Role of morphological variability in the evolution of nearshore sandbars

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A B S T R A C T
Computations using a depth-averaged morphological process-based model of a double nearshore bar system have been used to test the hypothesis that bathymetries with small variability adapt more easily to new hydrodynamic conditions than bathymetries with distinctly imprinted crescentic patterns. The computations are used to investigate the assumption that nearshore bathymetries tend to evolve toward a rip-channelled pattern matching concurrent constant hydrodynamic forcing, if these conditions prevail for an extended period of time. In each computation an initially alongshore uniform double barred bathymetry, seeded with a small random bed-level perturbation, was forced by two sequential constant hydrodynamic conditions. For each set of conditions, four different computations show the effect of a later transition moment – and thus more distinctly evolved patterns – on the level of adaptation to the second condition. After the transition to the second condition, different hydrodynamic circulations occur due to differences in the bathymetry at the transition moments. Depending on how pronounced the existing features were at the moment of transition, these circulations either reinforce the existing bathymetric pattern or allow the bathymetry to evolve to a new rip-channelled pattern with a spacing similar to the one that occurs if the second condition had been applied from the start. As hydrodynamic conditions generally change more rapidly than the adaptation time, which is at least in the order of days, it is highly unlikely that observed rip channel distances match length scales expected for concurrent hydrodynamic conditions, consistent with field observations (e.g. Holman et al., 2006). It is therefore concluded that nearshore patterns are formed by a combination of both the antecedent morphology – and thus antecedent hydrodynamics – and the current local hydrodynamic conditions, next to factors like sediment characteristics.

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1. Introduction

The morphology of nearshore sandbars is observed to vary in time, seemingly as a result of hydrodynamic conditions, the geometry and sediment characteristics. From field observations it is found that the lay-out of nearshore bars varies with the wave energy and runs through a cycle of beach states (Lippmann and Holman, 1990; Ranaasnghe et al., 2004; Wright and Short, 1984). With highly energetic conditions, the beach-state has been observed to ‘reset’: the nearshore bar moves offshore and becomes alongshore uniform. In subsequent lower energy conditions, rip channels form and the bars move onshore, possibly even welding to the shore. The rip channels appear at quasi-regular intervals without a clear relationship between concurrent hydrodynamic conditions and spacing (Holman et al., 2006; Turner et al., 2007). This can be explained by the fact that significant morphological changes only occur during the first few days after a reset where moderate waves create a new rip-channel pattern. Once significant alongshore variability in the bathymetry is present changes in rip-channels spacing are small with the arrival of new wave conditions.

From previous numerical modelling efforts it was found that with constant wave forcing an initially alongshore uniform barred bathymetry evolves toward a preferred length scale (e.g. Garnier et al., 2008; Smit et al., 2008) with a response time in the order of days (Smit et al., 2004). Hydrodynamic conditions in the field after a reset can vary significantly within that response time, and the question becomes under what conditions can the bathymetry still adapt to changes in the wave forcing to reach a preferred morphological pattern.

For constant wave forcing, the angle of wave incidence, wave height, wave period and wave spreading as well as the initial beach profile are important for the final beach state (e.g. Calvet et al., 2007; Garnier et al., 2008; Reniers et al., 2004; Smit et al., 2008). Only a few studies consider temporal variation in the wave forcing (Castelle and Ruesink, 2011; Drønen and Deigaard, 2007; Smit et al., 2005). Changing the normal wave incidence angle after 12 days to 30° Drønen and Deigaard (2007) observed an increase in the length scales of the outer bar crest similar to their case with 30° wave conditions only. This change in length scale was attributed to the bar-generating mechanisms associated with the quasi-three-dimensional flow they used in their modelling efforts. However, the short scale morphological variability inshore of...
the bar crest, resulting from the 12 day period of normally incident waves, showed a limited response to the changing wave conditions and was mostly maintained. Castelle and Ruessink (2011) consider the effects of time varying wave forcing on the morphological evolution of a single barred rip-channelled beach created by an initial model simulation of 4 days with time-invariant normally incident waves. For that transition moment they find that their modelling results for rip-channel spacing are particularly sensitive to temporal changes in the incidence angle. However, it is not clear what role the morphological variability at the transition moment plays in their study. We therefore set out to systematically investigate how the capacity of the morphodynamic system to adjust to new wave conditions depends on the morphological variability at the moment of changing conditions (transition moment $t = t_0$).

