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Morphological coupling in a double sandbar system

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Abstract

Subtidal sandbars often exhibit 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. This paper aims to present our recent findings on the understanding of finite-amplitude behaviour of crescentic sandbars, with a focus on morphological coupling in double sandbar systems. Our results, based on a combination of remote-sensing observations, numerical modelling and data-model integration, illustrate that morphological coupling can be common in multiple sandbar systems. It 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. The angle of wave incidence is crucial to the flow pattern, sediment transport, and thus the emerging morphology of the coupled inner bar. In addition, our results demonstrate that crescentic patterns predominantly vanish under high-angle wave conditions, highlighting the role of alongshore currents in straightening sandbars and challenging the traditional conception that crescentic patterns vanish under high-energy, erosive wave conditions only.

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; Shand et al., 1999; Almar et al., 2010; Kuriyama, 2002; Ruessink et al., 2003; Wijnberg and Terwindt, 1995, to mention just a few). Sandbars often have multi-annual lifetimes and can occur as a single feature, or as a multiple (most often 2, sometimes up to 5) bar system. 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 an imaginary line parallel to the coast. Depending on the wave conditions and the currents they induce in the nearshore zone, these sandbar patterns continuously change, vanish or reappear. 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 sandbars (e.g., Grunnet and Ruessink, 2005; Ojeda and Guillén, 2008). A comprehensive understanding of the processes that govern sandbar behaviour and the development of the capability to predict this behaviour are thus of significant importance when it comes to minimising human and economic losses.

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 Sørensen, 1970; Bowen, 1980; Roelvink and Stive, 1989; Sallenger Jr. 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; Walstra et al., 2012; Hoefel and Elgar, 2003; Van Enckevort and Ruessink, 2003b; Ruessink et al., 2007b, 2009; Pape et al., 2010). Similarly, the striking alongshore rhythmicity of crescentic sandbars has received plentiful studies. Field observations have indicated that the spacing between the horns varies from several tens of meters to more than 1 km; see Van Enckevort and Ruessink (2003a) 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 $2\,\mathrm{m\,s^{-1}}$) offshore flow through the bays. Their alongshore variability develops 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); a so-called downstate sequence (Wright and Short, 1984). 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 (an upstate sequence; Wright and Short, 1984), thus completing the cycle (Van Enckevort et al., 2004). 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., 2007a) and the shoreline (Sonu, 1973; Van de Lageweg et al., 2013). This can lead to localised beach and dune erosion and subsequent property loss during storms (Thornton et al., 2007).

Besides field observations, 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 *hydrodynamic* template in the water motion (Bowen and Inman, 1971; Holman and Bowen, 1982); present-day models rely on the principle of self-organisation, 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 linearised, 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., 2008) corroborate this self-organisation mechanism 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., 2009), the coupling of alongshore-variable patterns in an inner bar to similar patterns in a more seaward bar (e.g., Ruessink et al., 2007a; 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 paper aims to present our recent findings on the finite-amplitude behaviour of crescentic sandbars, based on both field observations and numerical modelling, with a focus on morphological coupling in double sandbar systems. We show that the angle of wave incidence determines to a large extent whether crescentic patterns develop or vanish (Sect. 2), and that it determines the flow pattern at the inner bar for a given crescentic outer bar, leading to different types of morphological coupling between both bars (Sect. 3). We conclude with a summary of our findings and perspectives for future research (Sect. 4).

2 Alongshore sandbar variability

2.1 Background

Numerous observations and long-term monitoring of the nearshore zone have revealed the wide range of shapes that nearshore sandbars may attain (e.g., Wright and Short, 1984; Lippmann and Holman, 1990; Van Enckevort et al., 2004; Ranasinghe et al., 2004). Despite each observed sandbar configuration being unique, and the continuous change in shape under the influence of waves and currents, a certain regularity in sandbar morphology has been observed. For single-barred beaches, Wright and Short (1984) developed the most widely accepted and applied beach state classification model, based on observations of beaches with contrasting environmental conditions over a period of 3 yr. Such an aggregation facilitates answers as to *when* certain behaviour, such as morphological coupling, actually happens. Whereas the Wright and Short (1984) classification model is essentially applicable to single-barred beaches only, Short and Aagaard (1993) devised a multi-bar state model where each bar can go through the same states as in the single bar model. The sandbars are essentially treated as independent features and the role of coupling between the bars for the behaviour of the composite double sandbar system is thus disregarded.

Although considerable research has been devoted to the state dynamics of a double-barred system, observations were mostly based on data which were either temporally limited to a single accretionary/erosional sequence (e.g., Van Enckevort et al., 2004; Ruessink et al., 2007a), spatially limited to (an alongshore transect of) the inner bar (e.g., Lippmann and Holman, 1990; Shand et al., 2003; Sénéchal et al., 2009) or based on data acquired at different locations or at irregular intervals (Short and Aagaard, 1993; Castelle et al., 2007). Furthermore, the large relaxation times of outer bars, in relation to the offshore wave forcing, have often prevented an abundance of state transitions of the outer bar to occur during the studied periods (see e.g., Goldsmith et al., 1982; Ferrer et al., 2009). To date, the sequential behaviour of the bar states of a double-barred system at a single site has thus not been studied under a wide range of wave conditions. Accordingly, an important first step in our study of the finite-amplitude behaviour of crescentic sandbars was to characterise the typical development of alongshore variability within a double sandbar system, based on multiple sequences.

