ALONGSHORE TOPOGRAPHIC VARIABILITY AT A NOURISHED BEACH

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Abstract

The present paper examines the generation and inter-annual evolution of alongshore variability in topography measured after the implementation of a sand nourishment. The magnitude of the topographic variability is quantified using 3.5 years of monthly survey data. The emergence and temporal change in alongshore morphological variability is compared with environmental and topographic controls previously suggested as governing processes in published literature. Results show that the variability at this site is slowly evolving on a monthly timescale. Magnitude of the variability in the first period after implementation of the nourishment was similar to the values found after 3.5 years. Temporal variation in the magnitude of the alongshore topographic variability was found to be related the incoming wave power offshore. Energetic storm events during winter resulted in a rapid increase in variability, followed by a gradual decrease in alongshore variability during spring and summer.

Key words: Alongshore topographic variability, sand nourishments, subtidal bar dynamics.

1. Introduction

This paper is on the magnitude of alongshore topographic variability in the sub-aqueous topography. Alongshore topographic variability is the deviation of the bed height in alongshore direction from an alongshore uniform topography. Alongshore variability in topography on the coast can be observed near the shoreline (*e.g.* beach cusps) or in the subtidal bar(s) (*e.g.* a bar-rip morphology) amongst others. This variability induces horizontal hydrodynamic circulations and offshore directed flows, which provide mixing of nutrients but can also bring swimmers in distress (McLachlan and Hesp, 1984; Talbot and Bate, 1987; Dalrymple et al., 2011; *amongst others*).

Alongshore variability and pattern formation in the nearshore has been a subject of vigorous research over the years. With the increase in man-made interventions in the coastal system it has become even more important to understand how topographic variability in the nearshore is created. In the last decades, nourishments have become progressively more applied to enhance beach width for recreation or to protect the hinterland from inundation (*e.g.* Valverde et al., 1999; Dean, 2002; Hanson et al., 2002). These projects are often situated near densely populated areas with a high level of beach usage. Evaluation of such projects has therefore become multidisciplinary, evaluating not only the efficiency of the added sediment volume, but also its effect on ecology and safety of recreational beach goers. In the light of these new criteria it is important to be able to understand the effect of nourishments and their design on the alongshore variability in topography.

Topographic variability is nowadays commonly thought to be originating from 'self-organisation'; the intrinsic instability of the nearshore topography and its forcing causes small initial perturbations in the bed level into grow to large bed forms and patterns (*e.g.* Hino, 1974; Falqués et al., 2000; Coco and Murray, 2007; *and references therein*). Detailed conceptual modeling has revealed that the magnitude and spacing of the variability is dependent on multiple parameters; on one hand related to the external forcing such as wave height, angle and period (*e.g.* Deigaard et al., 1999; Calvete et al., 2005; Castelle, 2007; Thiebot et al.,

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2011) and on the other hand dependent on the characteristics of the cross-shore profile such as bar volume and crest position (*e.g.* Damgaard et al., 2002; Calvete et al., 2007; Smit et al., 2008). These relations are difficult to test in nature, as often the signal is masked by antecedent morphology. Once a spatial pattern is developed, it can remain enforced by a variety of wave conditions (Smit et al., 2012), such that variability observed at a single instant does not need to be in balance with the concurrent conditions (Plant et al., 2006).

Little is known on how nourishment design can influence the generation of topographic variability; most nourishment evaluation is concentrated on the overall sediment balance and the cross-shore redistribution of the nourished sediment. Based on isolated conceptual modeling of the impact of beach slope a faster development of patterns is expected at the steep beach slopes after construction as 'cross-shore gradients in all processes are inversely scaled with the profile slope' (Drønen and Deigaard, 2007) leading to faster feedbacks. Such findings have however not been reported upon in the field to date, and it is therefore unclear whether nourishment design can be adjusted to reduce (or promote) the alongshore variability. Nourishments have been reported to impede the bar migration cycle (Grunnet and Ruessink, 2005; van Duin et al., 2004). Only at a single site, Terschelling, the Netherlands, variability was reported to increase after a nourishment (Grunnet and Ruessink, 2005), whilst after nourishments at Noordwijk, the Netherlands, no effect was found on the variability (Ruessink et al., 2012). The intersite differences are, based on these first observations, suggested to be related to the positioning of the nourishment with respect to the pre-existing and surrounding bars (Ruessink et al., 2012).

To avoid the interference with remnant and surrounding morphology it would be beneficial to investigate a nourishment project with complete regeneration of subtidal morphology. The objective of the current study is therefore to examine in detail the development of alongshore variability after implementation of a large beach and shoreface nourishment covering all subtidal bars and variability prior to the nourishment. Typically alongshore variability is examined over time using imagery data, showing in high temporal detail the alongshore length scales of the bar crest (rip spacing) and the planform variations in the bar or nourishment position from shore (*e.g.* Ojeda et al., 2008, Ruessink et al. 2012). Here we use a different approach, using frequent detailed bathymetric surveys to focus not only on the plan view variations in bar crest position but predominantly on the magnitude of the patterns (*i.e.* incorporating the vertical dimension). Special attention is paid to the temporal variations in alongshore variability and their relationship to the cross-shore profile evolution of the nourishment and wave forcing.

2. Nourishment field site

The nourishment under investigation was implemented at Vlugtenburg beach, on the south west part of the Holland coast, the Netherlands. In the years prior to the construction of the nourishment, this stretch of sandy coast from the Hague to Hook of Holland was characterized by rubble mound groynes around 250 m apart which were installed from the year 1791 onwards. In 2009, a large nourishment scheme (~18.10^6 m^3 of sand over 17 km) covered all groynes in this coastal cell and a new beach type was created. At the south side of this cell, at Vlugtenburg beach, the coastal profile was moved seaward 300 m by beach and shoreface nourishments (Figure 1). A new (steep) profile remained after construction which covered all antecedent bars and variability.

