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A Review of Net Offshore Bar Migration with Photographic Illustrations from Wanganui, New Zealand

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ABSTRACT

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Field studies, processes, and mechanisms associated with net offshore bar migration are reviewed. Net offshore bar migration (NOM) has been reported at multi-bar locations on the Dutch coast and at North Carolina on the eastern USA seaboard. NOM has also been documented by the present authors as occurring on the New Zealand west coast. Dutch researchers have developed a three stage 'life-cycle' morphological model based on data from sites in The Netherlands. These stages consist of bar generation near the shore-line (stage 1), systematic offshore migration of the bar across the surfzone (stage 2), and bar disappearance in the outer surfzone (stage 3). Non-linear morphological configurations have also been associated with net offshore bar migration. NOM phenomena are illustrated using sequential time-exposure imagery obtained from a field site at Wanganui, New Zealand. Consistency between the results from the different locations indicates that net offshore bar migration may be a phenomenon common to many multi-bar coasts.

This review suggests that while the overall net offshore bar migration 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. The timing and nature of offshore bar migrations are influenced by antecedent morphology. Finally, the overall NOM characteristics are related to the large-scale physical boundary conditions such as cross-shore slope and coastal orientation.

ADDITIONAL INDEX WORDS: *Multi-bar coast, image processing, morphodynamics, geomorphological scales.*

INTRODUCTION

Sand-bars are ridges on the sea-bed which are usually aligned parallel to the shoreline. These dominant morphological features are found on most sandy coasts. The number of bars can vary between sites. Morphological characteristics of sand bars are related to wave conditions, tidal range, sediment characteristics and topographical gradients (see *e.g.* Masselink and Short, 1993).

Conceptual models have been developed to account for the morphology and behaviour of coastal sand-bars. The earliest and simplest model involves two states or morphological configurations. Beach morphology oscillates between a dissipative profile with a seaward bar and a reflective barless profile with a landward berm terrace. The former state is associated with higher energy conditions and the latter with fair-weather conditions. The model was developed for single-bar oceanic coasts which display strong seasonality and is referred to as the storm/swell, summer/winter, or bar/berm profile model (see *e.g.* Komar, 1976; Hardisty, 1990). This model is two-dimensional (2D), in that it can be depicted by a single shore-normal profile.

Conceptual models incorporating three-dimensional (3D) states were subsequently developed for coasts which experienced rhythmic topography, *e.g.* see 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), and Sasaki (1983). A bench-mark in this work was Wright and Short's (1984) morphodynamic model which is often referred to as the 'Australian' model. This model consists of a sequence of six beach-states with end members similar to the morphologies of the bar/berm model. Four 'intermediate' configurations with three-dimensional topography complete the sequence. Distinctive 'process-signatures' are associated with each state. The Australian model primarily applies to sections of coast with a single bar, or to the innermost bar where multiple bars exist. Three-dimensional beach-state investigations of different coasts frequently identify variants of the Australian model, *e.g.* Nummedal *et al.* (1984), Shaw (1985), Marra (1991), and Short (1992). Sonnenfeld (1987) speculated that there is a single global nearshore bar sequence and each surfzone displays incomplete portions of the sequence in accord with its own combination of wave and tide conditions.

The 3D beach-state approach has been applied to multi-bar coasts by researchers such as Hom-ma and Sonu (1962), Goldsmith *et al.* (1982), Aagaard (1990), Short (1992),

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and SHORT and AAGAARD (1993). While such modeling has identified certain configurations and sequences the task has been thwarted by the greater morphological complexity and spatial extent of multi-bar surfzones. The data-bases have usually consisted of aerial photographs or relatively small areas of bathymetric map. In either case temporal limitations have occurred because of low sampling rates or the short time-spans of research projects. However, in a few instances temporally extensive data have been collected and new morphological phenomena have been identified. Of particular interest is a repeating (cyclic) offshore migration trend underlying sand-bar behaviour (*e.g.* see BIRKEMEIER, 1984; DE VROEG, 1988; RUESSINK and KROON, 1994; WIJNBERG, 1995; BAILEY and SHAND, 1996).

Net offshore bar migration (NOM) has been observed at sites on the Terschelling and Holland coasts (The Netherlands), the North Carolina coast (USA) and on the southwest coast of New Zealand's North Island (see Figure 1). The published data sets demonstrating NOM at these sites are shown in Figures 2.

Researchers from the Netherlands (*e.g.* RUESSINK and KROON, 1994; WIJNBERG, 1995) have proposed a general three-stage conceptual model to describe the NOM cycle. Authors describing data sets from Wanganui on the New Zealand west coast (SHAND, 1990; BAILEY and SHAND, 1996) and from Duck on the USA east coast (BIRKEMEIER, 1984; LIPPMANN *et al.,* 1993) have alluded to such a model. Reports of multi-bar sites on the Oregon coast (CHESSER, 1993) and along the Nile Delta (KHAFAGY *et al.,* 1992), suggest that the model may also apply at those locations. In this paper the conceptual NOM model will be referred to as the 'Dutch' model. The three stages of the Dutch model are: bar generation near the shore-line; bar maturity and systematic seaward migration across the inner nearshore; and finally bar dissipation (flattening out) and disappearance in the outer nearshore. Smaller scale detail and possible mechanisms underlying the NOM behaviour have been identified from those data sets which have higher sampling rates (BIRKEMEIER, 1984; LIPPMANN *et al.,* 1993; KROON 1994).

While the Dutch model describes shore-normal change, three-dimensional morphological configurations also appear to be important in the NOM cycle. For example: KROON (1994) and RUESSINK and KROON (1994) have discussed the influence of longshore migrating bars; WIJNBERG (1995) has described alignment changes in longshore bars; and KROON (1994) and BAILEY and SHAND (1996) have described double bar development in the mid surfzone.

This paper reviews the literature on net offshore bar migration within the framework of the three-stage Dutch model, i.e. bar-generation, systematic seaward migration, and bar disappearance. Three-dimensional morphologies associated with NOM are then reviewed. Sequences of photographic images from Wanganui (New Zealand) are used to illustrate the different NOM phenomena. Comments are made about additional aspects of NOM evident within the imagery. Detail is also provided about the imaging techniques and image interpretation. The paper begins by considering the different methods used to acquire data at the various NOM sites together with the steps taken to reconcile inherent measurement differences—thereby enabling meaningful comparisons to be made.

THE REVIEW

Methods

A range of measurement systems have been used for obtaining bar-crest data at the different NOM field sites. Field surveys for the Dutch data began in 1964 and have continued at yearly intervals using vertical aerial photogrammetry and echo-sounding (see RUESSINK and KROON, 1994; WIJBERG, 1995). Data collection at Duck, North Carolina, began in 1981 and has continued at approximately fortnightly intervals using ground-contact instruments (see GUAN-HONG LEE and BIRKEMEIER, 1993). Wanganui Rivermouth (New Zealand) data collection began in 1925 and has continued at two to four weekly intervals (see GIBB *et al.,* 1962; BURGESS, 1971; SHAND, 1990; SHAND, 1995). Data collection for the Wanganui coast began in 1991 at two to four weekly intervals using levelling, echo-sounding, vertical aerial photogrammetry and elevated oblique terrestrial photogrammetry (see PATTERSON, 1991; BAILEY and SHAND, 1993; BAILEY and SHAND, 1996; BAILEY and SHAND, 1997).