2.2 Field site

We based our study on an approximately 9.3 yr 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; Fig. 2). We 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, allowing us to quantify the alongshore variability of both bars (see Price and Ruessink, 2011). Measurements from nearby wave buoys provided concurrent wave data, i.e. root-mean-square wave height H_{rms}, peak wave period T_{p} and angle of wave incidence with respect to shore-normal in 15 m depth θ.

2.3 Findings

During the 9.3 yr studied, the outer bar was predominantly (two thirds of the time) alongshore variable, whereas the inner bar existed as a shore-attached terrace with a rhythmic terrace edge almost half of the time (shown in Fig. 2). For more alongshore-uniform outer bar shapes (a third of the time), rip channels dominated the inner-bar morphology. As mentioned in Sect. 1, the development of alongshore variability has traditionally been ascribed to self-organisation processes during low-energy, accretive wave conditions. 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 video data set challenge the need for high-energy wave conditions; instead, they stress the effect of wave obliquity in morphological evolution. For example, Fig. 3a illustrates that low-energetic wave conditions ($\bar{H}_{\mathrm{rms}} = 0.5-1\,\mathrm{m}$) generally resulted in the further development of rip channels in the outer bar, 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. Similarly, Fig. 3b illustrates that moderately-energetic wave conditions ($\bar{H}_{\mathrm{rms}} = 1-2\,\mathrm{m}$) generally led to sandbar straightening, while the further development of rip channels was observed during smaller angles of wave incidence ($\theta < 30°$).

Whereas the morphodynamics of the outer bar could be related to offshore wave conditions, the inner-bar morphodynamics were largely governed by the state of the outer bar. Moreover, the terrace edge of the dominantly shore-attached inner bar contained an alongshore rhythmicity, contrasting with shore-attached terraces in single-bar systems, which are mostly alongshore uniform. This implies some sort of morphological coupling at the site studied here, further discussed in the next section.

3 Sandbar coupling

3.1 Observations

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-organisation 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- organisation at the scale of the individual bar and the absence of interaction between sandbars. Other observations, summarised 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. Ruessink et al. (2007a), for example, found that the inner bar increasingly coupled to the outer-bar shape as the outer bar became more crescentic and migrated onshore, i.e. during a downstate transition of the outer bar. Coupling examples (Fig. 4) include the systematic occurrence of two inner-bar rip channels within one outer-bar crescent (Castelle et al., 2007; Fig. 4d), that of seaward perturbations in the inner bar facing outer-bar horns (a 180°, or out-of-phase relationship; Van Enckevort and Wijnberg, 1999; Fig. 4a), and that of shoreward perturbations in the inner bar facing outer-bar horns (a 0°, or in-phase relationship; Bowman and Goldsmith, 1983; Castelle et al., 2007; Fig. 4c). The out-of-phase relationship is reminiscent of the commonly observed relationship between inner-bar patterns and shoreline rhythms (Sonu, 1973; Orzech et al., 2011; Fig. 4b). Additionally, Ruessink et al. (2007a) and Quartel (2009) found coupled sandbar patterns with gradual phase changes (ranging from 0° to 180°), thought to be related to the persistent non-zero angle of wave incidence and larger alongshore migration rates of the subtidal bar with respect to the inner bar, respectively.

The aforementioned field observations of sandbar coupling were either based on sporadic observations (e.g., Bowman and Goldsmith, 1983; Castelle et al., 2007) or a short single event (e.g., Ruessink et al., 2007a). Although this previous work has provided clear examples of the phenomenon of sandbar coupling, the frequency or predominance of either of the coupling patterns remains unclear. As a first step towards understanding when and how often certain coupling types develop, we addressed the representativeness of these findings, using the barlines derived from the low-tide time-exposure video images described in Sect. 2 (Price and Ruessink, 2013). We 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, we distinguished 5 coupling types (Fig. 5). 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 (Wright and Short, 1984; 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 characterised by the presence of rip channels. These properties were used to give abbreviated names to the coupling types (Fig. 5): I or O (in-phase or out-of-phase), d or u (downstate or upstate) and t or r (terraced or with rips). By far the most common coupling type at the Gold Coast 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 (Fig. 2, and to the right in Fig. 5a).

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 summarised in Fig. 6, a large fraction of wave breaking over the outer bar leads to out-of-phase coupled sandbars (Fig. 6a). 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 (Fig. 6b). Figure 7 summarises 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 two coupling types explored in Castelle et al. (2010a), under shore-normal wave incidence, correspond to Odr (Fig. 6a) and Idr (Fig. 6b). The predominance of the Idt coupling type is related to the fairly large waves that persistently arrive with a large angle of incidence (30°). We hypothesised that such wave conditions drive a meandering alongshore current (Sonu, 1972; MacMahan et al., 2010) 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 Sect. 2); the outer-bar horns separate from the outer bar to become part of the inner bar (similar to Almar et al., 2010), resulting in an alongshore variable inner terrace, the upstate coupling type Out. If the straightening persists, both bars become alongshore uniform with alongshore continuous trough. 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 Fig. 6b).