The study site has a mean tidal range of 1.7 m and waves that enter predominantly from the south west and north sectors (85 and 50 degrees with respect to shore-normal). Mean annual wave height and wave period are H_{m0}=1.4m and T_{m01}=5s (Wijnberg, 2002). Median grain size around the shoreline is O (250 μm) and the overall surfzone and beach slope is 1:50 (de Vries et al., 2011). Generally, the profile on the Holland coast contains multiple nearshore subtidal bars, migrating offshore in cycles with return intervals of 4 to 16 years (Ruessink et al., 2003). The location of the field site showed less prominent temporal behavior over the decades before the project; generally only a single bar offshore of the groyne heads (Wijnberg and Terwindt, 1995). Possibly the less prominent bar behavior and cyclic migration at this site was influenced by the presence of the groynes, and as there are no records of the coastal profile in the 1700's (before the groynes) it was unclear a priori what kind of profile and bar behavior could be expected after completion of the project.

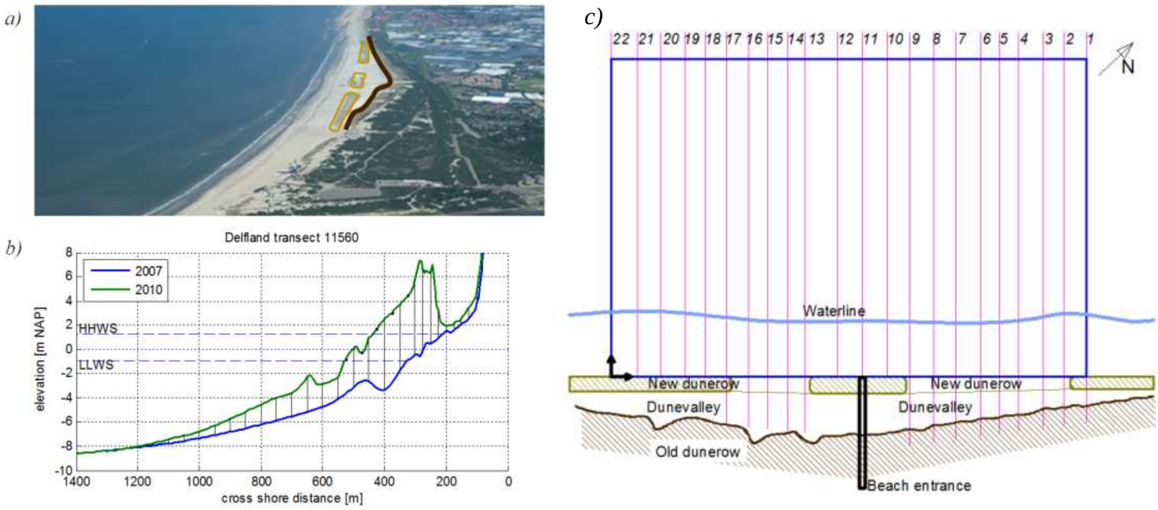

Figure 1. *a)* Overview of the Vlugtenburg field site. Old dune (approx. +10 m NAP) and newly constructed foredune (approx. +6 m NAP) indicated by the dark brown and beige lines, respectively. *b)* Coastal profiles of the Dutch ministry of public works (JARKUS) 2 years prior and 1 year after construction of the nourishment. *c)* Schematized overview of the survey area. 22 survey transects given by the magenta lines. Shaded areas indicate vegetated dunes.

3. Observations and Variability

3.1. *Surveys*

The topography of the newly constructed beach was surveyed approximately monthly since the completion of the construction in spring 2009, resulting in 38 surveys spanning 3.5 years. Surveys contained both the sub-aerial and sub-aqueous beach, where both parts were measured almost concurrently (< 3 days apart). The main part of the nourishment project was subdivided in 22 transects roughly 80 m apart (Figure 1*c*) resulting in an alongshore extent of the observed coastal cell of 1745 m centered around the beach entrance. Based on the transect spacing and the alongshore extent of the survey domain, emergent alongshore variability with length scales of *O* (200 - 1500 m) can be captured. Typical length scales on the Dutch coast are in the range 250 - 3000 m, where the larger length scales are observed in the (older) outer bar and the smallest length scales in the inner bar (van Enckevort and Ruessink, 2003). In cross-shore direction the surveyed profiles extend 900 m offshore to approximately 9 m water depth.

Surveys were executed using two techniques, walking and jetski (personal watercraft) surveys. Walking (RTK-GPS backpack) surveys for the sub-aerial part of the profile extend to the low water line and have accuracy of *O* (5 cm). The sub-aqueous part of the profile was surveyed using a jetski equipped with a single beam echo sounder and RTK-GPS, capable to obtain bed level measurements with accuracy in the order of 10 cm (van Son et al., 2010).

Linearly interpolated survey data are shown in Figure 2 for the years 2009 to 2012 at the beginning of summer.