The oblique terrestrial imagery from Wanganui (see Figures 2I and 2J) utilised photographic long-exposure (time-exposure) field sampling, analytical rectification, and further image processing to obtain the morphological data sets. Photographs were obtained using a neutral density filter and exposure times of approximately four minutes. The resulting time-averaged photographic image gave a statistically stable sample of the breaking wave pattern. As wave breaking is depth dependent the intensity variation provides an analogue of surfzone morphology (see HOLMAN and LIPPMANN, 1987; LIPPMANN and HOLMAN, 1989; LIPPMANN and HOLMAN, 1990). Oblique images were digitised and rectified using an algorithm which incorporates ground control points, the horizon, sea-level, and the camera geometry to solve the transformation parameters (see LIPPMANN and HOLMAN, 1989; BAILEY and SHAND, 1993; BAILEY and SHAND, 1996). BAILEY and SHAND used a mosaicing routine to splice an eight frame panorama of photographic images. By locating the camera on a cliff top approximately 40 metres above MSL, and using different focal length lenses, they were able to produce output images (morphological maps) of up to six kilometres of coast. Figures 5 and 6 show sections of these maps. Ground truthing by LIPPMANN and HOLMAN (1989) showed that intensity maxima approximated bar crest locations and the shoreline. To facilitate temporal analysis of bar crests within a sequence of images a time-series image termed a 'time-stack' was constructed using cross-shore segments from a particular longshore location. Such image processing is discussed in AAGAARD and HOLM (1989), BAILEY and SHAND (1994), HOLLAND and HOLMAN (1993), BAILEY and SHAND (1996) and the technique was used in creating the time-stacks in Figures 2, 5 and 6. The time-stacks in Figure 2 have also been smoothed horizontally, i.e. in time, to emphasise the bar-crest migration trends.

In all NOM studies the bar crests were detected using curve fitting techniques and the crest location was based on

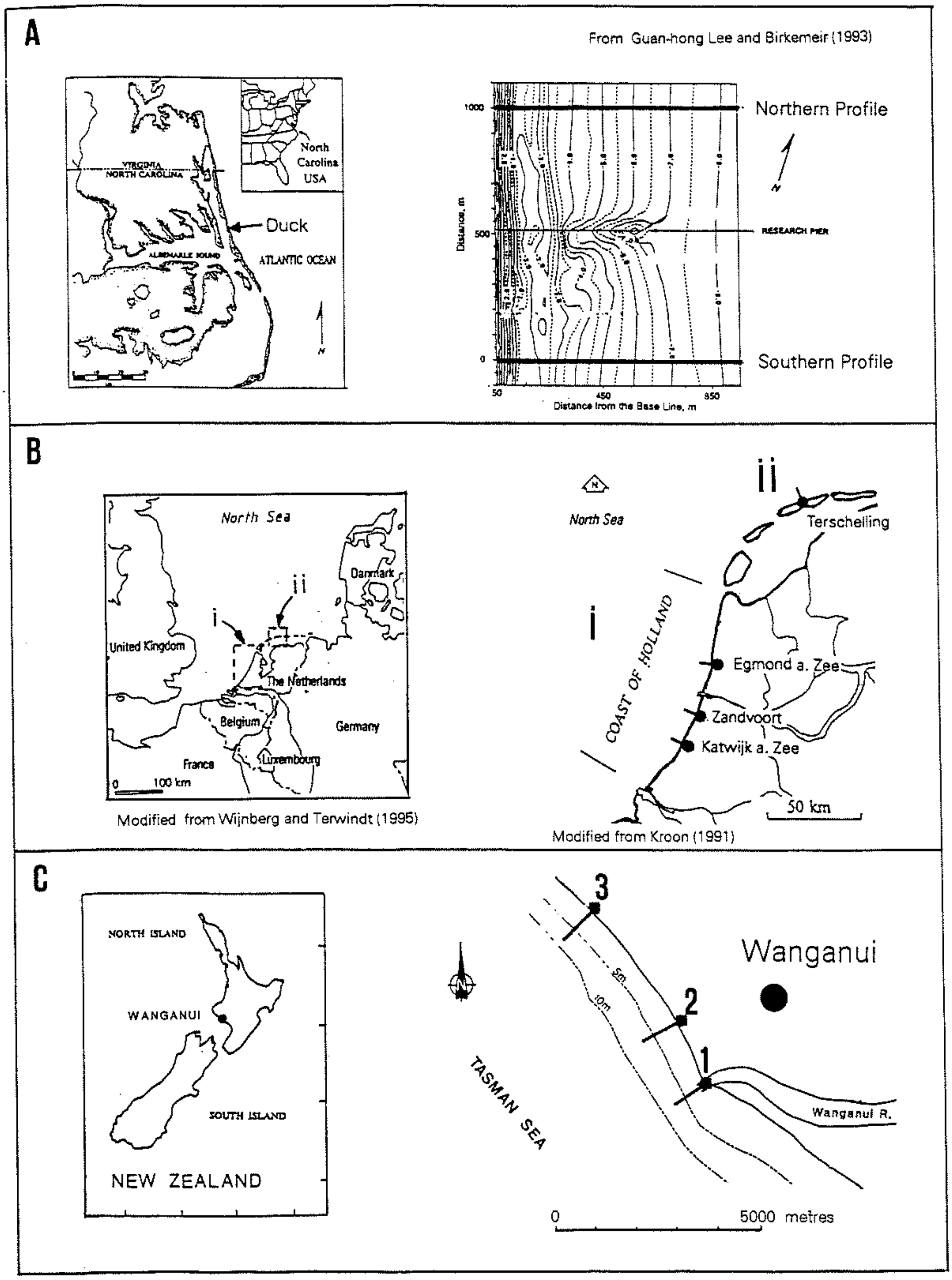


Figure 1. Location maps for the net offshore bar migration sites in North Carolina (A), The Netherlands (B) and New Zealand (C). The cross-shore survey transects are shown by bold lines.

