PERGAMON

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Continental Shelf Research 23 (2003) 501–512

CONTINENTAL SHELF RESEARCH

www.elsevier.com/locate/csr

Video observations of nearshore bar behaviour. Part 1: alongshore uniform variability

I.M.J. van Enckevort[a,*], B.G. Ruessink[b,1]

[a] Department of Physical Geography, IMAU, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, Netherlands
[b] WL|Delft Hydraulics, Marine and Coastal Management, P.O. Box 177, 2600 MH Delft, Netherlands

Received 19 November 2001; received in revised form 17 June 2002; accepted 9 December 2002

Abstract

Changes in nearshore sandbar morphology comprise of an alongshore uniform and non-uniform component. The former reflects the overall on/offshore migration, while the latter expresses changes in quasi-rhythmic non-uniformities, such as crescentic plan shapes. Here we focus on the alongshore-uniform component, quantified from a 3.4-year data set of daily time-exposure video images of the double barred nearshore at Noordwijk, Netherlands. The high temporal resolution and the long duration of the data set allowed us to quantify the cross-shore bar migration at weekly, seasonal and inter-annual time scales and, accordingly, to compare the contribution of all three components to the total variability in cross-shore bar position. The maximum observed offshore-directed weekly, seasonal and inter-annual bar migration rates were 10, 0.5 and 0.2 m/day. Maximum onshore rates at weekly and seasonal scales were 8 and 0.5 m/day, while onshore migration at the inter-annual scale was not observed. The inter-annual bar migration dominated the bar crest variability over time spans longer than 10–13 months, whereas changes on the weekly scale were the dominant source of variability on time spans shorter than 7–10 months. Seasonal bar migration only dominated the bar crest variability at the outer bar on time spans between 7 and 13 months. In general, Noordwijk appears to be a site with a strong inter-annual signal, with limited seasonal variability, and with fluctuations at weekly scales that are long compared to the characteristic time scale of individual events, suggesting a response to sequences of events rather than to individual events.

Keywords: Nearshore bars; Cross-shore bar migration; Time scales; Video imagery

1. Introduction

Nearshore bars are common subtidal features along sandy uninterrupted coasts. They are generally located in water depths less than about 8 m and are often oriented shore parallel, but also contain alongshore nonuniformities, such as rip channels or crescentic plan shapes. Changes in nearshore bar morphology therefore comprise of two components. The first component has an

*Corresponding author. Tel.: +31-30-2532982; fax: +31-30-2531145.
E-mail address: i.vanenckevort@geog.uu.nl (I.M.J. van Enckevort).

[1] Now at: Department of Physical Geography, IMAU, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, Netherlands

0278-4343/03/$ - see front matter
doi:10.1016/S0278-4343(02)00234-0

alongshore uniform (or two-dimensional, 2-D) character and reflects overall on/offshore bar migration. The second component is alongshore non-uniform (or three-dimensional, 3-D) and corresponds to changes in the non-uniformities in the bar, such as changes in their alongshore length, cross-shore amplitude or alongshore position. This paper is part 1 of a two-part study on nearshore bar behaviour determined from video imagery and focuses on its alongshore uniform component. Part 2 (Van Enckevort and Ruessink, 2003, henceforth referred to as Part 2) focuses on the alongshore non-uniform component.

Cross-shore bar migration has been studied extensively at various sites around the world, differing in environmental parameters such as sediment characteristics and the wave and tidal climate. Table 1 gives an extensive (although not exhaustive) overview of on/offshore migration rates reported in the literature. Most attention has been paid to bar migration in response to one or two (subsequent) high-wave events based on short intense field experiments. These responses typically cause variations in bar crest position on time scales of several days to a few weeks, hereafter referred to as weekly time scales. On these scales, reported offshore migration rates ranged from approximately 1 m/day to over 50 m/day, whereas onshore migration rates ranged from less than 1 to 29 m/day (Table 1). The weekly bar migration rates seem to be directly forced by the wave conditions, with large offshore rates during high-energetic conditions and small onshore rates during low-energetic conditions (e.g. Sallenger et al., 1985; Gallagher et al., 1998). Depending on the wave height, the migration rates may differ in magnitude and direction. Plant et al. (1999) described these changes in bar migration rate by a non-linear function consisting of four subsequent phases with increasing wave height: (1) an increase in onshore migration rate, (2) a decrease in onshore migration rate, (3) a change from onshore to offshore migration, and (4) an increase in offshore migration rate. Although the observation of summer and winter profiles along the Pacific ocean coast of the USA (e.g. Winant et al., 1975; Aubrey, 1979) has drawn attention to seasonal variations in nearshore morphology, bar migration rates have hardly been quantified on seasonal time scales. An exception is Plant et al. (1999), who computed monthly-averaged on/offshore bar migration rates of up to 1 m/day based on bimonthly bathymetric surveys at Duck, NC, USA. On the inter-annual time scale, cyclic offshore-directed bar migration has been observed at several sites with corresponding migration rates between 0.1 and 0.5 m/day (Table 1).

None of the studies listed in Table 1 has quantified bar migration on all three time scales simultaneously, either because the duration of the data set was too short, or because the data lacked sufficient temporal resolution. The data we consider consist of almost daily, video-based bar crest observations over a 3.4-year period at Noordwijk, Netherlands, and thus combines high temporal resolution with a long duration. The objectives of this paper are (1) to quantify bar migration on weekly, seasonal and inter-annual time scales and (2) to determine the relative contribution of these components to the total alongshore uniform bar crest variability. After a brief introduction to the field site in Section 2, the applied video method, the bar crest sampling and the decomposition of the bar position time series into its weekly, seasonal and inter-annual components are described in Section 3. Results of the weekly, seasonal and inter-annual cross-shore bar migration rates are shown in Section 4. In Section 5, the relative contribution of each component to the total cross-shore bar crest variability is determined. This contribution is not only determined based on our entire data set, but also on subsets in the data, showing that the relative contribution of the weekly, seasonal and inter-annual variability depends on the duration of the subsets considered. Our main findings on the alongshore uniform component of bar behaviour at Noordwijk are summarised and discussed in Section 6.