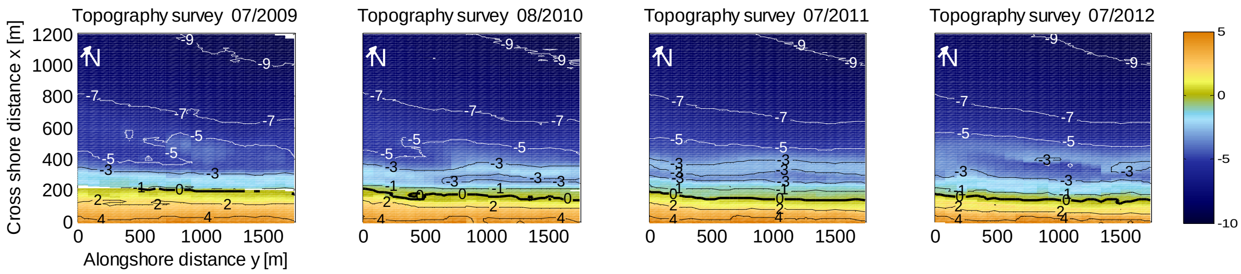

Figure 2. Vlugtenburg beach topographies in the summers of 2009 to 2012, Colors indicate bed level in meters NAP (Dutch datum at approx. MSL)

3.2. *Quantification of Topographic Variability*

Alongshore variability in bed level is the deviation of the bed level with an alongshore averaged (uniform) topography. The height of the bed level variability alone, z_{var} , can be separated by subtracting the alongshore averaged cross-shore profile $z_{b,mean}$ from the surveyed bed level along individual cross-shore profiles z_b :

$$z_{\mathrm{var}} = z_b - z_{b,mean}, \tag{1}$$

In this particular field site the lower depth contours are slightly oblique with respect to the shoreline (Figure 3a), making the construction of an alongshore uniform topography more complicated. If the alongshore uniform topography $z_{b,mean}$ is constructed from merely the alongshore averaged profile, it would result in large values of bed level variability z_{var} in the deeper zones. An alternative alongshore averaged topography, $z^*_{b,mean}$, including an ambient slope was proposed to overcome this issue, constructed from an alongshore averaged profile in combination with a linear alongshore slope:

$$z^*_{b,mean}(x,y) = p_2(x)\ \ y + p_1(x), \tag{2}$$

where *x* and *y* are the cross- and alongshore directions. Coefficients $p_1(x)$ and $p_2(x)$ are respectively the alongshore averaged cross-shore profile and an alongshore slope per cross shore location, chosen such that $z^*_{b,mean}$ had the best (least squares) fit with the measured profiles. The resulting profile is nearly alongshore uniform in the surfzone but matches the overall contour orientation of the measurements at deeper water (Figure 3b).

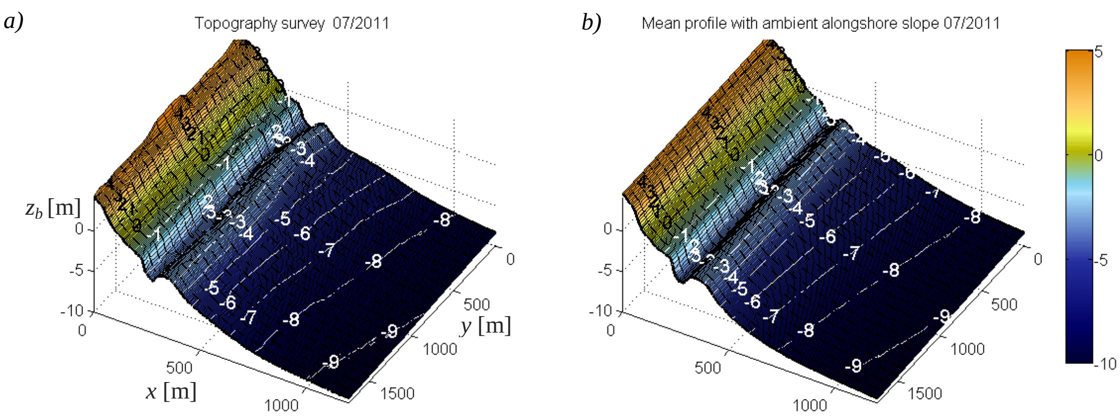

Figure 3. *a)* Interpolated survey profiles (z_b) and *b)* alongshore averaged profile ($z^*_{b,mean}$ Eq. 2) for June 2011. Note the angle of the deeper isobaths (-6 to -9 m) with respect to the shoreline.

Using the procedure outlined above, an alongshore averaged profile was constructed and removed from the profile for each survey, leaving only the medium scale alongshore variability for further analysis (Figure 4).

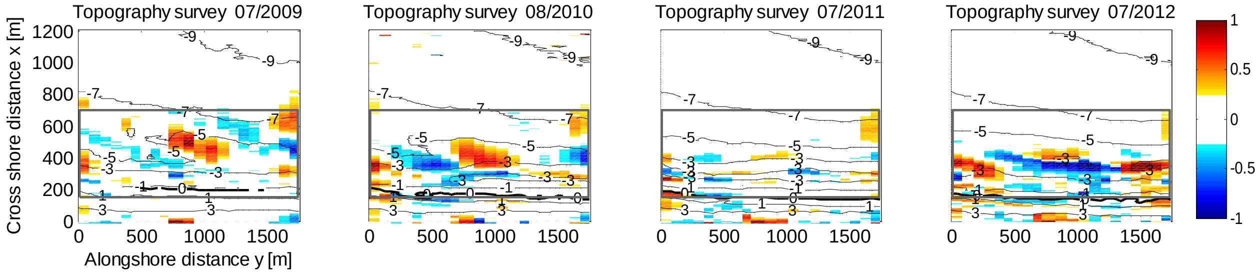

Figure 4. Planform images of alongshore variability z_{var} at Vlugtenburg beach in the summers of 2009 to 2012, Colors indicate the deviation z_{var} from the mean alongshore topography in meters. Contour levels indicate the bed level in m as displayed in Figure 2.