In a follow-up study, Castelle et al. (2010b) demonstrated that self-organisation 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-organisational processes alone. They further demonstrated that the relative importance of self-organisation and morphological coupling changes in favour of the latter with an increase in water depth variability along the outer-bar crest. An analysis of an event during which an Idt coupling type formed, however, indicated that, under oblique wave incidence, it was not necessarily the alongshore depth variation but the alongshore shape of the outer bar which is important for altering the wave- and current field at the inner bar. In the next section, we further discuss our findings on the role of the angle of wave incidence for the development of different coupling types.

3.2 Modelling

Although video observations provide a high-frequency long-term data set of coupled sandbar morphology, numerical models are often used to shed light on the processes underlying the observed morphodynamics. So far, numerical studies of sandbar morphology have largely focussed on single-barred beaches (e.g., Ranasinghe et al., 2004; Reniers et al., 2004; Garnier et al., 2006; Tiessen et al., 2011). The few existing numerical studies of double sandbar systems have mainly focussed on the initial development and subsequent evolution of crescentic patterns, either using linear stability analysis (e.g., Klein and Schuttelaars, 2006; Garnier et al., 2008; Coco and Calvete, 2009; Brivois et al., 2012), nonlinear depth-averaged models (Klein and Schuttelaars, 2006; Smit et al., 2008, 2012; Thiébot et al., 2012), or quasi-three-dimensional models

(Drønen and Deigaard, 2007). Whereas the simulations of Castelle et al. (2010a, b) were performed for shore-normal wave incidence only, Thiébot et al. (2012) performed numerical simulations for a large range of wave angles over initially alongshore-uniform sandbars. For slightly obliquely incident waves (10° and 15° with respect to shore normal at 8 m waterdepth), they found that initially the inner bar did not develop any alongshore variability due to the large alongshore current. However, when the outer bar started to develop alongshore variability, the alongshore current and the incoming wave field at the inner bar became perturbed, leading to the development of inner-bar features with an alongshore spacing similar to that of the outer-bar horns.

Building upon the hypotheses from Castelle et al. (2010a) for shore-normal wave incidence and the video observations from the Gold Coast, we applied the non-linear 2DH numerical model of Castelle et al. (2010a) to explore why different angles of wave incidence lead to the development of different coupling types. In contrast to earlier work, we drove the model with realistic bathymetric data, which were derived from the video observations using an assimilation model (Van Dongeren et al., 2008). We extracted the boundary conditions for the simulations from a representative 4 day period during which the development of an Idt coupling type was observed in time-exposure video images. Subsequently, 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°, with an initially crescentic outer bar (see Price et al., 2013, for details).

Figure 8 shows the flow pattern along the inner bar for all θ (in 15 m depth) simulations after 2 days of simulation. Here, the grey scaling indicates the strength of the rotational nature of the flow, termed the swirling strength, 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 9 shows the depth perturbations along the inner bar after 2 days of simulation. The most pronounced depth perturbations are found for the simulations with $\theta = 7^{\circ}$, which are relatively deep and narrow. As the flow is still rotational (see Fig. 8), these negative perturbations correspond to rip channels. For larger angles, the negative depth perturbations decrease and become increasingly wider. Toward $\theta = 20^{\circ}$, the depth perturbations have hardly developed at all. When we examine the simulations for $\theta = 10$–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 $\theta < 10^{\circ}$, 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, Figs. 8 and 9 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.

It is somewhat surprising that the most pronounced rip channels are found for the simulations with θ around 7° (Fig. 9), as previous modelling exercises of single bar systems (e.g., Castelle and Ruessink, 2011) found that rip channels were more pronounced when formed during shore-normal wave incidence. Also notice that the depth perturbations are located further to the left (downdrift) for larger angles of wave incidence. These findings may both be explained through the combination of the increased magnitude of the alongshore current on the one hand, and the alongshore migration and evolution of the outer bar (the morphological template for the inner bar) on the other hand (indicated by the black dots in Figs. 8 and 9a and b). Figure 9c shows that for small angles of wave incidence (up to $\theta = 7^{\circ}$), the alongshore variability of the outer bar increases with respect to the initial alongshore variability within the 2 day simulation period, whereas the outer bar becomes more alongshore uniform for larger angles of wave incidence ($\theta > 7^{\circ}$), corresponding with our observations (see Sect. 2; Price and

Ruessink, 2011). Although the inner-bar depth perturbations follow the alongshore migration of the outer-bar horns at first, the straightening of the outer bar reduces the effect of the outer-bar morphological template on the inner-bar flow pattern, inhibiting the further development of inner-bar features as the flow pattern becomes alongshore uniform. The numerical model study of Garnier et al. (2013) also stresses the effect of wave obliquity and the associated meandering current pattern 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 Fig. 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 (Fig. 3, $\theta \approx 30°$).