2. Field site

Alongshore uniform bar behaviour was investigated with video-based observations from Noordwijk, Netherlands (Fig. 1). The field site, part of the 120-km long uninterrupted central Dutch coast

Table 1
Overview observed cross-shore bar migration rates

Site	Geomorphology			Hydrodynamics		Data set		Migration (m/day)[a]		Reference
	Setting	Sediment	Slope[b]	Tides (m)	Waves	Region	Resolution	Onshore	Offshore	
Daily to Weekly time scales										
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Single bar	1–2 per day	12, 29	53, 34	Sallenger et al. (1985)
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Single bar	1–6 per day		*29* **50**	Howd and Birkemeier (1987)
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Inner bar	1–2 per month	0.5	3.9	Birkemeier (1984)
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Inner bar	2 per month	*1.4* **8.7**	*2.6* **18**	Larson and Kraus (1994)
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Outer bar	2 per month	*0.6* **6.1**	*1.1* **15.2**	Larson and Kraus (1994)
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Inner bar	8 per day	0–10	0–24	Gallagher et al. (1998)
Nags Head, NC, USA	Ocean	250 μm	1:30	≈1	Sea, swell	Sub–intertidal	1 per day	29		Sonu (1968)
Magdalen Island, Canada	Encl. sea	Medium sand	1:100	0.7	Sea	Sub–intertidal	3–4 per week	0.83–10 *7.5*		Owens and Frobel (1977)
Ventura coast, CA, USA	Ocean	Medium sand		≈2	Sea, swell	Sub–intertidal	1 per day	8.9–30.5		Orme (1985)
Black Sea, Bulgaria	Encl. sea	400 μm	1:60		Sea	Single bar	1 per day	4	21.6	Ostrowski et al. (1990)
Naka North, Japan	Ocean	760 μm	1:90	1.0	Sea, swell	Sub–intertidal	1–2 per week	2.3–11.5		Sunamura and Takeda (1984)
Naka South, Japan	Ocean	260 μm	1:90	1.0	Sea, swell	Sub–intertidal	1–2 per week	1.2–5.0		Sunamura and Takeda (1984)
Egmond, Netherlands	Sea	150–200 μm	1:120	1.3–1.7	Sea	Inner bar	3 per week	0.8–12.4 *3.6*	4.1–4.3 *4.2*	Wolf (1997)
Monthly time scales										
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Inner bar	24 per year[c]	0–1.0	0–1.0	Plant et al. (1999)
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Outer bar	24 per year[c]	0–1.0	0–1.2	Plant et al. (1999)
Yearly time scales										
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Inner bar	24 per year		0.11–0.14[d]	Shand et al. (1999)
Duck, NC, USA	Ocean	180 μm	1:80	1.0–1.3	Sea, swell	Outer bar	24 per year		0.33–0.41[d]	Shand et al. (1999)
Wanganui, New Zealand	Sea	160–200 μm	1:120	0.8–2.4	Sea, swell	Subtidal	4–12 per year		0.30–0.55[d]	Shand et al. (1999)
Hasaki, Japan	Ocean	180 μm	1:125	1.4	Sea, swell	Subtidal	5 per week		0.49[d]	Kuriyama (2000)
Terschelling, Netherlands	Sea	150–160 μm	1:220	1.2–2.8	Sea	Middle bar	1 per year		0.11–0.16	Ruessink and Kroon (1994)
Terschelling, Netherlands	Sea	150–160 μm	1:220	1.2–2.8	Sea	Outer bar	1 per year		0.33–0.38	Ruessink and Kroon (1994)
Egmond, Netherlands	Sea	150–200 μm	1:120	1.3–1.7	Sea	Subtidal	1–10 per year		0.04–0.08[d]	Houwing (1991)[e]
Katwijk, Netherlands	Sea	150–200 μm	1:150	1.4–1.8	Sea	Subtidal	2–11 per year		0.14–0.16[d]	Houwing (1991)[e]

[a] Maximum rates are in bold, mean rates are in italic.
[b] Mean slope of the nearshore area, preferably of the bar region only.
[c] Migration rates determined from monthly averages.
[d] Migration rates are determined from linear regression to bar position time series.
[e] In Dutch, summary of the results can be found in Van Rijn (1998).