The majority of the alongshore variability in topography was found to be located around -3 m water depth on the subtidal bar (cross-shore location x of ~400 m). Total alongshore topography variability was quantified per survey in a single value using a bulk alongshore variability metric σ_z^2 . Parameter σ_z^2 expresses the depth variations between the individual profiles and the mean profile as follows:

$$\sigma_z^2 = \frac{1}{L_x L_y} \int_{x_{onshore}}^{x_{offshore}} \int_{y_{north}}^{y_{south}} \left(z_{\text{var}}(x,y) \right)^2 dydx \tag{3}$$

With parameters $x_{offshore}$, $x_{onshore}$, y_{north} and y_{south} marking the domain used for the evaluation of the variability and L_x, L_y being the resulting size of the domain. For the results here onwards we used a seaward limit of 700 m (at approx. -7 m) to minimize the impact of survey noise in deep water and a shoreward limit of 150 m (at approx. MSL) to ensure the σ_z^2 contains all variability in the surfzone (Figure 4, gray boxes). Upcoming results are however not significantly altered if slightly different domain boundaries are selected since the majority of the variability is in the midst of this domain.

3.3. *Observations of Topographic Variability*

The bulk alongshore variability quantified using Equation (3) is displayed in Figure 5 for all surveys. Some variability was found in the first survey after completion of the nourishment, which remained from the construction (see also Figure 2 and 4, left panels). Overall, the variability appears to fluctuate on an inter-annual timescale, with a strong change in variability observed in the Dec '11- Feb '12. No strong trend is visible as the values of σ_z^2 in the last surveys (after 3.5 years) are similar to the values 0.5 years after implementation of the nourishment. Furthermore, the time series of σ_z^2 show a large auto correlation (auto correlation coefficients r for a lag of 1, 2 and 3 surveys are 0.88, 0.66, and 0.42) signifying that the magnitude of the alongshore variability is only slightly altered from month to month, as also observed visually in monthly topography plots (not shown here). Variability σ_z^2 was found to increase in jumps, generally in the period October to January. Decreases in variability were more gradual and mostly during spring and summer. These observations are in contrast to previous observations of bar rhythmicity at the US and Australian coast (*e.g.* Lippmann and Holman, 1990; Holman et al., 2006) showing faster changes in variability (timescales of days to weeks) as well as inverse development rates; a rapid episodic removal of variability followed by a slower increase in variability in subtidal bars.

Time series of the variability (Figure 5) do not show an apparent signature of different development of variability in the first period after completion compared to the rest of the time series.

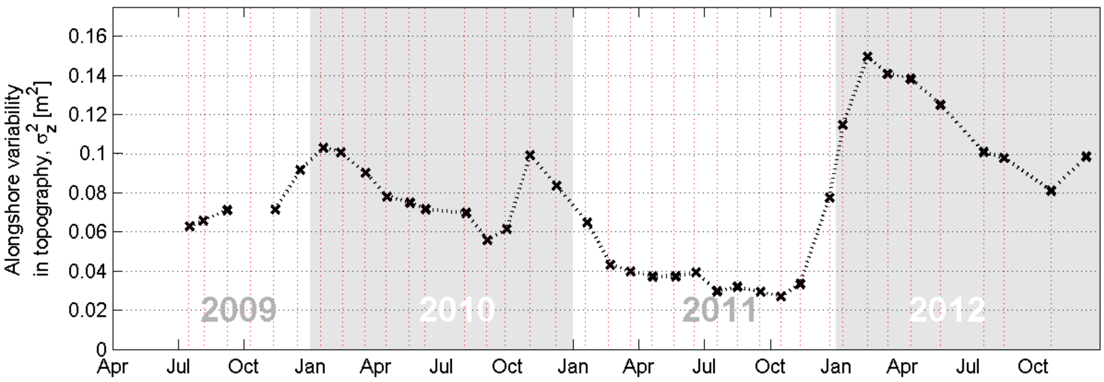

Figure 5. Bulk alongshore variability σ_z^2 for the 3.5 years after completion of the nourishment. Red lines indicate the survey dates. Survey of Oct. 2009 contained a data gap between the sub-aerial and sub-aqueous surveys and was therefore not used in the analysis.

4. Tested control parameters

Temporal evolution of observed variability σ_z^2 was compared to topographic controls (cross-shore profile characteristics) and environmental (wave forcing) parameters to investigate any dependency. The definition of the parameters used will be briefly discussed hereunder, before elaborating on the correlations.

4.1. *Topographic controls*

A number of topographic parameters were examined, which are illustrated in Figure 6.

1. Cross-shore shoreline position x_s, calculated from the weighted mean position of the profile between - 0.5 and 0.5 m NAP.
2. Change in supra tidal beach volume between two consecutive surveys, $\Delta V_{supra}/\Delta t$. The volume supra tidal beach (in m^3 per m alongshore) was obtained from the zone above + 1 m NAP. Δt is the number of days between the two surveys.

Both parameters are expected to provide a measure for the adjustment of the artificial construction profile to a more natural slope. Over the investigated time period the upper profile has lost approx. 100 m^3 per m alongshore and shoreline position has retreated *O* (50 m) due to the redistribution of sand in the profile (de Schipper et al., 2012). x_s and $\Delta V_{supra}/\Delta t$ are hypothesized to give an indication whether variability is related to the sediment redistribution from the upper beach towards lower profile changing the post construction profile to a more natural profile.

Secondly, various cross-shore subtidal bar characteristics were examined which previously associated with the growth rate or length scales of topographic variability:

3. Bar crest distance with respect to the shoreline (x_c-x_s). Bar crest position x_c was defined as the local maximum of the profile below the low water line.
4. Bar crest movement, $\Delta x_c/\Delta t$.
5. Waterdepth over the bar crest, d_c and
6. Bar volume V_{bar} (in m^3 per m alongshore). Calculated as the cross-sectional area above a line between the landward bar trough and seaward end of the bar. The seaward end of the bar was obtained as the point with maximum curvature dz^2/dx^2 in the profile or, in case the seaward slope of the bar merged smoothly with the profile, the profile crossing with the -5 m level. These criteria were taken based on visual examination of the profile data.

