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Invited review

Rip current types, circulation and hazard

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ABSTRACT

Rip currents are narrow and concentrated seaward-directed flows that extend from close to the shoreline, through the surf zone, and varying distances beyond. Rip currents are ubiquitous on wave-exposed coasts. Each year they cause hundreds of drowning deaths and tens of thousands of rescues on beaches worldwide and are therefore the leading deadly hazard to recreational beach users. The broad definition above masks considerable natural variability in terms of rip current occurrence in time and space, flow characteristics and behaviour. In particular, surf-zone rip currents have long been perceived as narrow flows extending well beyond the breakers, flushing out the surf zone at a high rate ('exit flow' circulation regime), while more recent studies have shown that rip flow patterns can consist of quasi-steady semi-enclosed vortices retaining most of the floating material within the surf zone ('circulatory flow' circulation regime). Building upon a growing body of rip current literature involving numerical modelling and theory together with emergence of dense Lagrangian field measurements, we develop a robust rip current type classification that provides a relevant framework to understand the primary morphological and hydrodynamic parameters controlling surf-zone rip current occurrence and dynamics. Three broad categories of rip current types are described based on the dominant controlling forcing mechanism. Each category is further divided into two types owing to different physical driving mechanisms for a total of six fundamentally different rip current types: hydrodynamically-controlled (1) shear instability rips and (2) flash rips, which are transient in both time and space and occur on alongshore-uniform beaches; bathymetrically-controlled (3) channel rips and (4) focused rips, which occur at relatively fixed locations and are driven by hydrodynamic processes forced by natural alongshore variability of the morphology in both the surf zone and inner shelf zone; and boundary-controlled (5) deflection rips and (6) shadow rips, which flow against rigid lateral boundaries such as natural headlands or anthropogenic structures. For each rip current type, flow response to changes in hydrodynamic and morphologic forcing magnitude is examined in regard to velocity modulation and changes in circulation regime, providing key force-response relationships of rip currents. We also demonstrate that in the real world, rip currents form through a mixture of driving mechanisms and the discrete rip types defined in fact form key elements in a wide and complex spectrum of rip currents on natural beaches. It is anticipated that this rip current type classification will serve as a resource for coastal scientists and non-specialists with an interest in the rip current hazard, and as a platform for future rip current studies. Finally, we suggest some important future research directions highlighting the need for coastal and beach safety communities to collaborate in order to improve rip current education and awareness.