We test the following hypothesis: low (high) morphological variability at the moment of changing hydrodynamic conditions will allow (inhibit) morphological adjustment to the new conditions. The hypothesis is tested by numerically computing the morphological evolution of an initially alongshore uniform double bar system as a response to two piecewise-constant sequential conditions. The first condition is applied for four different durations, resulting in a different level of variability at the moment of transition to the second condition. We know the patterns of the system for the individual conditions, if they were applied constantly to an initially alongshore uniform bar (Smit et al., 2008). Hence, to analyse whether a later transition moment will result in less adjustment, we compare the computed pattern with the expected pattern. Note that the duration of the morphological simulations presented in this paper is relatively short and more representative of the down-state transition of an alongshore uniform beach state to a quasi-rhythmic bathymetry after a reset than the long-term evolution considered by Garnier et al. (2008).

The applied model, computational set-up and parameters for analysis are described in Section 2; Section 3 describes the results. Subsequently, the work is discussed in Section 4 and conclusions are drawn in the final section.

2. Method

The modelling system Delft3D is used for the morphological computations (Lesser et al., 2004; Roelvink and Van Banning, 1994). It consists of several modules for simulating short waves, currents and sediment transport, which can be applied for coastal computations. The wave propagation, breaking and corresponding radiation stresses are computed with SWAN (Booij et al., 1999). The flow driven by radiation stress gradients is calculated with the depth-averaged nonlinear shallow water equations. The corresponding sediment transport rates due to currents and short waves are determined using Bijker (1971). This formulation takes into account the effect of wave stirring and suspended sediment transport. No specific cross-shore effects, like undertow, are taken into account at this stage. For further details the reader is referred to Smit et al. (2008).

The transport is calculated 'online'. This means that the transport and bottom changes are calculated for each flow time step, with a factor to speed up the computations, assuming that the flow field does not change significantly within that period (equal to the flow time step times the morphological acceleration factor) (Roelvink, 2006). For these calculations a morphological acceleration factor of 15 was used. This means that for every flow step of 6 s, the morphological adjustment over a period of 1.5 min is calculated. This loop is performed 60 times (which in this case corresponds to 1.5 h morphologically), after which the waves are recomputed with the new bathymetry.

2.1. Initial bathymetry and grid

The initial bathymetry resembles a cross-section at Egmond aan Zee, The Netherlands (Fig. 1). This measured cross-section is applied over a length of 6300 m, to obtain an alongshore-uniform stretch of coast. The model area has a cross-shore width of 1200 m. The grid cell size is 15 by 15 m. A small random perturbation (order of cm) is added over the whole model area reducing the time required to start the morphological evolution.

2.2. Boundary conditions

The wave grid is larger than the flow grid to avoid shadow zones associated with the fact that waves are incident at the seaward boundary only. As a result the wave forcing applied in the flow domain is not affected by its lateral boundaries. The lateral hydrodynamic boundaries of the flow model are defined as zero water level gradients in the alongshore direction (Roelvink et al., 2009). The seaward boundary is a zero water level boundary. The lateral bottom boundaries are defined as zero alongshore depth gradients.

Boundary conditions for the flow and sediment can have significant consequences for the ensuing morphological evolution, as disturbances created by imperfect boundary conditions can propagate into the domain at the upstream end or accumulate at the downstream end of the alongshore model domain. There are typically two approaches to mitigate the effects of boundary errors. One option is to extend the model domain such that the time it takes for boundary related disturbances to reach the area of interest is smaller than the total simulation time (e.g. Klein and Schutteelaars, 2006). For long-term morphodynamic computations this becomes impractical as it requires an ever increasing model domain. Alternatively one prescribes periodic boundary conditions which allow for long-term morphodynamic model predictions (e.g. Garnier et al., 2008) but this comes with a trade off in the number of discrete modes, defined by the finite length of the model domain, that can be resolved. To reach a more continuous representation of fluid flow, sediment transport and bed features one again has to increase the alongshore model domain, where a continuous representation requires an infinitely long model domain.

