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Controls on macrotidal rip current circulation and hazard

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ABSTRACT

Rip currents are strong, narrow seaward-flowing currents in the surf zone and are common on energetic sandy beaches. They are generally associated with distinct beach morphology, comprising nearshore sand bars and channels, and represent a real natural hazard to surf zone users. Rip current circulation is primarily driven by spatial gradients in wave breaking and water levels in the surf zone, which in turn are controlled by beach morphology, offshore wave conditions and tidal level. These factors, which are highly variable over hours (tides), days (waves) and weeks (morphology), also control the rip risk to bathers. However, the precise roles of these different environmental factors in controlling rip dynamics on meso- to macro-tidal beaches are not exactly known and thresholds separating different types of rip circulation and flow strengths, and hence rip risk, have not been quantified. Here, the analysis of 5-year lifeguard incident records from 20 beaches in southwest England showed that high-risk, high-exposure scenarios for bathers occur disproportionately around mean low water on days with low wave height ($H_s < 1$ m), long wave period ($T_p > 10$ s), shore-normal wave approach and light winds (>5 m s^{-1}). Detailed in-situ Lagrangian field measurements of rip currents collected on 23 different days from Perranporth beach, UK identified waves (characterised by H_sT_p) and active morphology (characterised by tidal elevation) as the key controlling factors determining the mode of rip behaviour. Maximum hazard was associated with the combination of maximum rip exits and rip flow speeds. These conditions occurred when H_sT_p was at or just below average values and when those waves were acting on the active morphological template, around mean low water. The thresholds in wave conditions and tidal elevation identified here were effective in discriminating between observed coast-wide high-risk incident events, illustrating that such mass rescue events have a considerable element of environmental control. Because many beaches along the west coast of southwest England are characterised by nearshore bar morphology just below the mean low water level, and are affected by similar wave and tide conditions, the results obtained from this beach are transferable to other locations. The findings of this study may also have implications for other beaches with nearshore bar–rip morphology at specific tidal levels.

1. Introduction

Rip currents are ubiquitous features in energetic surf zones. They can occur on many types of beaches under a variety of wave conditions and tidal levels. A concerted research effort over recent years, significantly aided by technological advances in field instrumentation and computer modelling, has dramatically improved our quantitative understanding of these wave-driven offshore-directed surf zone currents (Brander, 1999; MacMahan et al., 2004; Reniers et al., 2004; MacMahan et al., 2005; Brander and Short,, 2006; Reniers et al., 2006; Bruneau et al., 2009; Austin et al., 2010; MacMahan et al., 2010; Reniers et al., 2010; Bruneau et al., 2011; Austin et al., 2013). Rip currents are generated by alongshore variations in breaking wave heights (Bowen, 1969). Nearshore bathymetric variations on open-coast beaches, due to evolving sandbars and troughs, drive alongshore variation in depth-induced breaking. The resulting 'open-coast beach rip currents' are the most common type globally (MacMahan et al., 2011). The occurrence, scale, strength and behaviour of these rip currents are determined by nearshore and coastal morphology, wave characteristics (height, period and direction), tidal water level and wind (Dalrymple et al., 2011). Rip currents can also occur near rocky outcrops and coastal structures as well as headland-embayed beaches. These rip types are often referred to as topographic and megarip currents and their behaviour can vary significantly from open-coast beach rips. This paper focuses on open-coast beach rip currents driven by wave breaking over nearshore sandbar morphology.

Open-coast beaches not influenced by coastal structures or headlands display a wide variety of rip current shapes that are controlled

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by the beach morphology. The presence of rip currents is most commonly associated with intermediate-type beach morphology (Wright and Short, 1984). The active sandbar morphology often forms semi-rhythmic, shallow shore-connected shoals, incised by deeper rip channels. This longshore non-uniformity is important in determining the flow kinematics of a rip system (Brander and Short, 2001; MacMahan et al., 2006).

Until recently, rip current research has focussed on micro- and mesotidal environments (e.g. Shepard et al., 1941; McKenzie, 1958; Bowen and Inman, 1969; Huntley et al., 1988). Recent studies along the west coasts of France and UK, where mean spring tide ranges (MSR) are 3–8 m, have highlighted the important tidal control on rip current dynamics in macrotidal tidal regions (Castelle et al., 2006; Bruneau et al., 2009; Austin et al., 2010; Scott et al., 2011a).

Rip currents are known to be modulated by tidal level, with decreases in water surface elevation increasing rip current flows to a relative maximum (e.g. Aagaard et al., 1997; Brander, 1999; Brander and Short, 2001; MacMahan et al., 2005, 2006). This modulation has been linked to temporal changes in the expression of the morphological template causing: (1) spatial and temporal variation in the pattern of wave dissipation; and (2) morphological flow constriction (Austin et al., 2010). Brander (1999) presents a conceptual model from a microtidal beach whereby the morphodynamic behaviour of rip currents is placed within the context of the Wright and Short (1984) beach state model. Specifically, down-state accretionary transitions are linked to a decrease in the cross-sectional area of the rip channel and lead to the development of a rip head bar, which constricts flows and modifies the wave dissipation pattern. Field studies by Austin et al. (2010) at Perranporth, UK, a macrotidal (MSR = 6.3 m) low-tide bar/rip (LTBR) beach, show a similar modification of rip flows, but due to the tidal modulation of water levels at semi-diurnal frequencies rather than beach morphological evolution.

