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Alongshore variability of the multiple barred coast of Terschelling, The Netherlands

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Abstract

The alongshore variability of the behaviour of a multiple bar system in the nearshore zone along the barrier island of Terschelling, The Netherlands, is investigated using a bathymetric data set with an alongshore extent of 12 km sampled annually for 28 yr. The spatial and temporal variability of bar behaviour is quantified in terms of bar crest position in relation to morphometric parameters such as bar depth, height, width and volume. Along the entire study area, the bars were generated close to the shore, migrated seaward and eventually degenerated at the outer margin of the nearshore. The interannual migrational patterns of the nearshore sandbars are analysed in terms of time of residence, migration rates and return periods within the life cycle of a bar. The cross-shore nearshore bar behaviour was found to vary alongshore. For instance, cross-shore migration rates gradually increased from 35 to 70 m/yr from one end of the study area to the other. Concurrently, the duration of net seaward migration increased from 9 to 15 yr. The return period and total life span of bars were, however, found to be alongshore uniform on the order of 10–12 yr and 22 yr, respectively. Morphological characteristics of the nearshore bar zone such as slope and width also exhibit gradually alongshore-varying patterns. A strong causal association is established between nearshore slope and both bar migration rates and duration of net seaward migration. It is hypothesised that alongshore-increasing wave heights at the seaward end of the bar zone is coupled with a corresponding increase in nearshore slope. The presence of an important updrift ebb-tidal shoal is identified as key controlling factor in the variability of bar behaviour along the adjacent shoreline of Terschelling.

Keywords: multi-bar coast; nearshore bars; morphodynamics; bar migration

1. Introduction

Identifying nearshore morphological phenomena on multi-bar coasts requires comprehensive bathymetric data. Few such data sets are available, commonly due to difficulties involved in collecting surf zone data, to temporal limitations occurring because of low sampling rates or short project time spans, and to the required spatial magnitude of cross-shore as well as alongshore extent of surveys and soundings. Progress in investigating bar behaviour at multi-bar locations has therefore only been reported at few sites

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(Lippmann et al., 1993; Ruessink and Kroon, 1994; Wijnberg and Terwindt, 1995; Plant et al., 1999; Shand and Bailey, 1999; Kuriyama and Lee, 2001) because of the lack of systematic long-term monitoring of these bar systems. Nevertheless, morphological features that change on large temporal or large spatial scales, such as the cyclic offshore migration trend underlying sandbar behaviour on multi-bar coasts, have been identified and reported.

The existence of a systematic multi-year cyclic bar system behaviour has been observed on the multiple bar system in the nearshore zone along the island of Terschelling, The Netherlands (Ruessink and Kroon, 1994). This cyclic behaviour is a type of bar behaviour that has also been observed on other locations, such as along the Holland coast of The Netherlands (Wijnberg and Terwindt, 1995), at Duck on the eastern US seaboard (Lippmann et al., 1993; Plant et al., 1999), at Wanganui on the New Zealand west coast (Shand and Bailey, 1999) and at Hasaki on the Pacific coast of Japan (Kuriyama and Lee, 2001). This indicates that the cyclic multi-year bar behaviour observed along the island of Terschelling is not a unique phenomenon resulting from some unique set of site-specific conditions.

A general three-stage conceptual model was proposed by Ruessink and Kroon (1994) to describe the different stages each individual bar passes through during its existence: (1) generation close to the shore, (2) seaward migration and (3) degeneration at the outer margin of the nearshore zone. The behavioural characteristics of each stage of bar migration cycle were quantified at one particular cross-shore profile in the centre of the island. Wijnberg (1998) later identified a longshore coherence in the large scale cyclic behaviour of the bar system along Terschelling although the study did not fully incorporate the outer bar zone. Still, the alongshore variability of bar migration cycle characteristics coupled with alongshore changes in nearshore morphology needs further investigation. The understanding of the long-term behaviour of a multiple bar system over alongshore stretches of kilometres gives valuable insight into the relative importance of longshore representativeness of a single coastal profile in the cross-shore direction. Much coastal research effort has been based on 2D morphological field and model studies carried out either in a longshore or cross-shore direction under the assumption of longshore uniformity.

In this paper, a phenomenological analysis of the cyclic behaviour of the multiple barred coast of Terschelling is presented based on a time span of 28 yr and a longshore stretch of 12 km. The focus is on the behaviour of morphologic features rather than on the responsible hydrodynamic processes. The aim is to describe the coherence of alongshore variation in bar behaviour.

2. Study area and data set

2.1. Field site

Terschelling is an island along the northern part of the Dutch coast characterised by a chain of barrier islands separating the North Sea from the back-barrier system of the Wadden Sea (Fig. 1). The study area is situated along the northern coast between km-section 10 and 22. The central part of Terschelling has retreated by about 2–3 m/yr over the last decades (roughly between section 15 and 22), while both the western and eastern end of the island have accreted by 2–3 m/yr. The shoreline is slightly curved and concave; the overall orientation of the shoreline is WSW–ENE. The north coast of the island consists of sandy beaches and dunes.

The nearshore zone is characterised by the presence of two to three breaker bars (see inset in Fig. 1). The inner nearshore zone of Terschelling typically exhibits rhythmic patterns with wavelengths of 1.5–2 km Ruessink (1992). Alongshore crescentic inner bars are intersected by rip channels with a spacing on the order of 700 m. Such alongshore variability generally originates in the inner nearshore zone (within 600–700 m from the shoreline) and migrates offshore while migrating alongshore in an eastward direction at a rate of about 800 m/yr. The overall nearshore slope between the high-water line and the outer margin of the nearshore bar zone at a depth of approximately 8 m below NAP (Dutch Ordance Level ~ Mean Sea

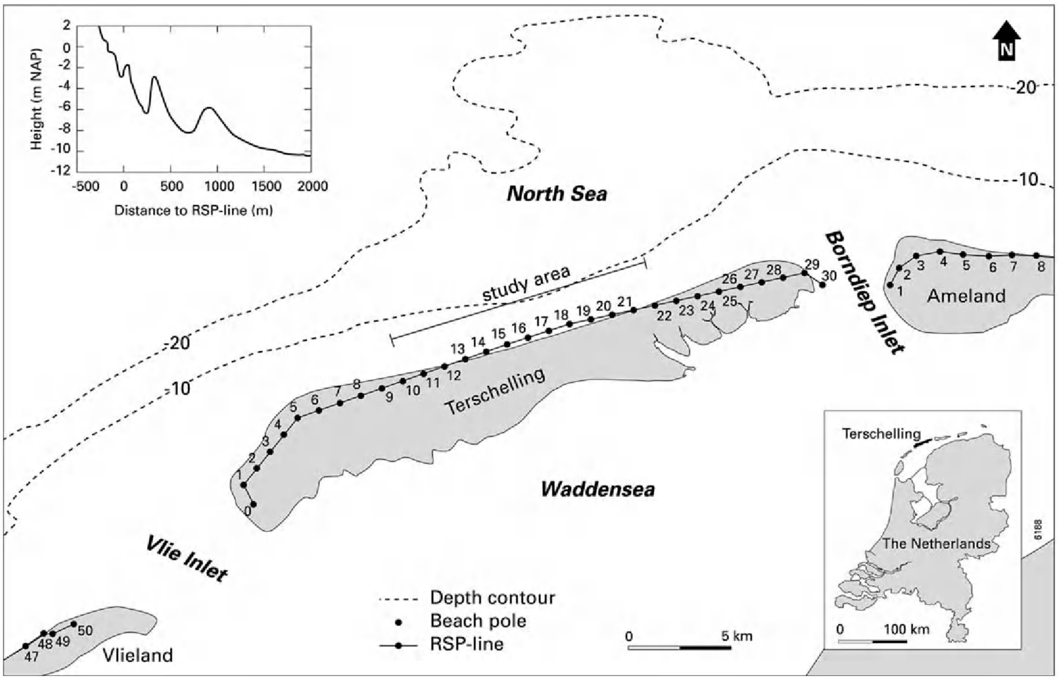

Fig. 1. Location of study area. The seaward extent of the outer deltas adjacent to Terschelling can be inferred from the bulges in the 10-m depth contour. A typical cross-shore profile at km-section 16 is shown in the inset.