4 Conclusions and perspectives

To summarise, the individual sandbars in a double-barred system should not be studied as independent features, but, instead, the interaction within the composite sandbar system should be taken into account. Coupling is an inherent property of the double sandbar system studied here, as the alongshore variability in the inner bar is coupled to that in the outer bar for some 40 % of the approximately 9 yr study period. Accordingly, the inner bar predominantly exists as a shore-attached terrace with a wavy terrace edge, a type of morphology not found in single-bar systems. Coupling is predominant when the outer bar is alongshore variable, both in position and depth, except for excessively large offshore angles of incidence (here, $\gtrsim 30°$) or wave heights (here, $\gtrsim 2$ m) leading to outer-bar straightening and sandbar de-coupling. In addition to offshore wave height and depth variation along the outer bar, the offshore angle of wave incidence is crucial to the type of coupling that emerges. It strongly controls the type of flow pattern over the inner bar, with a change from cell-circulation patterns for approximately shore-normal waves to an alongshore meandering current as the angle increases to 10–20°.

The latter type of currents lead to the development of the coupling type dominating the present data set – the in-phase coupling with an alongshore offset, Idt.

Although the results presented herein were based on frequent (daily) and long-term (over 9 yr) observations from the Gold Coast, Australia, it remains unknown to what extent the observed behaviour represents the behaviour of other double-barred beaches. Further work is necessary to test the generality of our findings. The obtained results and the developed and applied methodology provide a framework for studying and describing similar data sets of multiple sandbar systems. In general, we expect intersite variability to arise from differences in sandbar mobility, which, in turn, is ascribed to sandbar volume, grain size, bottom slope, tidal range, and wave climate (e.g., see Wright and Short, 1984; Masselink and Short, 1993; Shand et al., 1999). More generally, as also suggested by Pape et al. (2010), intersite differences in sandbar behaviour are expected to depend on the ratio between the response time of a sandbar and the variability of the wave climate. Besides identifying the role of these potential variables through intersite comparison, numerical modelling becomes essential in testing the concepts formed. For example, a numerical model with different initial inner-bar morphologies, and time-variant wave forcing could shed light on this aspect of morphological coupling behaviour (see also Drønen and Deigaard, 2007; Garnier et al., 2008; Castelle and Ruessink, 2011; Tiessen et al., 2011; Smit et al., 2012). Moreover, from this, it would be interesting to assess changes in the ratio between self-organisation processes and outer-bar forced development of the inner bar (see also Castelle et al., 2010b).

Bathymetric surveys of crescentic sandbar systems are scarce. Modelling the finite-amplitude behaviour of nearshore bars, however, requires correct estimates of the initial bathymetric state. Herein, we used the assimilation model of Van Dongeren et al. (2008) to estimate depth variations from the video images. The intensity of the breaker zone obtained from the time-exposure images was the only source of input for the assimilation model, and proved to give uncertainties as to the high-intensity areas represented. Although previous work has been devoted to unravel how the observed foam relates to the e.g. roller dissipation (Aarninkhof and Ruessink, 2004; Alexander and Holman, 2004), further investigation into the relation between the observed foam and the measured wave properties on a natural beach would likely benefit the use of this assimilation technique at other sites with scarce amounts of data (see e.g., Birrien et al., 2013). Moreover, it is expected that the inclusion of multiple proxies for the bathymetry, such as wave celerity (e.g., Wilson et al., 2010), wave height (Almar et al., 2012; Gal et al., 2013), and cross-shore wave height profiles from terrestrial laser scanners (Belmont et al., 2007; Blenkinsopp et al., 2012), will enhance the assimilation results (Van Dongeren et al., 2008).

Our study focussed on the alongshore variability of a double sandbar system. Although cross-shore (alongshore-uniform) bar variability was not specifically analysed herein, the observed effect of the outer bar on the inner-bar morphodynamics implicitly includes a cross-shore aspect. This stresses the need to establish an awareness of the state of the composite sandbar system when analysing sandbar behaviour within a multi-barred system, both in the case of alongshore- as cross-shore oriented studies. In fact, recent research (Plant et al., 2006; Splinter et al., 2011) has indicated that alongshore variations in bar crest position affect the alongshore-uniform behaviour. It was found that the horizontal cell-circulation coinciding with the growth of alongshore variability facilitates onshore migration under low-energetic conditions. Analogously, a decrease in three-dimensionality in the outer bar coincides with offshore migration of the outer bar. Although this offshore migration has been suggested to be driven by the increased undertow over the bar during high-energetic events, it remains unknown whether undertow leads to the straightening of the bar. Both our observations (Sect. 2) and modelling results (Sect. 3.2) showed that sandbars do not necessarily straighten during storms, with large wave heights, but that obliquely incident waves play a crucial role in the straightening of the bar through the generation of an alongshore current. Process-based models that focus on cross-shore migration (e.g., Hoefel and Elgar, 2003; Ruessink et al., 2007b, 2012) or on alongshore variability (e.g., Reniers et al., 2004; Calvete et al., 2005; Drønen and Deigaard, 2007; Castelle and Coco, 2012) alone, have become quite mature. The key challenge will be to integrate both model concepts into a single model that can adequately simulate the complete dynamics of double sandbar systems. As such, understanding the alongshore variable sandbar behaviour will lead to improved understanding of cross-shore behaviour.