Temporal modulation of rip circulation induced by the falling tide level observed by Austin et al. (2010) was considered akin to inner bar state transitions through the rhythmic bar-beach (RBB), RBB-transverse bar/rip (TBR) and TBR-low-tide terrace (LTT) states; as the tide fell, bar relief was maximised, increasing flow channelisation on the inner bar and wave breaking on the outer bar, leading to the modification of rip circulation patterns and behaviour at the semi-diurnal timescale. Further modulation occurs at the spring-neap timescale due to the variation in tidal range from 6 to 3 m, respectively.

Recent field (MacMahan et al., 2008; Austin et al., 2013) and laboratory (Castelle et al., 2010) studies have shown that on both the micro/mesotidal TBR beaches and the meso–macrotidal low-tide bar/rip (LTBR) and low-tide terrace and rip (LTTR) beaches (Masselink and Short, 1993; Castelle et al., 2007; Scott et al., 2011a), rip current circulations commonly form eddy-like cells, largely constrained within the surf zone, with occasional pulses beyond the surf zone, also referred to as 'exits'.

Using GPS-tracked surf zone drifters to measure these rip current circulations, recent studies found that in moderate-energy, micro/mesotidal settings the rip circulation retained the majority of drifters within the surf zone with only 19% (range: 4–28%) of exits. Similar experiments in France and the UK in moderate-energy, meso/macrotidal and double-barred environments found average drifter exits per hour to be 14% and 16%, respectively, but with ranges of 0 to 34% (MacMahan et al., 2010). Reniers et al. (2009) defined an exit parameter (E) based on extensive modelling and field measurements of rip current circulations on single barred beaches, where:

$$E = \frac{X_w}{H_{rms,0} T_{m01}} \tag{1}$$

where X_w is the surf zone width, $H_{rms,0}$ is the root-mean-squared wave height at the offshore boundary and T_{m01} is the mean wave period. Their results indicated that it is important to account for both Stokes drift and very low frequency motions (VLFs), typically O (10 min) time scales, to achieve modelled exit statistics similar to those observed on a microtidal beach.

Through the analysis of multiple surf zone drifter datasets over the full range of tidal regimes MacMahan et al. (2010) suggest that a morphodynamic threshold may exist for cross-shore exchange by rip currents where larger waves (breaking further offshore) induce coherent vortices on the order of surf zone dimensions and which retain material within the surf zone, thus reducing surf zone 'exits'. For lower wave heights, decreased morphodynamic coupling encourages cross- and alongshore exchange, resulting in an increase in surf zone 'exits' until the flow field becomes much less energetic and weak alongshore currents dominate. High-energy, meso- to macrotidal sandy beaches can have multiple bar systems, and Castelle et al. (2007) highlighted the importance of the intermittent morphodynamic coupling between outer and inner bars in controlling rip currents.

The dynamic relationship between morphology and rip current circulation has significant relevance for beach safety. Rip currents can quickly move swimmers spatially to regions of deeper water and/or greater hazard, and have globally been documented as a significant natural hazard (Shepard, 1949; Short and Hogan, 1994; Short, 1999). Recent investigations of beach hazards in the UK, Australia and the United States indicate that rip currents represent the single most significant cause of rescues and fatalities for beach users (Short and Brander,, 1999; Scott et al., 2007, 2008; MacMahan et al., 2011; Scott et al., 2011a; Brighton et al., 2013). Specifically, Scott et al. (2008) noted that 68% of all incidents recorded by the Royal National Lifeboat Institution (RNLI) on UK beaches were due to rips. Furthermore, over 90% of recorded UK rip incidents were shown to occur on beaches with identifiable rip channel morphologies (i.e., LTBR and LTTR). The macrotidal beaches that dominate the UK coast introduce unique tide-related complexities into understanding beach hazards.

Beach hazards, like morphodynamics, vary temporally. Fig. 1 presents a conceptual rip current hazard framework, termed the 'Temporal Hazard Signature' (THS), which describes the key controls on rip hazards in the UK over a range of time scales. (1) *Annual* long-term characteristic beach types, controlled by environmental setting, are linked with varying rip current activity. High energy beach types with dynamic sandbar systems (LTTR and LTBR in the UK) are associated with the highest rip hazard in the UK. (2) *Seasonal* changes in the wave climate, and in turn sand bar morphology, drive associated changes in rip current activity and hazard. (3) *Weekly* variations in rip activity are controlled by lunar (spring/neap) tidal modulation through vertical water level excursion and wave events. Finally, (4) *prevailing* rip dynamics and hazards can vary dramatically from hours to seconds controlled by variability in water level, wave conditions and wind.

Previous rip current hazard research described in Scott et al. (2011b) indicates that there are certain combinations of environmental controls, which are conducive to causing rip-related mass rescue events. In particular, the combination of well-developed low-tide bar/rip morphology and the onset of small-to-medium long-period swell waves and larger tides were observed to be a key factor in driving periods of high rip current risk. This study aims to quantify the dynamics of rip currents within these environments throughout a range of conditions, enabling the identification of the forcing conditions and rip dynamics controlling bathing hazards and high-risk scenarios. This paper will address these aims through a combination of in-depth analysis of rip current incident statistics, field measurements and numerical modelling.

2. Regional setting

2.1. Study region

The datasets presented in this paper were collected along the high-relief, mainly rocky west coasts of Devon and Cornwall in the southwest of England (Fig. 2). The Atlantic southwest coast of England represents a