Bar crest locations further from shore (*i.e.* large x_c-x_s) are thought to generally result in larger alongshore spacing (Van Enckevort et al., 2004 *and references therein*) but the effect on the magnitude of variability is unclear. The movement of the cross-shore bar crest is a proxy for the imbalance of the cross-shore bar position with respect to its equilibrium position based on the instantaneous wave forcing. Based on a simple empirical model, Plant et al (2006) show that bar crest movement and alongshore variability are interrelated state variables and cross-shore migration of the crest can also incite a change in alongshore variability. Water depth over the bar crest controls partly the activity of the bar as deep bar crests are only inside or close to the surfzone during extreme wave events. Conceptual modelling of the emerging variability has confirmed that different crest levels result in changes in growth rate of variability (*e.g.* Calvete et al., 2007). Similarly, the bar volume is suggested to be related to the response time of the system (Enckevort et al., 2004; Smit et al., 2008) as bar volume is a measure for the amount of sediment that has to be displaced to create the variability.

Profile parameters stated were calculated per transect (Figure 6) and alongshore averaged to obtain a single value per survey. For the bar crest height and position the median of all profile values was used rather than the average, since survey inaccuracies can lead to an outlier in the local maxima in the profile.

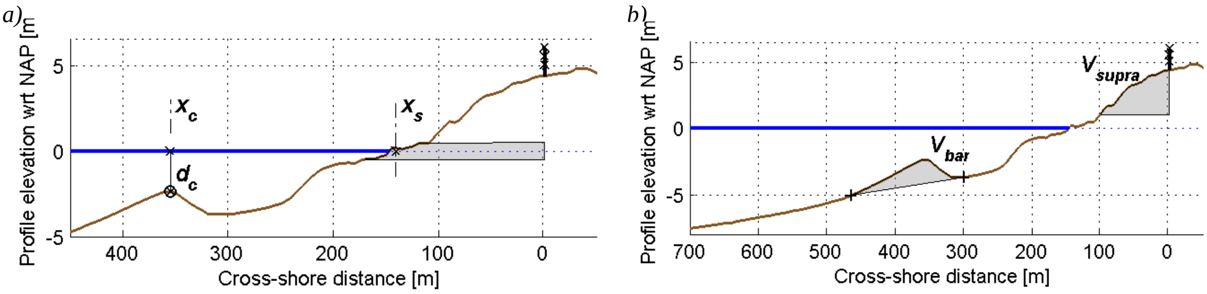

Figure 6. Profile parameters. *a)* Methodology to determine shoreline position x_s, bar crest location x_c and bar crest depth d_c, and *b)* Methodology to determine the volume of the supra tidal beach V_{supra} and the volume of the subtidal bar V_{bar}.

4.2. *Environmental controls*

Concurrent wave conditions offshore $H_{s,0}$, $T_{p,0}$ and direction Θ_0 were obtained from an offshore wave station 40 km from the site. Wave height showed a strong seasonal signal with largest waves occurring in the months September to December (autumn). The maximum recorded wave height $H_{s,0}$ over the entire 3.5 year period was 6.8 m during the December 2011 storm. During summer months very low wave heights were recorded, and the lowest average wave height $H_{s,0}$ in a period between two surveys was 65 cm.
Offshore values were converted into wave power P_0, combining the effect of wave height and wave period:

$$P_0 = E_0 c_{g,0} \tag{4}$$

where wave energy E_0 was taken as $E_0 = 1/16 \rho g H_{s,0}^2$ and group celerity $c_{g,0}$ was calculated using wave period, water depth and the wavenumber as given by the linear dispersion relation.

Secondly, a proxy for the alongshore wave power available for alongshore transport was examined, incorporating the effect of wave angle. The angle of incidence is found to have a large effect, such that the oblique incidence is of major importance for the removal of variability (*e.g.* Price, 2013) as well as the growth rate of emerging variability (*e.g.* Calvete et al., 2005; de Schipper et al., submitted). The wave power available for alongshore sediment transport was approximated by $P_{y,b}$ (Komar, 1988) :

$$P_{y,b} = P_b \sin(\theta_b - \theta_\perp)\cos(\theta_b - \theta_\perp) \tag{5}$$

where $\Theta_\perp$ is the wave angle of shore-normal incidence, 310 degrees with respect to North. $P_{y,b}$ is evaluated at breakpoint, and therefore the offshore wave measurements are translated inshore using the dispersion relationship for linear water waves and Snell's Law for straight and parallel offshore contours. Breakpoint values are taken at the point where the wave height exceeds 0.8 times the water depth. Sheltering by nearby (4 km) harbor moles for southerly waves or possible wave current interaction due to the harbor entrance are not included in this transformation. Mean and maximum values of both P_0 and $P_{y,b}$ for each time period between consecutive surveys were examined to investigate whether primarily high wave events or monthly wave climate properties are related to the variability.

Finally, the mean angle of wave incidence wave offshore for each period between surveys is computed. Mean offshore wave angle was weighted by wave power by integrating over all daily values of P_0 and Θ_0 between two consecutive surveys as follows:

$$\overline{|\theta|} = \frac{\sum_{t=T_i}^{t=T_j} P_0 |\theta_0 - \theta_\perp|}{\sum_{t=T_i}^{t=T_j} P_0} \tag{2}$$

with T_i and T_j being the dates of successive surveys. Values of mean angle of wave incidence $\overline{|\theta|}$ reflect the large angle of wave incidence offshore at this part of the coast; smallest $|\theta|$ value over a period between two surveys was 33 degrees, the largest value 77 degrees.

