component of surface wind stress (*e.g.* NUMMEDAL and FINLEY, 1978; HUBERTZ, 1986; WHITFORD and THORNTON, 1993) in combination with changes in the radiation stress from obliquely approaching broken waves (*e.g.* LONGUET-HIGGENS, 1972; KOMAR, 1976b; SHERMAN, 1988). A distinct similarity is evident between the theoretical curve for longshore current/energy approach angle (Figure 11B) and for the NOM duration/wind approach angle relationship identified in this study (Figure 11A). Influence of longshore currents on NOM activity may involve a number of mechanisms such as edge waves, flow continuity, or morphological configuration.

Table 5. *Average NOM durations and bar volumes for the study sites.*

Site	NOM Duration (y) For Zone #2	Average Bar Volume (m^3)
Duck	1.2–1.3	60–100
Wanganui sites 2 and 3	1.5–2.5	70–120
Zandvoort and Katwijk	3.7–5.2	125–180
Egmond	10.6	180–250
Terschelling	13.0	450–700

Sources: Kroon (1994), Larsen and Kraus (1993), Ruessink and Kroon (1994), Wijnberg (1995), Wanganui ground profile data.

HOWD *et al.* (1991) and HOWD *et al.* (1992) have shown theoretically that progressive edge waves moving in the same direction as a strong longshore current assist seaward bar migration. Progressive edge waves commonly occur in the presence of strong longshore currents and high incident wave energy (OLTMAN-SHAY *et al.*, 1989; HOWD *et al.*, 1991; and HOWD *et al.*, 1992).

Seaward bar migration may result when troughs and topographic constrictions are subjected to increases in longshore flow. Field and modelling evidence from the Terschelling nourishment programme gives some support to this mechanism. HOEKSTRA *et al.* (1996) found that troughs re-established across the nourishment zone in response to increased longshore flow. However, additional evidence of greater flow concentration on the seaward side of the trough would be required to account for offshore bar migration. Bar switching and the associated seaward migration (see SHAND and BAILEY, 1999) may be forced when constricted channels are affected by high longshore flows. Bar switching has been observed to occur at Wanganui during conditions of higher wind/wave energy with oblique approach.

Strong persistent longshore currents are associated with shore-parallel topography (SHORT, 1975; FOX and DAVIS, 1976) and this type of morphology may promote seaward bar migration. Such two-dimensional (2D) morphological configurations would be expected to increase the longshore uniformity of return flows, while the cellular hydrodynamics associated with 3D morphology (SONU, 1972; KOMAR, 1976a) would produce an irregular pattern of seaward flow. Two-dimensional morphology may therefore be capable of forcing more laterally continuous offshore bar migration.

CONCLUSION

The coastal environments of the NOM study sites are characterised by multiple bars, a wide range of physical boundary characteristics, short period waves, a narrow range of storm strength wind and wave conditions, and widely varying approach directions of the predominant wind relative to the shoreline. The environmental similarities may be conducive to NOM.

Both inter-site similarities and differences were observed in NOM parameter values. The consistent inter-site pattern of parameter values within each NOM zone suggest that each zone is characterised by distinctive bar migrational behaviour as would be expected by the three stage NOM model. However, the wide inter-site variability which occurs in NOM parameter values suggests that the actual morphodynamics are sensitive to differences in the environmental conditions occurring at each site.

NOM duration was identified as the parameter most discriminative of NOM morphological behaviour and was used as the system index parameter for inter-site comparison. The analysis found both lower cross-shore slopes and higher wave energy were associated with longer NOM durations. As bar volumes are greater at sites characterised by these type of conditions it appears that the different levels of NOM activity may result from the different lengths of time required for bars of different sizes to migrate seaward across the nearshore. NOM duration was found to be nonlinearly correlated with the angle that the predominant storm-strength wind approached the shoreline. This indicated that longshore current strength influenced NOM behaviour and possible mechanisms were suggested which incorporate edge-waves, flow continuity, and morphological configuration.

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