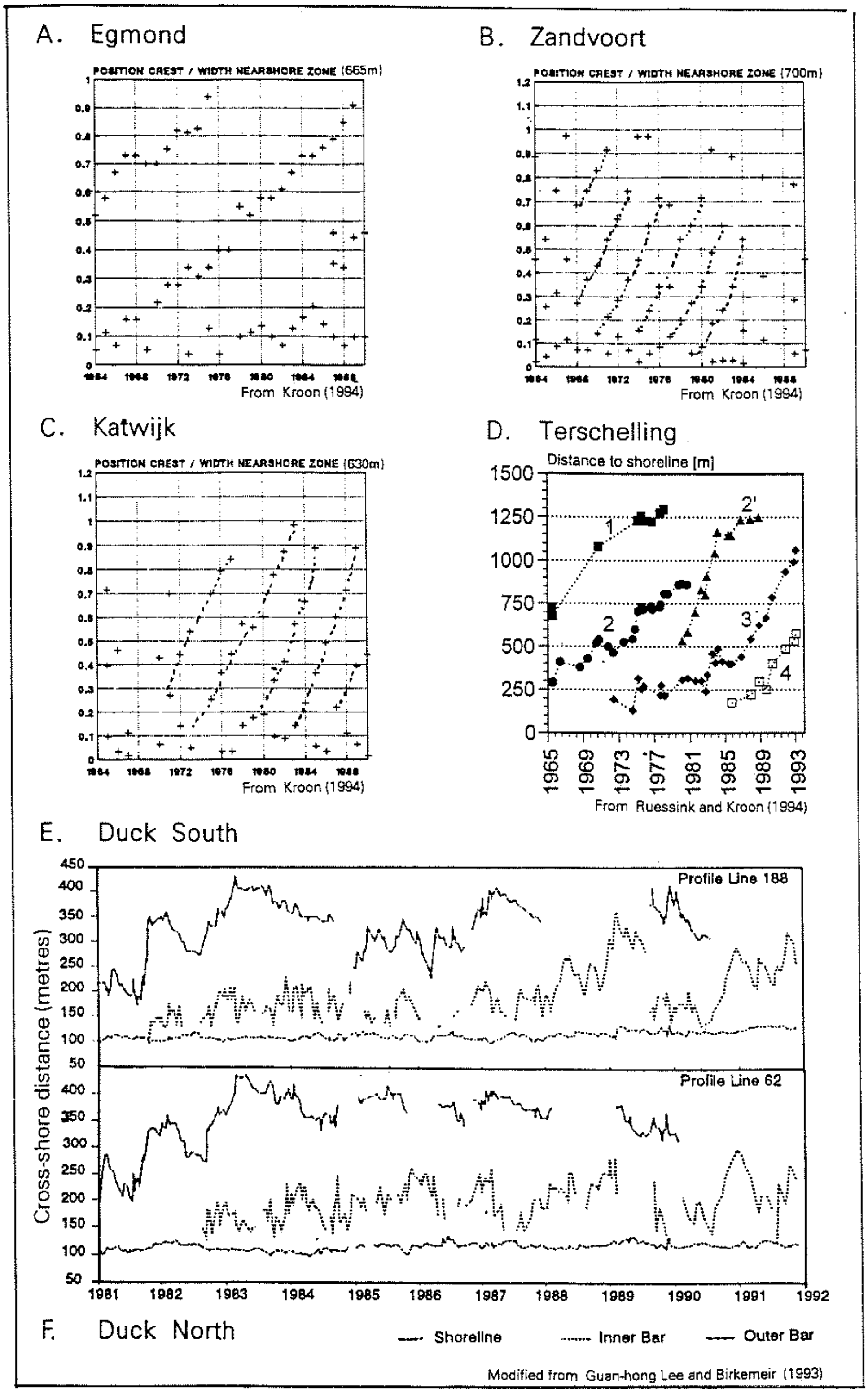
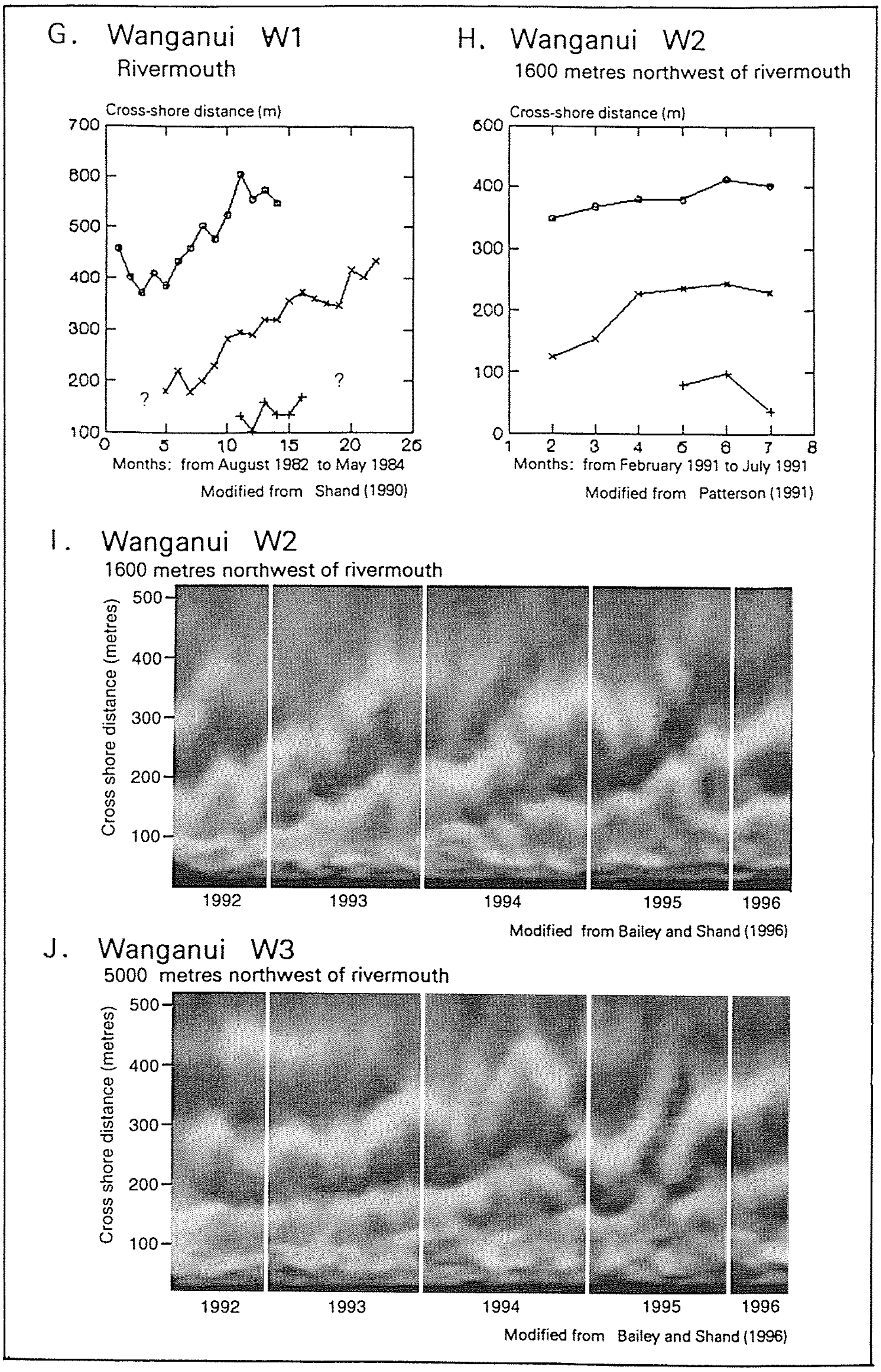


Figure 2. Published bar-crest time-series showing net offshore bar migration at sites in The Netherlands (A to D), North Carolina (E and F), and New Zealand (G to J).



