On the predictability of nearshore bar behaviour

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Abstract

The analysis of field observations of surf zone dynamics has revealed some 'unexpected' behaviour of the coastal system, generally referred to as 'free behaviour', which is behaviour that is unrelated to similar patterns in the external forcing. Present-day process-based modeling concepts are not capable to deal with these free modes of behaviour. In order to assess the validity of model-based predictions of bar dynamics, the relative importance of free behaviour versus forced response in the surf zone needs to be addressed. This work aims to contribute to the debate, by investigating the sensitivity of breaker bar behaviour to chronology effects from coastal profile modeling at a multiple-barred beach, with probabilistic forcing conditions. The results show chronology effects merely affect the predicted height of the bars, rather than their location which is remarkably consistent over the various runs. The latter observation has raised the question up to what extent predicted bar behaviour is controlled by model characteristics (concept, parameter settings), rather than system and forcing characteristics.

Introduction

Over the years, nearshore sand bar behaviour was believed to show a rather consistent pattern of delayed response to the wave energy input, featuring a rapid straightening of the outer bar during storms, and a gradual development of a crescentic bar pattern via some intermediate stages during subsequent periods of low-energy exposure (e.g. Wright and Short, 1984; Lippmann and Holman, 1990). However, another field observation of bar behaviour has been presented by Southgate and Möller (1998). They applied a fractal

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analysis technique to the Duck, NC, data base (10.5 years of monthly cross-shore surveys) to indicate the existence of self-organized (or free) behaviour in a coastal system. They arrive at the conclusion that the profile behaviour has a fractal structure and is uncorrelated to the input variations, but only within a certain time window. The width of this time window varies with the cross-shore location, featuring a maximum of 30-40 months well inside the surf zone. Within these time windows, the process of self-organization seems to be dominant, while outside, the profile behaviour is well-correlated to the forcing factors.

Considering the vast amount of plans for human interference in coastal systems (like large-scale land reclamations, artificial islands in sea and beach nourishments), the need for model-based predictions of coastal behaviour on the time scale of years to decades is evident. It would be interesting to see how the present generation of process-based profile models predict bar behaviour on these time scales, and up to what extend they are be able to deal with the types of 'unexpected' behaviour as given above. In the end a model-based investigation of bar dynamics might contribute to our understanding of the balance of free versus forced behaviour in coastal systems. This study is a first start to addressing these questions.

Concepts in relation to morphodynamics of breaker bar systems

Bed dynamics in the coastal zone occur at various time scales. At the smallest scale bedforms like ripples and mega ripples evolve (minutes to hours). Moving up, the evolution of features like nearshore bars becomes apparent (days to years). Channels on ebb deltas may evolve over decadal time scales, while at a time scale of centuries, we may for instance observe the steepening of the shore face, or changes in the global shoreline orientation. In this paper, the ripple scale is referred to as 'micro-scale', the nearshore bar scale (and tidal channel scale) as 'meso-scale', and the larger scales as 'macro-scale'.

Physical processes at a certain scale level will be in dynamic interaction with coastal behaviour of a similar scale. This is what is called the primary-scale relationship (De Vriend, 1991), see Figure 1.

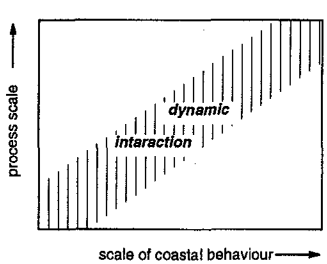

Fig. 1: Primary-scale relationship (after De Vriend, 1991)

A physical process at a certain scale acts as an extrinsic condition (or constraint) for dynamics at a lower scale level, whilst it is just noise for dynamics at a higher level. Within one scale level, a feedback between response and forcing is observed. For example, for the nearshore bars, wave energy input generates a flow field (FF) in the nearshore zone, causing sediment transport (ST) gradients across the bars and hence morphologic changes (MC), which again affect the nearshore flow field, see Figure 2. Furthermore, a coastal system is stochastically forced, dissipative and features various components which are highly non-linear (like transport rates). It is because of these characteristics that a coastal system might easily allow for unpredictable behaviour in a deterministic sense (De Vriend, 1998), i.e. the system develops very complex patterns that could be modeled in detail, however, without being able to predict when and where they occur (cf. turbulence).