In the present study we consider a relatively short morphological time scale which is in the order of 20 days. This means that any morphological anomalies generated at the lateral boundaries (which appear to be small as a result of the Neumann boundary conditions that we apply) will have only a relatively short time to travel into the model domain. With the observed celerity of 10 m/day only the first 200 m of the model domain would be affected, which is small (less than 5%) compared with our 6.3 km long model domain. Using a domain of 14 km showed no significant differences with the 6.3 km grid. Consequently we have used the full 6.3 km model domain in our analyses.

2.3. Computational set-up – hydrodynamic conditions

An initially alongshore uniform double barred beach is forced with two sequential wave conditions (referred to as condition I and II). Four individual conditions (A, B, C, D) are selected to create 4 sets of sequential conditions (Table 1). The four individual conditions are based on the different rip-spacing that result when each of these

![Fig. 1. Elevation (relative to mean sea level) versus cross-shore location used in the simulations.](image-url)
conditions is applied constantly on an initially alongshore uniform profile (Fig. 2). This allows analysis of the adaptability of the bar system, scored on adaptability of length scales (rip channel distances). The conditions are chosen using earlier work in which 16 different constant wave conditions were applied to an initially alongshore uniform double-bar system (Smit et al., 2008). The cross-shore profile of the bathymetry used in that study is identical to the cross-shore profile used in the current study so as to avoid geometry-induced effects on the expected length scales. The four selected conditions (Table 1) are sequentially combined into two sets with increasing wave energy (AB and CD) and two sets with decreasing wave energy (BA and DC, Table 2). The wave period for all computations is 6 s.

For each sequential set, four separate computations are performed where the times of transition between the first and second condition, denoted as transition moments (tT), were selected based on computations of the bathymetric variability involving the first condition only. The amount of change (at each moment) is expressed by the root mean square of the difference of the depth at that moment minus the alongshore-averaged depth at that moment (RMS) (e.g. for condition A: Fig. 3). The moments of transition are identified from the evolution of RMS of the inner bar (RMSin e.g. for condition A: Fig. 3). The first transition moment for the AB set is set at 1.5 days (when RMSin just starts to evolve), the second at 4 days (at maximum slope), the third at 6.5 days (at about the maximum RMSin value) and the fourth t4 one day later, after 7.5 days.

These transition moments thus correspond to different bathymetries to which the second condition is subsequently applied. The bathymetries range from hardly developed (first transition moment) to fully developed crescentic bars (fourth transition moment) with, in this case, small length scales, related to the shore normal wave conditions (condition A, Fig. 4). The second condition is then subsequently applied for a length of time that allows the bathymetry to evolve (RMSin > 0.1 m) with the total morphological evolution spanning 20 days (Table 2). This computational set-up allows the investigation of the role of the antecedent morphology in the subsequent morphological evolution.

2.4. Parameters for analysis

The patterns observed in the morphological evolution are described by their length scale. The length scales are defined by a Fourier analysis of the depth contour of each bar, resulting in a weighted length scale (λ), which is determined at each time step. For the exact definition refer to Smit et al. (2008). However, due to the prolonged duration of the present computations, this method (based on contour lines of the bathymetries) shows irregularities in the evolution of the λ of the inner bar in the later stages of the computations. These irregularities in λin are therefore smoothed using a running mean of almost one day (15 data points).

The scoring is computed for the evolution of λ(t) after the transition moment and is computed for both inner and outer bars separately and is defined as follows:

\[ S_{i,j,\text{bar}}(t) = 1 - \frac{\lambda_{i,j,\text{bar}}(t) - \lambda_{i,j,\text{bar}}(t)}{\lambda_{i,j,\text{bar, tend}}(t) - \lambda_{i,j,\text{bar, tend}}(t)} \] (1)

Table 1
Overview of conditions and their end-state length scales (inner and outer bar) for constant hydrodynamic forcing.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Hs (m)</th>
<th>θ°</th>
<th>λin (m)</th>
<th>λout (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.5</td>
<td>0</td>
<td>321</td>
<td>666</td>
</tr>
<tr>
<td>B</td>
<td>2.5</td>
<td>20</td>
<td>676</td>
<td>1604</td>
</tr>
<tr>
<td>C</td>
<td>1.5</td>
<td>10</td>
<td>570</td>
<td>1009</td>
</tr>
<tr>
<td>D</td>
<td>2.5</td>
<td>30</td>
<td>798</td>
<td>2032</td>
</tr>
</tbody>
</table>

with bar referring to either inner (in) or outer bar (out), t is time, tend is the last moment of the computation, i refers to condition I and j refers to condition II.