G. Wanganui W1
Rivermouth

Modified from Shand (1990)

H. Wanganui W2
1600 metres northwest of rivermouth

Modified from Patterson (1991)

I. Wanganui W2
1600 metres northwest of rivermouth

Modified from Bailey and Shand (1996)

J. Wanganui W3
5000 metres northwest of rivermouth

Modified from Bailey and Shand (1996)

Figure 2. Continued.

cross-shore distance from a benchmark landward of the beach. Crest detection for the ground profile data, i.e. data obtained by survey instruments that detect the sea-bed, was based on the maximum positive residual from a smooth fitted curve as advocated by HOLMAN and BOWEN (1982). Crest detection for the intensity profile data, i.e. data obtained by detecting intensity variation associated with broken wave foam, was based on locating the point on a fitted parabola with zero slope. Crest locations obtained by the two methods are similar but not identical. This is to be expected as intensity values are depth controlled whereas the ground profile crest locations are shape controlled. A correction must be applied if such data sets are to be quantitatively compared. BAILEY and SHAND (1997) have developed an empirical relationship which shows the image value to be 50 m seaward of the corresponding ground value at a depth of 1 metre below MSL, 50 m landward at 4.5 m below MSL, and approximately coincident at the two metre depth.

Errors associated with the different field methods and data reduction and processing proceedures have been discussed by; HORIKAWA (1988), SHAND (1990), GAUN-HONG LEE and BIRKEMIER (1993), SHAND (1995), WIJNBERG (1995), BAILEY and SHAND (1996), BAILEY and SHAND (1997). For temporal data the cross-shore accuracy for bar-crest detection varied between ±1 m for foreshore leveling to ±10 m for nearshore echo-sounding and photogrammetry. Locational resolution varied between 5 m on the foreshore and 25 m in the outer surfzone.

Historical Background

Reports of the systematic offshore migration of coastal sand bars have occurred since the 1970s. EDELMAN (1974) (cited in WIJNBERG 1995) described the phenomenon in data from the Holland section of the Netherlands coast (see Figure 1B). Net offshore bar migration was next identified by BIRKEMEIER (1984) at Duck on the North Carolina coast. Further field evidence and descriptions of NOM were subsequently presented in: DE VROEG (1988), KROON (1991), KROON and HOESKSTRA (1993), KROON (1994), WIJNBERG (1995) on the Holland coast; HOEKSTRA *et al.* (1994), and RUESSINK and KROON (1994) on the Terschelling coast; LARSEN and KRAUS (1992), and LIPPMANN *et al.* (1993) at Duck on the North Carolina coast; and PATTERSON (1991), and BAILEY and SHAND (1996) at Wanganui on the south west coast of New Zealand's North Island. NOM was also described at the Wanganui Rivermouth by SHAND (1990). The bar-crest location histories used by these researchers in identifying and describing NOM have been reproduced in Figure 2. RUESSINK (1992) (cited in HOEKSTRA *et al.*, 1994) appears to have been the first writer to report on a NOM system consisting of three distinct stages.

Bar Formation

Reports on NOM have consistently observed bars to form 'near' the shoreline and thereby initiate the cycle of offshore migration (BIRKEMEIER, 1984; LIPPMANN *et al.*, 1993; RUESSINK and KROON, 1994; WIJNBERG, 1995). Field evidence not associated with NOM investigations also supports bar formation about the lower foreshore/inner nearshore (*e.g.* SHORT, 1975; FOX and DAVIS, 1976; SALLENGER and HOWD, 1989). A landward origin has been found to occur in both wave tank experiments (*e.g.* SUNAMURA, 1989; ZHANG, 1993) and in numerical modeling (*e.g.* DALLY and DEAN, 1984; HEDEGAARD *et al.*, 1991) where formation occurred in response to depth controlled break-point processes. Such bars subsequently migrated well offshore if higher energy conditions (wave height and steepness) were maintained. Bar generation seaward of the foreshore has been observed by the authors to occur only when existing bars 'bifurcate'. This process will be described and illustrated in a later section.

Specific morphological configurations appear to accompany bar formation. LIPPMANN *et al.* (1993) described incipient bar formation upon a low tide terrace. Many authors also described offshore movement of adjacent seaward bars either prior to or contemporaneous with the formation of new bars (*e.g.* BIRKEMEIER, 1984; LIPPMANN *et al.*, 1993; KROON, 1994). These spatial relationships suggest that standing waves are important in the generation mechanism. Sediment transport mechanisms associated with standing infragravity waves and break-point processes (mentioned earlier) form the bases of the main theoretical explanations of bar generation (see HOLMAN and SALLENGER, 1993).

An example of bar generation on the lower foreshore at Wanganui is shown in Figure 3. The pre-generation foreshore morphology (Figure 3A) was relatively two-dimensional and characterised by a low-tide terrace configuration. This is consistent with the observation of LIPPMANN *et al.* (1993) noted earlier. Figure 3B was taken four days later and shows a well defined longshore bar developed at the seaward margin of the terrace. A longshore trough had formed in the mid-terrace region. The relatively small differences in environmental conditions experienced during pre- and post-generation sampling (Table 1) are not considered sufficient to distort the morphology depicted by the intensity patterns. The inter-survey process data, shown in Table 1, shows that this bar was generated under conditions of high wind, high and steep waves, and strong longshore currents. Bar generation therefore appears to occur under storm conditions coupled with strong longshore currents. This observation is consistent with the environmental conditions which accompanied two documented instances of bar formation/development on the lower foreshore at Duck (see SALLENGER *et al.* 1985; HOWD and BIRKEMEIER, 1987).

The length of time that new bars may reside near the formation zone is variable. RUESSINK and KROON (1994) observed that new bars at Terschelling remained near the formation zone for 'some time' before trending seaward. The higher temporal resolution data sets from Duck (Figures 2E and 2F) also show new bars to have variable periods of residence within the inner surfzone. However, at times the landward bar can be seen to disappear from the record. LARSEN and KRAUS (1992) note that bar disappearance at Duck can be the result of a bar welding to the shore; presumably to form a low tide terrace. Bar-crests may also disappear from a time-series record when rhythmic features migrate longshore. Such 3D configurations often occur closer to the shore; this will be described in the following section. A new bar may