These considerations allow us to schematize the coastal system of consideration, viz. that of nearshore bars. The morphodynamics at this scale level are supposed to be in dynamic interaction with the incoming wave energy and tide-induced variations in water level elevation. Larger scale phenomena like sea level rise and variations in the tidal current pattern act on the system as a constraint via the macro level, as they are affected by features at this higher level. Also, physical constraints like jetties are considered as a macro-level induced constraints, while a weak constraint might result from the lower level by means of bed-form induced friction. Besides forced response, possibly represented by the consistent tendency of bars to straighten during storm conditions, free behaviour needs to be taken into account. This results in the schematization as given in Figure 2. Though the meso-level breaker bar system also affects the lower and higher scales, these relations have been ignored in Figure 2.

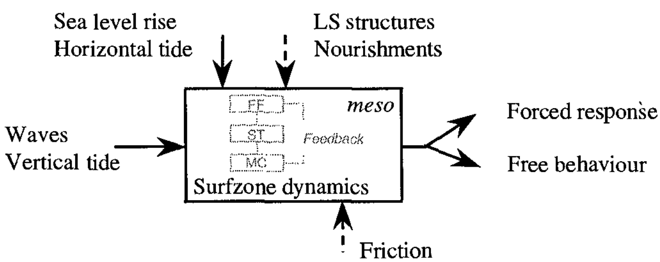

Fig. 2: Schematization of a meso-scale coastal system

In order to assess the predictive skills of profile models, the relative importance of forced response versus free behaviour needs to be determined, which requires the analysis of bar behaviour from both field observations and model simulations.

Positioning of present study

As stated, the predictability of breaker bar behaviour needs be assessed along two different ways:

1. By analyzing bar dynamics from field observations, in relation to the forcing conditions. This requires long time series of bar morphology, with high resolution in time. ARGUS-stations, which collect hourly video observations of the nearshore zone (Holman *et al*, 1993), provide such type of data. Different techniques to quantify bathymetry from video observations are presently under development, based on the inverse modeling of wave dissipation patterns (Aarninkhof *et al*, 1997) or wave celerities (Stockdon, 1997).
2. By investigating breaker bar behaviour from simulations with a process-based coastal profile model, both in terms of the sensitivity to various model parameters, as well as regarding the effect of different forcing sequences with similar statistics.

On the longer term, we aim at a comparison of both approaches, however, the present paper only discusses an initial step into the second approach. It concerns a model-based investigation of bar dynamics at Noordwijk, The Netherlands. Multiple model runs have been made, using different time series of hydrodynamic conditions with nevertheless similar statistical characteristics. If a considerable variability in final profile evolution over the various runs is observed (indicating the importance of chronology effects), the system's response is interpreted to be forced. Alternately, the dynamical quantities of the system might show fractal statistics (in space or time), indicating self-organized response or free behaviour.

The present work treats the sensitivity of model-predicted bar behaviour to chronology effects. To that end a model regarding a multiple-barred coastal system has been set up and calibrated, which will be the subject of the next sections.

1DV-model simulations of bar dynamics at Noordwijk, The Netherlands

Description of model concept

To do the model simulations, WL|DELFT HYDRAULICS' 1DV coastal profile model UNIBEST-TC has been applied. The UNIBEST-TC model consists of a wave, flow, transport and bed level change module, for which the initial formulations are given in Roelvink and Stive (1989). Although they arrive at a satisfactory calibration of the hydrodynamics in terms of wave height, wave set-up and flow moments, the Bailard transport formulation did not result in a correct description of transport rates, despite an extension of the original Bailard formulation to account for additional stirring of sediment by surface breaking-induced turbulence which penetrates toward the bottom. Consequently, the development and migration of the outer bar were (amongst others) simulated insufficiently.

Later on, the formulation for the breaking-induced turbulence was replaced by the roller concept after Svendsen (1984), and, for heuristic reasons, a breaker delay function was introduced (Roelvink *et al*, (1995)). Moreover, the transport formulations were modified according to Ribberink and Van Rijn (see Van Rijn *et al*, 1995) without however, significantly changing the basic concept of the quasi-steady transport model. These new formulations allowed for the modification of transport rates by means of breaker delay and slope effects (Bosboom *et al*, 1997), that finally resulted in the mimicking of cyclic bar behaviour. However, a robust validation of these formulations has not been performed yet.

