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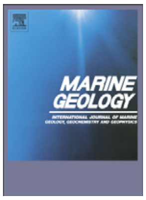

Wave breaking patterns control rip current flow regimes and surfzone retention

Sebastian Pitman [a,*], Shari L. Gallop [a,b], Ivan D. Haigh [a], Gerd Masselink [c], Roshanka Ranasinghe [d,e,f]

[a] Ocean and Earth Science, National Oceanography Centre, University of Southampton, UK
[b] Department of Environmental Sciences, Macquarie University, Australia
[c] School of Marine Science and Engineering, Plymouth University, UK
[d] UNESCO-IHE, Deltares, Delft, The Netherlands
[e] University of Queensland, Australia
[f] Water Engineering and Management, Faculty of Engineering Technology, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands

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ABSTRACT

Recent research into rip currents has revealed the existence of multiple circulation patterns, meaning that no single escape strategy is appropriate in all situations. Rip circulation is influenced by surfzone morphology, which can be inferred from wave breaking patterns in video imagery. Wave breaking often occurs over the bars adjacent to the rip channel, with little breaking over the seaward end of the rip. However, under varying wave and tide conditions, breaking can also occur at the seaward extent of rip channels. Here, we use this difference as a novel wave dissipation parameter to classify a rip channel as either 'open' or 'closed' in terms of rip-head wave breaking. A 4-day field study provided Lagrangian rip current data at a macrotidal, dissipative beach monitored by a coastal imaging system. Using this new parameter, rip channels that were identified as closed exhibited a 31% increase in current speeds and 43% increase in horizontal vorticity compared to open channels. The transition between open and closed channels occurred over a single tidal cycle, which altered surfzone retention rates. Closed channels promoted surfzone retention, with <25% of drifters exiting the surfzone. In comparison, open channels were more conducive to exchange, with exit rates up to 91%. Analysis of the Royal National Lifeboat Institution lifeguard rip incident database showed that open rips were disproportionately represented in the occurrence of rescue events, and calculated here to be twice as dangerous as closed rips. The use of this new open/closed parameter could be used by surf lifesaving organisations, and may have implications for the cross-shore exchange of sediment and pollutants.

1. Introduction

Rip currents (rips) are hazardous offshore flows in the surfzone of beaches worldwide, with typical velocities of 0.5–0.8 m s^{-1}, and can exceptionally reach 2 m s^{-1} (MacMahan et al., 2006). Rips are seen as key drivers of cross-shore shore sediment transport (Aagard et al., 1997), and have been observed to move significant amounts of sediment offshore to the inner continental shelf (Cook, 1970), with obvious implications for storm erosion and post storm recovery.

Unsuspecting bathers can be transported offshore in these narrow, fast currents, and often require rescue. Consequently, rips present a global problem for recreational beach use; in the U.K., 68% of incidents on beaches patrolled by the Royal National Lifeboat Institution (RNLI) are attributed to rips (Scott et al., 2008). In Australia, rips were a factor in 44% of recorded beach drownings over a seven-year period (Brighton et al., 2013). Recent research has focussed on assessing the effectiveness of various escape strategies for people caught in rips (Miloshis and Stephenson, 2011; McCarroll et al., 2014a, 2015; Castelle et al., 2015; Van Leeuwen et al., 2015). The traditional promoted strategy was (and still is in many places) to swim parallel to the shore (Castelle et al., 2015). This advice is based on the assumption of a 'typical' rip, where the current is directed offshore perpendicular to the shore, and exits the surfzone into deeper water (Shepard et al., 1941), herein referred to as *rip exits*. However, Lagrangian measurement of rips over the last decade (Austin et al., 2009, 2010, 2014; MacMahan et al., 2010; McCarroll et al., 2014b; Scott et al., 2014) have shown that there is a wide variety of rip circulation patterns, including circulatory, and angular flow (i.e., not perpendicular to shore). Under such flows, the 'swim-parallel' strategy may not be appropriate and could even reduce chances of escape (Castelle et al., 2015). The current circulation pattern is therefore of paramount importance when considering the risk posed by rips and the formulation of beach safety advice.