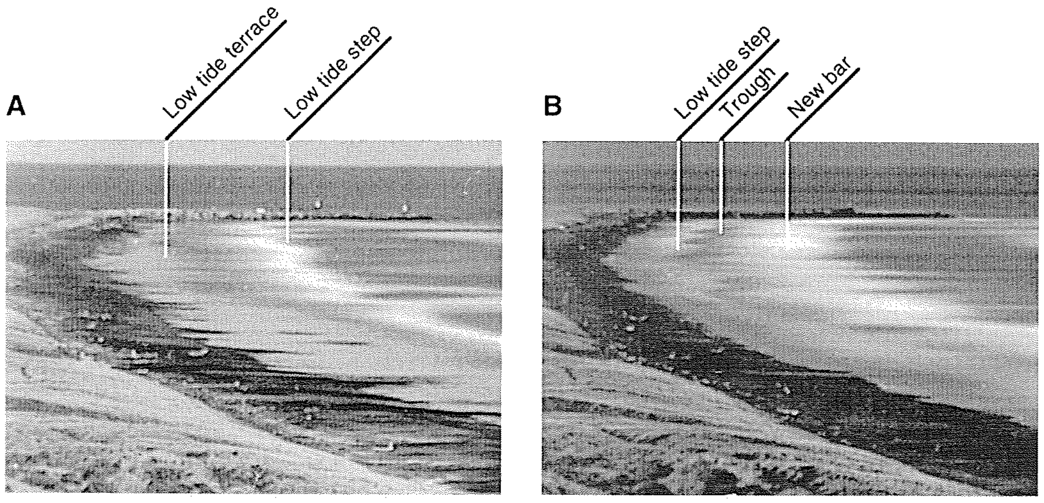


Figure 3. An example of pre-bar generation beach morphology (A) and post-generation morphology (B) on the lower foreshore at Wanganui, New Zealand, using non-rectified time-exposure photographs. Approximately 2500 metres of coast is depicted with the 200 metre long rivermouth jetty evident in the top of the image. The corresponding process variable data are provided in Table 1.

also disappear from the record following higher energy events as under such conditions the size and location of the bar offers little resistance to erosion (see Orme and Orme, 1988; Kroon, 1994). However, a number of positive feedback mechanisms are likely to occur following bar generation which encourage further growth (see Holman and Sallenger, 1993). This suggests that a bar's survival and continued development is assured once it reaches a certain size. While the Wanganui bar-crest time-series in Figures 2I and 2J also show variable residence time near the generation zone, a slow offshore migration trend appears to underlie this behaviour. Discontinuities also appear to occur within the Wanganui record; however these are somewhat obscured by the horizontal smoothing.

Systematic Offshore Bar Migration

The second stage of the Dutch model is characterised by behavioural regularity. Kroon (1994) described regularity in bar number and bar spacing. Kroon (1994), Ruessink and Kroon (1994), and Wijnberg (1995) described inter-bar coupling in which the seaward bar movement leads or coincides with landward bar change. This behaviour was also described at Duck by Birkemeier (1984), and Lippmann *et al.* (1993). Kroon (1994) also found that the bars at Egmond tended to temporarily reside at certain cross-shore locations. Such preferred locations are also evident at other sites by the undulations on time-averaged profile bundles (see Larsen and Kraus 1992; Kroon, 1994; Ruessink and Kroon, 1994). Furthermore, regular NOM behaviour at the Holland sites occurs despite annual storm variation (Wijnberg, 1995). These consistencies were considered by Ruessink and Kroon 1994, and Wignberg 1995 to indicate strong positive morphological feedback within the NOM system.

Large-scale boundary conditions appear to influence the underlying NOM behaviour. While longshore variation in the average rates of NOM occur along the Holland coast (see Table 2) there is no significant longshore variability in the mean annual wave climate (Kroon and Hoekstra, 1993). However, correlation between NOM characteristics and the internal boundary conditions of nearshore slope and coastal orientation are evident (Kroon and Hoekstra, 1993; Kroon, 1994; Wijnberg, 1995). The possible influences of ebb tide deltas and engineering structures on NOM behaviour were discussed in Wijnberg (1995).

Analysis of higher resolution data generally supported the Dutch model and also enabled identification of a number of superimposed (smaller-scale) bar-crest movements. Seasonality, i.e. net seaward bar migration during winter months and net landward movement during summer, was identified in the Duck bar-crest data by Birkemeier (1984) and Lippmann *et al.* (1993). Greater variability in bar-crest locations closer to the shore was observed by the Duck researchers who ascribed this to increased 3D development. This behaviour was also observed in three monthly data from Egmond by Kroon (1994), and it is discussed by Hoekstra *et al.* (1994) on the Terschelling coast and Wijnberg (1995) along the Holland coast. Birkemeier (1984) and Lippmann *et al.* (1993) found that the bars at Duck often experienced episodic seaward jumps. This behaviour was also observed by Kroon (1994) in the three monthly data set from Egmond. Kroon found differences in timing of the episodic jumps occurred between profiles separated by only 500 metres. Such out of phase behaviour is further evidence that antecedent morphology influences net offshore bar migration. From the Duck data, Birkemeier (1984) found that bar positions were relatively stable between the episodic jumps, with fluctuations reflecting storm-recovery cycles. Both Birkemeier (1984) and Lippmann *et al.* (1993) found that while high energy events always accompanied offshore episodic movements, at other times such high energy input may have little effect on

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Table 1. *Process variables associated with the bar formation morphology at Wanganui shown in Figure 3. Climatic values are included to indicate relative significance of the conditions experienced during the inter-sampling period.*

Date	Sampling Times (Photograph)	Wave Height (Metres)[1]	Period (Seconds)	Wind Direction (Degrees)[2]	Wind Speed (m/s)[3]	Longshore Currents (m/s)[4]	Pressure (hPa)[3]
930324	AM	1.41	11.7	38	5.15	+27	1018.3
	PM (15.15 hr)			297	2.92		1017.7
930325	AM	1.21	7.6	7	4.80	+73	1017.6
	PM			295	6.43		1017.2
930326	AM	1.21	6.8	335	5.15	+60	1017.2
	PM	1.94		293	13.90		1015.3
930327	AM	1.94	8.4	285	12.60	+70	1014.1
	PM			298	13.60		1012.5
930328	AM (09.30 hr)	1.27	7.0	295	8.90	+47	1012.4
	PM			193	4.44		1014.4
Climatic comparison values	Mean:	1.30	10.3		5.27		1015.7
	Other:	Upper 10% = 1.90		Predominant = 290	Upper 5% = 12.9	Upper 5% = 60	Range = 5.9

[1] Wave height (deepwater, significant) was estimated using the "line of sight method" described in Patterson and Blair (1983), and Patterson (1985). Wave climate parameters were based on daily observations between 28.7.89 and 25.5.97.

[2] Angle of coast = 147/327 degrees.

[3] Wind velocity and atmospheric pressure (at MSL) data were measured at Wanganui Airport by the National Institute of Water and Atmospheric Research. The airport is 5 km from the study site.

[4] Longshore currents were determined by timing floats in the swash zone at mid tide. Positive valued longshore currents are directed from northwest to southeast.

Table 2. *Approximate average values for parameters defining net offshore bar migration.*

Location[1]		Duration (y)	Rate (m/y)	Return Period (y)
Egmond	Dutch coast	15–20	30	15
Zandvoort		10	60–70	3–4
Katwijk		6–8	60	4–5
Tershelling		20	50	7.5
Duck south	North Carolina	4.6	67	3.2
Duck north		4.3	70	6.8
Wanganui 1	New Zealand	2.5	200	1.2
Wanganui 2		3.0	146	1.4
Wanganui 3		4.8	109	1.4

[1] Location details are shown in Figure 1.

the bar behaviour. The sensitivity of bar behaviour to the initial morphology, together with the apparent form/process feedback mechanisms, lead LIPPMANN *et al.* (1993) to suggest that the NOM bar system had the characteristics of a 'non-linear dynamical system' (see HUGGETT, 1990; MIDDLETON, 1990).

