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Water-level controls on macro-tidal rip currents ☆

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ABSTRACT

Field measurements and numerical modelling have been used to investigate the water-level control of rip current dynamics on a macro-tidal beach. Field data collected over 32 complete tidal cycles, spanning a range of wave and tide conditions, demonstrate that rip current strength and behaviour is modulated at the semi-diurnal frequency by tide-induced changes in the water-level over bar/rip morphology. Peak flow speeds in the rip neck $\langle uv \rangle$ correspond to the time of maximum wave breaking 1.5 h before and after low water.

Alongshore-directed water surface gradients $\partial\eta/\partial y$ were measured along the feeder channel and around the ends of the inter-tidal bar, with head differences $O(0.1\text{ m})$. The numerical model reproduced $\partial\eta/\partial y$ with a good level of skill and showed that $\partial\eta/\partial y$ and $\langle uv \rangle$ increase with the proportion of breaking waves Q_b over the inter-tidal bar; but $\langle uv \rangle$ was maximised during peak Q_b, maximum $\partial\eta/\partial y$ occurred when wave breaking moved offshore to the sub-tidal bar and Q_b was reduced. Around low water, the forcing of the rip current by the alongshore pressure-driven feeder current was reduced by the decrease in Q_b over the bar and feeder regions, but an offshore flow through the rip channel was maintained by a localised intensification of $\partial\eta/\partial y$ around the ends of the inter-tidal bar.

1. Introduction

Studies of rip currents in energetic macro-tidal environments have been limited (e.g. Bruneau et al., 2009; Austin et al., 2010), but have identified the strong tidal modulation of rip current speed and activity. Macro-tidal rip currents are typically associated with extensive, well-developed 3D morphology located around the spring low-tide limit, where there is sufficient tidal stationarity to allow large length-scale bar/trough systems to develop (Masselink and Short, 1993; Scott et al., 2011). The majority of previous studies have focused on micro-tidal environments where the length-scale of the bed perturbations is relatively small (e.g. McKenzie, 1958; MacMahan et al., 2008).

Large bathymetric non-uniformities lead to large spatial gradients in the depth-induced transformation of short waves across the nearshore. Radiation stresses are forced by this short wave transformation (Bowen, 1969) and during wave breaking energy is also transferred to the roller, which becomes an additional source of radiation stress (Deigaard, 1993). The set-up gradients within the surf zone are balanced by the formation of pressure gradient forces, leading to significant pressure-driven currents (e.g. Haas et al., 2003). Haller et al. (2002) analysed the alongshore momentum balance during a set of laboratory experiments and demonstrated that the magnitude of the alongshore rip feeder current was controlled by the balance between the alongshore pressure gradient force generated by high set-up over the bar crests and the opposing radiation stress gradient generated by larger waves propagating into the rip channel. The region of maximum feeder strength was also shifted into the trough landwards of the inter-tidal bar. These observations complement those of Nielsen et al. (2001), who measured the total water-level over-height landward of the bar driving the alongshore feeder channel.

Rapid changes in the water level in macro-tidal environments also provide a significant temporal control on rip current activity. The control is twofold: (1) changes in water level modulate the expression of the morphology (Castelle et al., 2006; Austin et al., 2010); and (2) result in limited stationarity across the nearshore and hence the rapid cross-shore translation of the surf zone. These two processes combine, to effectively switch the rip currents on and off several hours before and after low water, respectively, by controlling the spatial pattern of wave energy dissipation and thus the formation of the pressure-driven currents.

When bar/rip morphology is well-developed, rip flows become increasingly channelised by the morphology around low water (Brander, 1999; Austin et al., 2010). The emergence of the bar crests, over which waves are breaking, probably reduces the

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pressure-driven alongshore feeder current forcing of the rip currents. Significantly, although rip flows were reduced during these periods, they did not stop. One of the key observations of both Brander (1999) and Austin et al. (2010) was that water draining directly from the ends of the emergent inter-tidal bars appeared to be the main forcing for the rip currents at this extremely low stage of the tide; however, this drainage was not quantified.

The limited tidal stationarity of macro-tidal beaches introduces significant challenges to making field measurements. Arrays of sensors deployed across the complex bar/rip morphology dry-out at different times and it becomes difficult to obtain a complete synoptic overview of the rip circulation and forcing when water depths are very shallow. When combined with field observations, numerical modelling becomes a powerful tool to obtain additional information across the very shallow inter-tidal beachface. Several recent studies have used depth-averaged modelling approaches based on field measurements to investigate rip current hydrodynamics (e.g. Castelle et al., 2006; Bruneau et al., 2011). These studies have demonstrated that these models can reproduce wave-driven rip current circulation forced by wave groups (Reniers et al., 2006; Austin et al., 2013) or shear instabilities (Haller and Dalrymple, 2001).

The purpose of this paper is to investigate the dynamics of rip current flows on a macro-tidal beach around the period of dominant rip activity at low water. We hypothesise that the rip currents are forced by a combination of the wave dissipation-induced radiation stress gradient and locally generated water surface gradients around the terminal ends of the inter-tidal sandbars. We use Eulerian and Lagrangian field observations collected around well-developed low tide bar/rip morphology during a period of large spring tides and moderate wave conditions to quantify the rip current flow and forcing. The field data is augmented by a 2D depth-averaged wave/flow model, which is used to quantify the nearshore distribution of short-wave dissipation and the presence of alongshore water surface gradients.