4.3. *Correlations*

The observed variability σ_z^2 and temporal change evaluated over a period between two surveys $\Delta\sigma_z^2/\Delta t$, (with Δt being the number of days between two surveys) is compared to profile parameters and wave forcing parameters stated above. Relationships among variables are investigated with a least squares linear regression analysis. Resulting correlation coefficient *r* (*i.e.* Pearson coefficient ρ) for each cross-correlation is given in Table 1. Coefficient *r* is used rather than the more common r^2 to show the direction of the relationship (positive or negative).

Parameters are tested in pairs, testing individual relationships. Due to the large interconnectivity between parameters (*e.g.* bar volume, crest location and depth) the values indicate similar changes in parameter space rather than direct dependency. A relationship was stated to be significant if the null hypothesis (no relationship between parameters) could be rejected with 95 % confidence. The residuals of the linear regression (*i.e.* errors between linear model and the data) occasionally showed signs of autocorrelation, due to for instance the slow evolution of variability or the net seaward trend in bar position. For such observations, regression residuals where not independent and the number of independent observations to determine the 95 % significance threshold were adjusted based on the correlogram of the residuals. Furthermore, on some occasions outliers dominated a (significant) relationship. For these cases, correlation was recomputed without the outliers and significance was re-evaluated. Only if a significant relationship remained after the criteria above, it is listed in Table 1.

5. Results

Table 1 shows the correlation values between the variability and the forcing and profile parameters. None of the parameters show a significant relationship with the measured instantaneous variability σ_z^2 . This could be interpreted as that the response (variability) is changing slower than the forcing and profile or vice versa. Based on the slow changes observed in visual inspection of the survey data we conclude that the instantaneous variability is to a large extent dominated by the antecedent variability rather than the forcing or the profile shape. In spring and summer (March - September) in particular, magnitude of variability σ_z^2 is hypothesized to be dependent on the level of variability remaining after the winter season (Figure 5).

Table 1. Correlation coefficients *r* of instantaneous variability and evolution of variability with profile and wave forcing characteristics.
Only significant values (95% confidence interval) are given, non-significant relationships denoted as '-'.

	Variability		Beach		Bar characteristics				Wave Forcing between consec. surveys				
			Shoreline position	Volume change	Crest location	Crest migration	Crest depth	Volume	Wave power		Alongshore wave power. for Sed Tr		Wave angle
	σ_z^2	$\Delta\sigma_z^2 / \Delta t$	x_s	$\Delta V_{supra} / \Delta t$	$x_c - x_s$	$\Delta x_c / \Delta t$	d_c	V_{bar}	$\overline{P_0}$	$P_{0,\max}$	$\overline{\lvert P_{y\,b} \rvert}$	$\lvert P_{y\,b,\max} \rvert$	$\overline{\lvert \theta \rvert}$
σ_z^2	**1**	-	-	-	-	-	-	-	-	-	-	-	-
$\Delta\sigma_z^2 / \Delta t$		**1**	**-**	**-0.62**	**-**	**0.52**	**-**	**-**	**0.67**	**-**	**-**	**-**	**-**
x_s			1	-	-0.93	-	0.83	-0.93	-	-	-	-	-
$\Delta V_{supra} / \Delta t$				1	-	-	-	-	-0.75	-0.76	-	-0.57	-
$x_c - x_s$					1	-	-0.94	0.92	-	-	-	-	-
$\Delta x_c / \Delta t$						1	-	-	0.52	0.54	-	-	-0.42
d_c							1	-0.79	-	-	-	-	-
V_{bar}								1	-	-	-	-	-
$\overline{P_0}$									1	0.89	-	0.72	-
$P_{0,\max}$										1	0.44	0.73	-
$\overline{\lvert P_{y\,b} \rvert}$											1	0.55	-
$\lvert P_{y\,b,\max} \rvert$												1	-
$\overline{\lvert \theta \rvert}$													1

5.1. *Topographic controls*

A moderate relationship is found between the changes in variability ($\Delta\ \sigma_z^2/\Delta t$) and the reduction in the supra tidal beach volume. This signal was mostly determined by the winter months where variability was increasing and the beach was eroding. This is also reflected in the correlation with the bar migration, showing an increase in variability as the bar moves further offshore. No relation is found with the bar crest level and the bar volume which is remarkable as in the 3.5 years a nearshore subtidal bar is formed and migrated offshore, resulting in a wide range of crest levels and bar volumes over time. Bar crest depth starts in 2009 at d_c =-1.6 m (and located 180 m from shore) and moves to d_c = -3.4 m (at 360 m from shore) in late 2012, but as in the midst of this migration (medio 2011) alongshore variability was very low (see also Figure 2), this is not reflected in a significant relationship. Also, the field data provided a unique setting having a single subtidal bar with increasing bar volume from 50 m^3 to 150 m^3 per m alongshore over the years. This trend was however not reflected in an observable change in variability.

5.2. *Environmental / Hydrodynamic controls*

Although forcing parameters do not directly relate to instantaneous observed variability σ_z^2 , a moderate relationship is found between the changes in variability ($\Delta\ \sigma_z^2/\Delta t$) and incoming wave power. Significant correlation is only found for the mean value, $\overline{P_0}$, but not the maximum wave power. No significant correlation was found with the alongshore wave power available for alongshore sediment transport, nor the mean wave angle. Correlation coefficient with incident wave power $\overline{P_0}$ is positive, indicating that increases in variability often coincide with time periods with large incident wave power (see also Figure 7). This is in contrast to traditional conceptual models of cyclic behaviour of bar states, which prescribe that high wave events coincide with a decrease and removal of variability and less energetic conditions during the following period result in the formation of variability (Wright and Short, 1984; Lippmann and Holman, 1990). These models are confirmed by observations at Duck, NC, USA (Lippmann and Holman, 1990), Palm Beach (Holman et al., 2006) and the Gold Coast, Australia (Price, 2013) amongst others, but such relation between forcing and variability is less clear at the Dutch coast as previously reported by van Enckevort en Ruessink (2003). Our Vlugtenburg observations, contrasting the traditional model of removal of variability during storms, underline their earlier observation.

