FINITE-AMPLITUDE BEHAVIOUR OF ALONGSHORE VARIABILITY IN NEARSHORE SANDBARS: OBSERVATIONS AND MODELLING

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Abstract

Subtidal sandbars often contain alongshore variable patterns, such as crescentic planshapes and rip channels. While the initial formation of these patterns is nowadays reasonably well understood, the morphodynamic mechanisms underlying their subsequent finite-amplitude behaviour have been examined far less extensively. This behaviour concerns, among other aspects, the coupling of alongshore-variable patterns in an inner bar to similar patterns in a more seaward bar, and the destruction of crescentic patterns during high-energy conditions. In this paper, we review recent advances in our understanding of finite-amplitude behaviour of crescentic sandbars based on remote-sensing observations, numerical modelling and data-model integration. We illustrate that morphological coupling can be common in multiple sandbar systems and is governed by water depth variability along the outer-bar crest and by various wave characteristics, including the offshore wave height and angle of incidence. In addition, we demonstrate that crescentic patterns predominantly vanish under high-angle wave conditions, highlighting the role of alongshore currents in straightening sandbars. A more complete understanding of nearshore evolution will require the integration of cross-shore and alongshore sand transport processes within in a single modelling framework.

Key words: crescentic sandbars, numerical modelling, remote sensing, nearshore morphodynamics

1. Introduction

Subtidal sandbars are shore-parallel ridges of sand in less than 10 m water depth fringing wave-dominated coasts along great lakes, semi-enclosed seas and open oceans (e.g., Evans, 1940; Saylor and Hands, 1970; Greenwood and Davidson-Arnott, 1975; Lippmann et al., 1993; Ruessink and Kroon, 1994; Wijnberg and Terwindt, 1995; Shand and Bailey, 1999; Kuriyama, 2002; Ruessink et al., 2003; Almar et al., 2011; to mention just a few). Sandbars often have multi-annual lifetimes and can occur as a single feature, or as multiple systems. Numerous laboratory and field studies, as well as numerical modelling efforts, have been devoted to elucidate the hydrodynamics and sand-transport processes that lead to the initial formation of sandbars (e.g., Dyhr-Nielsen and Sorensen, 1970; Miller, 1976; Bowen, 1980; Roelvink and Stive, 1989; Sallenger and Howd, 1989; Black et al., 2002) and to their subsequent cross-shore migration in response to the ever-changing offshore wave conditions (e.g., Gallagher et al., 1998; Plant et al., 2001; Hoefel and Elgar, 2003; Van Enckevort and Ruessink, 2003a; Ruessink et al., 2007a, 2009; Pape et al., 2010; Walstra et al., 2012). Besides their intriguing morphological appearance and evolution, sandbars are also of significant societal importance by forming a natural barrier between the hinterland and the ocean. Sandbars safeguard beaches by dissipating storm waves before they impact the shore. Therefore, many present-day soft engineering measures to improve coastal safety, such as shoreface nourishments, involve direct or indirect modifications to nearshore sandbars (e.g., Grunnet and Ruessink, 2005; Ojeda et al., 2008).

Intriguingly, sandbars often exhibit quasi-regular undulations in their height and cross-shore position (Fig. 1). These so-called crescentic sandbars can be viewed as a more-or-less rhythmic sequence of shallow horns (shoals) and deep bays (cross-shore troughs) alternating shoreward and seaward of a line parallel to the coast. The spacing between the horns varies from several tens of meters to more than 1 km; see Van

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Enckevort and Ruessink (2003b) for an overview. Crescentic sandbars are associated with wave-driven circulation patterns that consist of weak onshore flow over the horns and strong (up to 2 m/s) offshore flow through the bays. They develop from a linear shore-parallel bar within a few days following a period of high, breaking waves (Ranasinghe et al., 2004; Van Enckevort et al., 2004). Under continuing low waves the horns of the crescentic bar weld to the shore, causing the initially alongshore continuous trough to disappear and the bays to evolve into distinct cross-shore troughs (rip channels) with strong currents. During the next period of high waves, a crescentic bar is reshaped almost immediately into a linear shore-parallel bar (Van Enckevort et al., 2004), thus completing the cycle. The strong offshore currents through the bays endanger the safety of recreational beach users and may also transport substantial quantities of beach sediment into deeper water. In addition, outer crescentic sandbars are often associated with similar rhythmic perturbations in onshore morphology, such as an inner sandbar (Ruessink et al., 2007b) and the shoreline (Sonu, 1973). This can lead to localized beach and dune erosion and subsequent property loss during storms (Thornton et al., 2007).