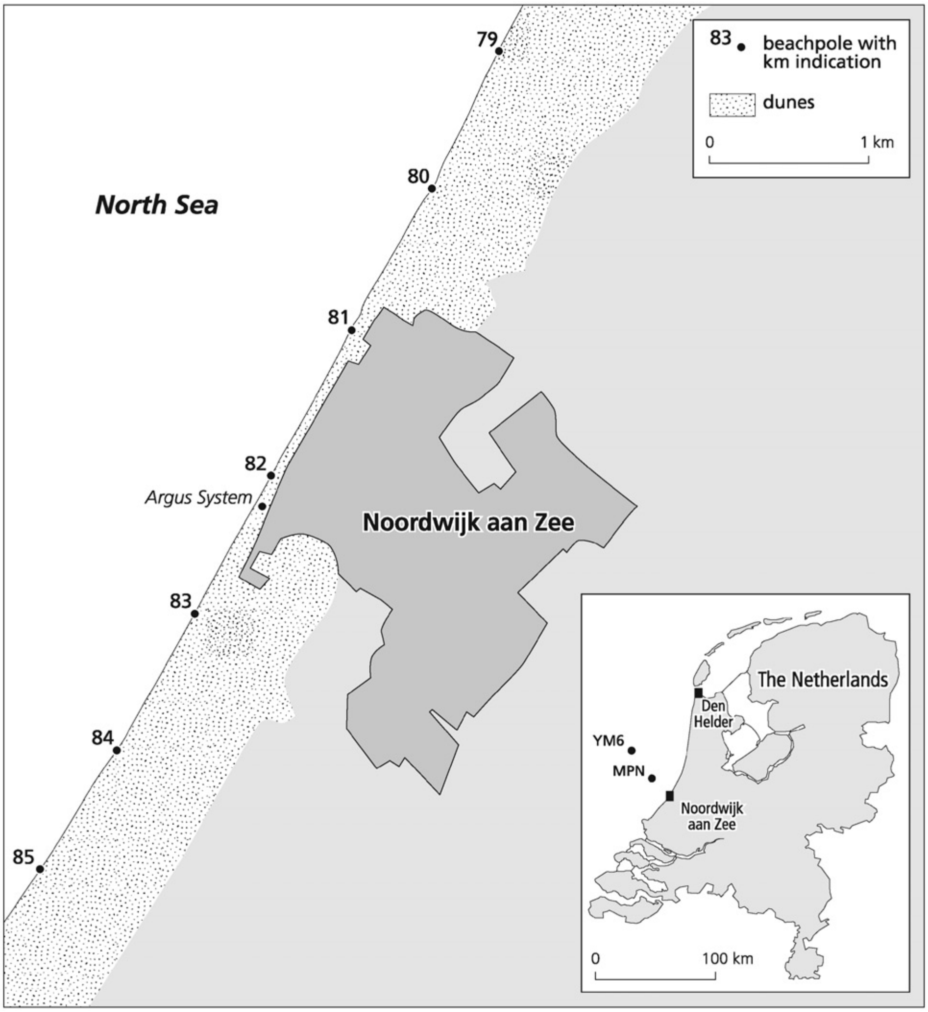

Fig. 1. Map of the field site, showing the location of the ARGUS system and the offshore measurement stations MPN and YM06.

and facing the semi-enclosed North Sea, is characterised by two well-developed shore-parallel subtidal bars, which often contain quasi-periodic alongshore variations with a wavelength of O(100−1000 m), see Short (1992) and Part 2. Wijnberg and Terwindt (1995) have shown that the bar behaviour at Noordwijk on inter-annual time scales is alongshore uniform with bar generation close to the shore, offshore bar migration through the surfzone and bar decay at about 500 m from the shore, resulting in cyclic bar behaviour with a recurrence interval of about 4 years. Offshore root-mean-square (rms) wave height $H_{\mathrm{rms}0}$, wave period T_0 (represented by the significant zero-downcrossing period) and the angle of incidence with the shore normal θ_0 (represented by the energy-weighted mean wave angle) were recorded on an hourly basis by a directional wave buoy at IJmuiden (YM06 in Fig. 1) in 21-m depth. The waves, mainly incident from southwestern to northwestern directions, have an average offshore rms wave height of 0.7 m and a corresponding period of 6 s. Storm waves (height >1.5 m) are mainly obliquely incident and occur throughout the year, although fall and winter are usually slightly more energetic than spring and summer. Water levels were recorded on an hourly basis at MPN (see Fig. 1) directly off the coast of Noordwijk in 18 m depth. The tide at Noordwijk is semi-diurnal with a mean neap (spring) tidal range of 1.4 (1.8) m. During storms water levels may increase by 1 m owing to storm surges.

3. Data set

Ten-minute time-exposure video images (e.g., Fig. 2a) were collected automatically every daylight hour with a digital video camera (ARGUS system, see Lippmann and Holman, 1989), equipped with a 12.5-mm lens and mounted on the roof of a hotel at about 60 m above mean sea level. The analysed period started in March 1995, when the ARGUS system was installed, and ended in September 1998, shortly after the implementation of a shoreface nourishment just offshore of the outer bar. The time-exposures were transformed to geometrically correct plan views (Holland et al., 1997) on a 5 × 5 m grid (see Fig. 2b for an example). The rectified images extend 1.2 km in the cross-shore (x) and 3 km in the alongshore (y) direction, and have a spatial resolution in the bar area of about 4–20 m in the cross-shore and 10–100 m in the alongshore direction, with the higher values farther away from the camera. The rectified images contain high-intensity (i.e. white) areas where most waves are breaking. As wave breaking tends to concentrate on the shallows such as nearshore bars, the shape and location of high-intensity areas may be used as a proxy for the nearshore bar crest morphology. The bar crest location was computed by sampling the cross-shore location of the breaking-related intensity peaks alongshore, as detailed by Van Enckevort and Ruessink (2001). In this way, a matrix $X(y, t)$

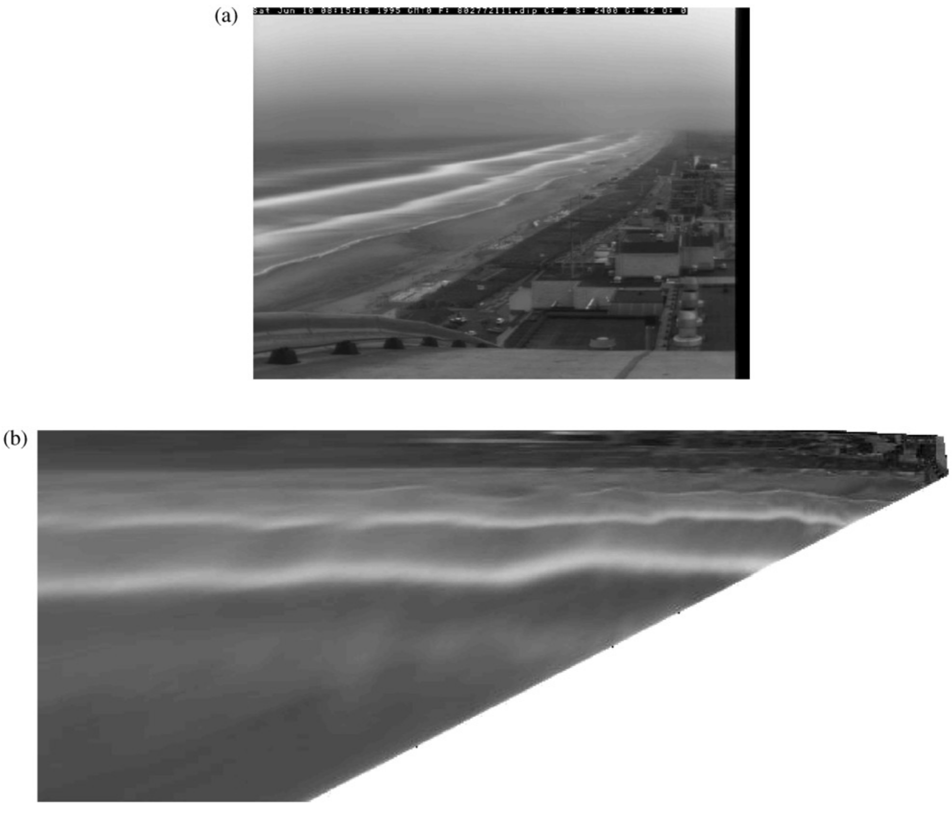

Fig. 2. Example of (a) an oblique image and (b) a rectified image at Noordwijk, Netherlands.

was constructed, consisting of bar crest locations X at times t and alongshore locations y. Time series of the cross-shore bar crest position $X_y(t)$ were computed by averaging the data set $X(y,t)$ alongshore. As the alongshore extent is typically about equal to or larger than the length scale of alongshore features such as crescentic shapes, $X_y(t)$ reflects the overall cross-shore bar migration, unaffected by changes in the alongshore shape of the bar.