The scoring shows how well the length scales in the system adjust to the expected length scale, when changing the conditions at increasingly later moments in time. The expected length scale is the length scale occurring when condition II is applied constantly on an initially uniform bathymetry. The difference between the computed and expected λ (numerator) is taken relative to the difference between the end values of λ for conditions I and II (denominator). Scores of 1 indicate a complete match where the computed parameter has adjusted toward the expected value. The score is 0 when there is no change in the computed λ after the transition moment. The score will be negative when the computed λ moves further away from the expected λ.

3. Results

3.1. Results for AB set of computations

The four different moments of transition have a distinct effect on the final bathymetries for the AB set (Fig. 5). The final pattern of AB1, corresponding to a sequence of condition A followed by condition B at transition time 1 (see Table 2), resembles the expected pattern for condition B best (compare Figs. 5(upper panel) to 2 (second panel). This corresponds to the hypothesis that small initial variability, i.e. not too distinct pattern had evolved, facilitates the adaptation of the morphology to changing wave conditions. The evolution of the patterns is quantified by λ(t) and Sout(t) (Fig. 6). The evolution of λ(t) for the AB computations adapts increasingly better to the second condition for earlier tT (illustrated for λout in Fig. 6). For computations with later tT (e.g. AB3, AB4), the score decreases.

Table 2
Computational sequences; times are in days.

<table>
<thead>
<tr>
<th>Computation Set</th>
<th>Cond I</th>
<th>Cond II</th>
<th>t1</th>
<th>t2</th>
<th>t3</th>
<th>t4</th>
<th>t5</th>
<th>tend</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>1.5 m 0°</td>
<td>2.5 m 20°</td>
<td>1.5</td>
<td>4</td>
<td>6.5</td>
<td>7.5</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>BA</td>
<td>2.5 m 20°</td>
<td>1.5 m 0°</td>
<td>4</td>
<td>8.5</td>
<td>13</td>
<td>14</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>1.5 m 10°</td>
<td>2.5 m 30°</td>
<td>3</td>
<td>5.5</td>
<td>8</td>
<td>9</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td>2.5 m 30°</td>
<td>1.5 m 10°</td>
<td>4</td>
<td>11</td>
<td>16</td>
<td>17</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
3.2. Results for all computations

Also for the BA, CD and DC sets, the final bathymetries show the impact of the moment of transition. For all four sets of computations the scores at the end of the computation are presented as a function of the variability at the moment of transition \( \text{RMS}_{ij} \) for both the inner and outer bar (Fig. 7, Table 3). For both outer and inner bars most trends are decreasing, meaning that with a lower level of variability at \( t_i \), the system adapts better than with a higher RMS, corresponding with our hypothesis.

After the transition, the evolving length scale generally starts to deviate from \( X_i \) within one day, but reaching a new level typically takes a considerable amount of time (order of days to 10 days, e.g. Fig. 6). For almost all computations, condition II was applied for at least 5 days (see Table 2), allowing time to adjust with the exception of sequences DC3 and DC4, which experienced only 4 and 3 days of condition II respectively. Analysing \( X_{ij} \) for these computations shows minimal change of the length scale after the transition moment. With the observed low rate of change it is expected that the RMS will remain the same even if the condition would have persisted for an extended period of time.

Although the expected length scales for outer and inner bars are generally different, the scoring for both bars shows similar results. From this it may be concluded that the initial depth of the bar and volume of the bar do not affect the scoring significantly.

In contrast to the other cases, the computational results for the CD-outer bar suggest that an increased transition time, and expected length scales. However, in all CD-outer bar cases the variability at the moment of transition is small, increasing from order cm for the first transition moment to at most 10 cm for the last transition. With variability this small it may act like the random perturbations, speeding up the initial morphological evolution, resulting in a higher score for increasing transition times.