Level) is steepest in the centre of the island at about 1:180 and gradually flattens to approximately 1:230 towards both ends of the island in section 10 and 22, respectively. The slope of the foreshore between the high-water line and a depth of about 5 m below NAP is, however, nearly constant alongshore and is on the order of 1:80. The median grain size varies from 220–260 μm on the foreshore to 150–160 μm in the outer nearshore bar zone.

The mean annual significant offshore wave height at the −15 m isobath ($H_{s,o}$) is about 1.1 m and the mean annual significant offshore wave period ($T_{s,o}$) is about 7 s. During severe autumn and winter storms $H_{s,o}$-values increase up to 5–6 m with corresponding $T_{s,o}$-values of about 10–15 s. These highest waves are commonly incident from W to NW.

Tides along the north coast of Terschelling are semidiurnal and mesotidal with a neap tidal range of about 1.2 m and a spring tidal range of about 2.8 m. The flood (ebb) tidal flow is in an ENE (WSW) direction. Associated tidal currents are slightly stronger during flood than during ebb and tidal current ellipses are basically oriented parallel to the shore and are almost flat and rectilinear (Hoekstra et al., 1996). Important wind-driven currents are generated in the study area as the coastline is oriented parallel to the predominant westerly winds. Wind-driven flow velocities frequently have the same order of magnitude as the tidal currents. Even for moderate westerly winds (6–7 Bft) the wind-driven currents generated towards the east suppress the ebb flow and strongly enhance the flood flow. For stronger winds, wind-driven longshore and cross-shore flows in combination with wave-driven flow processes will dominate nearshore flow patterns (Houwman, 2000).

The barrier island of Terschelling is flanked by two tidal inlets, the Vlie Inlet to the west and the Borndiep Inlet to the east (Fig. 1). Both inlets have important ebb tidal deltas extending seaward over 9 and 6 km respectively. A large field of sandwave-like undulations northwest of Terschelling is postulated to be part of the bypass mechanism for the Vlie Inlet. The maximum amplitude of the undulations is on the order of 2 m and their wavelength is nearly constant at about 1 km (Biegel and Spanhoff, 1996). This bar pattern migrates in a southeasterly direction with an average rate of about 500 m/yr and eventually makes landfall along the western part of the island, approximately near section 14. The longshore sediment transport in the nearshore zone is predominantly towards the east. Estimates of net yearly averaged longshore transport rates vary from 0.5–0.6 Mm^3/yr (Tànczos et al., 2001) to 1.0 Mm^3/yr (Spanhoff et al., 1997).

Human intervention along the eroding central part of Terschelling was limited to the maintenance and management of sand dunes from the 18th century up to the mid 20th century (Biegel and Spanhoff, 1999). There are no groins or other hard structures interfering with the natural development of this coast.

2.2. Long-term bathymetric surveys

The morphological data set consists of series of echo-sounding data obtained from two ongoing bathymetrical monitoring programmes, the yearly JARKUS programme and an additional 5-yr programme. All survey lines are oriented perpendicular to a longshore reference line (RSP-line, see Fig. 1) in both programmes. The monitoring programmes supplement each other by their different survey characteristics.

Within the JARKUS programme activated on Terschelling in 1965, annual soundings have been carried out with a longshore spacing of 200 m along the coast of Terschelling. The profiles are measured from the foredune to approximately 1 km seaward of the shoreline at a maximum depth of 6 m below NAP. These profile soundings do not include the outer nearshore bar zone. Since 1985 the JARKUS soundings have been extended to reach the −8 m isobath, thus including the outer nearshore bar zone. In the additional 5-yr programme, soundings have also been carried out since 1965. These soundings are carried out with an alongshore spacing of 1000 m and extend 2 km seaward to a maximum depth of 12 m below NAP. In both programmes the cross-shore distance between consecutive points of depth measurement ranges from 10 m near the shoreline to 20 m offshore. A sounding accuracy of about 0.3 m has been established for both monitoring programmes and the inaccuracy in the positioning is up to 10 m (Wijnberg and Terwindt, 1995). The data set consists of 28 yr of soundings in the period 1965–1993; the last year of autonomous bar behaviour is 1993 because of the implementation of a shoreface nourishment in that year (Hoekstra et al., 1994).

3. Methodology

3.1. Cross-shore shifting of shoreline

Morphological profile behaviour can be expressed in terms of change in shape of profile and change in cross-shore position of the profile. The former relates to the barred topography and is the main interest of the present study. The latter deals with the prograding or retreating nature of a coast. Removing the cross-shore shifting of the shoreline from the bathymetric time series allows for the temporal analysis of long-term morphological development of a coastal profile regardless of the overall accretionary/erosional state of the shoreline.

The +1 m NAP contour line, hereafter referred to as the shoreline, was chosen as the reference line for cross-shore distance as it approximates the high water level along the coast of Terschelling. The high water level was selected instead of mean sea level or low water level as it separates the daily sub-aerial from the sub-aqueous part of the profile and its cross-shore position is less subject to back and forth movement owing to the presence of short-term morphological features such as swash bars. Such short-term phenomena are in the present long-term context considered as noise for the description of morphologic features that change on large spatial and temporal scales.

Trends of shoreline position were derived in two steps. Firstly, time series of shoreline position were fitted using linear regression, thereby yielding a temporal trend for each survey line (Fig. 2a with $r^2 = 0.79$). Secondly, to ensure alongshore co-

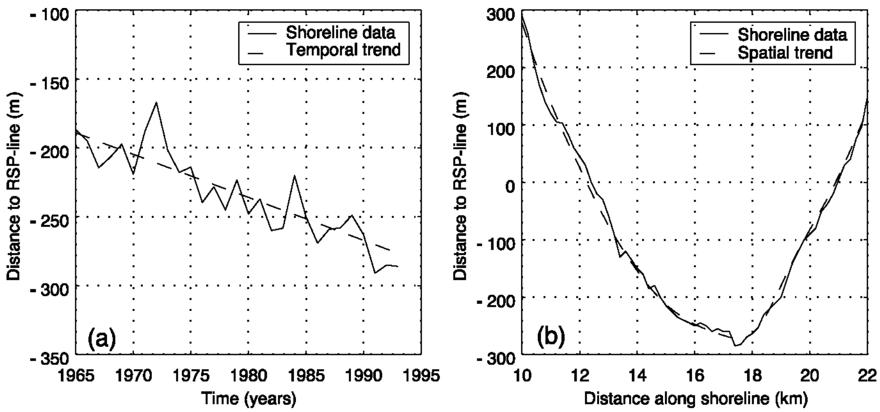

Fig. 2. Temporal and alongshore position of shoreline here shown (a) for section 16 and (b) in 1985, respectively.

herence in shoreline position, a spatial trend was obtained using a fifth order lowpass Butterworth filter with a cut-off wave length of 1000 m (Fig. 2b with $r^2 = 0.99$). Deviations from the temporal trend as a result of episodic changes following storm events and seasonal changes are considered to be related to shorter term fluctuations from the trend. All profile data was hereafter analysed relative to a floating datum (i.e. the +1 m NAP contour) determined by the long-term shoreline trend. The temporal changes in cross-shore position of the overall coastal profile were thereby removed from the long-term bathymetric data set.

3.2. Mean profile shape

The mean profile shapes were defined at 200 m alongshore intervals from section 10 to 22 and extended approximately 2 km seaward. The surveyed cross-shore profile data were made equidistant with an interval of 10 m using linear interpolation between two consecutive measuring points of depth. By averaging the JARKUS profiles over the period 1965–1993, 28-yr averaged mean profile shapes were obtained. Prior to 1985, the bathymetry of the outer nearshore zone, when unresolved by the yearly soundings, was obtained by longshore interpolation between the extended 5-yr soundings. Time-averaged profiles exhibit minor variations along their overall shape (Fig. 3a). Also, the location of a preferential bar residence in the outer margin of the nearshore bar zone is observed to leave a stationary signature in the form of an upwardly directed protuberance.