Van Enckevort and Ruessink (2001) showed that the videoed bar crest position X_y is located close to the actual bar crest position x_c, but moves on- and offshore with the breaker line resulting in a time-varying deviation Δx $(= X_y - x_c)$ of O$(1-10)$ m. The variability in Δx mainly depends o the offshore water level Van Enckevort and Ruessink (2001), causing Δx to vary on a semi-diurnal time scale in response to the semi-diurnal tide (Section 2) and on longer time scales in response to neap-spring cycles and storm surges. To remove the Δx variability from $X_y(t)$ we follow the approach outlined in (Van Enckevort, 2001) and (Ruessink et al., 2002). This approach involves the reduction of $X_y(t)$ to a single observation per day, preferably at low tide, and a subsequent time-averaging of the daily $X_y(t)$ with a symmetric Hanning window. The first step, the reduction to a single observation per day, removes the semi-diurnal variability in Δx, but not that owing to neap-spring tidal variations and storm surges. The remaining Δx variability is obvious from the daily $X_y(t)$ by the significant (at the 95% confidence level) linear relation between the change in consecutive X_y observations and the corresponding change in water level during image collection. The second step, the time-averaging, affects this remaining Δx. The optimal width of the Hanning window is chosen such that the slope of the best-fit linear line between consecutive observations of bar position and water level is zero, assuming that the bars do not respond to changes in water level (Carter and Kitcher, 1979). For the present data, it was found that this is the case for a window width of 10 observations. As the window width is variable in time, the cut-off period is variable in time as well, typically varying between 1 and 2 weeks. The time-averaged time series, referred to as $\tilde{X}_y(t)$, thus describe the cross-shore bar crest position on weekly and longer time scales. In total, $\tilde{X}_y(t)$ was determined 632 times for the inner bar and 391 times for the outer bar within the analysed 3.4-year (1282 days) period.

The inner- and outer-bar $\tilde{X}_y(t)$ (Fig. 3a) both show a clear inter-annual, offshore directed trend. Superimposed upon this trend, seasonal fluctuations in bar crest position are apparent, with generally more seaward positions in the winter months and more shore ward positions in the summer months. Also apparent, but less than the seasonal and inter-annual signal, is bar crest variability on the time scale of a few weeks (about 7–8 weeks, on average). The identified inter-annual, seasonal and weekly components were extracted from $\tilde{X}_y(t)$ using a method equivalent to that developed by Plant et al. (1999). First, $\tilde{X}_y(t)$ were yearly-averaged by applying a Hanning (cosine-squared) filter with a half-width of 365 days, producing the inter-annual component, X_{ia} (Fig. 3b). The residuals, $\tilde{X}_y(t) - X_{ia}(t)$, were seasonally-averaged by applying a Hanning filter with a half-width of 91 days, isolating the seasonal component, X_s. The residuals, $\tilde{X}_y(t) - X_{ia}(t) - X_s(t)$, give the weekly component, X_w. Note that the time-averaging described in Section 3 to remove apparent bar migration affects $X_w(t)$ only, limiting the temporal resolution of $X_w(t)$ to a minimum of 1–2 weeks. The time series of X_{ia} and X_s are not affected.

4. Cross-shore bar migration

Interannual bar migration rates were computed as the temporal derivative of $X_{ia}(t)$, seasonal rates as the temporal derivative of $X_{ia}(t) + X_s(t)$, and weekly rates as the temporal derivative of $X_{ia}(t) + X_s(t) + X_w(t)$ (i.e., from $\tilde{X}_y(t)$). The inter-annual offshore migration rates were less than 0.15 m/day at the outer bar and less than 0.08 m/day at the inner bar (Table 2). On average, the outer bar migrated offshore with a yearly-averaged rate of 0.07 m/day, while the inner bar migrated offshore at a yearly-averaged rate of 0.04 m/day. The seasonal migration rates varied between 0 and 0.53 m/day in both the onshore and the offshore

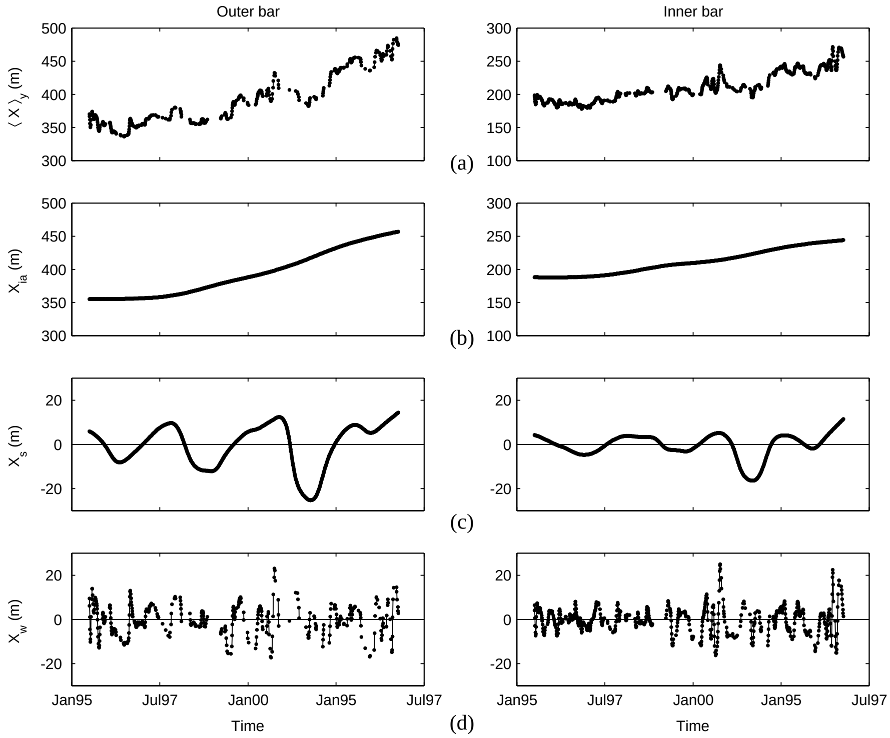

Fig. 3. Time series of cross-shore bar position and the inter-annual, seasonal and weekly component for the outer and inner bar.