3.3. Role of initial random perturbation

To ensure that the observed trends in adaptability as a function of RMS for the CD-outer bar cases the variability at the moment of transition is small, increasing from order cm for the first transition moment to at most 10 cm for the last transition. With variability this small it may act like the random perturbations, speeding up the initial morphological evolution, resulting in a higher score for increasing transition times.

In this way 5 values are computed for each group of five computations with the same transition moment. The mean and standard deviation of these scores as a function of the mean and standard deviation of the corresponding RMS values (i.e. computations with the same transition moment) result in a total of five slightly different bathymetries: the patterns and variability are similar, but the exact features and rip locations showed variability. Subsequently, condition A was applied to these bathymetries for the remainder of the computation.

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3.4. Role of energy flux

Above, the level of adaptation was analysed as a function of the variability at the moment of transition. In the field, however, the exact level of variability will generally be unknown due to the difficulty of measuring nearshore bathymetries. It would be beneficial if predicting whether a system in the field will adapt to new conditions can be based on parameters that are more readily available. Wave information is frequently available, either from a buoy or from a local wave model. The dissipation of wave energy within the nearshore is the primary forcing, either directly through the shear stress at the roller interface or indirectly through pressure gradients, of the cross-shore and alongshore currents which subsequently transport the sediment and thus represents a potential for reworking the existing morphology. This dissipation, $D$, can be estimated by considering the wave energy balance:

$$\frac{dE_{g,x}}{dx} = -D$$  \hspace{1cm} (2)

where $E$ is the wave energy and $c_{g,x}$ the cross-shore component of the group velocity. Assuming negligible losses due to bottom friction and zero-wave reflection at the shore line we find that the dissipation within the surf zone, $D$, is given by:

$$D = \int_{x=x_0}^{x=x_s} Ddx = E_{g,x}|_{x=x_0}$$  \hspace{1cm} (3)

where the right-hand side is evaluated at a location $x_0$ outside of the surf zone and $x_s$ is the shore line. The cumulative dissipation which acts as a proxy for the wave forcing, is obtained by integrating the offshore energy flux over time. To analyse the role of the energy flux in the adaptation level, $E_{g,x}$ is computed at the offshore boundary of the domain, to analyse the scores for the outer bar.

$$E_{g,x} = \frac{1}{8} \rho g H^2 c_g \cos \theta$$  \hspace{1cm} (4)

with

$$c_g = nc$$

<table>
<thead>
<tr>
<th>Table 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{AB,\text{in}}(t_{\text{out}})$ as presented in Fig. 7.</td>
</tr>
<tr>
<td>Inner bar</td>
</tr>
<tr>
<td>AB</td>
</tr>
<tr>
<td>BA</td>
</tr>
<tr>
<td>CD</td>
</tr>
<tr>
<td>DC</td>
</tr>
</tbody>
</table>
wave number and creasing trends in a similar way to the trends as observed for Figs. 10b and 11b. The patterns reinforce the existing rip channel location (950, 5500) and the one at (950, 5800) in Figs. 10b and c). For the AB computations where the pre-transition rip channels remain and migrate down drift in time (e.g. compare the rip channel at (950, 5200) and the one at (950, 5800) in Fig. 10b and c). The current patterns around the existing rip channel change. The main aspect is the appearance of an alongshore component in the flow circulation. When the post-transition rip currents have both a down-drift directed component (alongshore) as well as a cross-shore component, existing rip channels seem to remain and migrate down drift in time (e.g. compare the rip channel at (950, 5200) and the one at (950, 5800)).

3.4.1. Antecedent morphology, hydrodynamics and morphological change

We hypothesized that large morphological variability does not adapt as easily to changed hydrodynamic conditions than small morphological variability. Morphological features affect the local hydrodynamic patterns, which, in turn, may reinforce existing features. When a different hydrodynamic condition forces the system (here condition II), the previous hydrodynamic pattern will change and thus subsequently change the antecedent morphological features. The new hydrodynamic pattern will determine whether existing features will be reinforced (e.g. deepening of rip channels) or change (e.g. filling in of existing rip channels). With more evolved morphological features the hydrodynamic pattern changes less than with less evolved morphological features. The following illustrates how the level of morphological evolution (due to condition I) affects the subsequent hydrodynamic patterns and responses to condition II.