Several mathematical expressions have been proposed in the literature to describe the mean shape of a coastal profile (Dean, 1977; Larson, 1991; Bodge, 1992); however, the resulting fit is commonly most apparent near the shoreline with a seaward increasing over-prediction of profile curvature and depth. Specifically, profiles which exhibit bar/trough features are fit relatively poorly by these expressions as most of them do not account for a barred topography. To retain the intrinsic characteristics of the mean profile shape, a filter was designed with an appropriate cut off wave length, which allowed for the smoothing of variations along the profile but did not remove the bar-like protuberance. Fitting a smooth profile through the mean profile was obtained using a fifth order lowpass Butterworth filter with a cut-off wave length of 400 m. An illustration of the filtering is presented in Fig. 3a where the averaged and subsequently filtered nearshore profiles of section 18 are shown. A distinct protuberance remains present in the outer margin of the nearshore bar zone with a wave length in the range of 600–800 m.

At all alongshore sections, the shoreward end of the profile was set at the shoreline; the seaward end was chosen such that the location where the standard deviation drops to approximately constant values was included in the cross-shore pro-

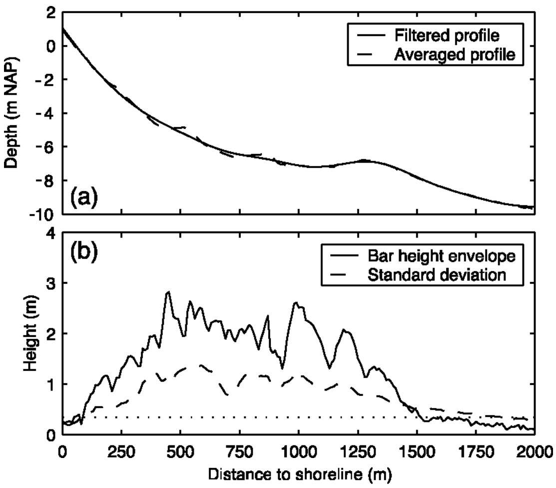

Fig. 3. Profile shown for section 18: (a) average profile and smoothing of 28-yr averaged profile, and (b) standard deviation and envelope of the bar height. The dotted line in (b) is the threshold value 0.3 to compute the cross-shore extent of the bar zone.

files (Fig. 3b). A threshold value of 0.3 m, below which bar amplitudes were considered unreliable in relation to measurement errors, was chosen to separate the barred part of the profile from the non-barred part. The shoreward and seaward limit of the bar zone and, respectively, the mean depths at these locations, were computed at the intersection of the bar envelope with this threshold. The nearshore slope of the bar zone was computed based on these limits.

3.3. Extracting bar parameters

With the recognition of bars representing the dominant morphological features of nearshore profiles, morphological changes are often reported in terms of morphometric bar parameters in relation to bar crest locations (Larson and Kraus, 1992; Ruessink and Kroon, 1994; Enckevort and Ruessink, 2003). In the present study, cross-shore bar parameters were defined as outlined in Fig. 4. The computed parameters were P_b the bar crest position with respect to the shoreline in (m), d_b the depth of bar crest below NAP in (m), h_b the bar height in (m), W the bar width in (m) and V the bar volume in (m^3/m). Based on the findings of Ruessink and Kroon (1994), in which a general shoreward skewed bar shape was observed regardless of the distance of the bar crest to the shoreline, the asymmetry of bars in terms of skewness was not included in the present study. Bars with computed heights below a threshold value of 0.3 m (~order of sounding accuracy) were considered unreliable and bars located within the intertidal zone were not included in the analysis (i.e. with depth of bar crests above −1 m NAP).

To identify the alongshore morphological behaviour of each individual bar in the study area from 1965 to 1993, bar numbers were assigned to all computed cross-shore bar positions. These bars were numbered approaching from offshore, so that a bar positioned shoreward of another always has a higher number than the more seaward positioned bar. The assignment of a bar number for the same bar at all alongshore locations and for all soundings was performed for all subtidal bars. This procedure resulted in alongshore bar crest lines for all bars present in the data set. The alongshore spacing of 200 m between survey lines implied that alongshore features smaller than 200 m were not represented in the bar crest lines. However, with the aim of studying long-term variability of large-scale bar behaviour, the main focus was on the structure of persistent features that were present in consecutive soundings.

The great variability characterising the along-

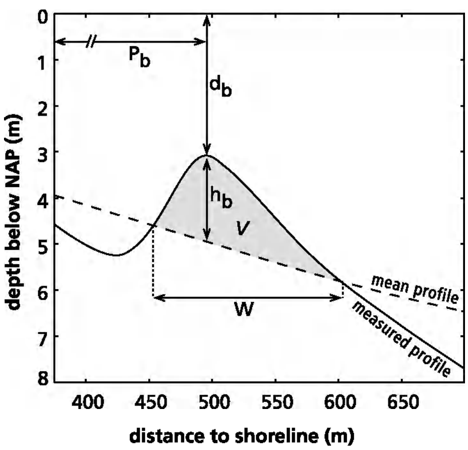

Fig. 4. Definition of morphometric parameters.

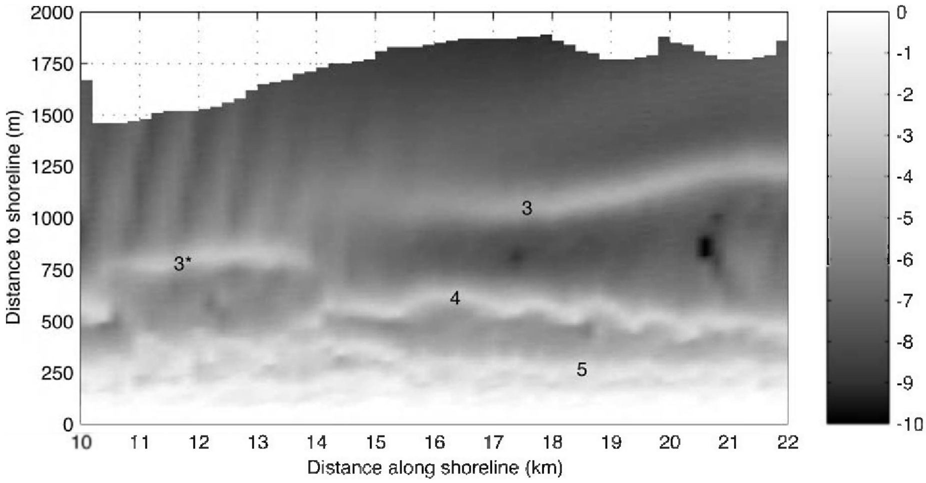

Fig. 5. Plan view of 1992 bar morphology with assigned bar numbers.

shore bar shapes in the nearshore zone of Terschelling is illustrated in Fig. 5 with a plan view of a yearly snapshot of bar morphology. The alongshore variability is expressed by the presence of large-scale 3D-features such as the landfall of sandwaves to the west (until km 14), a discontinuity in outer bar alignment (bar 3/3*, km 13–15), an undulating outer bar (bar 3, km 15–22), alongshore-irregular (bar 4, km 14–17) and regular (bar 4, km 17–21) crescentic shapes in the middle bar, and an irregular inner bar with rips (bar 5).

Morphometric data for all bars present in the study area in the period 1965–1993 were divided in six cross-shore sections, A (km 10–12), B (km 12–14), C (km 14–16), D (km 16–18), E (km 18–20) and F (km 20–22), each section including 11 transects spaced 200 m apart. To characterise alongshore-varying cross-shore parameters, fitting of the morphometric data was subsequently performed by second order polynomials; an example hereof is shown in Fig. 6. The fitted curve represents bar characteristics specific for a 2-km longshore-averaged section. A measure of the fit was obtained by linear regression between fitted and observed data.