A possible hypothesis for the different behavior was suggested to be the large bar volume at the Dutch coast (van Enckevort en Ruessink, 2003). Based on our data however, this argument does not hold as the subtidal bar volume in this study was small (*O* 100 m^3 per m alongshore) and of same order or magnitude as the bar volume in the US and Australia (based on the profiles displayed in Ruessink et al. (2003) and Price (2013)). Possibly the 'counter intuitive' behavior at the Dutch coast can also be explained by different environmental setting, such as the short-crested sea states or the large angles of wave incidence and variations therein.

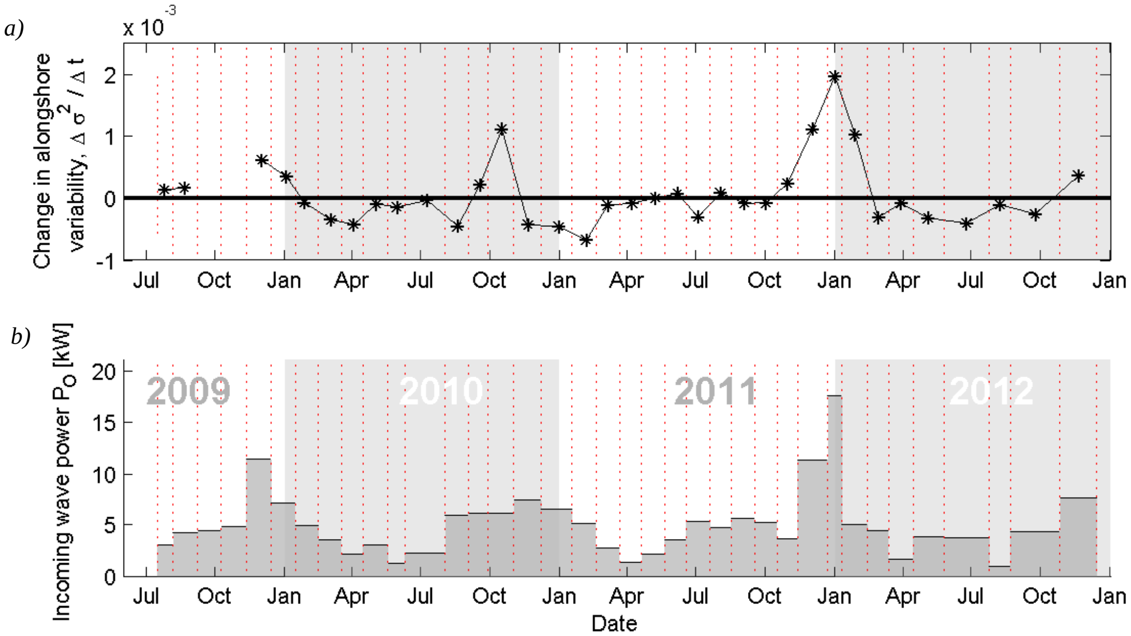

Figure 7. *a)* Change in alongshore variability between two consecutive surveys.
b) Mean wave power P_0 in the period between two surveys. Red lines indicate the survey dates.

Conclusions

Over 3.5 years of nearly monthly bathymetric surveys were executed to examine the development of alongshore variability in topography after installation of a beach and foreshore nourishment. Alongshore variability at the site is primarily found in the subtidal bar and evolved slowly on a monthly timescale. Magnitude of the variability is found to be changing in concert with the variations in forcing over the year. Late autumn and winter months (October to January) with larger incoming wave power result in an increase in alongshore variability, and milder spring and summer months show a gradual decrease in variability. The angle of wave incidence or a proxy of for wave power available for alongshore sediment transport were not significantly correlated with the instantaneous variability or change in variability.

The first period just after completion of the nourishment did not show different magnitudes or evolution rates of variability than the total period investigated. This obscures the effect of the nourishment on the emergence of variability and whether variability can be affected by selecting a different nourishment design (e.g. by applying a milder construction slope). To this end it is recommended to perform a similar analysis for a natural beach as well as nourishments with different designs to compare against in the future.

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References

Coco, G. and Murray, A.B., 2007. Patterns in the sand: From forcing templates to self-organization. *Geomorphology* 91(3), 271-290.

Calvete, D., Dodd, N., Falqués, A., and van Leeuwen, S. M., 2005. Morphological development of rip channel systems: Normal and near-normal wave incidence. *Journal of Geophysical Research* , 110(C10).

Calvete, D., Coco, G., Falqués, A., and Dodd, N., 2007. (Un) predictability in rip channel systems. *Geophysical Research Letters*, 34(5)

Castelle, B., 2007. Modélisation de l'hydrodynamique sédimentaire au-dessus des barres sableuses soumises à l'action de la houle: application à la côte Aquitaine (Doctoral dissertation).

Dalrymple, R.A., MacMahan, J.H., Reniers, A.J.H.M. and Nelko, V., 2011. Rip currents. *Annual Review of Fluid Mechanics*, 43, 551-581.

Damgaard, J., Dodd, N., Hall, L., and Chesher, T., 2002. Morphodynamic modelling of rip channel growth. *Coastal Engineering*, 45(3), 199-221.