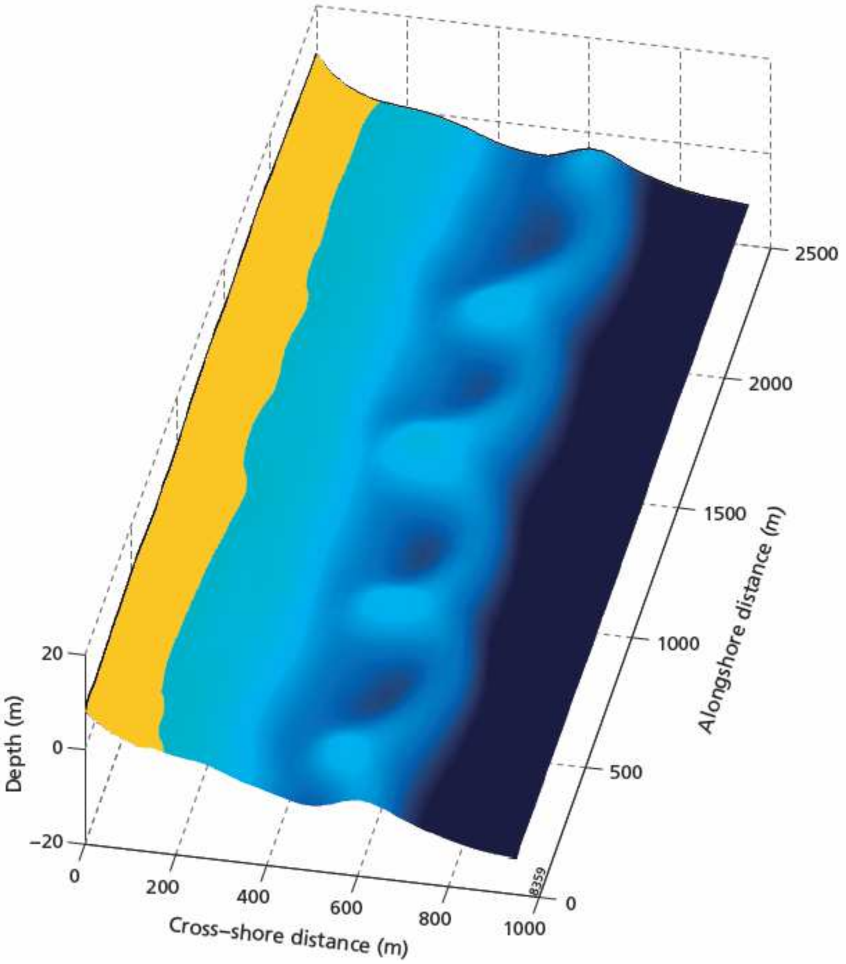

Figure 1. Bathymetry of a beach with a crescentic sandbar. This bathymetry was measured during the ECORS-Truc Vert’08 field experiment, see Almar et al. (2010).

The intriguing appearance of crescentic sandbars has resulted in a myriad of models to explore the processes underlying their initial formation. Model studies first explained alongshore sandbar variability from a template in the water motion (Bowen and Inman, 1971; Holman and Bowen, 1982); present-day models rely on the principle of self-organization, in which a crescentic sandbar forms spontaneously through the positive feedback between the flow, sediment processes and the evolving morphology. This feedback has been mainly explored through linear stability analysis (e.g., Deigaard et al., 1999; Falqués et al., 2000; Calvete et al., 2005), in which the temporal development of small, periodic perturbations superimposed on an initially uniform morphology is investigated using linearized, depth-integrated equations for mass and momentum conservation. Wave breaking on the bar induces circulation currents and sediment transport that reinforce the perturbations and lead to the initial growth of rhythmic crescentic bed patterns. Non-linear models (e.g., Damgaard et al., 2002; Reniers et al., 2004; Smit et al., 2010) corroborate this self-organization mechnism and additionally simulate the small alongshore variation in wavelength typical of natural crescentic sandbar systems (Van Enckevort et al., 2004; Holman et al., 2006).

While the genesis of crescentic sandbars is thus reasonably well understood, the morphodynamic mechanisms underlying their subsequent finite-amplitude behaviour have been examined far less extensively. This behaviour concerns the merging and splitting of individual crescents and rip channels (e.g., Van Enckevort et al., 2004), the saturation in the growth of their cross-shore amplitude (e.g., Garnier et al., 2010), the coupling of alongshore-variable patterns in an inner bar to similar patterns in a more seaward bar (e.g., Ruessink et al., 2007b; Castelle et al., 2010a,b), and the destruction of crescentic patterns during high-energy conditions (e.g., Van Enckevort et al., 2004). The increasing availability of high-resolution (daily), long-term (many years) time series of nearshore video imagery (Holman and Stanley, 2007), together with advances in the non-linear modelling of nearshore morphodynamics and in data-model integration techniques, have recently advanced our knowledge of the finite-amplitude behaviour of alongshore sandbar variability considerably. This keynote paper is devoted to presenting an overview of recent progress on sandbar coupling and straightening; we conclude with a non-exhaustive list of challenges for sandbar research in the coming years.

2. Sandbar coupling

In a double sandbar system, with a more landward inner bar and a more seaward outer bar, the distinction between a forcing template and self-organization becomes blurred. Various observations indicate that the inner bar may possess remarkably smaller and often more variable alongshore scales than the outer bar (e.g., Bowman and Goldsmith, 1983; Van Enckevort et al., 2004). This has long been interpreted as self-

Figure 2. Examples of coupled morphology, showing (a) out-of-phase (180°) coupled sandbars, (b) out-of-phase coupling between sandbar and shoreline (courtesy of A.D. Short), (c) in-phase (0°) coupled sandbars (taken from Bowman and Goldsmith, 1983), and (d) two inner-bar rip channels for each single outer-bar bay.

organization at the scale of the individual bar and the absence of interaction. Other observations, summarized in Castelle et al. (2010a), demonstrate that inner-bar patterns can also couple to those in the outer bar, indicative of a type of interaction that Castelle et al. (2010a) termed morphological coupling. Coupling examples (Fig. 2) include the systematic occurrence of two inner-bar rip channels within one outer-bar crescent (Fig. 2d), that of seaward perturbations in the inner bar facing outer-bar horns (a 180°, or out-of-phase relationship, Fig. 2a), and that of shoreward perturbations in the inner bar facing outer-bar horns (a 0°, or in-phase relationship). The out-of-phase relationship is reminiscent of the commonly observed relationship between inner-bar patterns and shoreline rhythms (Sonu, 1973; Fig. 2b). Using a numerical model with synthetic wave-input conditions and bathymetries, Castelle et al. (2010a) demonstrated that, under shore-normal waves, coupling processes arise because of alongshore variability in wave height, and associated flow patterns, over the inner bar that are induced by the water depth variability along the outer-bar crest. As summarized in Figure 3, a large fraction of wave breaking over the outer bar leads to out-of-phase coupled sandbars. For a small fraction of wave breaking, wave focusing by refraction over the outer-bar horns overwhelms the effect of wave breaking, leading to in-phase coupled sandbars. In a follow-up study, Castelle et al. (2010b) demonstrated that self-organization and coupling processes can co-exist on an inner bar; in fact, their modelling suggests that the combination of both processes leads to stronger variability in the alongshore inner-bar scales, rather than self-organizational processes alone. They further demonstrated that the relative importance of self-organization and morphological coupling changes in favour of the latter with an increase in water depth variability along the outer-bar crest.