Model set-up

The numerical model has been set up for a characteristic profile along the Central Dutch coast. Bed elevations along this coast have been surveyed yearly since 1963, which makes its long-term behaviour relatively well understood. A profile at Noordwijk was chosen because this site is also monitored with ARGUS cameras, which gives a reference to short- and medium-term behaviour. The actual profile applied was surveyed in 1980 and extends to 2500 m off-shore; it features 3 bars, which exhibit cyclic behaviour over about a 4 year time span (Wijnberg, 1995).

Time series for the off-shore hydrodynamic conditions have been generated from a wave-climate, measured 6 km off-shore of Noordwijk in 18 m water depth, at 3-hour intervals during a 12-year period of time. The statistics of the wave heights and angles of incidence that occur in the time series obey the frequencies of occurrence as prescribed by the measured wave climate. The adjoining wave period and mean water level elevation have been chosen accordingly, depending on the randomly selected wave height and angle of incidence. At presence, tidal variations are not accounted for, which allows for a simplification of the problem by means of a reduction of the number of independent variables.

The computational grid extends from 2500 m off-shore (14.9 m water depth) to the dune foot; wave conditions measured at 6 km off-shore are translated to the seaward boundary of the model, taking into account the effects of shoaling and refraction. The horizontal grid spacing decreases towards the shore so that a higher resolution is obtained in the active zone, yielding a total of 147 grid points. The time step characteristically amounts 0.25 days for short term runs (180 days).

Sensitivity of bar behaviour to model parameters

Three model parameters are of particular importance in view of bar behaviour, viz. the breaker parameter γ, the breaker delay parameter λ and the subaquous angle of natural repose $\tan(\varphi)$. γ merely affects the migration of bars, while λ and $\tan(\varphi)$ are important with respect to the growth, maintenance, and damping of bars. Their role in the model formulations, as well as their effect on final profile evolution is shortly discussed here.

The wave breaking parameter γ stems from the Battjes-Janssen wave propagation model and affects the maximum local wave height H_{max}, which is determined as a function of local water depth h and wave steepness, according to

$$H_{max} = \frac{0.88}{k} \tanh\left(\frac{\gamma k h}{0.88}\right) \qquad \text{(Eq. 1)}$$

where k is the wave number. Waves smaller than H_{max} are assumed to be non-breaking and Rayleigh distributed, while all waves higher than H_{max} are breaking. An increase of γ allows for higher wave heights at a certain depth, hence shifting the process of wave dissipation to more shallow water. Consequently, an increase of undertow-induced off-shore directed transport rates is induced, yielding a faster off-shore migration of the breaker bars. Figure 3 illustrates this, showing the final profile evolution after 50 days in case of a constant wave height H_{rms} = 1.5 m.

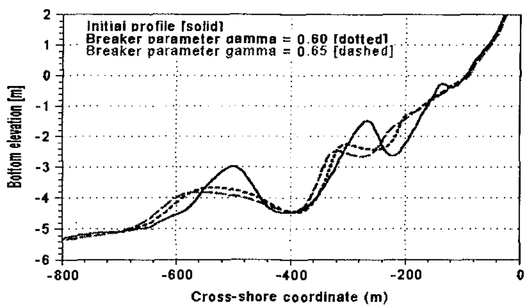

Fig. 3: Effect of breaker parameter γ on final profile evolution

The concept of breaker delay (Roelvink *et al*, 1995) was introduced based on field observations of breaking waves, which showed that waves – having inertia – need a distance of the order of one wave length to actually start or stop breaking. Roelvink *et al.* accounted for this by replacing the local water depth h in Eq. 1 with a seaward weighted reference depth h_r. Consequently, slightly higher waves are allowed at the seaward flank of breaker bars while the concept also allows for ongoing wave breaking in the trough – because of the seaward weighted water depth - hence shifting the undertow currents somewhat towards the trough. The latter allows for offshore-directed sediment transport towards the bar crest, which originally suffered from heavy erosion in the concept without breaker delay. In this way some sediment accumulates in the region close to the bar crest, yielding a better-preserved bar shape. Figure 4 shows the effect of breaker delay after 50 days of constant forcing conditions with H_{rms} = 1.5 m.