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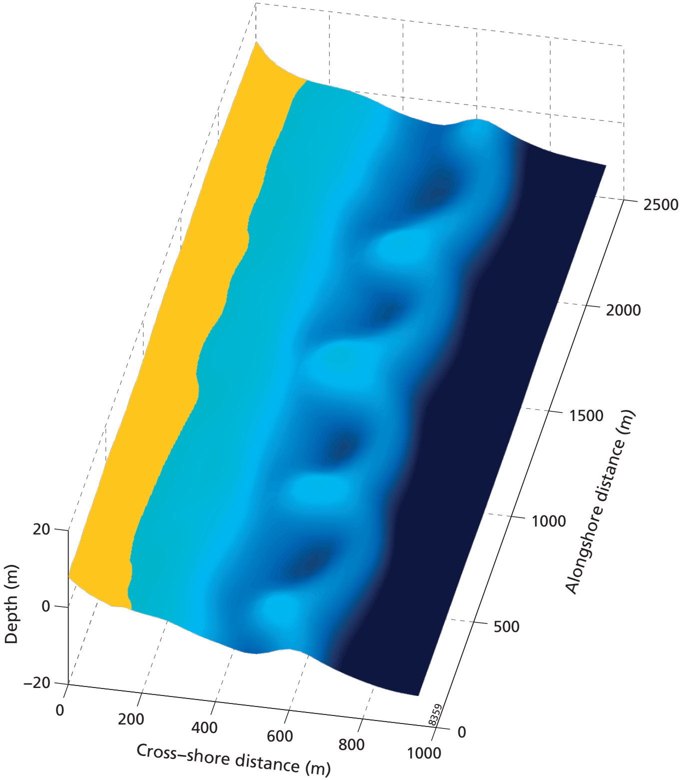

Fig. 1. Bathymetry of a beach with a crescentic sandbar. This bathymetry was measured during the ECORS-Truc Vert '08 field experiment, see Almar et al. (2010).

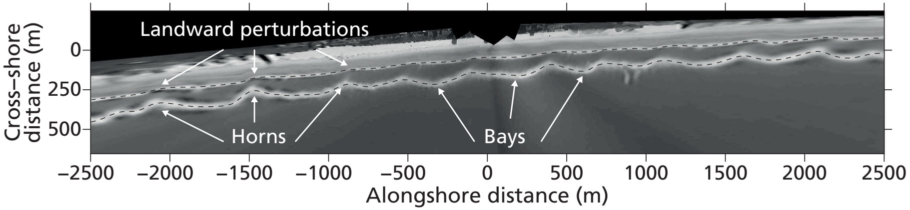

Fig. 2. Example of a time-exposure image from the Gold Coast, Australia, showing the Idt coupling type, with a crescentic outer bar and a terraced inner bar with landward perturbations coupled to the alongshore positions of the outer-bar horns. The dotted lines indicate the video-derived inner and outer barlines. Source: Price et al. (2013).

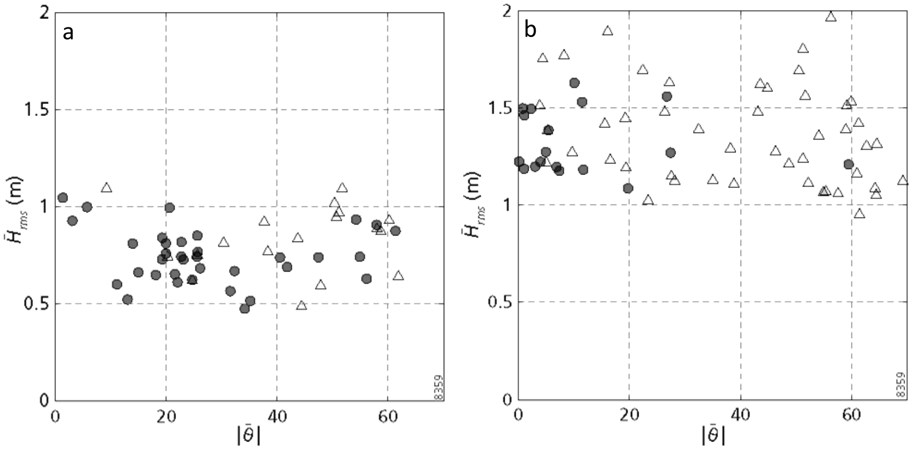

Fig. 3. Mean wave conditions during **(a)** low-energetic and **(b)** moderately-energetic downstate (circles) and upstate (triangles) transitions of the outer bar, showing mean root-mean-square wave height $\bar{H}_{\text{rms}}$ vs. mean absolute angle of wave incidence $|\bar{\theta}|$. A downstate transition corresponds to the further development of rip channels, an upstate transition to a sandbar straightening. Adapted from: Price and Ruessink (2011).