We do this by investigating the morphological evolution and hydrodynamic patterns of computation AB2 and AB4 after $t_f$ plus 1 day (to allow condition II to propagate throughout the domain) and at $t_f$ plus 10 days. The two bathymetries at $t_f$ differ in how distinct and well-developed the rip channels are (Figs. 10a and 11a), although the location of evolved features is the same. After $t_f$, both morphologies are forced with the same offshore wave condition (condition B). The difference in both the hydrodynamic pattern at $t_f$ plus 1 day as well as in the morphological evolution thereafter is due to the difference in morphology at the moment of transition and the subsequent different hydrodynamic pattern. At the moment of transition, the hydrodynamic forcing of the system changes, resulting in different current patterns over the evolved bathymetry. These new current patterns may either steer the bathymetry toward a new pattern by relocating sediment, or the currents may reinforce existing features by deepening existing channels. For computation AB2 (Fig. 10), the existing rip channels at $y = 5500$ and 5650 m, formed after forcing with shore-normal waves of 1.5 m (condition A), disappear after condition II has been applied (condition B). Directly after the transition ($t_f$ plus 1 day), the current patterns around the existing rip channel change. The main aspect is the appearance of an alongshore component in the flow circulation. When the post-transition rip currents have both a down-drift directed component (alongshore) as well as a cross-shore component, existing rip channels seem to remain and migrate down drift in time (e.g. compare the rip channel at (950, 5200) and the one at (950, 5800)) in Fig. 10b and c).

For computation AB4, where the pre-transition rip channels remain after the transition and the length scales hardly adapt to condition II, we see that the hydrodynamic pattern on the inner bar directly after the transition stays almost unchanged throughout the remainder of the computation and so does the bathymetry (Fig. 11). In this case, after the transition, all rips have large cross-shore as well as alongshore components, due to the more distinct rip channels in the morphology (e.g. compare the rip channel at (950, 5500)).
4. Discussion

4.1. Role of cross-shore profile at $t_T$

The hypothesis tested in this paper is that the system tends to evolve to a certain configuration, which is governed by the initial profile, and the local hydrodynamic conditions. The bathymetries at $t_T$ in the current work are partly evolved and therefore both the variability and the mean cross-shore profile may be different from the initial bathymetry (Fig. 12 for AB set), indicating that the expected evolution might not be realistic (due to the sensitivity of the length scales to the initial cross-shore profile) as this was based on the evolution of a specific alongshore uniform profile (as it was at $t=0$ days). The main differences are that the crest height of the outer bar decreases with increasing $t_T$ and that the inner bar moves onshore. The trough between the inner and outer bar remains the same. These differences in the profile are however presumed to have only a small effect on the expected length scale and it is therefore not anticipated to qualitatively change the computed trends in scoring.

Calvete et al. (2007) tested how sensitive the length scales were to both the initial cross-shore profile and the wave heights for shore-normal wave conditions. They found that both parameters resulted in wavelength variations of about 13%. For the cases in the current work, the differences between the expected length scales – related to the different conditions – are much larger and it is expected that the effect of hydrodynamic conditions is larger than the effect of the

Fig. 10. Bathymetry and velocities of computation AB2 at a: $t_T$ (condition A still applies), b: 1 day after transition (condition B applies), c: 10 days after $t_T$. The colour indicates the elevation in a range from −8 to 2 m; note that the velocities are plotted on a 30×30 m grid for clarity.

Fig. 11. Bathymetry and velocities of computation AB4 at a: $t_T$ (condition A still applies), b: 1 day after transition (condition B applies), c: 10 days after $t_T$. The colour indicates the elevation in a range from −8 to 2 m; note that the velocities are plotted on a 30×30 m grid for clarity.
changed alongshore mean cross-shore profile at \( t_f \). This allows the use of \( \bar{h}_{AB,1-4}(t) \) (for \( t > t_f \)) as the expected values in determining the scoring of the adaptation level.