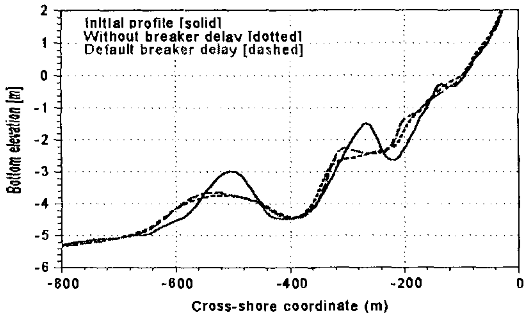

Fig. 4: Effect of breaker delay on final profile evolution

The subaquous angle of natural repose tan(φ) accounts for slope effects (Bosboom *et al.*, 1997) and affects the computed transport rates in two ways. First, the threshold criterion for the initiation of motion is adapted using the Schoklitsch factor. With increasing tan(φ), the non-dimensional critical shear stress θ_{cr} (according to Shields) decreases in case of upslope transport, and increases for downslope transport. In other words, upslope transport is stimulated with increasing tan(φ), downslope transport hindered. Second, bed load transport rates are affected by means of a Bagnold multiplication factor β_s, which increases with increasing tan(φ) in case of upslope transport, and decreases in conditions of downslope transport. Again, upslope transport rates are facilitated by increasing values of tan(φ), downslope rates hampered. Both modifications to the computed transport rates result in the same effect: a higher value of tan(φ) stimulates accumulation of sediment around the bar crest, hence bar development, a lower value causes the damping of bars.

Figure 5 shows the effect of different subaquous angles of natural repose on the final profile evolution after 50 days in case of a constant wave height H_{rms} = 1.5 m. The values of tan(φ) are constant along the beach profile, though generally, they are set to decrease somewhat in off-shore direction, to facilitate the damping of bars at deeper water.

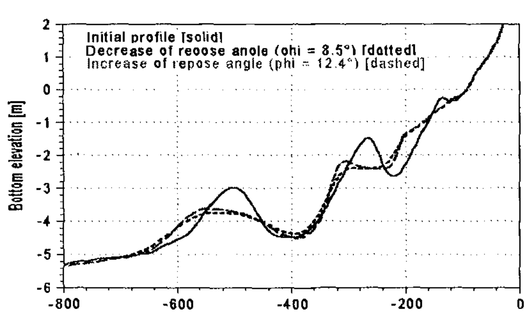

Fig. 5: The effect of tan(φ) on final profile evolution

Selection of appropriate model settings

As a robust validation of the modified transport module has not been performed yet, the present model can be considered as a (for heuristic reasons) modified version of the original model according to Roelvink and Stive (1989). The heuristic element lies in the transport formulation, and is dealt with by adopting appropriate settings of the wave breaking parameters and the slope effect. Though this might enable a satisfactory representation of cyclic bar behaviour, it does not guarantee that the morphodynamic concept of the model is fully correct.

Lacking local field data on surf zone hydrodynamics, the model has been tuned by carefully choosing the parameters of relevance as mentioned above, such that it represents medium-term bar behaviour reasonably well. Whenever possible, default settings have been applied. In order to obtain sufficient damping of bars at deeper water, the value of φ needed to be lowered to 9.1° at deeper water as compared to 12.4° at the waterline. The resulting bar behaviour is shown in Figure 6.

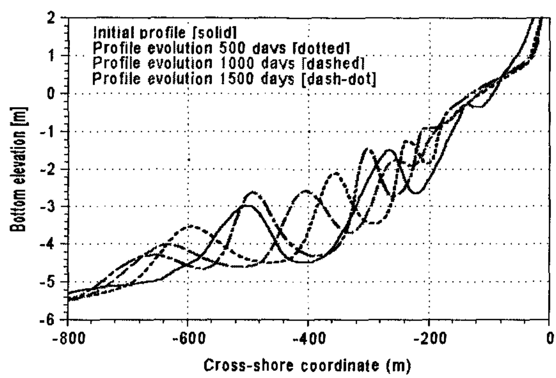

Fig. 6: Bar behaviour in calibrated model

Clearly, the erosion and formation of the steep berm around the waterline are not realistic. This might be attributed to the absence of tidal variations, cf. Southgate (1995). However, in view of bar behaviour, the 4-year bar cycle is clearly recognized while a new bar is being generated in the upper part of the profile.

Overview of model runs

In order to test model-predicted bar behaviour on its sensitivity to chronology effects, multiple model runs have been made with statistically similar input conditions. The sequence of wave events was randomly generated as described above. The statistics of each time series were determined by means of its mean wave height, the standard deviation around the mean and the lowest respectively highest wave of the series.

Statistics of various series show good comparison, as can be seen from 5 representative cases in the table below.