Contents

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1. Introduction

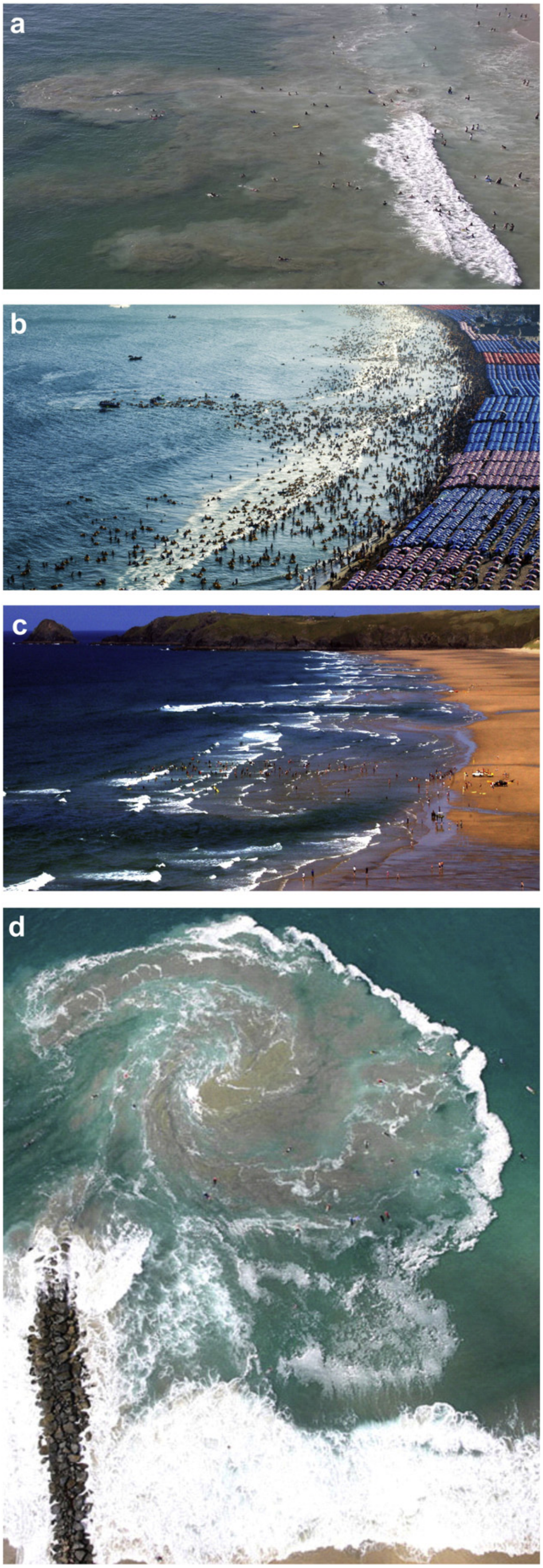
Many global beaches are characterized by the presence of narrow and concentrated seaward flowing rip currents that extend from close to the shoreline, through the surf zone, and varying distances beyond. Rip currents are fundamentally driven by the action of breaking waves (Bowen, 1969) and are therefore found on a range of beach types (Wright and Short, 1984; Lippmann and Holman, 1989; Masselink and Short, 1993; Scott et al., 2011a; Loureiro et al., 2013) along oceanic, sea and lacustrine coasts exposed to different wave climates. It is well established that rip currents are important for the transport and cross-shore mixing of heat, pollutants, nutrients and biological species (Talbot and Bate, 1987; Shanks et al., 2012; Sinnett and Feddersen, 2014). However, rip currents have long been of both scientific and societal interest mostly due to the coastal hazard they represent. Their flow is often sustained over sufficient temporal periods (hours–days) and mean velocities (often >0.5 m/s) enable transport of large volumes of sediment offshore, particularly during storm events (e.g. Cook, 1970; Thornton et al., 2007; Loureiro et al., 2012b, Castelle et al., 2015). This can accentuate localized shoreline and dune erosion making them a threat to shoreline infrastructure and coastal communities. However, arguably the greatest impact that rip currents present to society is through the hazard they represent to beach users who find themselves caught in one (Fig. 1). Indeed, the earliest studies on rip currents (e.g. Davis, 1925; Shepard, 1936) brought attention to the hazard by coining the term 'rip current' in an attempt to differentiate them from the conceptually misleading terms 'undertow' and 'riptide', which were gaining popularity in the public vernacular at the time and are unfortunately still often incorrectly used by the public and media to describe rip currents.

Rip current flows can quickly carry unsuspecting bathers of all swimming abilities (Drozdzewski et al., 2012, 2015) into deeper water (Fig. 1), often against their will, where a combination of exhaustion and panic too often results in a drowning death (Brander et al., 2011). Each year hundreds of people drown and tens of thousands more are rescued from rip currents globally (e.g. Klein et al., 2003; Hartmann, 2006; Gensini and Ashley, 2009; Brewster, 2010; Brighton et al., 2013; Scott et al., 2011b; Arun Kumar and Prasad, 2014; Arozarena et al., 2015; Barlas and Beji, 2015) and it is now well established that they are the primary physical hazard facing recreational bathers on surf beaches worldwide (Brander, 2015; Brander and Scott, 2016).

While the severity of the rip hazard to bathers has been shown to be influenced by various demographic, social, behavioural, knowledge-based and emotional factors (Sherker et al., 2010; Hatfield et al., 2012; Williamson et al., 2012; Caldwell et al., 2013; Woodward et al., 2013, 2015; Brannstrom et al., 2014), in terms of physical factors it is primarily dictated by a combination of rip current flow speed and circulation patterns (Scott et al., 2014). As outlined by Brander and MacMahan (2011), our understanding of rip current flow behaviour has had a strong influence on existing global rip current hazard safety messaging promoted to the public, particularly in terms of self-escape strategies. From this perspective it is therefore useful to consider the historical progression of scientific research and knowledge in relation to both rip current flow and the rip current hazard (Fig. 2).

Fig. 2 presents temporal patterns of rip current related publications in internationally refereed journals based on a detailed search of the literature. A total of 236 publications from 1925 to April 2016 were sourced and the publication list and criterion for their inclusion are provided in Supplementary Material. Publications were coded into five dominant subject themes, some with sub-themes. Some papers (if applicable) were coded with multiple themes. As evident from Fig. 2a, scientific interest in rip currents experienced a relatively slow and modest progression until a marked and rapid increase post-2000 that continues today. In terms of themes, early studies on rip currents were clearly qualitative in nature either providing a descriptive review of existing rip current knowledge or describing different types of rip currents and there is some evidence of increased interest in both areas in recent years (Fig. 2b). There has been a noticeable increase in numerical process-based modelling studies, particularly since 2000, while the number of physical laboratory studies and conceptual empirical based models (e.g. Wright and Short, 1984) have remained relatively low over time (Fig. 2d).