Table 2
Statistics of cross-shore bar migration rates

	Offshore migration (m/day)			Onshore migration (m/day)		
	Weekly	Seasonal	Inter-annual	Weekly	Seasonal	Inter-annual
Outer bar						
Mean	1.57	0.16	0.07	1.21	0.11	0.00
St. dev.	1.80	0.09	0.05	1.27	0.07	0.00
Max.	10.12	0.53	0.15	6.73	0.53	0.00
Inner bar						
Mean	1.17	0.09	0.04	1.04	0.05	0.00
St. dev.	1.34	0.07	0.02	1.13	0.04	0.00
Max.	9.98	0.39	0.08	7.48	0.29	0.01

direction (Table 2). On average, the offshore migration rates were 0.09 m/day at the outer and 0.07 m/day at the inner bar, whereas the onshore migration rates were 0.07 m/day at the outer and 0.04 m/day at the inner bar (Table 2). Again, offshore rates were typically larger than onshore rates, and the outer bar migrated faster than the inner bar on a seasonal scale. The weekly migration rates varied between 0 and 8 m/day in the onshore and 0 and 10 m/day in the offshore direction, with a peak at small (<1–2 m/day) on/offshore migration rates (Fig. 4 and Table 2). The offshore migration rates were, on average, 1.6 m/day at the outer and 1.2 m/day at the inner bar, whereas the onshore migration rates were on average 1.2 m/day at the outer and 1.0 m/day at

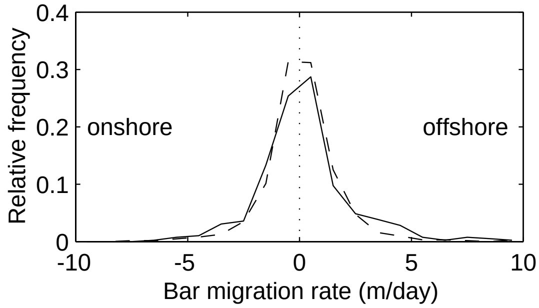

Fig. 4. Relative frequency of occurrence of onshore and offshore weekly bar migration rates for the outer (solid line) and inner (dashed line) bar.

the inner bar (Table 2). The onshore and offshore migration rates at the inner bar were generally smaller than at the outer bar (Fig. 4). Offshore migration rates were typically larger than onshore rates, especially at the outer bar (Table 2).

5. Dominant time scales

5.1. Method

In this section we address the question whether bar crest variability at Noordwijk is dominated by its weekly, seasonal or inter-annual component. Knowledge of the dominant component is important for a justified simplification of the nearshore bar system. When, for instance, the inter-annual component is dominant, a process-based model with wave input aggregated over daily to seasonal variations, or a data-driven model based on yearly observations of bar behaviour may be used to predict bar behaviour over years. From a first glance at Fig. 3 it is clear that the change in $\tilde{X}_y(t)$ at the inner and outer bar over the entire data set duration is dominated by the inter-annual, offshore directed trend. Indeed, the ratio between the variance of $X_{ia}(t)$ and $\tilde{X}_y(t)$ amounts to 86% and 91% at the inner and outer bar, respectively. It is unlikely that these ratios would have been the same when we had based them on a subset of the present data. For instance, over the period 1 January 1997–31 October 1997 (10 months), X_w, X_s and X_{ia} represent 26%, 56%, 18% of the variance in outer-bar crest variability and 15%, 40%, 45% of the variance in inner-bar crest variability. This example does show two intriguing results. First, the answer to the question whether bar crest variability is dominated by weekly, seasonal and inter-annual components depends on the length of the time series considered. Secondly, the bar crest variability in a time series with a length of several seasons is not necessarily dominated by its seasonal component, as at the inner bar it is dominated by its inter-annual component.

To determine the relative contribution of the weekly, seasonal and inter-annual components to total cross-shore bar variability over a range of time spans τ, the total variance and the variances explained by each of the three components were computed for subsets of the data set with length τ of $10, 20, 30, \ldots, 1200$ days. For each subset, the total 2-D bar crest change was quantified as the variance of $\tilde{X}_y(t)$ in time span τ

$$S_{all}(\tau) = \frac{1}{N_t} \sum_{t=t_1}^{t_1+\tau} (\tilde{X}_y(t) - \overline{\tilde{X}_y(t)})^2, \tag{1}$$

where N_t is the number of observations in time span τ and the overbar represents averaging over τ. The 2-D bar crest change associated with the inter-annual, seasonal and weekly components displayed in Fig. 3 were computed as

$$S_{ia}(\tau) = \frac{1}{N_t} \sum_{t=t_1}^{t_1+\tau} (X_{ia}(t) - \overline{X_{ia}(t)})^2, \tag{2}$$

$$S_s(\tau) = \frac{1}{N_t} \sum_{t=t_1}^{t_1+\tau} (X_s(t) - \overline{X_s(t)})^2, \tag{3}$$

$$S_w(\tau) = \frac{1}{N_t} \sum_{t=t_1}^{t_1+\tau} (X_w(t) - \overline{X_w(t)})^2. \tag{4}$$