### 4.2. Effect of duration of condition

To illustrate the effect of the persistence of wave forcing, computations with continuously varying wave conditions were performed over a period of 14 days. All computations have identical initial alongshore uniform bathymetry with identical random perturbation (order of cm), similar to the other computations in this paper. The significant wave height is 1.5 m and the average angle of wave incidence for each of these computations is 10°. The first computation has a constant angle of wave incidence of 0°. The wave angle of the second computation varies gradually with 1° every 1.5 h, ranging from 0° to 20°. The angle of wave incidence of the third computation varies more abruptly: the angles change 5° every 1.5 h where the extreme angles 0° and 20° persist for 24 h (Fig. 13).

For all three computations, the morphological evolution of the inner bar is similar (Fig. 14). For the outer bar, however, the time-varying forcing with longer persistence on the extreme values shows the strongest reaction of the outer bar. From computations with constant conditions (Smit et al., 2008) it was seen that, for \( H_s = 1.5 \) m, the outer bar reacted strongest to orthogonally incoming waves. For the other angles of wave incidence (and \( H_s = 1.5 \) m), the outer bar hardly evolved. It is expected that the persistence of the 0° angle of wave incidence causes the stronger reaction on the outer bar. This indicates that persistence and re-occurrence of conditions play a role in the response of the system. These computations further illustrate that a system may respond differently to constant conditions than to time-varying conditions, even when the mean hydrodynamic conditions are identical. This agrees with conclusions from Castelle and Ruessink (2011) from their analysis of rip channel formation and evolution in response to time-varying and time-invariant wave forcing. These findings are important in predicting expected behaviour of a nearshore bar system from field observations and indicate that using mean conditions will most likely not result in a prediction that matches observed behaviour.

### 4.3. System behaviour

In the field, it has been observed that beaches seem to run through a cycle of ‘beach-states’ in response to offshore wave forcing (Wright and Short, 1984). An alongshore variable bathymetry, forced by higher energetic conditions may lead to an upstate transition: the alongshore variability decreases. Ultimately, the bathymetry may evolve into an alongshore uniform bathymetry: a reset-event. With subsequent smaller energy conditions, bathymetries have been observed to go through a down-state transition: rip currents evolve and crescentic patterns appear, the variability increases. This can prolong until another high energy event occurs and the system returns to a state with smaller alongshore variability. The current work presents down-state morphological evolution of a bathymetry from a reset-situation (alongshore uniform), followed by a transition of hydrodynamic conditions, which may either simulate an up-state evolution (set AB and CD) or down-state evolution (BA and DC).

Plant et al. (2006) described the response of a nearshore bar system as a dynamical attractor. In their model, the morphology is described by the offshore bar location and the cross-shore amplitude of the crescentic features. The evolution in time of these is described by both interaction of these components and the offshore wave height. The parameter values describing the interactions were based on a 2 month video-based data set, describing a storm-event with a post-storm down-state evolution. For example, the system describes that shoreward migration must be coupled to a growth of alongshore variability. According to Plant et al. (2006), due to the large response time with respect to the duration of conditions, the system continually orbits through time-varying equilibrium points. Earlier work based on a computation with a constant condition showed that the behaviour of the system could be described with the proposed model (Plant et al., 2007). The present results suggest that the dynamical attractor model would benefit from adding the wave incidence angle, as this is found to be equally important as the offshore wave height in understanding and predicting nearshore morphological evolution.

We found that in the case of significant variability in the morphology at the moment of transition, no more adjustments are possible. This agrees with some field observations (Van Enckevort et al., 2004) where the variability first decreases before the morphology adjusts to the new length scale, though this has not been investigated specifically in detail yet. Tiessen et al. (2010) and Tiessen et al. (2011) used both linear stability analyses as well as a non-linear model to investigate how large the effects of the amplitude of the perturbation

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**Fig. 12.** Mean cross-shore profiles at \( t_f \) for the AB1.4 computations.