Dean, R.G.., 2002. *Beach nourishment: theory and practice* (Vol. 18). World Scientific.

Deigaard, R., Drønen, N., Fredsøe, J., Jensen, J. H., and Jørgensen, M. P., 1999. A morphological stability analysis for a long straight barred coast. *Coastal Engineering*, 36(3), 171-195.

Drønen, N., and R. Deigaard (2007), Quasi-three-dimensional modelling of the morphology of longshore bars, *Coastal Engineering*, 54(3), 197–215

van Enckevort, I.M.J., and Ruessink, B.G., 2003. Video observations of nearshore bar behaviour. Part 2: alongshore non-uniform variability. *Continental Shelf Research*, 23(5), 513-532

van Enckevort, I.M.J., Ruessink, B.G., Coco, G., Suzuki, K., Turner, I.L., Plant, N.G., and Holman, R.A., 2004. Observations of nearshore crescentic sandbars. *Journal of Geophysical Research*, 109(C6).

Falqués, A., Coco, G., and Huntley, D.A., 2000. A mechanism for the generation of wave-driven rhythmic patterns in the surf zone. *Journal of Geophysical Research*, 105(C10).

Hanson, H., Brampton, A., Capobianco, M., Dette, H. H., Hamm, L., Laustrup, C., Lechuga, A., and Spanhoff, R., 2002. Beach nourishment projects, practices, and objectives—a European overview. *Coastal Engineering*, 47(2), 81-111.

Hino, M., 1974. Theory on formation of rip-current and cuspidal coast. *Coastal Engineering Proceedings*, 1(14).

Holman, R.A., Symonds, G., Thornton, E.B., and Ranasinghe, R., 2006. Rip spacing and persistence on an embayed

beach. *Journal of Geophysical Research*, 111(C1).
Komar, P. D., 1998. *Beach processes and sedimentation*. Prentice Hall
Lippmann, T.C., and Holman, R.A., 1990. The spatial and temporal variability of sand bar morphology. *Journal of Geophysical Research*, 95(C7), 11575-11590.
McLachlan, A., and Hesp, P., 1984. Faunal response to morphology and water circulation of a sandy beach with cusps. *Marine ecology progress series*, 19(1), 133-144.
Ojeda, E., Ruessink, B.G., and Guillen, J., 2008. Morphodynamic response of a two-barred beach to a shoreface nourishment. *Coastal Engineering,* 55(12), 1185-1196.
Plant, N.G., Holland, T.K., and Holman, R.A., 2006. A dynamical attractor governs beach response to storms. *Geophysical Research Letters*, 33(17).
Price, T.D., 2013. Morphological coupling in a double sandbar system (Doctoral dissertation).
Ruessink, B.G., Miles, J., Feddersen, F., Guza, R. and Elgar, S., 2001, Modeling the alongshore current on barred beaches, *Journal of Geophysical Research*, 106(C10).
Ruessink, B.G., Wijnberg, K.M., Holman, R.A., Kuriyama, Y., and Van Enckevort, I.M.J., 2003. Intersite comparison of interannual nearshore bar behavior. *Journal of Geophysical Research*, 108(C8).
Ruessink, B.G., Grinten, R.M., Vonhögen-Peeters, L., Ramaekers, G., and Lodder, Q.J., 2012. Nearshore evolution at Noordwijk (NL) in response to nourishments, as inferred from Argus video imagery. *Proceedings of the 25th NCK days*
de Schipper, M.A., Ranasinghe, R., Reniers, A.J.H.M., Holman, R.A., and Stive, M.J.F., *submitted*. Emergence of alongshore variability in nearshore bars: a field data analysis.
de Schipper, M.A., Vries de, S., Ranasinghe, R., Reniers, A.J.H.M. and Stive, M.J.F., 2012. Morphological developments after a beach and shoreface nourishment at Vlugtenburg beach. *Proceedings of the 25th NCK days*
Smit, M.W.J., Reniers, A.J.H.M., Ruessink, B.G., and Roelvink, J.A., 2008. The morphological response of a nearshore double sandbar system to constant wave forcing. *Coastal Engineering*, 55(10), 761-770.
Smit, M.W.J., Reniers, A.J.H.M., and Stive, M.J.F., 2012. Role of morphological variability in the evolution of nearshore sandbars. *Coastal Engineering,* 69, 19-28.
van Son, S.T.J., Lindenbergh, R.C., de Schipper, M.A., de Vries, S., and Duijnmayer, K., 2010. Monitoring bathymetric changes at storm scale. *PositionIT*
Talbot, M.M.B., and Bate, G..C., 1987. Rip current charactersitics and their role in the exchange of water and surf diatoms between the surf zone and nearshore. *Estuarine, Coastal and Shelf Science*, 25(6), 707-720.
Thiebot, J., Idier, D., Garnier, R., Falqués, A., and Ruessink, B.G.., 2011. The influence of wave direction on the morphological response of a double sandbar system. *Continental Shelf Research.*32, 71-85.
Valverde, H.R., Trembanis, A.C., and Pilkey, O.H., 1999. Summary of beach nourishment episodes on the US east coast barrier islands. *Journal of Coastal Research*, 1100-1118.
de Vries, S., de Schipper, M.A., Stive, M.J.F., and Ranasinghe, R., 2011. Sediment exchange between the sub-aqueous and sub-aerial coastal zones. *Coastal Engineering Proceedings*, 1(32).
Wijnberg, K. M. (2002). Environmental controls on decadal morphologic behaviour of the Holland coast. *Marine Geology*, 189(3), 227-247.
Wijnberg, K. M., and Terwindt, J. H., 1995. Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. *Marine Geology*, 126(1), 301-330.