Values of S_{all}, S_{ia}, S_s and S_w were then averaged over all possible subsets. The relative contributions F of the inter-annual, seasonal and weekly component to the total cross-shore bar crest variability were determined as

$$F_{ia}(\tau) = \frac{S_{ia}(\tau)}{S_{all}(\tau)}, \tag{5}$$

$$F_s(\tau) = \frac{S_s(\tau)}{S_{all}(\tau)}, \tag{6}$$

$$F_w(\tau) = \frac{S_w(\tau)}{S_{all}(\tau)}. \tag{7}$$

5.2. Results

Both at the outer bar and at the inner bar, S_w and S_s increased with τ for $\tau' < 50$–100 and $\tau \leqslant 300$ days, respectively, and remained about constant at larger τ (Figs. 5a and b). Thus S_w and S_s increase as long as τ is shorter than the main periodicities in X_w and X_s, being about 7–8 weeks and 1 year, respectively. In contrast, S_{ia} increased with τ for all τ reflecting the net trend in X_{ia} (Figs. 5a and b). Analogous to S_w and S_s, S_{ia} is expected to level off at a τ equal to the main periodicity in the inter-annual bar behaviour, about 4 years at Noordwijk (Section 3). As can be seen in Figs. 5c and d, F_w decreased with τ and this decrease was strongest at $\tau < 200$ days. F_s increased with τ up to $\tau \approx 300$ days, and decreased as τ further increased (Figs. 5c and d). F_{ia} continuously increased with τ, although the increase levelled off at $\tau > 800$ days (Figs. 5c and d).

The shape of F_w, F_s and F_{ia} as a function of τ may seem general. Intuitively, one expects F_w to be large as τ is small, F_s to reach a maximum value for $\tau \approx$ several seasons, and F_{ia} to increase as τ increases. However, the precise shape of F_w, F_s and F_{ia} versus τ is likely to be bar and site specific. A first indication hereof is given by the difference between the inner and outer bar plots. The corresponding lines in Figs. 5c and d have similar shapes. However, F_s is smaller at the inner bar than at the outer bar. In addition, the decrease in F_w with τ is much stronger for the outer than for the inner bar. Consequently, X_w dominated (i.e., $F_w > F_s$ and $F_w > F_{ia}$) the bar crest variability at the inner bar at $\tau < 400$ days, whereas, at the outer bar, X_w was the dominant source of variability at $\tau > 200$ days, only. Furthermore, X_s dominated at the outer bar for τ between 200 and 400 days, while X_s never dominated at the inner bar. The relative contribution of X_{ia} was similar at both bars with X_{ia} dominating at $\tau > 400$ days. In general, Noordwijk appears to be a site with a strong inter-annual signal and rather limited

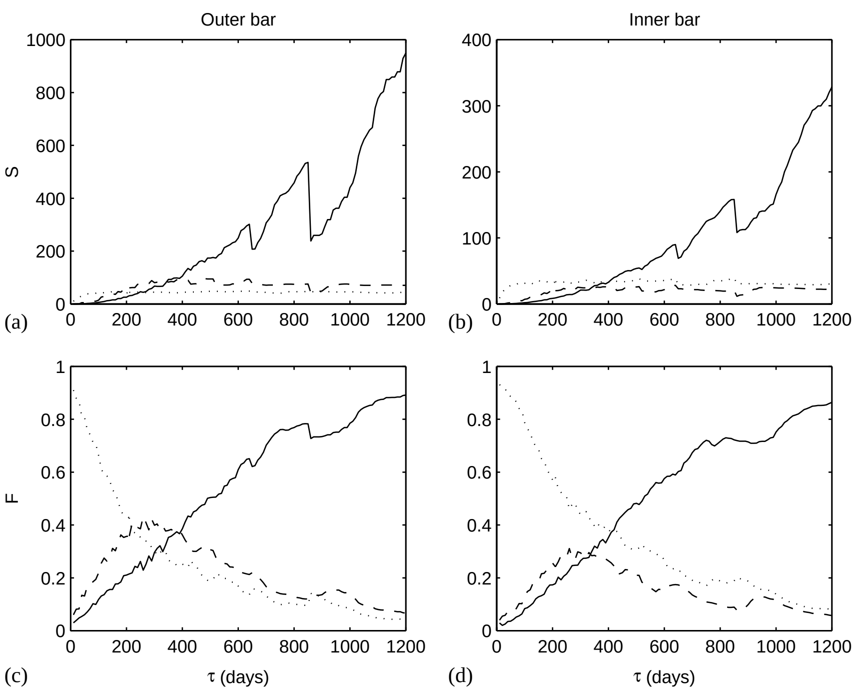

Fig. 5. Absolute (S) and relative (F) contribution of inter-annual (solid line), seasonal (dashed line) and weekly (dotted line) components to total along-shore uniform bar crest change as a function of the time span τ for the outer and the inner bar.

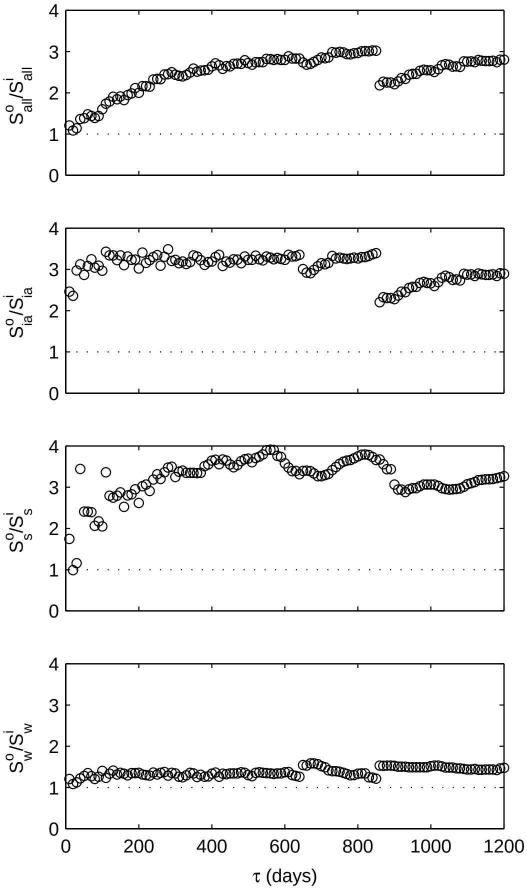

Fig. 6. Ratios of outer to inner bar estimates of total, inter-annual, seasonal and weekly alongshore uniform bar crest change as a function of the time span τ.