3.4. Quantifying cyclic bar behaviour

The cycle in the development of a multi-bar system describes the return to a formerly exhibited bar topography due to systematic and repetitive behaviour of the bars. This cycle is composed of the distinct stages in the total life span of each individual bar, consisting of the generation near the shoreline, the subsequent net offshore migration, and the final degeneration at its most offshore position. A definition of the parameters and terminology used to describe the bar cycles is schematically illustrated in Fig. 7. Various researchers have used similar parameters to quantify the variables of bar migration cycles (Ruessink and Kroon, 1994; Wijnberg and Terwindt, 1995; Shand et al., 1999). The following parameters

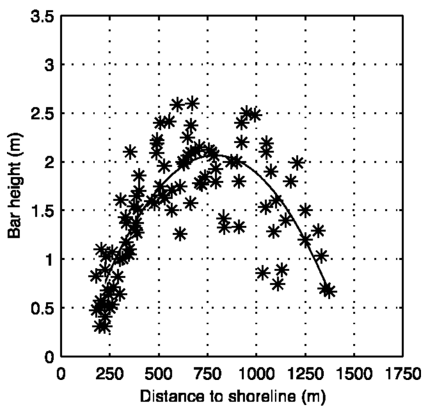

Fig. 6. Polynomial fitting of data, here shown for bar height in section E ($r^2 = 0.78$).

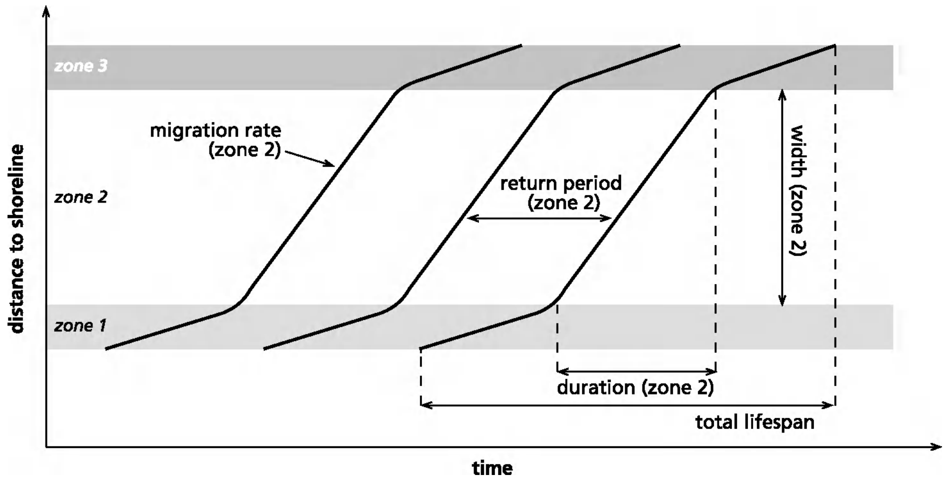

Fig. 7. Parameters used to define bar life cycle.

were defined for each of the three stages of the life cycle of bars:

- Width of zone (m): cross-shore range for a bar in a distinct stage identified by a landward and seaward boundary of the zone;
- Duration (yr): defined as the time of residence of a bar within a zone;
- Migration rate (m/yr): computed net offshore migration rate of a bar from the landward to the seaward boundary of zone;
- Return period (yr): defined as the time interval between two successive appearances of bars in a distinct zone.

The different stages of migrational behaviour are related to cross-shore zones delimited by boundaries at which transition from one bar stage to another occurs. Stage boundaries were determined by studying behavioural characteristics of each bar sequence as depicted on time series of cross-shore bar crest locations. The landward boundary of zone 1 was defined at the low water line. The location of onset of net seaward migration, indicated by a sudden increase in migration rate (Fig. 7), defines the transition boundary between zone 1 and 2. Following several years of net seaward migration under continued growth, a bar reaches its maximum height at the outer margin of the nearshore bar zone before eventually de-

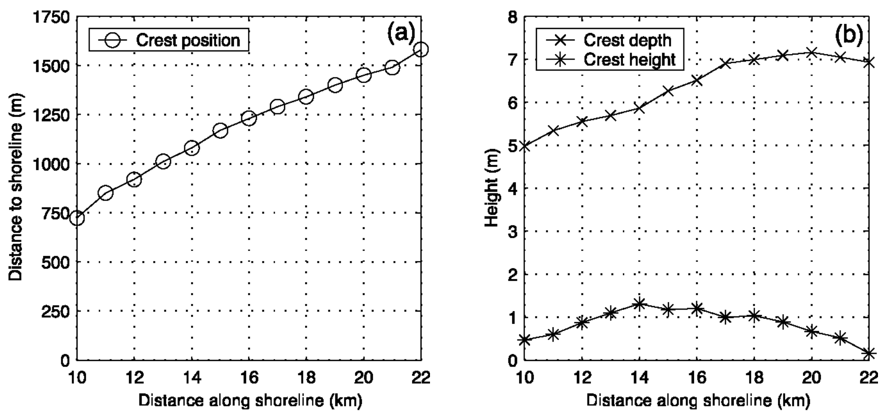

Fig. 8. Characteristics of protuberance versus distance along shoreline: (a) crest position and (b) crest depth and height.

caying. The location of the onset of degeneration, indicated by a sudden decrease in migration rate, defines the transition boundary between zone 2 and 3. Bars were also observed to migrate slightly offshore during their degeneration. As bars disappear from the nearshore profile, they have reached the seaward boundary of zone 3.

4. Results

4.1. Preferential bar location

The cross-shore location of the bar-like protuberance in the outer margin of the nearshore zone presented in Fig. 8 indicates that on the island of Terschelling preferential location of bar residence is associated with bar degeneration. Upon reaching a maximal seaward distance, bars degenerate by decrease in height until the bar relief ultimately disappears from the profile. A protuberance on the foreshore associated with bar generation could also have been expected as both bars in stages 1 and 3 remain stationary within a narrow cross-shore range for periods of several years. However, located in the day to day surf zone, bars in stage 1 experience an energetic back and forth cross-shore movement with an apparently equal amount of time with presence of alternating troughs and bars at a given depth.

The cross-shore position of the protuberance is nearly alongshore-linear along the 12 km length of the study area with a strongly increasing seaward location towards the east (Fig. 8). The crest in section 22 is located almost twice as far seaward as in section 10, as the crest location increases gradually from 750 m at the western end to 1500 m in the eastern end. The angle of the crest line with the shoreline is approximately four degrees. The crest height of the barred feature in the mean profile was obtained as the maximum difference in elevation between the mean profile and a smoothed profile with the bar-like protuberance filtered away; bar crest depth was determined at that same location. The protuberance crest depth was found to be overall increasing with increasing offshore distance with values on the order of 5–7 m. The protuberance crest height reaches its maximum at 1.2 m around the centre of the island. It should be noted that the morphometric parameters of degenerating bars are related to a mean profile including the protuberance. In the further morphometric analysis, a degenerating bar is thus superimposed on the protuberance and not a part of it.

4.2. Migrational bar behaviour

Seven nearshore bars were present in the study area from 1965 to 1993. The assigned bar numbers are 1, 2, 2*, 3, 3*, 4 and 5. Bar crest lines of the entire study area for the years 1965, 1970, 1975 and 1980, and the years 1985, 1987, 1991 and 1993 are presented in Figs. 9 and 10, respectively. Not all soundings covered the entire nearshore bar zone prior to 1985; however, the overall bar location could be inferred.

Bar 1 was in its net offshore migrational stage located about 750–900 m from the shoreline at the time of the first sounding in 1965. The crest line of the bar was relatively straight with no large-scale rhythmic features. Bar 1 migrated in a net seaward direction from 1965 to 1975. During its migration the bar disappeared progressively from the east; it was no longer observed in section 22 in 1969 and in section 10 in 1979.

Bar 2 was leaving its generation zone in 1965. In 1970 a discontinuity occurred in the alignment of the bar as it split into a more landward bar west of the discontinuity (bar 2*) and a more seaward bar east of the discontinuity. At the time of appearance of the discontinuity, the transition zone occurred around section 11. The transition zone then migrated longshore while migrating offshore. Bar 2 subsequently migrated in a net seaward direction until 1982, where it disappeared from the study area by longshore migration to the east.

Bar 2* appeared in the western end of the study area in 1970 as the result of the longshore discontinuity of bar 2. It remained in the inner nearshore bar zone until 1974 and then migrated in a net seaward direction until 1985. Hereafter, bar 2* degenerated within a few years and could no longer be observed in the soundings of 1989. The eastern end of the bar shifted to the east while migrating offshore.