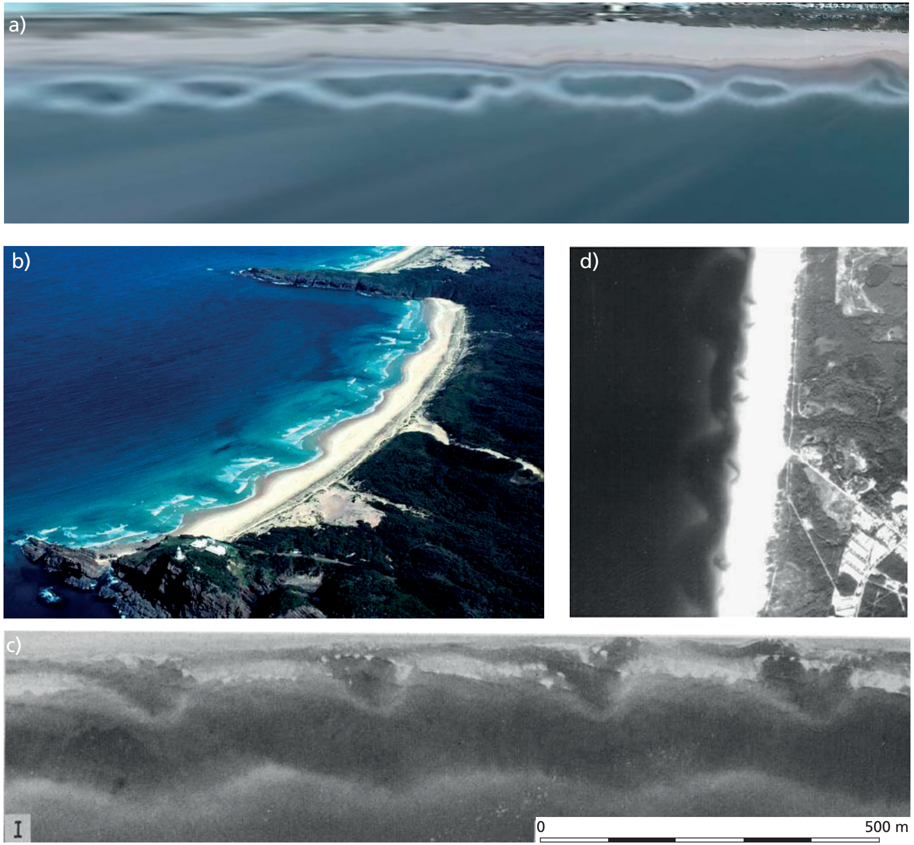

Fig. 4. Examples of coupled morphology, showing **(a)** out-of-phase (180°) coupled sandbars, **(b)** out-of-phase coupling between sandbar and shoreline (courtesy of A.D. Short), **(c)** in-phase (0°) coupled sandbars (taken from Bowman and Goldsmith, 1983), and **(d)** two inner-bar rip channels for each single outer-bar bay (taken from Castelle et al., 2007).

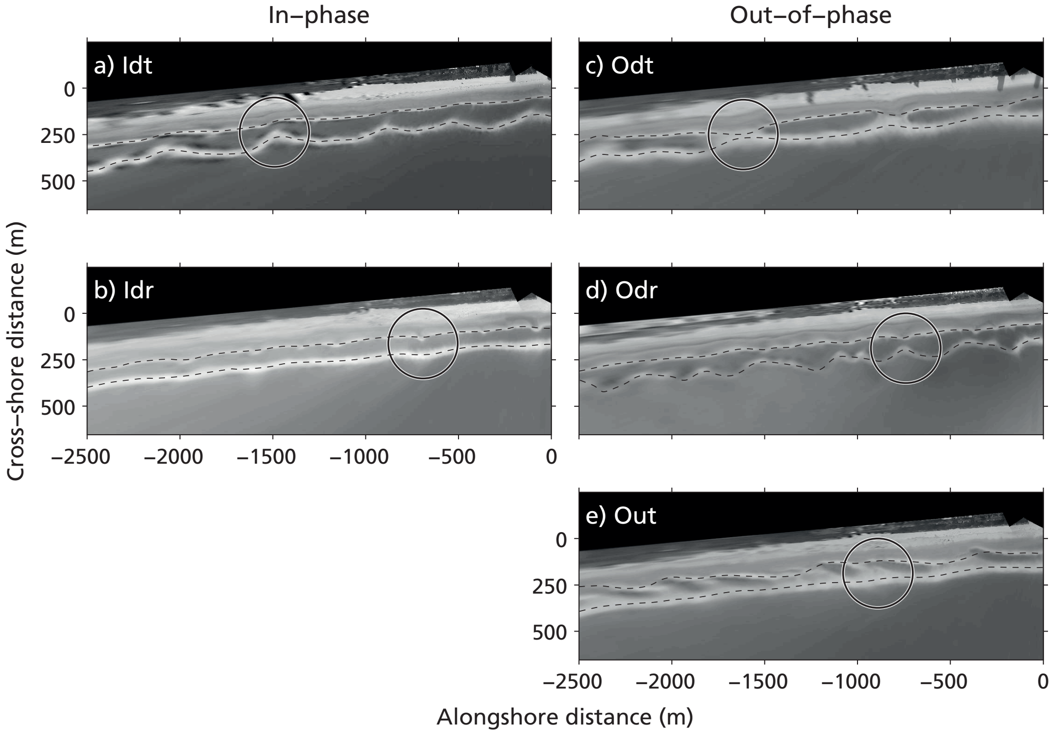

Fig. 5. Examples of observed types of morphological coupling between the inner and outer barlines; low-tide time-exposure planview images of in-phase images with **(a)** an inner terrace and **(b)** inner rips, out-of-phase coupling with **(c)** an inner terrace and **(d)** inner rips in downstate direction, 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).