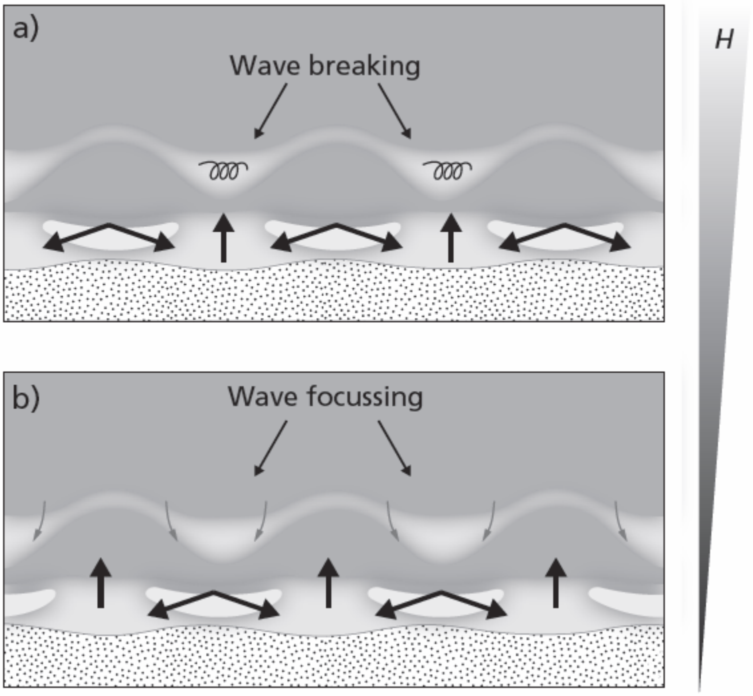

Figure 3. Coupling patterns found by Castelle et al. (2010a), showing (a) out-of-phase coupling and (b) in-phase coupling, depending on the wave height *H*. The thick black arrows indicate the associate flow patterns, whereas the gray arrows indicate wave refraction.

The aforementioned field observations of sandbar coupling (e.g., Fig. 2) were either based on sporadic observations (e.g., Bowman and Goldsmith, 1983) or a short single event (e.g., Ruessink et al., 2007b). Price and Ruessink (2013) addressed the representativeness of these findings, in particular to as when and how often certain coupling types develop. They based their study on an approximately 9.3-year long data set of low-tide time-exposure video images of the double-barred Surfer's Paradise, Gold Coast, Queensland, Australia, a swell-dominated site where the waves are usually obliquely incident. The most conspicuous elements in such images are the alongshore continuous white bands that represent the foam created by wave breaking above the sandbars (Lippmann and Holman, 1989). Price and Ruessink (2013) tracked the optical breaker line (hereafter referred to as the barline) of both the inner and outer bar on all available (2995) low-tide images and cross-correlated the barlines to detect coupled inner and outer bar morphology.

Intriguingly, 40% of all observations were found to have statistically significant (at the 98% confidence level) coupling. Based on a further visual inspection of the images, Price and Ruessink (2013) distinguished 5 coupling types (Figure 4). The bars either coupled in-phase, with an outer-bar horn facing a shoreward perturbation of the inner barline, or out-of-phase, where the outer-bar horn coincided with a seaward bulge in the inner barline. Four of the five observed coupling types coincided with a downstate sequence (Price and Ruessink, 2011) of the outer bar. The morphology of the inner bar was found to be either terraced (with no trough or channels intersecting the bar) or characterized by the presence of rip channels. These properties were used to give abbreviated names to the coupling types (Figure 4): *I* or *O* (in-phase or out-of-phase), *d* or *u* (downstate or upstate) and *t* or *r* (terraced or with rips). The two coupling types explored in Castelle et al. (2010a) correspond to Odr (Fig. 3a) and Idr (Fig. 3b). By far the most common coupling type at the Gold Coasts was, however, the Idt type, with a wavy terraced inner bar showing landward perturbations displaced slightly (≈ 100 m) alongshore with respect to the outer-bar horns (to the right in Fig. 4a).