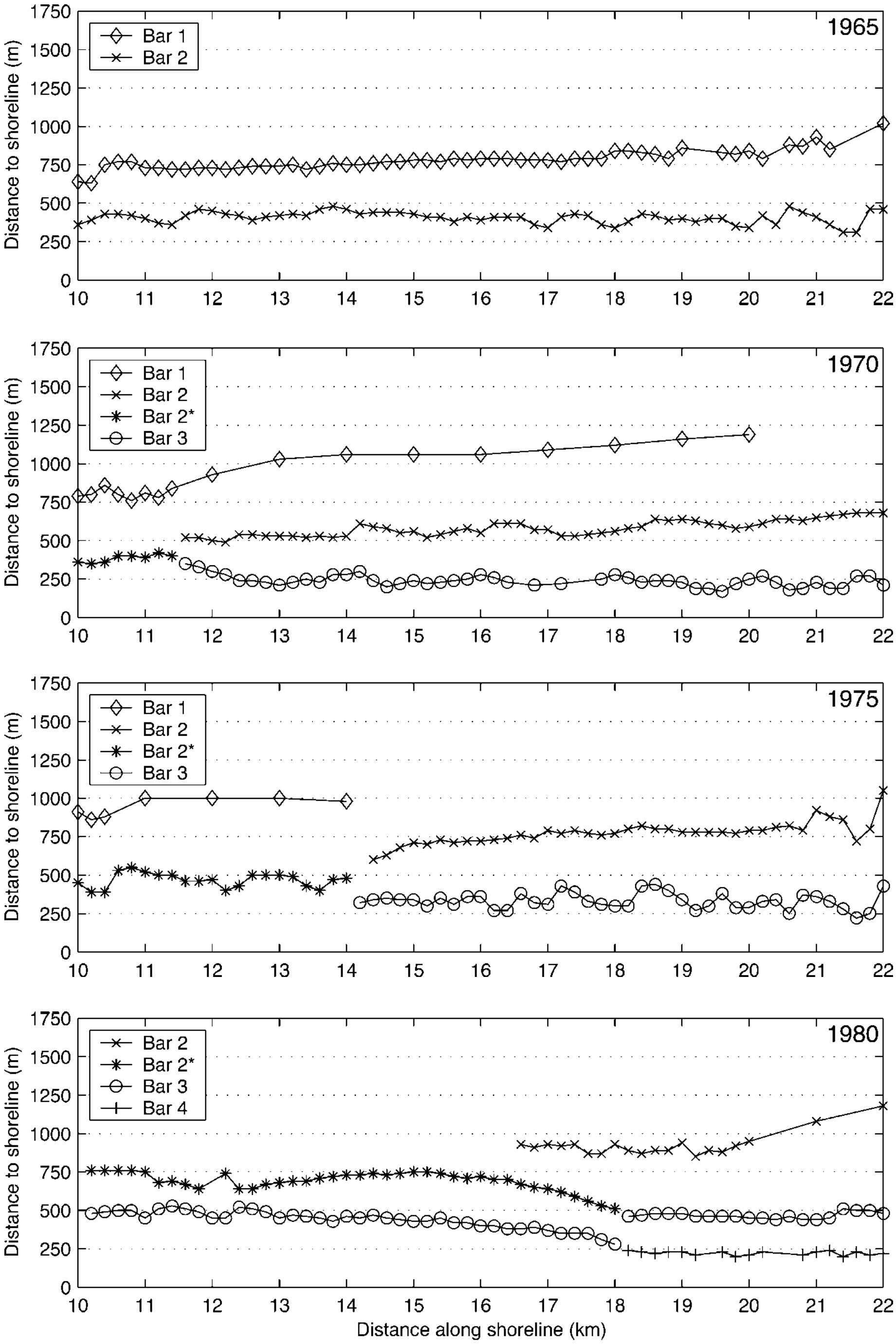

Fig. 9. Alongshore position of bar crests in 1965, 1970, 1975 and 1980 based on 5-yr JARKUS soundings (only extended beyond 1000 m seaward of the shoreline at beach pole locations).

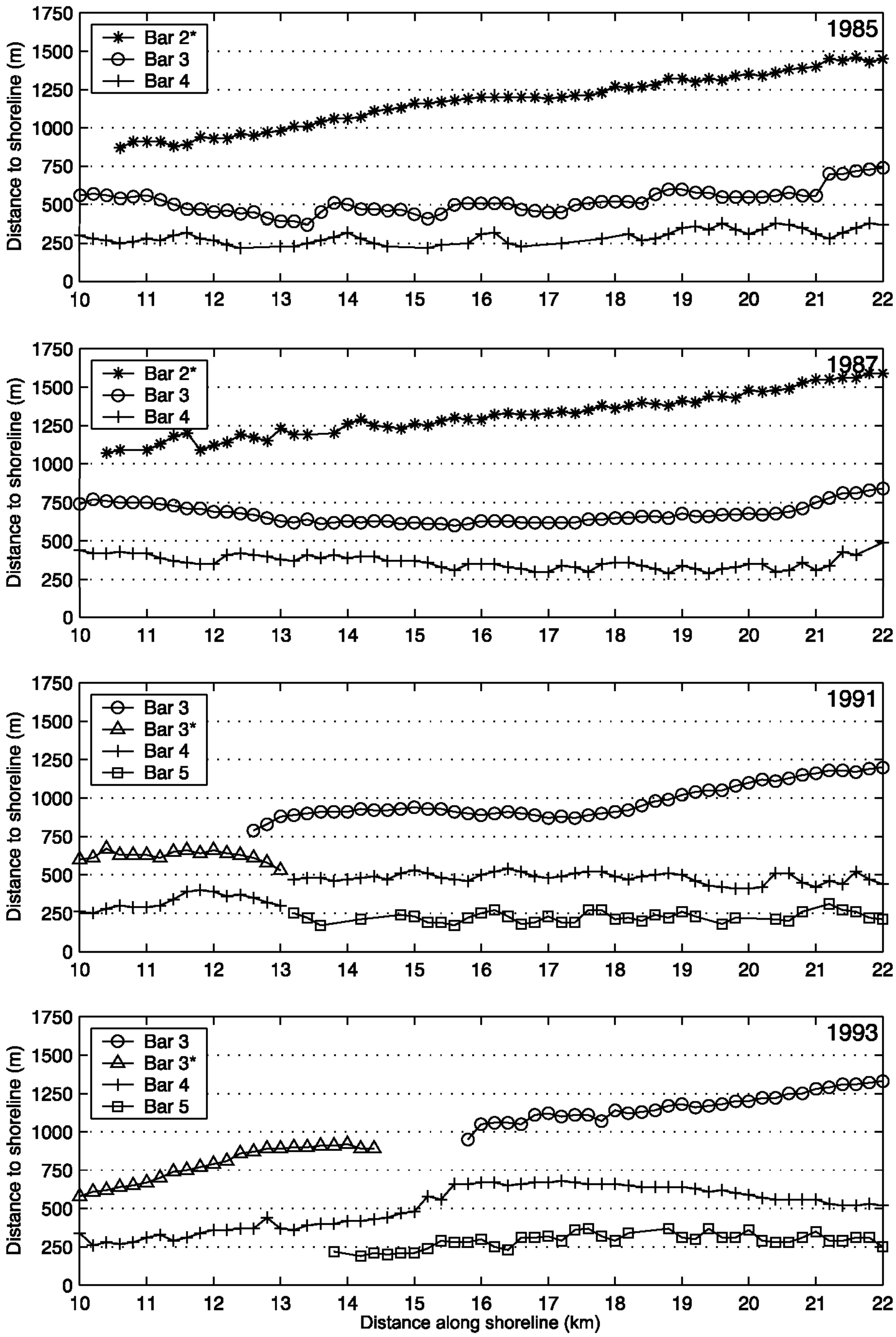

Fig. 10. Alongshore position of bar crests in 1985, 1987, 1991 and 1993 based on yearly JARKUS soundings (extended throughout the nearshore bar zone).

Bar 3 was observed in 1969 for the first time. The western end of the bar was located around section 12. By 1978 the bar became continuous along the entire length of the study area and exhibited rhythmic features (see also 1975). Bar 3 remained within 400 m of the shoreline until 1984, when it started to migrate in a net seaward direction. Following the degeneration of bar 2* in 1990, the migration rate of bar 3 increased. In 1991 bar 3 experienced a discontinuity at the western end of the study area.

