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Observations of shoreline–sandbar coupling on an embayed beach

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ABSTRACT

We analyse a seven-year dataset (1999–2005) of shoreline and sandbar variations derived from video observations at the embayed Tairua Beach, New Zealand, to explore sandbar–shoreline coupling and to determine how this coupling is related to alongshore-averaged sandbar–shoreline separation and beach rotation. Our results quantify the coupling between the sandbar and the shoreline which is directly related to the reduced separation between the sandbar and the shoreline. Using a simple predictive shoreline model, we show that this behaviour is related to the energy of the incoming waves. Our observations are obtained from a headland-enclosed beach and show aspects of the morphological state that relate to the existence of headlands that are not considered in the Wright and Short beach state classification. Both the sandbar and shoreline at Tairua Beach rotate relatively quickly (<1 month) during the winter storm events, when the storms are accompanied by strong alongshore components, gradually returning during the summer months. The sandbar–shoreline coupling length scale is controlled by this rotation, with large wavelengths occurring when the sandbar is strongly rotated.

1. Introduction

Wright and Short (1984), inspired by the vast variability in their observations of beach morphology in Australia, outlined a framework of beach states which, together with the earlier work of Sonu (1973), has guided subsequent thinking on nearshore pattern development. Their observations showed six discrete states, ranging from the longshore uniform two-dimensional (2D) dissipative state during relatively higher wave energy conditions, through the increasingly three-dimensional (3D) forms which accompany relatively lower wave energy 'intermediate' beach conditions, to the 2D reflective state associated with prolonged periods of low-energy waves. A key element of the original Wright and Short classification in these intermediate states was the separation between sandbar and shoreline, and the degree to which the shoreline pattern reflects the sandbar patterning, such as the mirroring of rip-current embayments and the troughs of crescentic sandbars. Sonu (1973) defined both 180° phase coupling where the embayments occur in the crescentic bar bays (which extend seaward), and 0° phase coupling where the horns of the crescentic bars lie inside the shoreline embayments (see also Castelle et al., 2010, their Fig. 2A and B).

With the advent of video imagery as a technique for quantifying sandbar variations (Lippmann and Holman, 1989), the existence of these beach states has been well substantiated at sites globally, ranging, for example, from the dissipative beaches of Wanganui, New Zealand (Shand et al., 2001), to the more intermediate conditions of Palm Beach and Surfer's Paradise, Australia (Ranasinghe et al., 2004b; Holman et al., 2006; Price and Ruessink, 2011) and Duck, U.S.A. (Lippmann and Holman, 1990). It is clear from these studies that a beach changes states in response to both episodic storms and seasonal wave climate variations, where the movement of the sandbar offshore during storms is accompanied by quick 'up-state' transitions to a more continuous longshore trough (Van Enckevort et al., 2004). Conversely, 'down-state' transitions in response to lower wave conditions occur more slowly, as the sandbar moves shoreward.

Much of the subsequent work expanding on the Wright and Short observations has concentrated on the variability of sandbars (Lippmann and Holman, 1990) and the associated rip currents. Although early observations suggest a regular sandbar wavelength that scales with wave energy or surf zone width (Shepard et al., 1941; Short and Brander, 1999), the much more detailed and spatially-extensive datasets that are collected using video show that the sandbar patterns can be extremely variable (Van Enckevort and Ruessink, 2003), with crescentic sandbar horns splitting and merging through time as the pattern gradually becomes more regular (Van Enckevort et al., 2004). Also, inner and outer sandbars can exhibit different patterns, with the outer sandbar generally being in a higher energy state than the inner sandbar (Short and Aagaard, 1993; Ruessink et al., 2007; Price and Ruessink, 2011). As wave energy decreases, the outer sandbar moves shoreward so that eventually, the breaking patterns of the outer sandbar increasingly influence the circulation of the inner sandbar, with the end result that

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their patterning becomes coupled. Modelling studies have provided insight into this coupling mechanism, where the outer sandbar acts as a template driving the patterning on the inner sandbar. The relative importance of wave focussing and wave breaking patterns on the outer sandbar determine the strength and phase of the coupling, where wave breaking patterns cause 180° phase coupling (Castelle et al., 2010).

Although sandbar–shoreline coupling is a dominant feature of the classification devised by Wright and Short (1984) and numerous studies (e.g., Sonu, 1973; Coco et al., 2005; Thornton et al., 2007; Quartel, 2009; Price and Ruessink, 2013) indicate that rhythmic sandbar patterns often appear coupled to alongshore shoreline patterns, the vast majority of models treat the sandbar and shoreline separately. In many process-based models for the nearshore zone, the shoreline is simply set as a fixed boundary (Falqués et al., 2000) or modelled separately (Dodd et al., 2008). More recently, some models allow the shoreline to evolve in response to the sandbar, although this was not the primary aim of these studies (Castelle and Ruessink, 2011; Orzech et al., 2011). These models predominantly show a 180° phase coupling. In the field, Thornton et al. (2007) use beach surveys and video imagery to demonstrate that variations to rip currents can cause erosional scarps along the beach at 180° phase coupling. Because their shoreline and sandbar measurements were not simultaneous, they were limited in their ability to quantify the sandbar–shoreline cross-correlation. Also, Coco et al. (2005) use wavelet analysis to investigate sandbar and shoreline cross-correlations using a two-year dataset, and show that the wavelength and phase of the coupling can vary between 0 and 180°, but it was not clear what drove these variations. Moreover, the beach length of their particular study site limited the ability of the wavelet to differentiate between beach states.