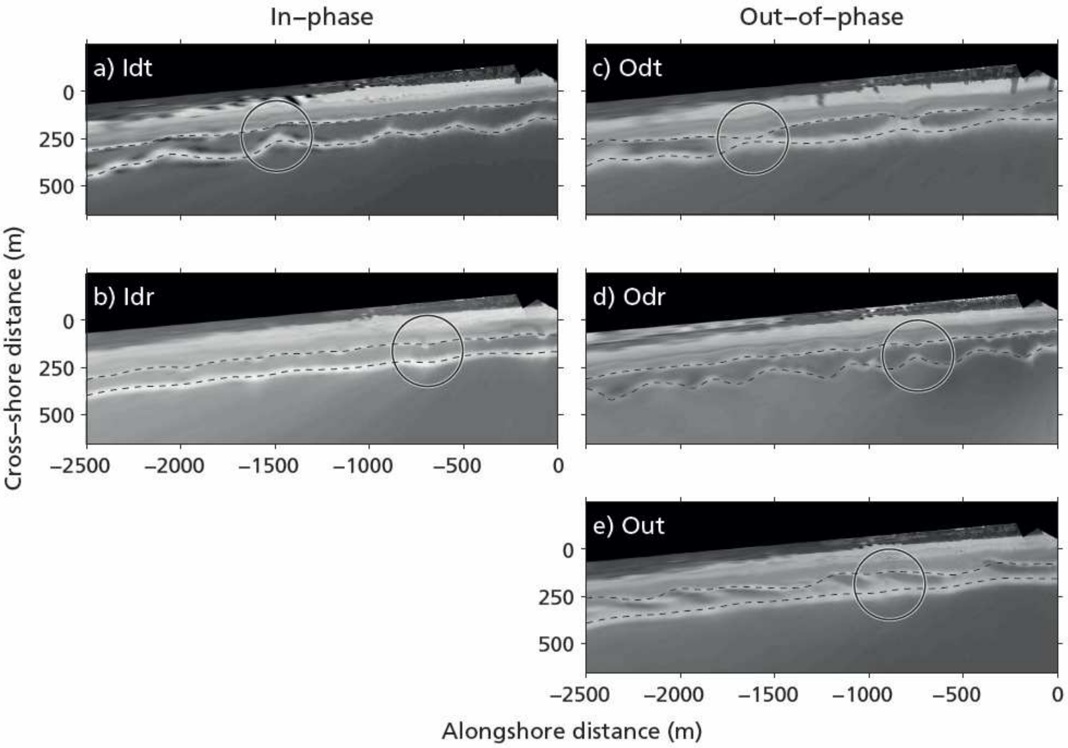

Figure 4. Examples of observed types of morphological coupling between the inner and outer barlines; low-tide time-exposure planview images of in-phase images with (a) an inner terrace and (b) inner rips, out-of-phase coupling with (c) an inner terrace and (d) inner rips in downstate direction, and (e) out-of-phase coupling with a clear alongshore offset between the inner and outer barline features in upstate direction. The dotted lines indicate the detected barlines, and the circles indicate a characteristic coupling feature for each coupling type. Source: Price and Ruessink (2013).

Figure 5 summarizes the Gold Coast observations in a conceptual model, in which the type of coupling is governed by the offshore wave height, the angle of wave incidence and the depth variation along the outer bar. The pre-dominance of the Idt coupling type is related to the fairly large waves that persistently arrive with a large angle of incidence (30° in 15-m depth). Price and Ruessink (2013) hypothesized that such wave conditions drive a meandering alongshore current that prevents the outer-bar horns from welding to the inner bar and leads to downdrift-positioned landward perturbations in the inner terrace. When the meandering current is less strong (smaller wave height or more shore-normal incidence), the outer-bar horns can weld ashore and lead to the Odt coupling type. When the waves are highly energetic and obliquely incident, the outer bar becomes more alongshore uniform (see also Section 3); the outer-bar horns separate from the outer bar to become part of the inner bar (similar to Almar et al., 2010), resulting in

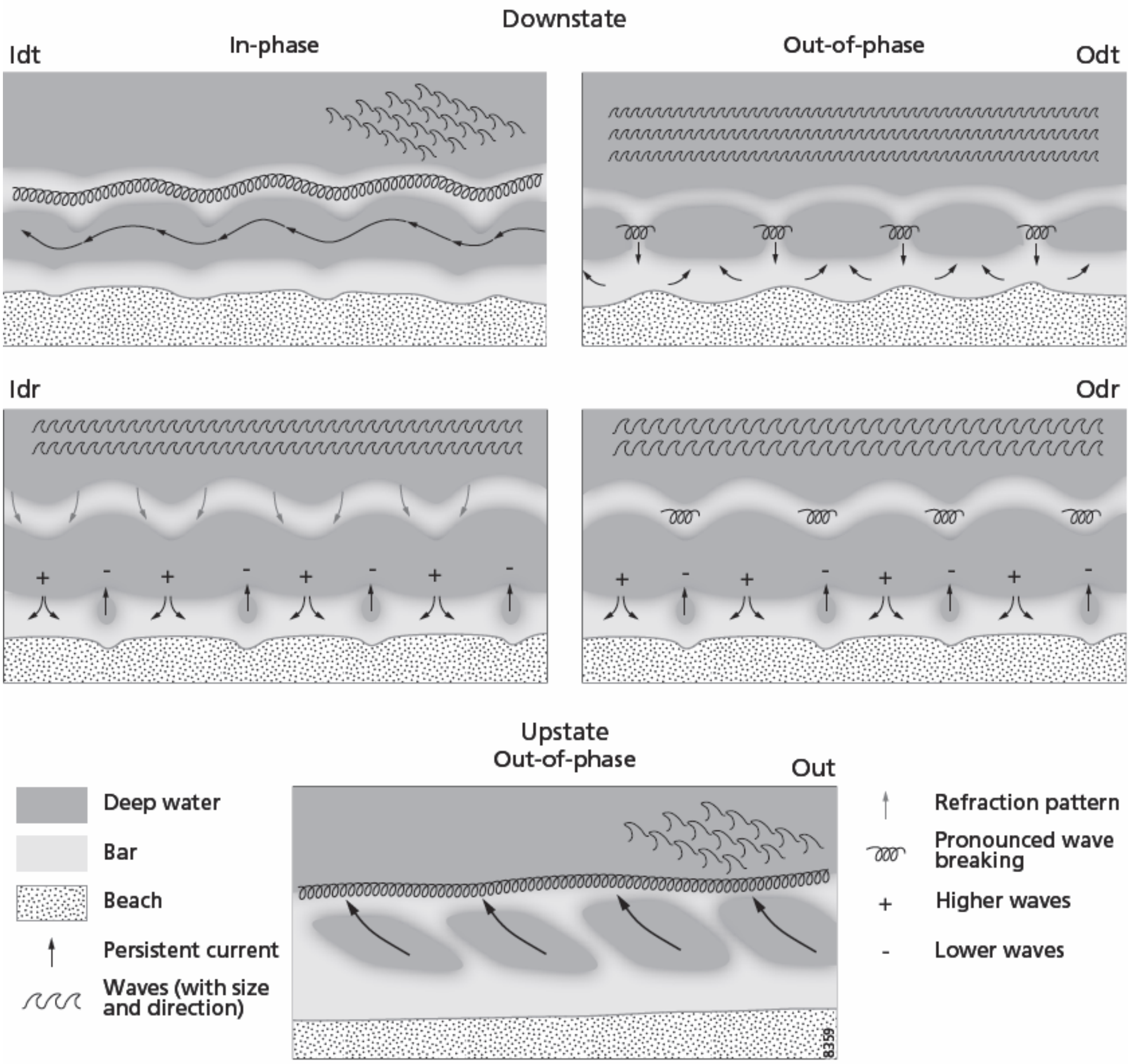

Figure 5. Conceptual model of the development of different coupling types. Source: Price and Ruessink (2013).