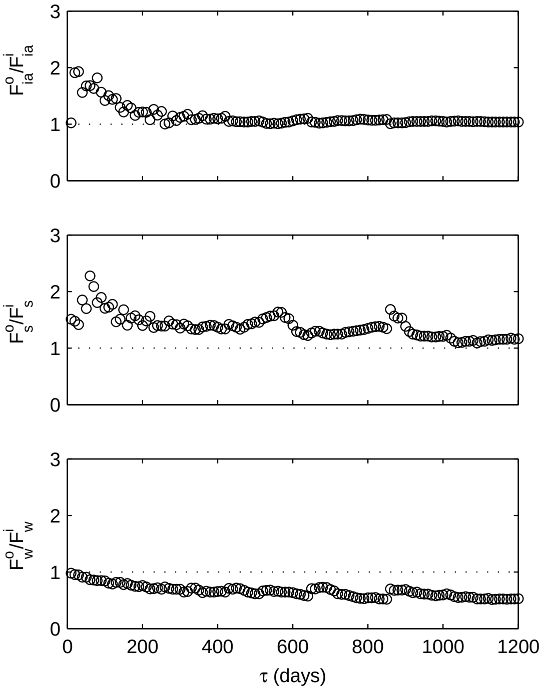

Fig. 7. Ratios of outer to inner bar estimates of the relative contribution of inter-annual, seasonal and weekly alongshore uniform bar crest change as a function of the time span τ.

seasonal variations, particularly at the inner bar. It is feasible that at sites where the inter-annual bar cycle takes longer than 4 years, X_{ia} starts to become the dominant source of 2-D bar crest variability at a τ larger than observed here for Noordwijk.

S_w, S_s and S_{ia} were all observed to be larger at the outer than at the inner bar, but the difference was smallest (factor 1.4, on average) for S_w (Fig. 6). This confirmed the larger bar migration rates at all time scales observed for the outer bar (Section 4). Relatively, X_{ia} and X_s were more important at the outer bar than at the inner bar ($F^o_{ia}/F^i_{ia} = 1.1$ and $F^o_s/F^i_s = 1.4$ on average), whereas X_w was relatively more important at the inner bar ($F^o_w/F^i_w = 0.7$ on average; Fig. 7).

In summary, the cross-shore bar migration at Noordwijk is dominated by weekly fluctuations on time spans shorter than 7–10 months (200–300 days) and by the gradual offshore directed inter-annual trend on time spans longer than 10–13 months (300–400 days). Seasonal fluctuations in bar crest position, although visible in the time series of $\tilde{X}_y$ (Fig. 3, only dominate at the outer bar on time spans between 7 and 13 months (200 and 400 days).

6. Discussion and conclusions

Alongshore uniform bar crest position was quantified over weekly, seasonal and inter-annual time scales from a 3.4-year data set of video-based bar crest lines at Noordwijk, Netherlands. These time series were used (1) to quantify weekly, seasonal and inter-annual bar migration rates and (2) to determine the relative contribution of these components to the total 2-D variability over a range of time spans. In general, Noordwijk appears to be a site with a strong inter-annual offshore directed trend in bar migration, limited seasonal variability in bar position and periodicities for weekly bar migration that are long compared to the characteristic time scale of storm events ($\approx$1–2 days). Below, the inter-annual, seasonal and weekly migration rates for Noordwijk are compared to values reported in the literature for other sites, and the differences and similarities are discussed.

The observed weekly cross-shore bar migration rates at Noordwijk (0–8 m/day in the onshore and 0–10 m/day in the offshore direction) are comparable to those at other sites, see Table 1. Only the values for the single bar at Duck (Sallenger et al., 1985; Howd and Birkemeier, 1987) and those for the sub- to intertidal bar at Nags Head (Sonu, 1968) and at Ventura Coast (Orme, 1985) are considerably larger. Maximum migration rates may be slightly underestimated by ARGUS observations, because the ARGUS bar crest position is based on smoothed observations with an average frequency of once per 2–3 days. The weekly fluctuations at Noordwijk have an average period of $\approx$7–8 weeks, suggesting that the bars mainly respond to sequences of high-wave events rather than to individual events. However, the time-averaging operation needed to remove apparent bar migration (Section 3) may have masked any response of the bar to individual storm events. Nevertheless, we feel that the predominant response to sequences of events rather than to individual events is likely to be characteristic of well-developed multiple barred coasts like Noordwijk. For instance, approximately bi-daily bathymetric surveys of the inner bar at nearby Egmond showed that the bar migrated gradually offshore during a sequence of storm events without abrupt offshore jumps at any of the individual storm events (Ruessink et al., 2000). Single bars are, because of the absence of more seaward located bars, more exposed to the incident storm waves and may, accordingly, respond to individual events, see Gallagher et al. (1998) for an example from the single barred nearshore at Duck, NC.

The seasonal cross-shore bar migration rates at Noordwijk varied between 0 and 0.53 m/day, which is slightly smaller than the monthly-averaged rates reported by Plant et al. (1999) for Duck. Especially at the inner bar, the seasonal variability is limited. Reduction of the wave height by dissipation of wave energy at the outer bar may reduce the seasonal variability at the inner bar, thus explaining the limited importance of seasonal bar migration at the inner bar.

Over years, the bars at Noordwijk gradually migrated in an offshore direction with maximum rates of 0.08 m/day for the inner bar and 0.15 m/day for the outer bar. Interestingly, the inner bar migration rates were smaller than the outer bar migration rates, similar to observations at Duck (Lippmann et al., 1993) and Terschelling (Ruessink and Kroon, 1994). The inner outer bar difference suggests that the net inter-annual bar migration varies with offshore distance, which may be coupled to the stage in the bar cycle as described by Ruessink and Kroon (1994). Typically, net offshore bar migration rates are minimum close to the shore, just after bar generation, and at the outer margin of the bar zone, during the bar degeneration stage, and are maximum inbetween. The bars at Noordwijk migrated slower offshore than the bars at Duck, Wanganui and Hasaki (see Table 1) in comparable stages of the bar cycle. Such intersite differences in bar migration rate likely depend on intersite differences in the cycle duration and the width of the bar zone. Both the cycle duration and the bar zone width were observed to be larger on higher energetic sites (characterised by the storm wave height, Shand et al., 1999; Ruessink et al., submitted). The net effect hereof on the inter-annual bar migration rates is, however, unclear. Furthermore, bar switching, a process during which an alongshore discontinuous bar attaches to a landward located bar (Shand et al., 2001), may retard inter-annual bar migration locally and temporally.