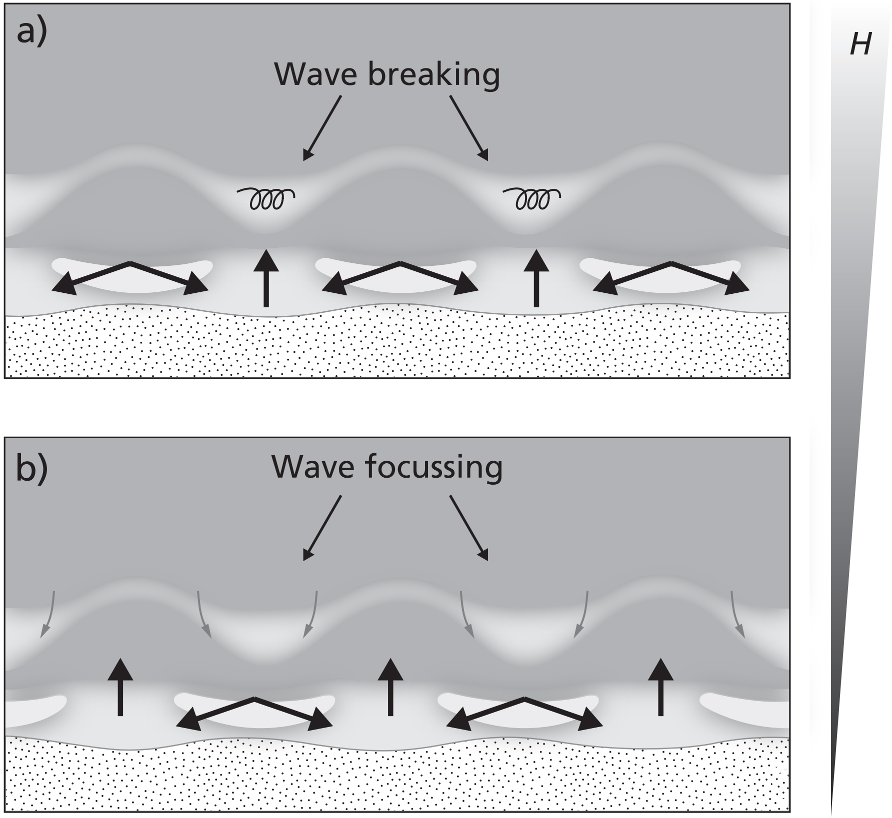

Fig. 6. Coupling patterns found by Castelle et al. (2010a), showing **(a)** out-of-phase coupling and **(b)** in-phase coupling, depending on the wave height *H*. The thick black arrows indicate the associate flow patterns, whereas the gray arrows indicate wave refraction.

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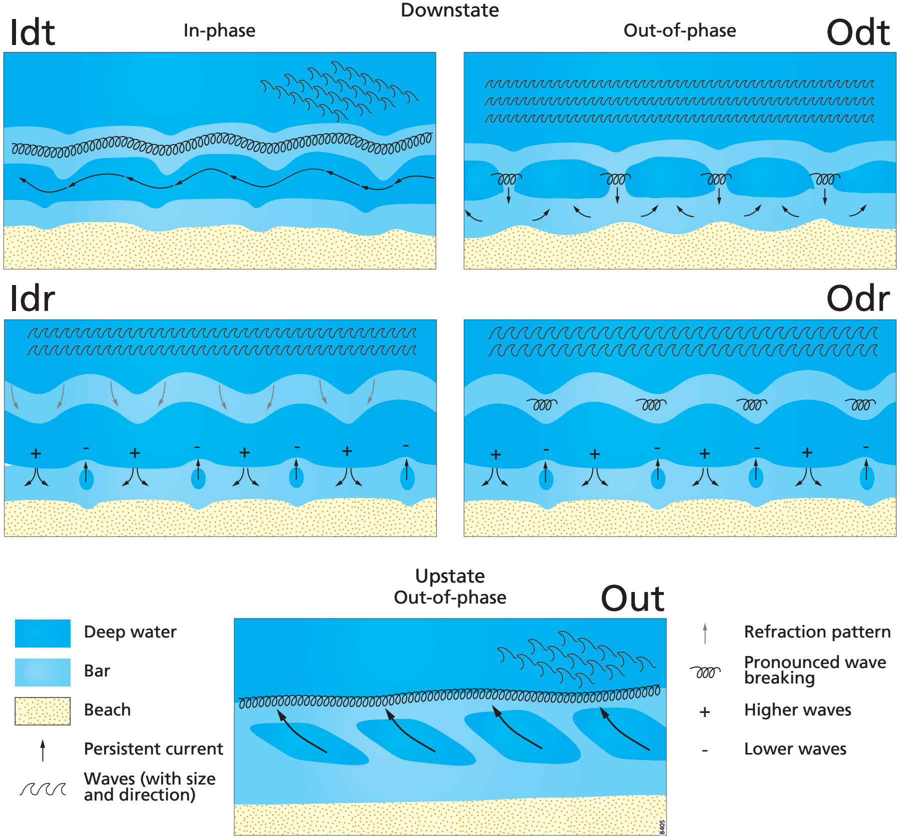

Fig. 7. Conceptual model of the development of different coupling types. Source: Price and Ruessink (2013).