an alongshore variable inner terrace, the upstate coupling type Out. If the straightening persists, both bars become alongshore uniform with alongshore continuous trough, often referred to as a morphological reset. A sudden change toward the end of this straightening, however, leads to the Idr coupling type. Now, the small remaining depth variations along the outer bar cause wave focussing through refraction, driving a weak cell-circulation pattern over the inner bar (see also Figure 3b).

Price et al. (sub judice) then applied the non-linear 2DH numerical model of Castelle et al. (2012) to explore why different angles of wave incidence lead to the development of different coupling types. In contrast to earlier work, they drove the model with realistic bathymetric data, which were derived from the video observations using an assimilation model (Van Dongeren et al., 2008). The model was run with time-invariant forcing (offshore significant wave height and period of 1.1 m and 9 s, respectively) for angles of wave incidence θ ranging from 0° to 20°. Figure 6 shows the flow pattern along the inner bar for all θ simulations after 2 days of simulation. Here, the grey scaling indicates the strength of the rotational nature of the flow over the inner bar. It can be seen that the flow is rotational (i.e., contains cell-circulation patterns) for angles of wave incidence up to $\approx 10°$. As θ approaches 10°, the feeder current directly downdrift of the rip channel becomes weaker and eventually disappears as it becomes overridden by the alongshore current. Now, the flow field above the inner bar is dominated by a meandering alongshore current. Figure 7 shows the depth perturbations along the inner bar after 2 days of simulation. The most pronounced depth perturbations are found for the simulations with $\theta = 7°$, which are relatively deep and narrow. As the flow is still rotational (see Figure 6), these negative perturbations correspond to rip channels.

For larger angles, the negative depth perturbations decrease and become increasingly wider. Toward θ = 20°, the depth perturbations have hardly developed at all. When we examine the simulations for θ = 10 - 20° in more detail, we find that the meandering alongshore current erodes the inner terrace downstream of the outer-bar horns, where more onshore-directed flow and accretion turn to more offshore-directed flow and erosion. This results in a landward perturbation in the terrace edge, consistent with the observations of the Idt coupling type. As such, the landward perturbations in the inner terrace for the Idt coupling type are erosional features. For $\theta < 10°$, cell-circulation patterns govern the flow at the inner bar, with offshore flow and the development of rip channels in the inner bar at the locations of the outer-bar horns, the Odr coupling type also found by Castelle et al. (2010a). On the whole, Figures 6 and 7 confirm that the angle of wave incidence is crucial to the flow pattern, sediment transport, and thus the emerging coupling type at the inner bar.