Bar Degeneration

When a bar migrates into the outer surfzone it begins to flatten out. An example of such outer bar degeneration at Wanganui is shown in Figure 4. Bar degeneration in The Netherlands data occurred at critical offshore distances and depths after which the crest depth increased, the shape flattened, and the crest tended to move further offshore (RUESSINK and KROON, 1993; KROON, 1994; WIJNBERG, 1995). However, at Duck outer bar disappearance consisted of shoreward crest migration during periods of amplitude reduction (BIRKEMEIER, 1984; LARSEN and KRAUS, 1992; LIPPMANN *et al.*, 1993). At Wanganui, the data presented in Figures 2I, 2J,

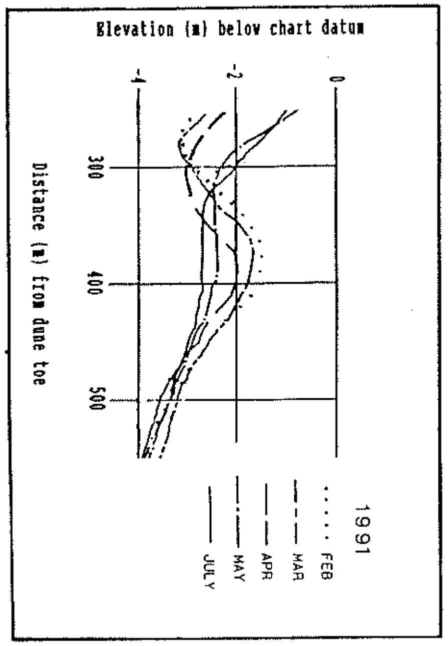

Figure 4. A typical outer-bar degeneration sequence at Wanganui, New Zealand. These echo-sounded profiles are located 1600 metres northwest of the Wanganui Rivermouth (Transect 2 in Figure 1C). Modified from Patterson (1991).

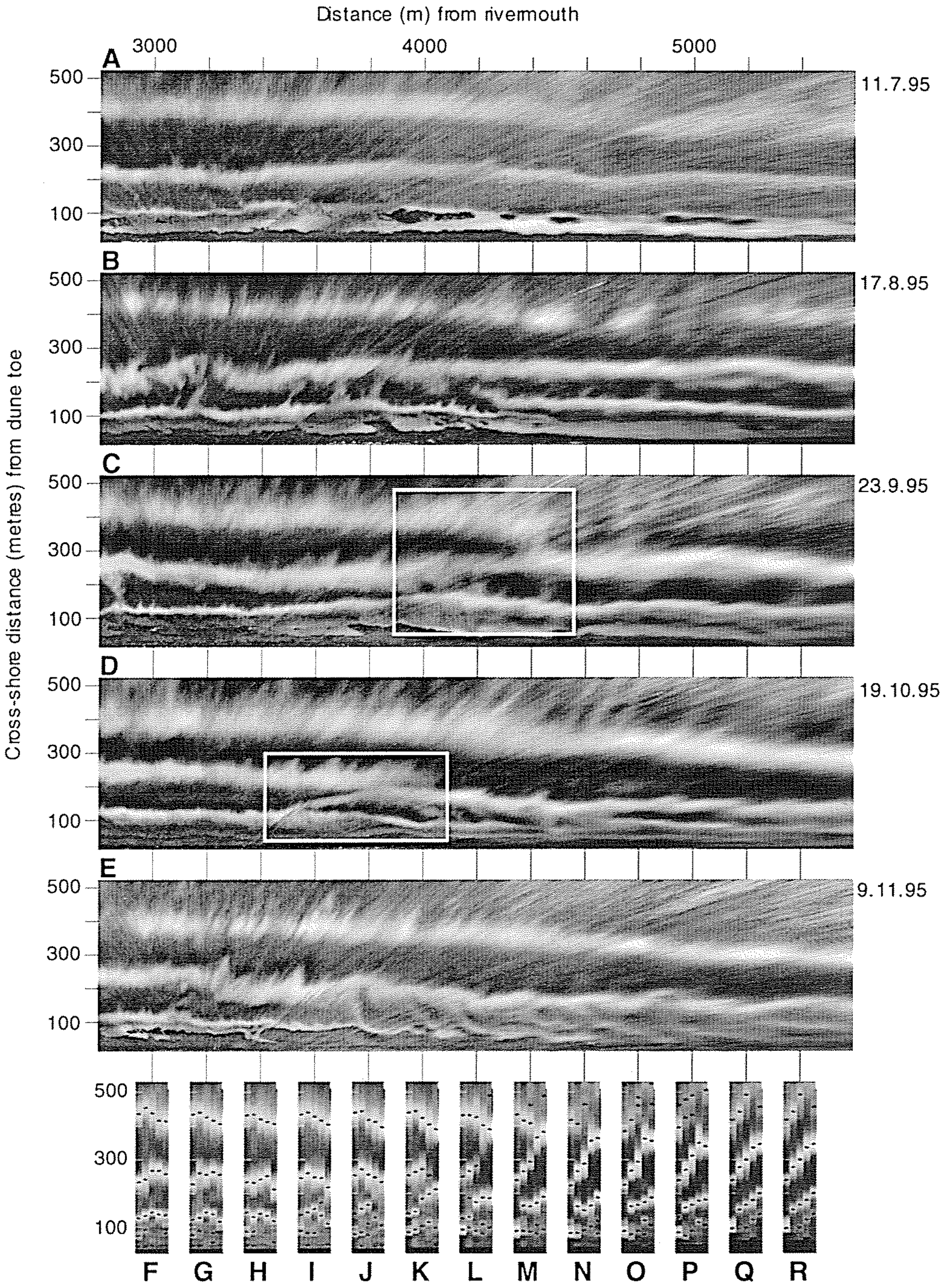

Figure 5 An example of bar switching at Wanganui, New Zealand, using a sequence of rectified time-exposure photographs with the coastline straightened (A - E). Bar switching occurs within the transition zones defined by the rectangles in C and D. The landward bars to the right of the transition zones are realigning with the seaward bars to the left. Time-stack images showing bar-crest behaviour at the marked cross-shore transits are shown in F to R. The black dots in the time-stacks mark the location of relative intensity maxima which represent morphological features such as bar-crests and the low tide step.