Bar 3* appeared from the longshore discontinuity of bar 3 at the western boundary of the study area in 1991. It appeared at a cross-shore location seaward of the bar generation zone about 650 m from the shoreline. From 1988 to 1993 it migrated in a net seaward direction while migrating alongshore.

Bar 4 made its appearance in 1984 along the entire length of the study area. It remained within 400 m from the shoreline until 1989. After 1989 in the eastern half of the study area, bar 4 migrated in a net seaward direction; bar 5 appeared in 1990 in this area where the offshore migration of bar 4 was greatest.

The observed discontinuities are bifurcations in the alongshore bar pattern known as bar switching (Shand and Bailey, 1999; Shand et al., 2001). In the case of Terschelling, it involves bars becoming alongshore discontinuous with a well-developed seaward bar on the western side of the discontinuity realigning and joining with a landward bar on the eastern side. Three switching episodes were identified along the study area including both single and multiple bar realignments: in 1970 and again in 1980 bar 2* realigned with bar 3, also in 1980 bar 3 realigned with bar 4, and in 1991 bar 3* realigned with bar 4 concurrently with the realignment of bar 4 with bar 5. In a single bar realignment the outer bar was observed to join with the middle bar and in a multiple bar realignment the middle bar was also joining the inner bar. Bar switching is observed to originate towards the ends of the study area around sections 11–13 and 18–19, respectively. All switching episodes were propagating in the alongshore direction to the east at a rate of 600–800 m/yr. In the years following a switching episode, the attachment of joined bars became less pronounced and was observed as a deepening of bar crest between the realigned bars. Note that bars on opposite sides of a switching area are temporarily in different phases of the bar cycle.

In summary, along the entire length of the study area a bar passes through three stages of migration during its existence: (1) generation in the nearshore bar zone, (2) net seaward migration in the inner and outer nearshore bar zone and (3) degeneration at the outer margin of the outer nearshore bar zone. This bar behaviour is consistent with Ruessink and Kroon (1994) and Wijnberg (1998) and extends their results both throughout the entire nearshore bar zone and alongshore. Also, the presence of a seaward positioned bar, often observed as the sudden appearance of a new outer bar from alongshore, appears to temporarily arrest the next most landward positioned bar in its cross-shore location before eventually allowing it to migrate again but at a lower rate. Despite this consequent cross-shore pattern along the study area, the bar behaviour indicates an alongshore variability in the time of residence in each stage, the boundaries between the zones and the net offshore migration rates within each zone. In addition, as the bars leave the inner nearshore zone they have an oblique orientation relative to the shoreline with an angle of the bar crest line of about 3–4°. The obliqueness of the bar crest lines in itself suggests that bar characteristics vary alongshore.

4.3. Longshore-averaging of bar parameters

An example of the spatial and temporal evolution of all bars present in section 17 and 21 is presented in Fig. 11. These sections have been selected to allow for alongshore comparison within the study area. As can be seen in Fig. 11, the alongshore variability is related to the cross-shore position of the bars: in the inner nearshore zone, bars have a similar behaviour along the study area, variability is first introduced as the bars transit to stage 2 approximately 500 m from the shoreline. This alongshore variability becomes gradually more pronounced at greater distance offshore. The increasing seaward positioning of

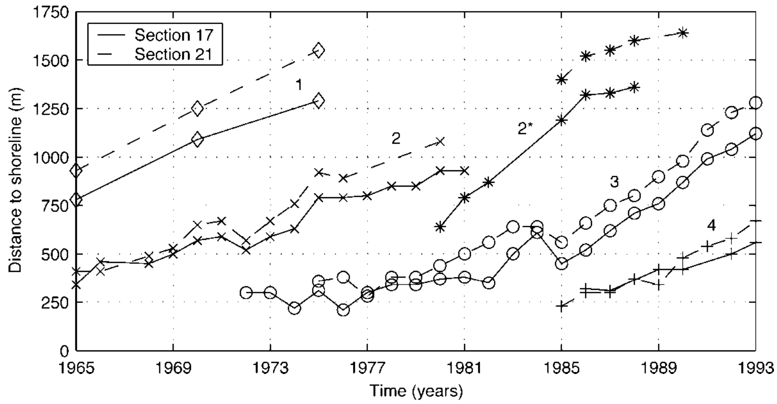

Fig. 11. Position of bar crests in sections 17 and 21 from 1965 to 1993.

the bars towards the east presents evidence of alongshore-varying cross-shore bar characteristics within the study area.

The alongshore-specific bar characteristics are presented in Fig. 12 as a function of cross-shore distance. The amount of explained variance is relatively high with r^2 typically on the order of 0.80 (Table 1). Bar depth, height, width and volume all increase with increasing offshore distance during the first two stages of bar life cycle. However, significant alongshore variation is observed with a gradual transition from west to east: all bar parameters reach a maximum at a greater distance to the shoreline towards the eastern end of the study area. Bar height and volume reduce to zero during the third stage of bar life cycle whereas bar depth and width further increase. Bar width could be expected to reduce to zero as degenerating bars gradually disappear from the nearshore profile but this is an artefact of including the outer nearshore protuberance in the underlying mean profile.

Table 1
Here, r^2 is the correlation coefficient squared between fitted and observed morphometric bar parameters and N is the number of observations

Section	r^2 (d_b)	r^2 (h_b)	r^2 (W)	r^2 (V)	N
A	0.92	0.81	0.77	0.82	105
B	0.88	0.75	0.75	0.78	112
C	0.89	0.74	0.86	0.75	115
D	0.90	0.76	0.83	0.83	109
E	0.91	0.78	0.90	0.84	109
F	0.92	0.83	0.92	0.91	111

Within the inner nearshore bar zone extending approximately 500 m from the shoreline, all bar parameters increase almost linearly with increasing offshore distance with an approximately equal slope at all alongshore locations. As the bars leave this inner nearshore zone, they exhibit an alongshore coherence in their oblique orientation relative to the shoreline. This indicates that alongshore bar variability does not result from the alongshore propagation of shore-oblique bars. This variability increases both offshore and towards the east. Within the study area maximum bar height increases from about 1.5 m at the western end to about 2.3 m at the eastern end; concurrently, maximum bar volume exhibits a significant increase from 170 m^3/m to 300 m^3/m, and both parameters would have exhibited somewhat higher values if the protuberance had been included as part of the outermost bar. In addition, upon reaching maximum values for height and volume, a more abrupt transition with steeper decrease would be expected without including the protuberance. At alongshore-varying distance to the shoreline, maximum bar crest depth is reached around 6 m and maximum bar width is on the order of 400 m.

Interestingly, the gradual increase of bar crest depth with increasing distance offshore is nearly constant alongshore. In contrast to other bar parameters, the crest depth appears to be less related