Acknowledgements

We would like to thank the staff of Grand Hotel 'Huis ter Duin' in Noordwijk for the permission to use the roof of their hotel as home for the ARGUS system and for their logistic support. Comments received on the Ph.D. thesis version of this paper from Huib de Swart, Marcel Stive, Mark Davidson and Aart Kroon are greatly appreciated.

References

Aubrey, D.G., 1979. Seasonal patterns of onshore/offshore sediment movement. Journal of Geophysical Research 84, 6347–6354.

Birkemeier, W.A., 1984. Time scales of nearshore profile changes. In: Proceedings Coastal Engineering'84, ASCE, New York, pp. 1507–1521.

Carter, R.W.G., Kitcher, K.J., 1979. The geomorphology of offshore sand bars on the north coast of Ireland. In: Proceedings Royal Irish Academy Biological, Geological and Chemical Science, Royal Irish Academy, Dublin, pp. 1507–1521.

Gallagher, E.L., Elgar, S., Guza, R.T., 1998. Observations of sand bar evolution on a natural beach. Journal of Geophysical Research 103, 3203–3215.

Holland, K.T., Holman, R., Lippmann, T., Stanley, J., Plant, N., 1997. Practical use of video imagery in nearshore oceanographic field studies. Journal of Oceanic Engineering 22, 81–92.

Houwing, E.J., 1991. Analyse van de TAW-profielen, Egmond aan Zee en Katwijk aan Zee. Technical Report GEOPRO 1991.019, Institute of Geographical Research (in Dutch).

Howd, P.A., Birkemeier, W.A., 1987. Storm-induced morphology changes during Duck85. In: Proceedings Coastal Sediment'87, ASCE, New York, pp. 834–847.

Kuriyama, Y., 2000. Medium-term bar movement and sediment transport at HORS. Technical Report 39-4, Port and Harbour Research Institute.

Larson, M., Kraus, N.C., 1994. Temporal and spatial scales of beach profile change, Duck, North Carolina. Marine Geology 117, 75–94.

Lippmann, T.C., Holman, R.A., 1989. Quantification of sand bar morphology: a video technique based on wave dissipation. Journal of Geophysical Research 94, 995–1011.

Lippmann, T.C., Holman, R.A., Hathaway, K., 1993. Episodic, nonstationary behavior of a double bar system at Duck, North Carolina, USA, 1986–1991. Journal of Coastal Research SI 15, 49–75.

Orme, A.R., 1985. The behavior and migration of longshore bars. Physical Geography 5, 142–164.

Ostrowski, R., Pruszak, Z., Zeidler, R.B., 1990. Multiscale nearshore and beach changes. In: Proceedings Coastal Engineering'90, ASCE, New York, pp. 2773–2784.

Owens, E.H., Frobel, D.H., 1977. Ridge and runnel systems in the Magdalen Islands, Quebec. Journal of Sedimentary Petrology 47, 191–198.

Plant, N.G., Holman, R.A., Freilich, M.H., Birkemeier, W.A., 1999. A simple model for interannual sandbar behavior. Journal of Geophysical Research 104, 15,755–15,776.

Ruessink, B.G., Kroon, A., 1994. The behaviour of a multiple bar system in the nearshore zone of Terschelling: 1965–1993. Marine Geology 121, 187–197.

Ruessink, B.G., Van Enckevort, I.M.J., Kingston, K.S., Davidson, M.A., 2000. Analysis of observed two- and three-dimensional nearshore bar behaviour. Marine Geology 169, 161–183.

Ruessink, B.G., Bell, P.S., Van Enckevort, I.M.J., Aarninkhof, S.G.J., 2002. Nearshore bar crest location quantified from time-averaged x-band radar images. Coastal Engineering 45, 19–32.

Ruessink, B.G., Wijnberg, K.M., Holman, R.A., Kuriyama, Y., Van Enckevort, I.M.J. Inter-site comparison of interannual nearshore bar behavior. Journal of Geophysical Research, submitted for publication.

Sallenger, A.H., Holman, R.A., Birkemeier, W.A., 1985. Storm induced response of a nearshore bar system. Marine Geology 64, 237–257.

Shand, R.D., Bailey, D.G., Shephard, M.J., 1999. An inter-site comparison of net offshore bar migration characteristics and environmental conditions. Journal of Coastal Research 15, 750–765.

Shand, R.D., Bailey, D.G., Shephard, M.J., 2001. Longshore realignment of shore-parallel sand-bars at Wanganui, New Zealand. Marine Geology 179, 147–161.

Short, A.D., 1992. Beach systems of the central Netherlands coast: processes, morphology and structural impacts in a storm driven multi-bar system. Marine Geology 107, 103–137.

Sonu, C.J., 1968. Collective movement of sediment in littoral environment. In: Proceedings Coastal Engineering'68, ASCE, New York, pp. 373–400.

Sunamura, T., Takeda, I., 1984. Landward migration of inner bars. Marine Geology 60, 63–78.

Van Enckevort, I.M.J., 2001. Daily to yearly nearshore bar behaviour. Ph.D. Thesis, Utrecht University.

Van Enckevort, I.M.J., Ruessink, B.G., 2001. Effect of hydrodynamics and bathymetry on video estimates of nearshore sandbar position. Journal of Geophysical Research 106, 16969–16980.

Van Enckevort, I.M.J., Ruessink, B.G., 2003. Video observations of nearshore bar behaviour. Part 2: alongshore non-uniform variability. Continental Shelf Research 23, 513–532.

Van Rijn, L.C., 1998. Principles of Coastal Morphology. Aqua publications, Amsterdam.

Wijnberg, K.M., Terwindt, J.H.J., 1995. Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. Marine Geology 126, 301–330.

Winant, C.D., Inman, D.L., Nordstrom, C.E., 1975. Description of seasonal beach changes using empirical eigenfunctions. Journal of Geophysical Research 80, 1979–1986.

Wolf, F.C.J., 1997. Hydrodynamics, sediment transport and daily morphological development of a bar-beach system. Ph.D. Thesis, Utrecht University.