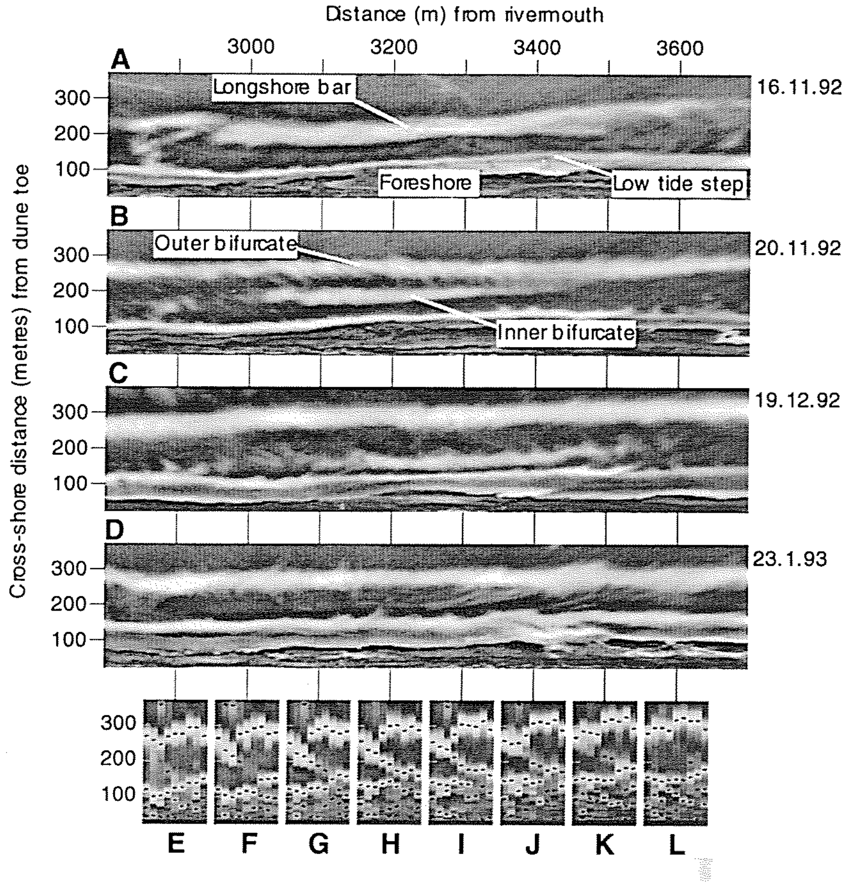

Figure 6. An example of bar bifurcation at Wanganui, New Zealand, using rectified time-exposure photographs (A–D). The bifurcation has occurred in B and the inner bifurcate is merging with the lower foreshore in D. Time-stack images showing bar-crest behaviour at the marked cross-shore transects are shown in E to L. Nine samples were used to construct each time-stack with slices from A,B,C,D appearing in the time-stacks as samples 3,4,6,9 respectively. The black dots in the time-stacks mark the location of relative intensity maxima.

and 4 show both landward and seaward migrations occur in the outer surfzone. While the field evidence shows landward migration can accompany degeneration, bars do not appear to undergo significant return movement. Analysis of the higher depth/temporal resolution data from Duck suggests that while bar degeneration is a one way process, outer bar regeneration does occur at times (LARSEN and KRAUS, 1992).

Processes associated with asymmetric waves appear to accompany degeneration of the outer bar. At Duck, BIRKEMEIER (1984), and LARSEN and KRAUS (1992) observed that both lowering of bar height and reduction in bar volume were associated with extended periods of non-breaking wave conditions. LARSEN and KRAUS (1992) also noted that steady onshore sediment transport appeared to occur across the bar during the disappearance phase. WIJNBERG (1995) used sediment budget evidence from the Holland coast to argue that some sediment from the outer bar moved further landward than the adjacent trough during the degeneration stage. In some cases the final disappearance of a bar has been observed to accompany a major storm event (LIPPMANN *et al.*, 1993; KROON, 1994). However, LARSEN and KRAUS 1992 also noted that at Duck outer-bar rejuvenation occurred under higher energy (fall and winter) conditions. Recently WIJNBERG (1995) has hypothesised that bar maintenance occurs under intense breaking of waves while bar degeneration occurs with highly asymmetric waves. Once degradation begins positive feedback mechanisms then prevent significant bar redevelopment or shoreward migration as increasingly severe storm waves are required to maintain the bar and increasing wave size is required to produce effective wave asymmetry. Field measurements by HOEKSTRA and HOUWMAN (1994), together with results from an applied theoretical analysis by WIJNBERG (1995), provided further support for this hypothesis.

The characteristics of the outer bar appear to control landward bar behaviour in a multi-bar system. Observations from the Holland sites (KROON, 1994; WIJNBERG, 1995), the Terschelling site (RUESSINK and KROON, 1994), and at Duck (LIPPMANN *et al.*, 1993) indicated that systematic offshore migration of landward bars only occurred when outer bars were poorly developed, i.e. when the trough depth to bar-crest depth ratio is low. Furthermore, a well developed seaward bar was observed to prevented offshore migration. KROON (1994), and RUESSINK and KROON (1994) speculated that the depth/location of the seaward bar controls the cross-shore wave height distribution and the cross-shore structure of standing infragravity waves. Whether landward bars are fixed or free to move offshore may therefore be governed by break-point or standing wave-based sediment transport mechanisms (see KIRBY *et al.*, 1981; THORNTON and GUZA, 1983).

Defining Net Offshore Bar Migration

A variety of parameters and terminology has been used to define and describe overall NOM by different researchers (DE VROEG, 1988; KROON and HOEKSTRA, 1993; KROON, 1994; RUESSINK and KROON, 1993; WIJNBERG, 1995). The time a bar exists for has been referred to as the duration or the lifespan. The frequency with which a bar recurs at any location in the surfzone has been called the return period or the passage interval. The average rate of offshore migration is also used as a NOM parameter.

Parameter values for the nine NOM sites in Figure 1 are provided in Table 2. The values for the Holland sites are those reported in KROON and HOEKSTRA (1993). Values for the other sites were approximated from the published data sets shown in Figure 2. The intensity data from Wanganui (Figure 2 I and J) were transformed to ground-profile distances by using the empirical calibration referred to earlier in the Methods section. Wide inter-site variation is evident for all parameters with average duration ranging between 2.5 and 20 years, average rate ranging between 30 and 200 m per year, and average return period ranging between 1.2 and 15 years. As noted earlier, the Dutch researchers (KROON and HOEKSTRA, 1993; KROON, 1994; WIJNBERG, 1995) considered that large-scale boundary conditions are associated with the variation in overall NOM behaviour evident in the Holland data.

Oblique Bar Orientations

Net offshore bar migration has been associated with three-dimensional bar behaviours. The most obvious 3D influence is where obliquely oriented sand bars with a shore attachment migrate alongshore. Such morphologies have been reported on different coasts and occur at a variety of scales (*e.g.* BRUUN, 1955; SHORT, 1976; HUNTER *et al.*, 1979; SHORT, 1979; STEWART and DAVIDSON-ARNOTT, 1988; KROON, 1991; TROWBRIDGE, 1995; ANITA, 1996). In some of these cases, however, the proximal (landward) end of the bar lags behind the distal (seaward) end in the longshore translation so a net onshore bar migration occurs at each cross-shore location. KROON (1991), LIPPMANN *et al.* (1993), and KROON (1994) have suggested that the NOM phenomenon may simply be a consequence of the longshore migration of oblique bars where the proximal end leads. However, WIJNBERG (1995, p.166) used the results of a sediment budget/profile volume analysis of data from the Holland coast to argue that such "cyclic bar dynamics are essentially a cross-shore sediment redistribution process within the nearshore zone."