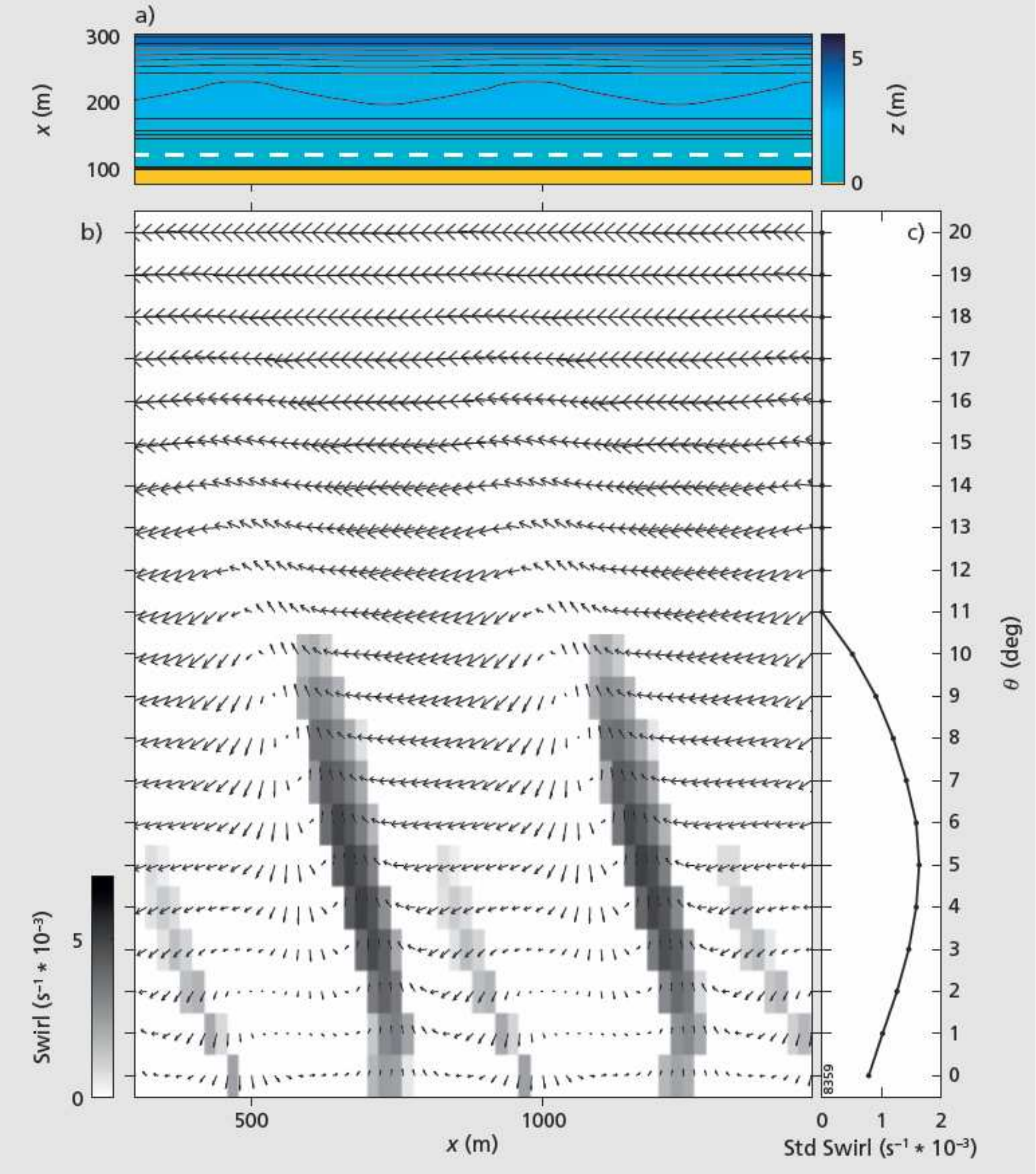

Figure 6. Model results, showing (a) the initial bathymetry, with isobaths (0.5 m intervals) contoured in the background, (b) flow velocity (arrows) and swirling strength (shaded) along the inner bar at y = 120 m (white dashed line in a) for all simulations after 2 days of simulation. (c) depicts the alongshore standard deviation of the swirling strength along the inner bar at y = 120 m. The swirling strength is a measure of the rotational nature of the flow. Non-zero values imply the presence of cell-circulation patterns. Source: Price et al. (sub judice).

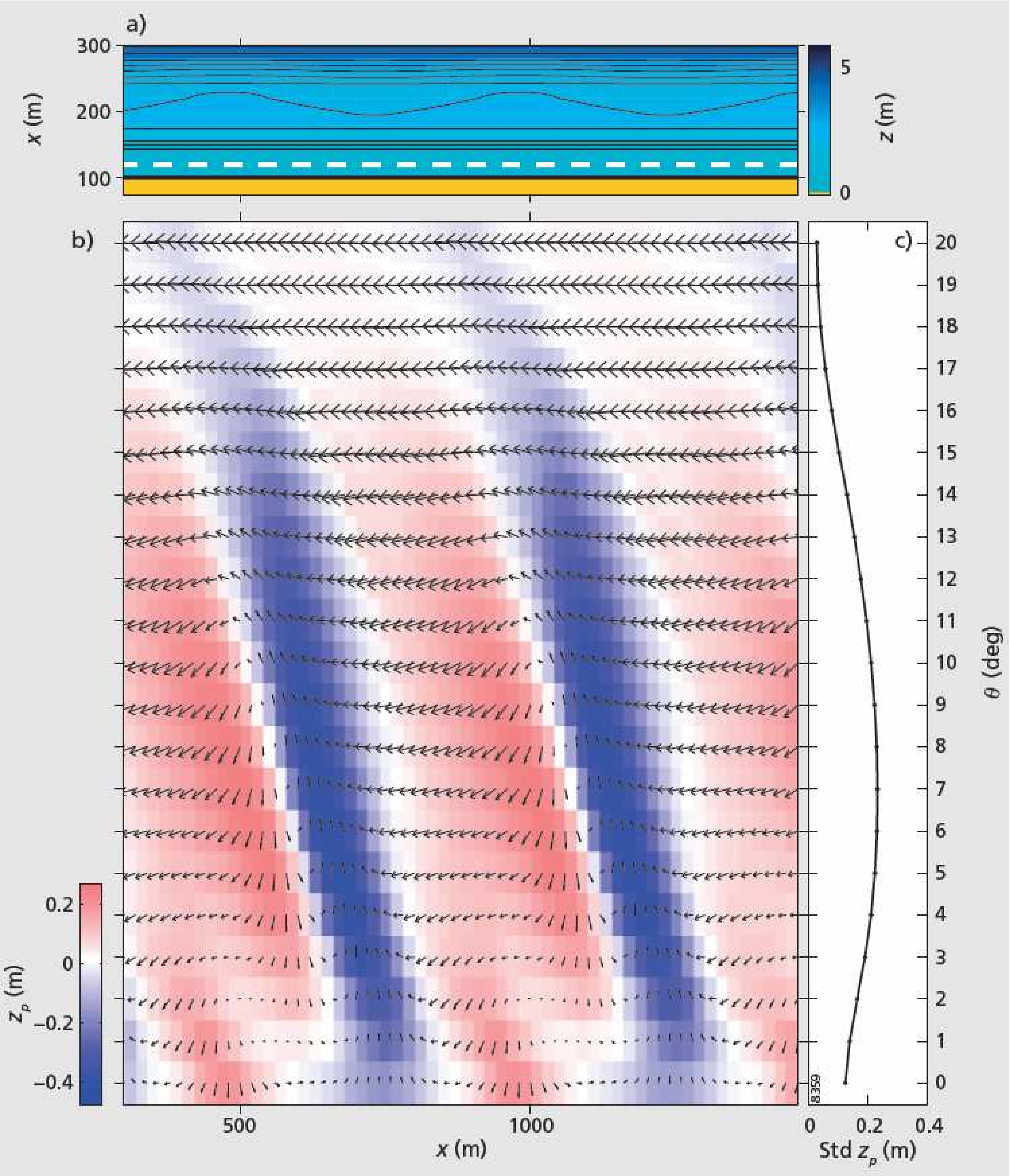

Figure 7. Model results, showing (a) the initial bathymetry, with isobaths (0.5 m intervals) contoured in the background, (b) flow velocity (arrows) and depth perturbations z_p (colour) along the inner bar at y = 120 m (white dashed line in a) for all simulations after 2 days of simulation. (c) depicts the alongshore standard deviation of z_p along the inner bar at y = 120 m. Source: Price et al. (sub judice).