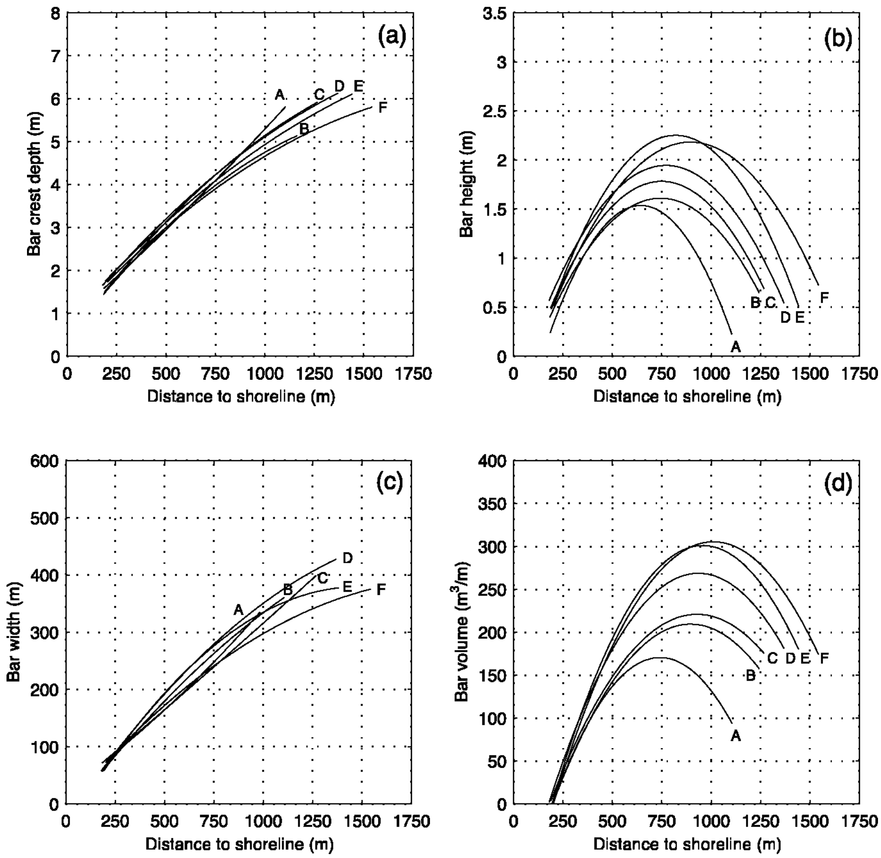

Fig. 12. Longshore-averaged morphometric parameters versus distance of the bar crest to the shoreline: (a) bar crest depth, (b) bar height, (c) bar width and (d) bar volume. The sections are A (km 10–12), B (km 12–14), C (km 14–16), D (km 16–18), E (km 18–20) and F (km 20–22).

to key nearshore morphological characteristics such as nearshore slope and surf zone width. This suggests that for equal offshore forcing, bar crest depths are primarily linked to prevailing hydrodynamic conditions whereas bar size is mostly related to varying nearshore bathymetry and nearshore processes.

4.4. Bar migration cycle

The parameters used to quantify the different stages in bar life cycle as defined in Fig. 7 are presented in Fig. 13. A wide variation in parameter values is evident between the different longshore sections. Significant inter-zonal variation occurs for width, duration and rate: higher values occur in zone 2 than in zones 1 and 3. While parameter values in zone 1 and 3 are of a similar order, zone 1 values show greater variation than those in zone 3. However, inter-zonal return periods are approximately constant at all sections.

The extensive width of zone 2 and narrowness of zone 3 are notable, as noted earlier by Shand et al. (1999). The width of zone 2 increases from 300 to 1200 m at a nearly constant rate in the eastern direction. The width of zone 1 and 3 are constant throughout the study area at about 200 and 100 m respectively. While the duration in zone 3 is constant at 3 yr, opposite trends in duration values occur in zone 1 and 2: both show a duration of 9 yr at section 10 while at section 22, zone 2 increases to about 16 yr and zone 1 decreases to about 4 yr. The alongshore rate of change is constant but of opposite sign. It is noticeable that

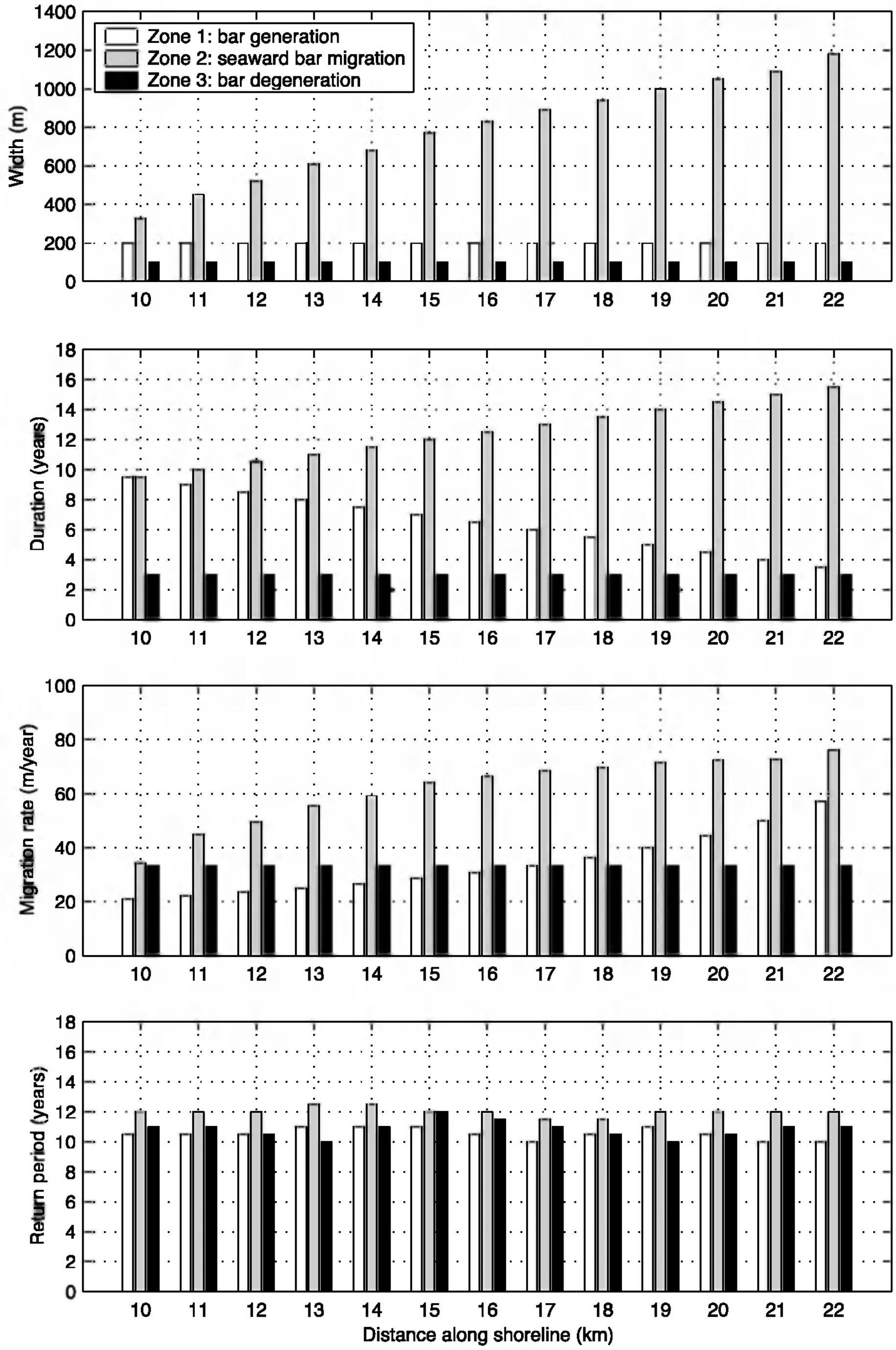

Fig. 13. Alongshore values of bar migration parameters.

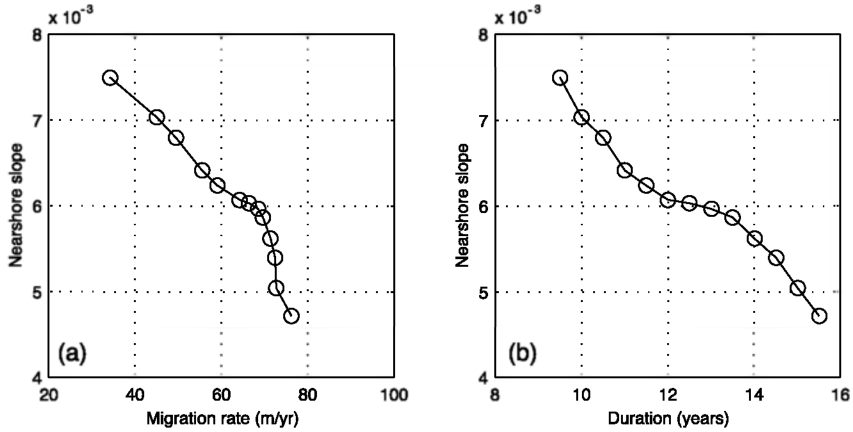

Fig. 14. Parameters in zone 2 versus nearshore slope: (a) migration rate and (b) duration.

despite great alongshore variability in the time of residence in every stage, the total life span of a bar is constant throughout the study area and on the order of 22 yr. Similarly, inter-zonal return periods are approximately equal along the coast and in the order of 10–12 yr.