	Statistics of wave height H_{rms}			
Series	Mean	SD	Min	Max
# 01	0.91	0.57	0.23	4.04
# 02	0.89	0.57	0.23	3.51
# 03	0.88	0.54	0.23	4.04
# 04	0.88	0.53	0.23	3.56
# 05	0.89	0.54	0.23	4.04

Table 1: *Wave height statistics of generated time series*

25 Randomly generated time series at 3 hour intervals have been generated for use in the short-term computations, yielding 25 different profile evolutions after 180 days. Each of the 25 time series were then sorted based on wave height, both ascending and descending. This again yielded 25 different realizations of bathymetry after 180 days for both sortings.

Results of short-term (180 days) tests on chronology

In case of the random wave input, general bar behaviour seems to be consistent throughout the 25 cases. All of the three bars migrate seaward, over rather similar distances of about 75 m. Figure 7 shows the mean profile evolution after 180 days, averaged over 25 runs (lower panel), as well as the cross-shore variability in final profile evolution by means of the standard deviation of final bottom elevation over 25 runs and its extreme realizations (upper panel). Maximum variability occurs around the initial location of the bars and their final positions, indicating that the system has not run through a full cycle yet. Moreover, it points out that the horizontal variability (i.e. the variability in the final location of the bars) is rather weak, whereas the vertical variability is more significant: the standard deviation amounts up to 10-15% of the absolute changes of bottom elevation, which is in good correspondence with values found by Southgate (1995). Vertical variability slightly decreases towards the shore.

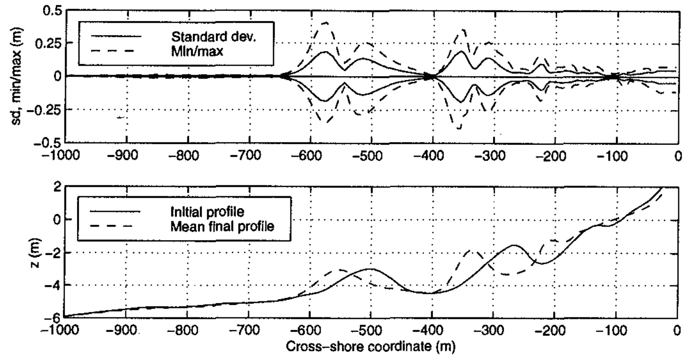

Fig. 7: Variability in final profile evolution (180 days) over 25 runs, random waves

The results of the runs with sorted input conditions are given in Figure 8. Analogous to the upper panel of Figure 7, the upper and middle panel of Figure 8 show the cross-shore variability in final profile evolution expressed in terms of the standard deviation and extreme realization over 25 runs, for the cases of ascending and descending wave heights respectively. The lower panel visualizes the mean profile evolution for both cases, averaged over 25 runs.

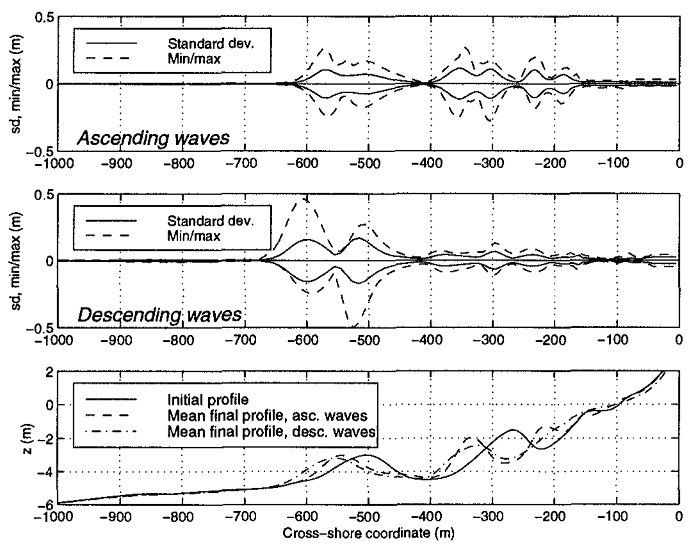

Fig. 8: Variability in final profile evolution in case of sorted wave height input

Again, the observed mean bar behaviour is remarkably consistent: after 180 days, all bars have migrated off-shore over a distance of about 75 m, though the bar-shape tends to be better preserved in the case of ascending wave heights. The variability in final profile evolution clearly differs amongst the 2 cases: the system exposed by ascending wave heights shows moderate variability over 25 runs, which is rather constant along the profile, featuring relatively minor extremes around the initial and final locations of the bars. The case of descending wave heights, on the other hand, shows large variability around the outer bar which drops to almost zero through the central and inner surf zone, indicating very consistent behaviour of the middle and inner bar over the 25 runs.