3. Sandbar straightening

The straightening of an alongshore variable sandbar, also coined a morphological reset, has traditionally been associated with high-energy, erosive wave conditions, without an actual account of which processes lead to the straightening. Observations from the same video data set used in Section 2 (Figure 8) challenge the need for high-energy wave conditions; instead, they stress the effect of wave obliquity in morphological evolution. For example, Figure 8b illustrates that an offshore root-mean-square wave height of around 0.8 m generally resulted in the further development of rip channels, especially when θ is small (say, less than 30°), while the same waves with a larger angle of incidence ($\theta > 20°$) were observed to cause a reset.

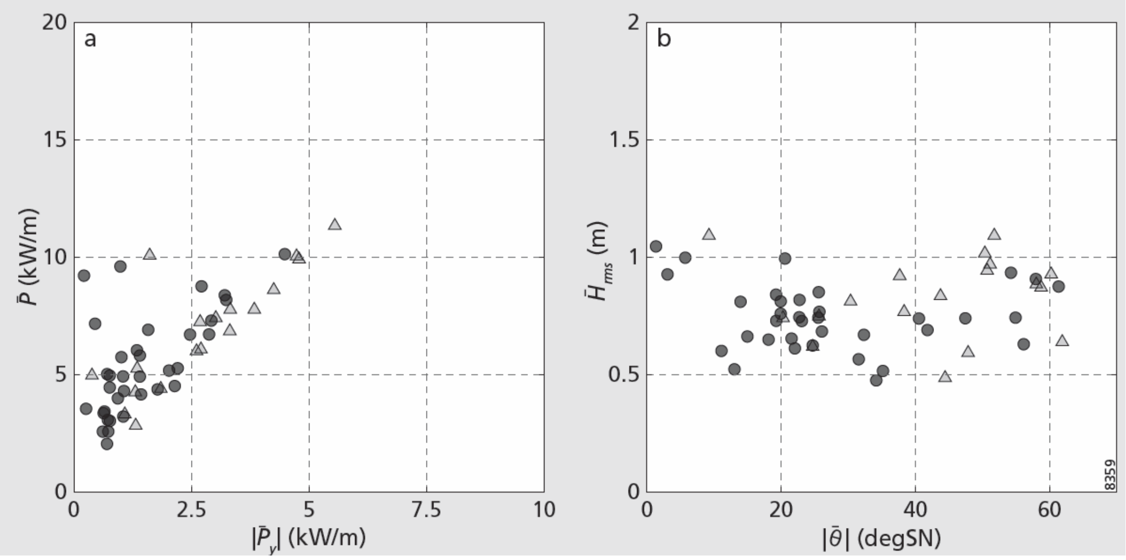

Figure 8. Mean wave conditions during gradual downstate (circles) and upstate (triangles) transitions of the outer bar. (a) Mean wave power versus mean absolute alongshore wave poser and (b) mean root-mean-square wave height versus mean absolute angle of wave incidence. A downstate transition corresponds to the further development of rip channels, an upstate transition to a sandbar straightening. Source: Price and Ruessink (2011).

Figure 9 shows the results of a numerical simulation with the same 2DH model used in Section 2. The initial bathymetry contains well-developed rip channels and associated embayments in the beach. The offshore significant wave height was set to 1 m, the peak period to 10 s and θ to 8°. During the simulation, the rips migrate with the alongshore flow and, after 3 days of simulation, have become so shallow that the bar is essentially straight. The beach embayments are more subdued too but the beach is still alongshore variable. The numerical model study of Garnier et al. (in press) also stresses the effect of wave obliquity and the associated meandering current pattern (see also Section 2) in bar straightening. Their results indicated that the rip currents through the bays weakened in intensity with an increase in θ and that, at the same time, the strongest current shifted to a location downstream of the deepest part of the bay. As in Figure 9, this shift causes the rip channels to migrate and decay. Interestingly, the transition from rip growth to rip decay takes place at substantially lower θ (say, 5-10°) than in the observations (Figure 8, $\theta \approx$ 30°).

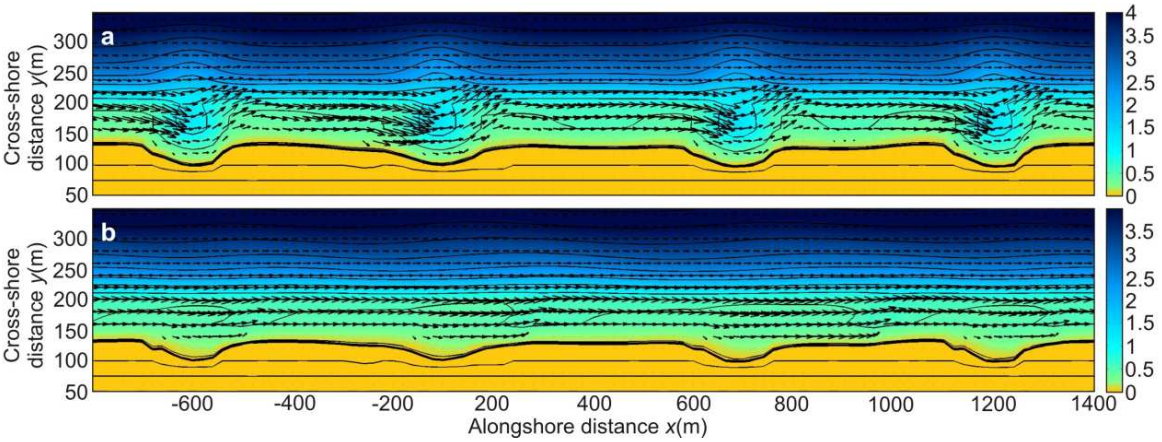

Figure 9. Simulation of sandbar straightening starting from well-developed rip channels for H_s = 1 m, T_p = 10 s and θ = 8°. (a) t = 0 and (b) t = 3 days. In both panels, the water depth is in meters; iso-contour lines are drawn at 0.5 m interval. The sandbar morphology in (a) was obtained at the saturation of the bedform growth from a previous simulation starting from an alongshore-uniform sandbar with H_s = 1 m, T_p = 10 s and θ = 8°. Source: Castelle et al. (in preparation).