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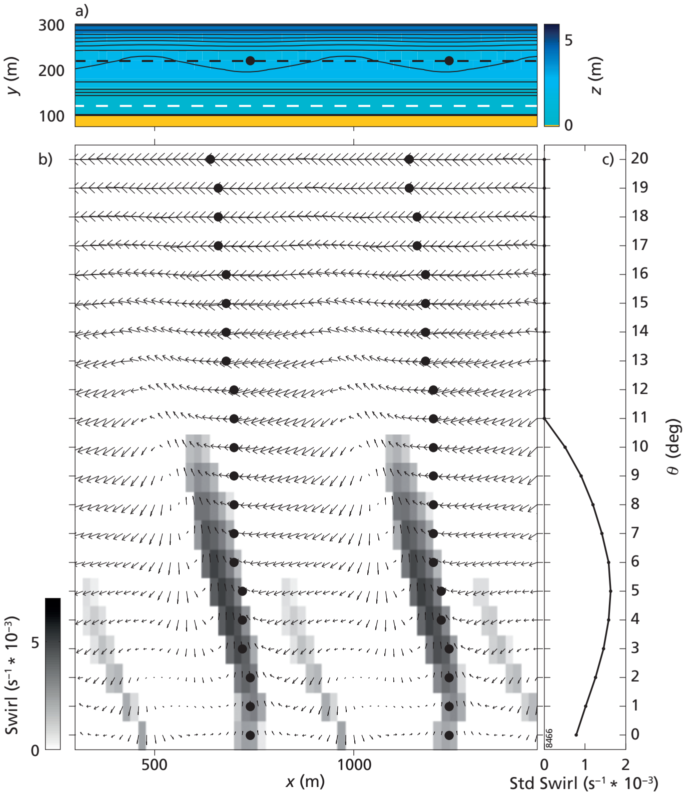

Fig. 8. Model results, showing **(a)** the initial bathymetry, with isobaths (0.5 m intervals) contoured in the background, **(b)** flow velocity $\boldsymbol{U}$ (arrows) and swirling strength (shaded) along the inner bar at $y = 120$ m for all simulations after 2 days of simulation, and **(c)** the corresponding standard deviation of the swirling strength along the inner bar at $y = 120$ m. The black dots in **(a)** and **(b)** indicate the alongshore positions of the outer-bar horns along $y = 220$ 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. (2013).

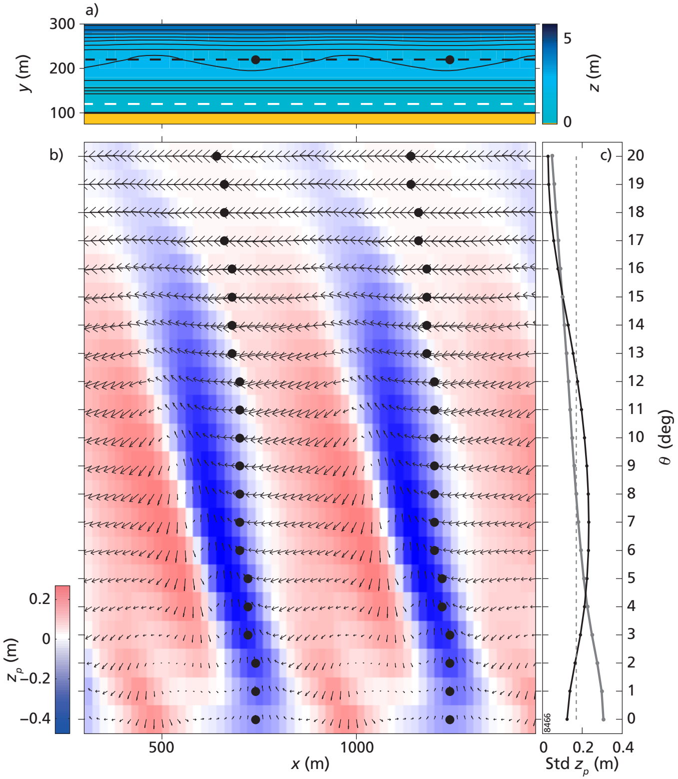

Fig. 9. Model results, showing **(a)** the initial bathymetry, with isobaths (0.5 m intervals) contoured in the background, **(b)** flow velocity ***U*** (arrows) and depth perturbations z_p (colour) along the inner bar at $y = 120$ m (white dashed line in **(a)** for all simulations after 2 days of simulation. **(c)** depicts the alongshore standard deviation of z_p along the inner bar at $y = 120$ m (black) and the outer bar at $y = 220$ m (grey), and the initial standard deviation of z_p along the outer bar at $y = 220$ m (dashed). The black dots in **(a)** and **(b)** indicate the alongshore positions of the outer-bar horns along $y = 220$ m. Source: Price et al. (2013).

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