Discussion

The results described above generally show a decrease of vertical variability in bottom elevation towards the shore, indicating a weaker response of inner surf zone morphodynamics to chronology-related variations in the input conditions. This can be explained from the presence of the outer bar, which filters the wave climate for the central and inner region of the surf zone with respect to high waves, hence reducing the temporal variations in the central and inner surf zone wave conditions. Apparently, the behaviour of the inner bars is not only controlled by the forcing conditions, but also by internal parameters like the height of the outer bar, which might more easily allow for free behaviour in this region. This observation is in accordance with Southgate (1998) who states that 'generally, fractal responses are found at locations ... where the temporal variations of wave forcing conditions are relatively weak'.

The important role of the outer bar in view of central and inner surf zone morphodynamics is also observed from the runs with sorted wave height input. Significant changes of the outer bar are assumed to be induced by the highest waves of the input time series, therefore the outer bar, in case of descending wave heights, is affected at the very beginning of the simulated time period, whilst in the case of ascending waves, this occurs only at the end of the 180-days period. Consequently, the height of the inner bars after 180 days is more reduced in case of descending wave heights, as they are exposed to more energetic wave conditions during the simulation period. This again stresses the importance of internal system parameters like the height of the outer bar in view of the morphodynamics of the central and inner region of the surf zone.

Nevertheless, though it seems like the observed vertical variability in bottom elevation along the cross-shore profile can be explained reasonably well, the absence of variability in the final position of the bars has not been explained yet. Particularly, the close correspondence between the position of the outer bar resulting from runs with ascending and descending waves respectively - suggesting that bar migration depends on the cumulative amount of energy input rather than the sequence of events – would indicate that chronology is of hardly any importance to the morphodynamics of the outer bar at Noordwijk. This seems counter-intuitive since bars are expected to migrate onshore during periods of low-energetic conditions, and off-shore during storms. Hence the question is raised up to what extend predicted bar behaviour is controlled by model characteristics (concept, parameter settings), rather than system and forcing characteristics.

Apparently, this might be not the only source of unpredictability that arises when addressing the possibility of model-based predictability of long-term bar behaviour. Generally, we can identify 4 possible sources of unpredictability:

1. The limited time horizon of predictability of wave conditions.
2. The numerical discretization of model equations.
3. The model concept, i.e. the dimension of the concept (1DV in the present case) and the schematization of real-world physics in terms of model equations.
4. The complexity or 'irregularity' of natural beach behaviour.

The first source is related to the limited horizon of predictability of weather conditions (characteristically up to 10 days), hence wave conditions, and forms a fundamental limitation to the deterministic predictability of bar behaviour, both from model runs and field observations. However, knowing statistics on the wave climate from long-term field measurements, the probabilistic approach based on randomly generated, realistic time series of wave events seems the best way to cope with this problem.

Also the second source is fundamentally related to the application of a process-based modeling approach. Even in case of a 'perfect' model concept, small errors, caused by the inevitable discretization of model equations, tend to accumulate to become significant in case longer-term computations, justifying the question which part of the model prediction is realistic behaviour and which part can be considered to be error-induced noise. The unrealistic damping of bars after 1 cycle can be attributed to this accumulation of errors, either concept- or discretization-related. Given a certain model-concept, the application of sufficiently small computational steps and the careful selection of parameter settings are ways to reduce this source of unpredictability as much as possible.

The third source of unpredictability seems to play an important role in the present study. Although the model predicts the 4-year bar cycle reasonably well, some essential characteristics of bar behaviour as observed in the field are clearly missing in the present model. The absence of onshore migration (and adjoining growth) of bars during periods of low-energetic conditions and the weak sensitivity of the behaviour of the outer bar to chronology effects can be mentioned in this respect. Further investigation of the present model concept and parameter settings in terms of bar behaviour is necessary to improve acceptability of a model-based approach to assess the predictability of bar behaviour. Questions to be addressed in this respect are: What are the governing processes causing the consistent off-shore movement of sand bars? What is the effect of the initial profile? Would long-period swell affect the predicted bar behaviour? Would the same behaviour be observed at different sites?