4. Future research direction

We end this paper with a non-exhaustive list of what we see as major challenges for sandbar research in the near future.

- All 2DH model results presented here were, to some extent, idealized by using synthetic bathymetries and time-invariant wave forcing. In this way, the models were used as exploratory models and focused on elucidating the hydrodynamic and sand-transport processes underlying pattern dynamics. While this is a highly justified approach, it does limit data-model comparison. We see bridging the gap between synthetic numerical simulations and field observations as a major challenge that must be reached to increase the credibility of model results and to better understand field observations. The use of video-based bathymetry in Price et al. (sub judice) and of time-variant forcing in Castelle and Ruessink (2011) can be considered as first steps.
- Furthermore, all model results were based on the assumption that the cross-shore sand transport by cross-shore processes, including undertow and wave non-linearity, balance with the gravitational downslope transport. In other words, cross-shore beach profile changes (by cross-shore processes) are assumed to be slower than the dynamics of alongshore variable morphology. Field observations question the appropriateness of this time-scale separation. For example, fast bar straightening is often associated with fast (up to 10-20 m/day, see Gallagher et al., 1998 and Van Enckevort and Ruessink, 2003a) offshore bar migration. On the other hand, onshore bar migration is substantially slower and never exceeds a few m/day, but this matches the slow initial and finite-amplitude evolution of alongshore-variable morphology. A major challenge would be to integrate the formulations for cross-shore hydrodynamics and sand transport embedded in cross-shore profile-evolution models into area models as to allow for a more complete predictive understanding of the nearshore. The combined formulations may help us to explain the combined cross-shore oriented and alongshore-variable response during both mild and high-energy wave conditions and may shed light on bar straightening during high-energy, shore-normal wave conditions, when alongshore currents are weak. Once we are able to more reliably predict the full complexity of sandbars on the timescale of a few days, we can also develop operational modeling tools for such societal highly relevant topics as storm-impact studies and swimmer safety (e.g., rip-current strength, location and mobility).
- The results on, in particular, sandbar coupling have demonstrated that morphological features cannot be studied (and modeled) in isolation. This is equally true for the surf zone and the (intertidal) beach. Yet, we barely understand the exchange of sand between the surf zone and the beach face. Here, various processes, such as wave breaking turbulence and swash/backwash motions, are highly important and our present sand-transport equations, largely based on regular non-breaking waves, will not apply. In fact, most morphodynamic sandbar models do purposely not attempt to estimate sand transport rates here (e.g., Plant et al., 2004; Ruessink et al., 2007a). This is a serious shortcoming because bed-level changes in shallow water are often large and, from a practical viewpoint, understanding sand transport through the shallow-water region onto the beach is crucial to the successful design of beach-restoration and nourishment projects. Furthermore, errors in the prediction of bed-level change in shallow water rapidly propagate seaward to worsen predictive skill in deeper water (Ruessink, 2005), including that of sandbars.
- When we take a longer-term (years – decades) view of nearshore evolution, we believe that we cannot restrict ourselves to marine processes only. Beaches are intrinsically linked to the neighbouring dunes by the incessant exchange of sand, not only by marine processes during high-energy conditions, but also by aeolian processes during non-storm conditions. Our quantitative understanding of aeolian processes on beaches is rather limited. A major challenge will be to embed a robust module for aeolian coastal growth / recovery in marine morphodynamic models or to realistically couple independent marine and aeolian modules.
- With this multi-year view of the nearshore zone, the question at what level we need to care about sandbar behaviour opens up automatically. Do we then need to accurately understand the generation, evolution and decay of crescentic sandbars? What is their net effect on long-term nearshore evolution? Potentially, we should move from process-based models to more behavioural landform models working at km-scale to explore key feedbacks between the various landscape sub-systems and between landscape evolution and changes in the input (e.g., wind- and wave-climate, sediment availability).

- Are the only challenges related to modelling? No, certainly not. Maintaining and, preferably, extending the current number of coastal observatories is a key (sometimes largely logistic) challenge too. Video systems (e.g., Holman and Stanley, 2007), like the one deployed at the Gold Coast, have revolutionized our view on nearshore sandbar variability. Intriguingly, each coastal site has similarities with other sites but also its own unique characteristics. Great value may arise from combining in-situ observations with multiple remote-sensing platforms, including optical video, X-band radar, and terrestrial laser scanning. Measuring and monitoring is adamant to explore the impact of rare high-energy events on nearshore evolution, to allow for inter-site comparison studies, to bridge scales from short-term variability to long-term net behaviour, to identify new phenomena, and to integrate across different (e.g., marine and aeolian) landscapes. Beyond data analysis and interpretation, we believe *the* (data) way to go is data-model integration for depth-inversion (e.g., Van Dongeren et al., 2008) and dynamic assimilation for the prediction of, for example, surf zone currents (e.g., Wilson et al., 2010), wave properties (e.g., Garcia et al., 2013), and coastal evolution (e.g., Thornhill et al., 2012; Chu et al., 2013). For instance, depth-inversion through data assimilation could provide the third (depth) dimension of sandbar evolution which, from remote sensing, has so far been addressed primarily geometrically (i.e., two-dimensional) with barlines (e.g., Van Enckevort et al., 2003a,b; Price and Ruessink, 2011, 2013). This could strongly improve our understanding of sandbar morphodynamics (see our first point, and Price et al., sub judice) and also provide robust data to initialize, calibrate and validate models (e.g., Smith et al., 2013). To summarize, data are crucial to face all our modeling challenges.

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