2. Methodology

2.1. Study site

During October 2011 a 16-day field experiment was conducted at Perranporth beach, Cornwall, UK over a spring–neap–spring tidal cycle (Fig. 1). Perranporth is a macro-tidal beach with a semi-diurnal tidal regime and a mean spring range of 6.3 m. It is classified as a low tide bar/rip beach (Scott et al., 2011) and thus exhibits a pronounced inter-tidal bar/rip morphology around the Mean Low Water Spring (MLWS) region and a sub-tidal bar, which vary on seasonal and storm-event timescale. The intertidal beach is relatively flat ($\tan\beta = 0.015$–0.025) and the beach is composed of medium quartz sand ($D_{50} = 0.34$ mm). The beach faces west–north-west and is predominantly exposed to Atlantic swell, but also receives locally generated wind waves (typically from the north). A directional wave rider (DWR) buoy is located close inshore in approximately 13 m water depth, and reported an annual average significant wave height and a peak period of $H_s = 1.4$ m and $T_p = 10.5$ s, respectively, between 2006 and 2012.

2.2. Field experiment

In situ instrument rig arrays were deployed around the MLWS shoreline region to record water level, wave height and flow velocity across the inter-tidal bar, feeder and rip channels (Fig. 1). Two instrument arrays were deployed. The first was an array of three rigs over the intertidal bar (R1, R2 and R4), each mounting a pair of bi-directional miniature electromagnetic current meters (EMCM) and a high-precision pressure transducer (PT). The second array was orientated across the feeder and rip channel with two rigs along the feeder channel (R5 and R6), each mounting a 3D-Acoustic Doppler Velocimeter (ADV) and a PT, and two rigs (R7 and R8) in the rip channel, each also mounting a 3D-ADV and a PT. Four additional bottom-mounted self-recording PT's were deployed around the bar/rip region and a further two were deployed $\sim$500 m offshore to record the wave conditions input to the beachface. The beachface PT's were buried $\sim$0.25 m to measure hydrostatic pressure and avoid contamination of the water-level signal by the dynamic pressure variation (i.e. accelerating/decelerating flows reducing/enhancing pressure). All of the instrument rigs were self-recording and sampled at 4 Hz. This instrument configuration was designed to maximise the spatial coverage over the bar/rip system and data were sampled over a total of 33 complete tidal cycles.

Fifteen GPS-tracked surf-zone drifters were used to record the Lagrangian currents over the bar/rip system. The drifters were of a robust design modified from that of Schmit et al. (2003), Spydell et al. (2007), and MacMahan et al. (2009), and were modular in

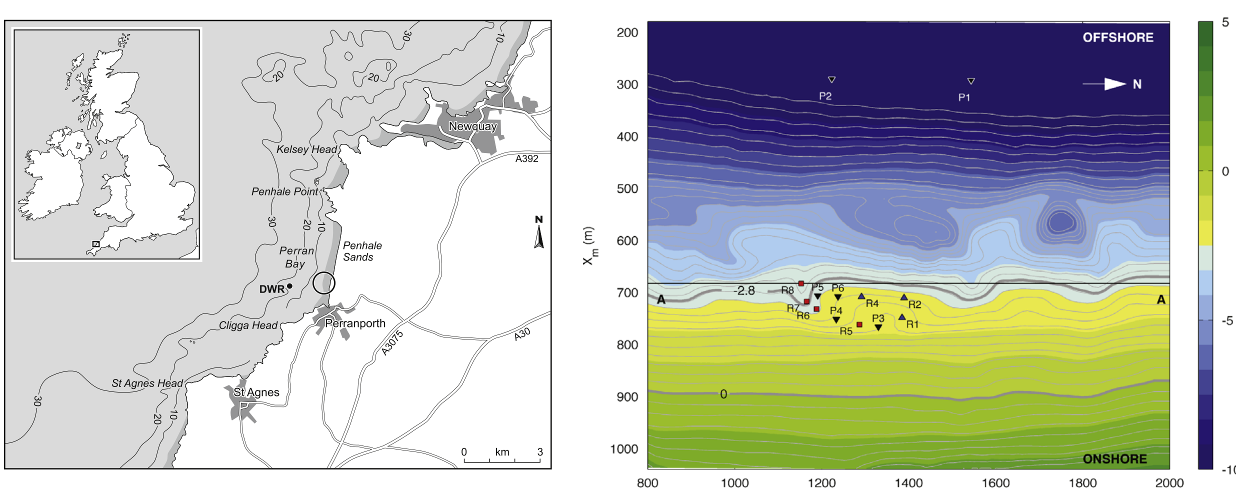

Fig. 1. (Left) Location map of Perranporth indicating the experimental region (circled) and the nearshore directional wave-rider buoy (DWR). (Right) Perranporth bathymetry and instrument locations transformed onto the XBeach model grid. Shading indicates bottom elevation relative to Ordnance Datum Newlyn (ODN) and is contoured at 0.5 m intervals. Heavy contours plot the MLWS and MSL elevations. Alongshore transect A–A is indicated.