Bar Switching

Bar switching is also a 3D morphological behaviour which influences net offshore bar migration. In this situation, bar alignments alter, following the development of a discontinuity in which landward bars on one side of the discontinuity join with the seaward bars on the other. The term 'bar-switching' is used by the authors to describe this phenomenon. WIJNBERG and WOLF (1994), and WIJNBERG (1995) referred to this behaviour as 'longshore out-of-phase development' and the area in which the switch occurred as a transition zone. These researchers found on the Holland coast that the transition zones had a longshore length scale of one to three kilometres, and that they could migrate alongshore. WIJNBERG and WOLF (1994), and WIJNBERG (1995) used the term 'out-of-phase' to describe bar switching phenomena because they observed that bars to each side of a transition zone were longshore 'incoherent' and 'out-of- phase' with respect to their offshore migration cycles. WIJNBERG and WOLF (1994), and WIJNBERG (1995) further observed that the development of large-scale rhythmic topography appeared to be a prerequisite for the onset of switching and that out-of-phase bar morphologies were most persistent where NOM rates were low. Other examples of apparent bar switching are shown in RUESSINK and KROON (1994) at Tershelling, in LIPPMANN *et al.* (1993) at Duck and in CARTER (1986) on the Magilligan coast of Northern Ireland.

An example of bar switching at Wanganui is illustrated by the images in Figure 5. Figures 5A to 5E show a four month sequence of rectified images with the coastline straightened. Each image represents the morphology over a 2800 m (longshore) by 500 m (cross-shore) area. The pre-switch morphology has a shore-parallel bar configuration (Figure 5A). In Figure 5B the outer bar has lowered to the right of *c.* 4200 m. Bar switching is occurring within the transition zones defined by the rectangles in Figures 5C and 5D. Translation of the transition zone suggests that bar switching begins in the outer surf zone and progresses landward. Some longshore migration towards the rivermouth, *i.e.* to the left, is evident. The post-switch morphology (Figure 5E) has regained the shore-parallel configuration. During the switch the time-stacks (Figures 5F to 5R) demonstrate how bar behaviour is differs on either side of the transition zone. The bars to the left of the transition zone (Figures 5F to 5H) either remain approximately stationary or trend landward. The present authors refer to this situation as a 'negative' switch. In contrast, the bars to the right of the transition zone move rapidly seaward (Figures 5N to 5R) and this is referred to as a 'positive' switch. The time-stacks within the transition show variable and complex bar behaviour which is often characterised by discontinuities.

Bar Bifurcations

Bar bifurcation is another 3D morphological behaviour which influences net offshore bar migration. In this situation a section of bar splits longitudinally. The seaward bifurcate 'jumps' seaward while the inner bifurcate moves into the landward trough. The inner bifurcate then either disappears or migrates further shoreward to merge with the adjacent bar/low tide step which results in the seaward movement of that feature. Such bar behaviour was recently described by Bailey and Shand (1996). Kroon (1991), Kroon (1994), and Wijnberg (1995) have described the occurrence of 'double bars' on the Holland coast which are probably the result of bar bifurcations. Kroon (1994) found double bar development at Egmond appeared to be necessary to reinitiate seaward bar migration after a period of inactivity. Other field examples of possible bar bifurcations are shown in Greenwood and Davidson-Arnott (1975), Owens (1977), Holman and Sallenger (1986), Holman and Lippmann (1987), and Bauer and Greenwood (1990). Greenwood and Davidson-Arnott (1975) referred to the inner bifurcate as a 'tail', while Holman and Lippmann (1987) used the term 'winged bar' for this feature. In all the documented examples the apparent bifurcations occur where bars broaden, e.g. at the horn area of a cresentic bar.

An example of bar bifurcation at Wanganui is illustrated by the image sequence in Figure 6 which was sampled over a nine week period. The rectified and straightened images (Figures 6A to 6D) show the morphology over a 900 m (longshore) by 375 m (cross-shore) section of coast. The pre-bifurcation morphology (Figure 6A) shows a broad inner bar. As noted earlier, this appears to be a pre-requisite for the onset of bar bifurcation. The bifurcation is shown in Figure 6B and within two months the inner bifurcate merged with the lower foreshore (Figure 6D). The accompanying time-stacks show the outer bifurcate and low tide step trending seaward during the bifurcation process (Figures 6G to 6K) while the morphology on either side of the bifurcation zone maintains a shore-parallel configuration (Figures 6E, 6F, and 6L). These patterns contrast with the time-stack histories associated with bar-switching. Furthermore, these examples of a bar switch and a bar bifurcation suggest that the spatial and temporal scales of switching are at least double that associated with bar bifurcation. However, as with bar switching, the onset of bar bifurcation appears to require the prior development of three-dimensional morphological configurations. Both bifurcation and switching result in the surfzone morphology returning to a more two-dimensional configuration.

Edge waves may be an important control in the bifurcation mechanism. Kroon (1991) speculated that the development of double bars resulted from a changing cross-shore structure of a low mode edge wave in the infragravity range. Bauer and Greenwood (1990) observed bar bifurcation to occur at a multi-bar field site in the presence of a standing infragravity edge wave. Laboratory experiments have shown a bifurcation to develop on a crescentic bar which was evolving in response to a standing edge wave field (Bowen and Inman, 1971). A change in the type of edge wave may also be important. For example, on multi-bar coasts Aagaard (1991) found progressive infragravity waves to be associated with large storms while standing infragravity waves were associated with moderate energy situations. With the onset of high energy conditions the structure and associated drift velocities of progressive edge waves (see Bowen, 1980; Carter *et al.*, 1993) would be expected to be associated with trough development on landward extending shoal zones thereby generating a bifurcation. The extensive 300 metre long shore-parallel split defining the bifurcation in Figure 6B is consistent with the suggested progressive edge wave influence in bar bifurcation morphodynamics.

CONCLUSION

Similar bar behavioural characteristics appear to occur at all sites where NOM has been observed. The three stage Dutch conceptual model seems to apply to the data from Wanganui—New Zealand, and Duck—North Carolina. Furthermore, 3D configurations and behaviour such as bar switching and bar bifurcations, are also evident at all NOM sites. Such inter-site consistency supports Wijnberg's (1995, p. 164/5) contention that the sequential process of the NOM cycle may be a common generation mechanism for multiple bar systems.

This review suggests that while the overall net offshore bar migration 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 scales. Episodes of offshore bar migration are driven by storm events, *i.e.* smaller-scale. The timing and nature of offshore bar migrations are influenced by small to moderate-scale antecedent morphology. Finally, the overall NOM characteristics are related to large-scale physical boundary conditions such as cross-shore slope and coastal orientation.

Inter-site variation in NOM parameter values provides a means to further investigate large-scale NOM morphodynamics. A detailed inter-site comparison of NOM characteristics, physical boundary conditions, and process variables has recently been completed by the authors and will be reported in a following paper (Shand and Bailey submitted).

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