Despite their common occurrence (Short and Masselink, 1999), relatively few observations demonstrate the importance of headlands in controlling beach morphology. Gallop et al. (2009) show that large rip currents on embayed beaches can persist for surprisingly long time depending on the scale of the surf zone relative to the intensity and duration of the storm event. Silva et al. (2010) show numerically that a semi-elliptic shaped headland-enclosed beach can drive a persistent rip current exactly at the centre of the beach, and provide photographic evidence of shoreline morphology adjusting to this rip pattern. Castelle and Coco (2012) use numerical simulations of morphological change of an embayed beach and show the persistent development of rip channels at the headland and that their presence can propagate alongshore over the whole embayment. Embayed beaches are known to rotate in response to changes in the alongshore energy flux (Short et al., 2000; Klein et al., 2002; Ranasinghe et al., 2004a; Ojeda and Guillén, 2008; Bryan et al., 2009; Loureiro et al., 2012) or cross-shore sediment exchange processes (Harley et al., 2011). So it is likely that beach rotation will play some role in controlling rip-channel development and the associated sandbar–shoreline patterns.

A number of processes and physical parameters have been hypothesised to affect the coupling between the sandbar and shoreline. First, water depth variability along the crescentic sandbar has been suggested as a key physical parameter steering (Coco et al., 2005; Castelle and Bonneton, 2006; Ruessink et al., 2007) since it controls the degree of alongshore variability in wave height and the resulting circulation patterns near the shoreline. Second, the angle of wave incidence has been hypothesised to affect the phase of the coupling since circulation patterns give rise to meandering currents if the angle with shore normal increases from 0 to a few tens of degrees (Price and Ruessink, 2013); an even larger angle of incidence drives strong longshore currents that destroy sandbar variability and cause the sandbar and the shoreline to decouple. Third, the cross-shore distance between the sandbar and shoreline also affects sandbar–shoreline coupling, as the degree to which the shoreline pattern reflects the sandbar patterning depends on this separation distance (Wright and Short, 1984). However, the development of these coupling patterns and their role in determining the evolution of beach state remains a complicated problem, depending on the interplay between wave transformation, wave breaking, wave-driven currents, and the geometry of the sandbar and shoreline. Quantitative observations regarding the conditions resulting in sandbar–shoreline coupling and the temporal variability therein are therefore needed to inform and advance the theoretical modelling. Moreover, natural beaches do not have infinite domains in the alongshore direction (as assumed by these models), and detailed observations are therefore needed on the role of headlands, which affect the circulation patterns and therefore modify the development of beach state.

Here we examine a 7-year video data base of sandbar and shoreline variations on the embayed beach of Tairua Beach, New Zealand, to explore how the spacing between sandbar and shoreline, and the rotation of these can play a role in controlling the nature and temporal changes in sandbar–shoreline coupling.

2. Methods

2.1. Field site

Tairua Beach, located on the east coast of the Coromandel Peninsula in the North Island of New Zealand (Fig. 1), is an embayed beach constrained at the north end by a promontory (Pumpkin Hill) and an extinct volcano at the south end (Paku Hill). The 1.2 km long beach faces northeast and is mainly exposed to northerly and easterly swells generated in the Southern Pacific Ocean (Bogle et al., 2001). The wave climate is generally moderate and dominated by energetic winter storm events (deep water significant wave height $H_{s0} \approx 4$–6 m) (Gorman et al., 2003a). The tidal range is between 1.2 m (neap) and 2 m (spring) (Bogle et al., 2001).

The beach is classified as an intermediate beach (according to Wright and Short, 1984) characterised by the presence of crescentic sandbar patterns and well-developed rip channels (Coco et al., 2005). The beach face is generally steep ($\approx 6^\circ$) and consists of medium-coarse sand with a median grain size (D_{50}) of 0.6 mm.

2.2. Video analysis

A video-monitoring station was installed on Paku Hill 70.5 m above chart datum as part of the NIWA-based ‘Cam-Era’ network in 1998 (http://www.niwa.co.nz/our-services/online-services/cam-era). The system automatically collects 600 oblique individual images (‘snapshot’, Fig. 2A) over a 15 min period every daylight hour (Bogle et al., 2001). The breaking wave pattern in the instantaneous snapshots is highly variable due to fluctuations in the height of the individual waves and therefore the 600 images are averaged (‘time-exposure’, Fig. 2B) resulting in a statistically stable image of the wave breaking pattern (Lippmann and Holman, 1989). Waves predominantly break on shallows such that the shape and location of the high-intensity areas can be used as a proxy for nearshore morphology (Lippmann and Holman, 1989; Kingston et al., 2000; Van Enckevort and Ruessink, 2001).

The resulting time-exposures were rectified using standard photogrammetric techniques (Heikkila and Silven, 1997) (Fig. 2C) to a plan view on a 0.5 × 0.5 m grid, and were then used to detect the sandbar and shoreline position. The rectified images extend approximately 0.5 km in cross-shore (x) and 1.0 km in alongshore (y) direction. The position of the sandbar crest is assumed to relate to peaks in cross-shore intensity and is detected by using the intensity maximum at each cross-shore location. In order to minimise noise a second-order polynomial was fitted to each cross-shore transect and this line was used to detect the maximum at subgrid level. The shoreline position was detected using the algorithm of Smith and Bryan (2007) based on gradients in colour intensity at the water-to-land interface. Fig. 3 gives examples of detected sandbar–shoreline configurations showing 0° (Fig. 3C) and 180° coupling (Fig. 3D).