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[*] Corresponding author.
E-mail address: sjp1e13@soton.ac.uk (S. Pitman).

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Rip activation (the establishment of a depth-uniform offshore-directed flow) has been attributed largely to alongshore gradients in the radiation stresses of breaking waves (Longuet-Higgins, 1970), and variations in nearshore bathymetry that induces spatially variable patterns of wave breaking (Bowen, 1969). The requirement for wave breaking on offshore bars is widely accepted as a pre-requisite for topographic rip activation, with increasing intensities of wave breaking creating stronger rip circulations (Sonu, 1972; Dalrymple, 1975; Wright et al., 1979; Aagard et al., 1997; MacMahan et al., 2006). Rip flow is also tidally-modulated, with water level controlling the degree to which waves interact with bathymetry. This interaction transforms wave breaking patterns and varies flow constriction through channels over the tidal cycle (Austin et al., 2010). Maximum rip speeds are generally observed around low tide, when the interaction of breaking waves with the morphology is greatest (Aagard et al., 1997; Brander, 1999; Austin et al., 2010, 2014; McCarroll et al., 2014b; Scott et al., 2014). In macrotidal environments, higher tidal levels can switch off rip circulation entirely as a result of the cessation of wave breaking over the bar (Austin et al., 2014).

The combination of these controls on nearshore circulation create one of two responses in an active rip: 1) rip exit, or 2) recirculation within the surfzone. Previously, the effect of wave breaking patterns on circulation has been opportunistically and qualitatively discussed as a result of field measurement (Scott et al., 2014). However, no quantitative link between breaking patterns and circulation type has been investigated. Therefore, here we hypothesise that an important control on this circulation is whether the rip exhibits an ‘open’ connection to the region offshore of the surfzone (hereafter referred to as the offshore) in terms of wave breaking, or whether wave breaking acts to ‘close’ the rip channel. A rip channel that is ‘closed’ in terms of wave dissipation (i.e., waves are breaking at the seaward edge of the rip, across the rip channel and/or on the rip head bar) may be more likely to exhibit circulatory behaviour, as a result of wave setup in the region of breaking. Conversely, a rip channel that is ‘open’ to the offshore region (i.e., no wave breaking at the seaward edge) may be unhindered by wave breaking processes, and therefore the current may exit the surfzone.

Observational changes in wave breaking have been documented by various researchers; Brander (1999) provided a conceptual model of rip activity based on the Wright and Short (1984) beach state model, and discussed changes in morphology that are inferred from changes in the breaking pattern. Brander (1999) describes downstate change in morphology as a result of decreasing wave conditions, and the associated changes in rip channel configuration. The shift in channel configurations is accompanied by different patterns of wave breaking over the reconfigured bar system. Of particular interest was the longshore bar-trough state proposed, which is akin to an open rip, and the transverse bar rip which exhibits a welded rip head bar, akin to a closed rip described above. Whereas Brander (1999) showed virtual state transitions as a result of wave conditions, the work of Austin et al. (2010) took a similar approach with tidal control. They highlight how lowered water levels produce behaviourally similar results to that of a wide-spread accretion (down-state transition) in the beach state model, maximising bar relief. Quartel (2009) later attempted to classify intertidal rip channels as either open or filled, in terms of sedimentation, rather than wave breaking patterns, which is the focus of the current contribution. Both types were defined as funnel-shaped, where open rip channels showed a shoreward narrow end, with a clear opening through the wave break point to deeper water, similar to the definition of open used here. In contrast, a filled rip channel was an inverse-funnel (wider end towards the shore). A filled rip is said to develop as a result of sediment infilling, whereas a closed channel in terms of wave breaking is the result of lower water levels inducing wave breaking at the offshore extent of a rip channel. Channels were classified from low tide video images, using the visual contrast between dry sand and water or wet sand.