Longshore variation also characterises the values for cross-shore migration rates. While rate values in zone 3 are constant at 30–40 m/yr, rate values for zone 1 and 2 increase towards the east. It is remarkable that in zone 2 the migration rate at section 22 is twice as large than at section 10: rates increase from approximately 35–70 m/yr. Rate values in zone 1 experience a similar increase towards the east.

4.5. Net offshore migration activity

The systematic offshore migration in zone 2 is the dominant type of behaviour characterising the migrational pattern of bar cycles. In the following, relationships between morphological characteristics of the nearshore bar zone and migrational bar behaviour are therefore only based on zone 2 parameters.

Considerable alongshore variability exists in the nearshore slope of the bar zone with slope values almost linearly decreasing from 1/130 to 1/230 in sections 10–22, respectively. The lower slopes towards the east correspond to wider and deeper nearshores as suggested in Fig. 8 by the alongshore seaward-increasing crest position of the protuberance in the time-averaged profiles. Fig. 14 shows the variation of the nearshore slope relative to migration rates and durations of net offshore migration. The results suggest that nearshore slope has a strong influence upon bar migrational behaviour during stage 2; both migration rates (Fig. 14a) and durations (Fig. 14b) are observed to increase with decreasing nearshore slope. Nearly alongshore-constant slope/migration and slope/duration relationships seem to hold throughout the study area.

Based on the results of Section 4.2, it appears that the degeneration of the outer bar in zone 3 triggers the net offshore migration of the next most landward positioned bar in zone 2. Fig. 15 provides evidence of a such a relationship: the decay of outer bars in zone 3 is followed by increasing cross-shore migration rates in zone 2 (Fig. 15a) concurrently with increasing bar heights in this zone (Fig. 15b). These degeneration/migration relationships are valid at all alongshore sections despite strong alongshore-variation in both migration rates and bar heights.

5. Discussion and conclusions

The identification of three different migrational bar stages in well-delimited cross-shore zones was observed to be valid throughout the study area

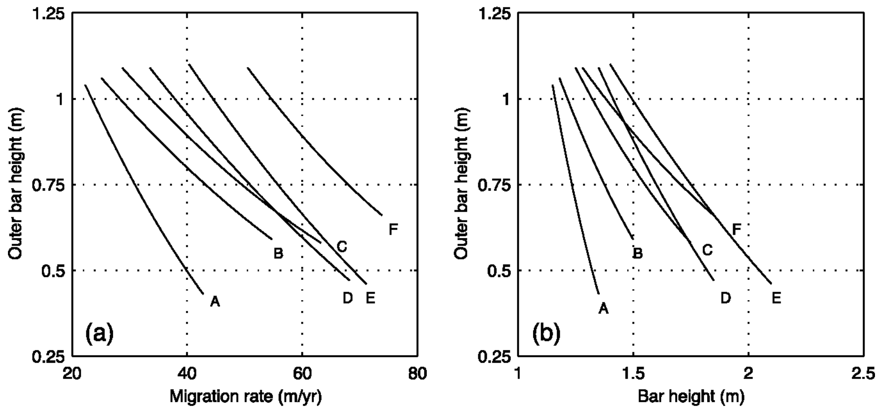

Fig. 15. Bar height in zone 3 versus bar parameters in zone 2: (a) average migration rate and (b) bar height.

along the nearshore zone of Terschelling. However, significant inter-zonal and alongshore variability was observed within the characteristics of each of the stages. The variability is specifically apparent in the most spatially and temporally extensive zone 2 because systematic offshore migration is the dominant type of behaviour. The alongshore varying bar migration parameter values strongly imply that studies of the morphological evolution in a single cross-shore profile are not representative of the nearshore zone in the alongshore direction. In view of the predominant alongshore variability, it is noticeable that the number of bars is constant throughout the study area regardless of the surf zone width: the return period and the total life span of bars were found to be alongshore independent. Even with a doubling of the surf zone width within the study area, bars are able to complete all stages of bar migration within the same time span as coastal sections with a small surf zone width. The bar migration cycle regulates itself by concurrently adjusting the time of residence of bars within the first two stages of migrational cycle as well as the migration rates in these stages. Despite great alongshore variability, the observed cyclic bar system behaviour seems to be an inherent behaviour of the multiple bar system of Terschelling.

The alongshore variability in migration parameter values indicates that the morphodynamics are alongshore-specific at Terschelling. The high variability in migration rates and duration of net offshore migration is of particular significance in this regard. The results illustrate a strong causal association of these two parameters with the nearshore slope of the bar zone. A possible explanation for the slope/migration and slope/duration association is suggested by the alongshore varying cross-shore width and the corresponding seaward depth of the nearshore bar zone. Results conclusively show that as depth increases cross-shore width increases. Although not supported by hydrodynamic data in the present analysis, a causal mechanism with wave heights is probable. It is hypothesised that the alongshore-increasing cross-shore width of the nearshore bar zone is coupled with the presence of alongshore-increasing wave heights at the seaward end of the nearshore bar zone. Given that wave energy is depth-limited, cross-shore widths increase owing to the increasing breaking depths achieved by the highest waves. This hypothesis is reinforced by the natural setting of Terschelling in which the shoreline is oriented nearly parallel to the predominantly westerly winds and thereby is partly sheltered by the outer delta of the Vlie Inlet with its important ebb-tidal shoals. Wave energy is transformed around the tidal shoals before reaching the adjacent nearshore zone of Terschelling, likely with a decreasing sheltering effect of the shoal towards the east and consequently, with corresponding increasing wave heights. Interestingly, in response to alongshore-increasing wave energy, larger bars not only migrate faster across the nearshore than smaller bars but larger bars also migrate over a longer period of time.

As a result of island curvature, shoreline orientation with respect to incident wave climate varies alongshore and consequently gives rise to gradients in longshore sediment transport along the study area. In addition, it appears that the sandwaves in the western end of the study area are part of the natural inlet bypass mechanism constituting a large sediment supply to the shoreface of Terschelling. It is however, unlikely that alongshore variability in bar migration patterns results from gradient adjustment in longshore sediment transport. On the island of Terschelling, cyclic bar behaviour exhibits alongshore coherence across boundaries delimiting erosional and accretionary parts of the study area. Along the Holland coast, cyclic bar behaviour is also found on longshore stretches of both eroding and accreting shorelines (Wijnberg and Terwindt, 1995). This suggests that on the alongshore scale of a coherent offshore moving bar, cyclic bar behaviour appears to be essentially a cross-shore sediment redistribution process within the nearshore zone. Longshore sediment transport, and gradients hereof, is closely related to the overall erosional or accretionary nature of the profile whereas the cyclic migrational pattern of bars is a behavioural pattern superimposed on the overall state of the cross-shore profile.

Episodes of bar switching occurred at given spatial and temporal conditions. In space, bar switching appeared to have a preferential location in the western and eastern parts of the study area and in time, bar switching occurred when the increase in alongshore differences in the position of the offshore propagating middle bar was greatest and always in combination with the decay of an outer bar. These preferential locations also have the flattest overall nearshore slope. This suggests the existence of a threshold value for nearshore slope above which a well-developed bar migrates offshore more freely than for flatter slopes. Triggered by the degeneration of the outer bar, the next most landward bar is suddenly released to migrate faster on the steeper side of the discontinuity than on the other flatter side. Three large-scale episodes of bar switching were identified throughout the 28-yr study period at an average spacing of approximately 10–11 yr. Return periods were found to be alongshore uniform and in the same order of 10–12 yr. This certainly suggests that this phenomenon is controlled by the outer bar and thus that antecedent morphology in a cyclic offshore progressive bar system plays an important role in the morphodynamics of bar switching. The origins of bar switching are not well understood but Wijnberg and Wolf (1994) and Shand et al. (2001) also noted the importance of the outer bar and in particular the depth of the outer bar in causing small differences in the wave climate at the inner bar. An inner bar opposite of a low outer bar experiences more energetic wave conditions and will migrate offshore, whereas an inner bar shoreward of a high outer bar is more constrained close to the coast. The resulting alongshore differences in migrational behaviour is believed to result in bar switching.

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