Regarding the fourth aspect, it might be questioned whether process-based numerical models will ever be capable to predict natural 'irregular' behaviour, commonly referred to as free behaviour of coastal systems. Nevertheless, a fundamental understanding of the relative importance of forced response versus free behaviour will help to assess the validity of model-based predictions of coastal morphodynamics. Both the analysis of

ARGUS video-based obsei vations of bar behaviour and the investigation of model-based predictions are expected to attribute to the assessment of this balance.

Conclusion

The present study has attempted to contribute to our understanding of sand bar dynamics by means of coastal profile modeling of a multiple-barred beach with probabilistic forcing conditions. In the case of 180-days simulations, chronology effects turn out to play a role throughout the surf zone, the importance of which increases with distance offshore. Chronology effects merely affect the predicted height of the bars, rather than their final location which is remarkably consistent over the various runs. Moreover, the onshore migration of bars during periods of low-energetic wave conditions was not clearly observed. These observations raise the question up to what extent predicted bar behaviour is controlled by model characteristics (concept, parameter settings), rather than system and forcing characteristics. Further investigation of the model concept and a sensitivity analysis, more extensively than the one presented in this paper, are needed to address this problem.

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References

Aarninkhof, S.G.J, Janssen, P.C. and Plant, N.G. (1997). Quantitative estimations of bar dynamics from video images. *Proc. of Coastal Dyn. Conf.*, Plymouth, UK, 1997

Battjes, J.A. and Janssen, J.P.F.M. (1978). Energy loss and set-up due to breaking in random waves. *Proc. of 16th Conf. on Coastal Eng.*, ASCE, pp. 569-587

Bosboom, J., Aarninkhof, S.G.J., Reniers, A.J.H.M., Roelvink, J.A. and Walstra, D.J.R. (1997). Unibest-TC 2.0. Overview of model formulations. Delft Hydraulics report H2305.42

Holman, R.A., Sallenger Jr, A.H., Lippmann, T.C. and Haines, J.W. (1993). The application of video image processing to the study of nearshore processes. *Oceanography*, Vol. 6, No 3.

Lippmann, T.C. and Holman, R.A. (1990). The spatial and temporal variability of sand bar morphology. *J. Geoph. Res.*, 95(C7): 11575-11590.

Lippmann, T.C, Holman, R.A. and Hathaway, K.K. (1993). Episodic, nonstationary behavior of a double bar system at Duck, North Carolina, USA, 1986-1991. J.Coastal Res., 15(SI): 49-75.

Rijn, L.C. van, Reniers, A.J.H.M., Zitman, T. and Ribberink, J.S. (1995). Yearly-averaged sand transport at the -20 m and -8 m NAP depth contours of the Jarkus-profiles 14,40,76 and 103. Delft Hydraulics report H1887.

Roelvink, J.A., Meijer, Th.J.G.P., Houwman, K., Bakker, R. and Spanhoff, R. (1995). Field validation and application of a coastal profile model. *Proc. Conf. Coastal Dynamics*, ASCE, pp. 818-828.

Roelvink J.A., and Stive, M.J.F. (1989). Bar generating cross-shore flow mechanisms on a beach. *J. of Geophysical Research*, 94: 4785-4800.

Southgate, H.N. (1995). The effects of wave chronology on medium and long term coastal morphology. Coastal Engineering 26:251-270

Southgate, H.N. and Möller, I. (1998). Fractal properties of beach profile evolution at Duck, North Carolina. Submitted to *JGR Oceans*.

Stockdon, H. (1997). Estimations of wave phase speed and nearshore bathymetry using video techniques. M.Sc. Thesis, Oregon State University, College of Oceanic Atmospheric Sciences, Augst 1997.

Svendsen, I.A. (1984). Wave heights and set-up in a surf zone. *Coastal Eng.*, 8:303-329

Vriend, H.J. de (1991). Mathematical modelling and large-scale coastal behaviour, Part 1: Physical processes. *Journal of Hydraulic Research* 29, pp. 727-740.

Vriend, H.J. de (1998). On the predictability of coastal morphology. In: Proc. 3rd Marine Science and Technology Conf., Lisbon, 1998.

Wijnberg, K.M.(1995). Morphologic behaviour of a barred coast over a period of decades. Ph.D. Thesis, Utrecht University, Utrecht, The Netherlands, Netherlands Geographical Studies 195, KNAG, 245 pp.

Wright, L.D. and Short, A.D. (1984). Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology* 56, 93-118.