While Brander's (1999) model and the work of Quartel (2009) discussed variability over timescales of *O*(days-weeks), the control exerted by tidal modulation of wave breaking can produce similar transitions over a single tidal cycle (Austin et al., 2014), whereby low tide levels can mimic a down-state transition in beach state. Quantifying these wave breaking patterns using in situ measurements is difficult. However, such patterns can be relatively easily identified using coastal imaging systems, such as Argus (Holman and Stanley, 2007), Cam-Era (Gallop et al., 2011; Blossier et al., 2016), and WavePack (Gal et al., 2014). These cameras typically take high frequency, half-hourly images of the beach and nearshore during daylight hours (Holman and Stanley, 2007). Time exposure (timex) images are the most commonly used output, representing the time-mean of all frames over a sample period, typically 600 images collected at 1 Hz (Guedes et al., 2011). Timex images can reveal persistent processes, such as wave breaking over submerged sand bars (Lippmann and Holman, 1989), which appear as distinct, high-intensity white bands (Lippmann and Holman, 1989, 1990; Plant and Holman, 1998; Kingston et al., 2000); while deeper areas, such as rip channels between sand bars, appear as darker areas (Ranasinghe et al., 1999, 2004; Holman et al., 2006).

Many studies have measured rips in situ (Austin et al., 2009, 2010, 2014; MacMahan et al., 2010; McCarroll et al., 2014b; Scott et al., 2014), and using video imagery (Ranasinghe et al., 1999; Bogle et al., 2001; Whyte et al., 2005; Holman et al., 2006; Turner et al., 2007; Gallop et al., 2009, 2011), but very little research has attempted to combine in situ measurement of rips with video images for quantitative means. One study addressing this previously was Austin et al. (2010), which quantified wave roller dissipation over the sand bar at Perranporth, U.K., and linked the intensity of breaking to rip pulsations. They determined how changes in the intensity of wave dissipation activated the rip, but not how patterns of dissipation influenced circulation pattern, i.e., if a rip is retained within, or exits the surfzone. A possible link between readily observable phenomena, such as wave breaking, and the danger level of prevailing rip currents could have practical benefits. For instance, an indication of whether rip currents are likely to be retained within, or exit, the surfzone based purely on real time video imagery could be very useful to beach safety practitioners, who may elect to increase coverage or patrols on days where rips appear more dangerous in imagery.

The overall aim of the present study is to gain new insights regarding the influence of wave breaking patterns on rip current circulation and therefore the hazard presented to beach users. In this contribution we define a new parameter to classify wave breaking patterns around rip currents. The aim was addressed through two objectives. The primary objective is to quantify the influence of open and closed rips on surfzone exit rate and the second objective is to determine the influence of wave breaking patterns on rip rescue events. To this end, we use an exemplar of an exposed macrotidal, low tide bar/rip beach in southwest England. Data were collected from a single north Cornish beach but are transferable to other exposed sandy beaches with large tidal ranges and low-tide rip morphologies.

2. Field site

Perranporth beach (Fig. 1) is a 3.5-km long beach comprised of medium ($D_{50} \approx 0.3$ mm) sand (Austin et al., 2014). Perranporth is a popular swimming and surf beach, and holiday destination. The beach is patrolled by the RNLI during summer, and some public holiday weekends throughout the year. The beach has a wide (500 m) intertidal area at the southern end, which narrows into a 250 m wide intertidal area to the north. The mean spring tidal range is ~6.3 m (macrotidal) (Austin et al., 2014). The beach faces west-north-west towards the Atlantic and is subject to medium energy conditions with mean offshore significant wave height (H_s) of 1.5 m, maximum wave heights (H_m) of 2.4 m, and peak periods (T_p) of 10.5 s. Research on surfzone currents at Perranporth is well established, through a number of field deployments (Austin et al., 2009, 2010, 2013, 2014; Scott et al., 2014).