**Fig. 13.** Offshore angle of wave incidence \((\theta(t))\) for three computations.

**Fig. 14.** Final bathymetries for computations with (from left to right): constant conditions, smoothly varying conditions and abruptly varying conditions with longer persistence, grey levels indicate depth in m.
on an initially alongshore uniform bathymetry are, when this bathymetry evolves. They investigated which length scale would be dominant and when this is determined by the initial perturbation. They find, similar to our findings, that when the initial perturbation has a small amplitude, it does not have a strong effect on the subsequent evolution of the bar. In this case, the evolution could in their opinion, be predicted by linear stability analysis. However, when the initial variability increases, the evolving morphological pattern depends on the length scales in the bathymetry and those fitting the forcing and their fastest growing modes.

**Turner et al. (2007)** analysed three years of video-based data of a nearshore bar system and found no correlation between the observed rip channel distances and the offshore wave height, period or energy (similar to Holman et al., 2006). They stated that their analysis of observed rip channel locations cannot be ‘reconciled with the majority of existing template and instability models for rip formation, that predict a relationship between incident wave conditions and regular spacing of rips alongshore’. We find that such relationships may still be valid, but should be perceived as the intention of the nearshore bar system in case the condition would prevail long enough and the antecedent morphology would facilitate adaptation. Turner et al. (2007) further state that it is moreover the morphology that governs rip channel distances and not so much offshore wave heights, period or energy. We would like to add that not only the morphology, which evolved in response to past hydrodynamic conditions, but also the response time to hydrodynamic conditions plays a significant role in the response of nearshore morphology. It is not so much the morphology at a single moment in time, which determines all, but it is the whole morphological process: the evolution in response to local hydrodynamic conditions, including morphological processes which damp or amplify the response.

In observations the hydrodynamic conditions regularly change and nearshore sandbars generally are alongshore non-uniform. Castelle and Ruessink (2011) found that the effect of mean conditions on the evolution of rip channels is different from the effect of time-changing conditions, agreeing with our findings. They added that the mismatch between sandbar morphology and the prevailing wave conditions can drive net longshore migrations which would not be predicted when mean wave forcings would have been used. We therefore argue that the prediction of the evolution of nearshore bars will benefit from forcings based on actual time-varying conditions (e.g. Smit et al., 2010). Further, as the evolution is very sensitive to the pattern of the initial bathymetry, this bathymetry should in a prediction reflect the observed bathymetry as closely as possible.

5. Conclusions

This paper has tested the hypothesis that small morphological variability on a nearshore bar system facilitates a better adaptation to changing hydrodynamic conditions than a morphology with distinct and deeply imprinted rip channels. Using a process-based model, computations were performed to simulate the morphological evolution of a nearshore double bar system in response to two successive piece-wise constant hydrodynamic conditions. Different moments of transition – resulting in different levels of morphological variability – indicated that a more distinctly developed bathymetry hardly adjusts to a new hydrodynamic condition. Due to more distinct morphology the current patterns reinforce the existing pattern, thus preventing the system changing toward a new configuration.

Next, sets of different successive hydrodynamic conditions show that the importance of the level of variability holds for both increasing and decreasing wave energy fluxes. This indicates that it is not so much the total energy flux, but the relation between cross-shore and alongshore components of the local velocities which determines whether existing channels will remain or disappear. Computations with different initial perturbations (all done for one set of hydrodynamic conditions) show a similar decreasing trend between the variability and the level of adaptation of the system, though with a small range due to the different initial perturbations. Similar variability at the moment of transition resulted in similar levels of adaptation, reinforcing the hypothesis that the variability plays a large role in the level of adaptation of the system.

In the field, wave conditions change significantly within the computed adaptation times, preventing the conditions to leave a remaining imprint. It can therefore be concluded that observed bathymetries are a result of antecedent morphology – and thus antecedent hydrodynamic conditions – and the current conditions.

The current work illustrates why observed rip channel distances in the field may not match with concurrent conditions. The main three reasons are: 1) the response time of the morphological system, 2) the relatively short duration of hydrodynamic forcings and 3) the level of existing morphological variability in the nearshore bar system. The forcing needs to prevail long enough, but it will change the length scales in the system only when the bathymetry has a low level of variability and the condition has sufficient energy to change the existing level of variability. It is therefore concluded that the response is governed by the change in hydrodynamic forcing, the morphology itself and the resulting local hydrodynamics and morphological processes combined with the duration of the hydrodynamic conditions.

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