The increase in modelling studies is clearly a reflection of improved computing power and theoretical framework just as the rapid increase in rip current field measurements since 2000 (Fig. 2c) is largely due to technological advances and reduced costs of data gathering equipment (e.g. MacMahan et al., 2005, 2009; Schmidt et al., 2003). This is evident from the gradual temporal increase in Eulerian measurements, which



record rip current flow past a fixed point and typically involve deployment of one or more flowmeters in a rip current system. While Eulerian approaches offer limited spatial coverage, they have been particularly useful in examining and understanding the temporal variability of rip current flow, such as the tidal modulation of rip current velocity and flow pulsing at infragravity frequencies (e.g. Sonu, 1972; Aagaard et al., 1997; Brander and Short, 2001; MacMahan et al., 2004, 2006). Also apparent from Fig. 2d is the increase in Lagrangian field measurements in the last decade. Lagrangian methods involve observing, or measuring, trajectories of specific fluid parcels through the rip current system and are useful for providing a two-dimensional representation of the spatial variability of rip current circulation and surface velocity patterns over time (e.g. Schmidt et al., 2003; Spydell et al., 2007; Austin et al., 2010; MacMahan et al., 2010a; Houser et al., 2013; McCarroll et al., 2014b; Winter et al., 2014; Scott et al., 2016). The move towards Lagrangian measurements is reminiscent of the earliest field measurements of rip current flows conducted near the Scripps Institute of Oceanography at La Jolla, California (Shepard et al., 1941; Shepard and Inman, 1950) using floating objects and drogues.

In terms of studies related to the rip current hazard, while the earliest rip current publications (e.g. Davis, 1925; Shepard, 1936; Shepard et al., 1941) acknowledged the drowning hazard represented by rip currents, a dearth of dedicated hazard research existed until the data-driven models/forecasts studies by Lushine (1991) and Lascody (1998). However, since 2010 there has been a rapid proliferation of interest in the rip current hazard, particularly from social science studies (Fig. 2e) relating to human understanding, perception of, and behaviour in relation to the rip hazard (e.g. Drozdzewski et al., 2012; Brannstrom et al., 2014; Woodward et al., 2015). In this time, there has also been increased interest in statistical data reporting (e.g. Brighton et al., 2013; Arozarena et al., 2015; Barlas and Beji, 2015) and physical studies involving measuring or modelling swimmer behaviour in rip currents (e.g. McCarroll et al., 2014a; McCarroll et al., 2015; Castelle et al., 2016; Van Leeuwen et al., 2016). Overall, it is evident from Fig. 2 and Supplementary Material that scientific interest in rip currents is high, with continued rapid growth largely being driven by hazard related studies, followed by field measurements and modelling works.

1.1. Rip current structure and circulation regime

The traditional and widely accepted view of rip current circulation regime and rip current system structure (Fig. 3a) is based on early Lagrangian studies and observations by Shepard et al. (1941) and Shepard and Inman (1950) and describes nearshore circulation involving rip currents and the continuous interchange of water between the surf zone and areas offshore (Inman and Brush, 1973). The onshore mass transport due to breaking waves results in the formation of longshore feeder currents close to the shoreline, which converge into a narrow and shore-normal rip neck. This fast flowing rip neck extends seaward through the surf zone and beyond (Fig. 3a) where it eventually decelerates and dissipates as an expanding rip head. This water is then available to be transported shoreward again by breaking waves, thus completing the cell (Fig. 3a). This traditional view is found in many popular coastal textbooks (e.g. Komar, 1998; Woodroffe, 2002; Davis and Fitzgerald, 2004; Davidson-Arnott, 2010) and depicts a rip current that is narrow, flows largely perpendicular to shore, and extends significant distances beyond the surf zone (Fig. 3a). This depiction has had a major influence on the long standing and globally promoted

Fig. 1. Rip currents as a coastal hazard: (a) rip current flowing seaward from surf zone near swimmers at Zuma Beach, California (www.fire.lacounty.gov/lifeguard/rip-currents/); (b) bathers caught in a rip current at Haeundae Beach, Korea (photo Jooyong Lee); (c) bathers on exposed sandbar and shoreline in close proximity to rip current channels at Perranporth Beach, UK (photo Tim Scott). (d) Surfers paddling in a rip current and associated sediment plumes adjacent to a groyne at Newport Beach, California (photo Tom Cozad).

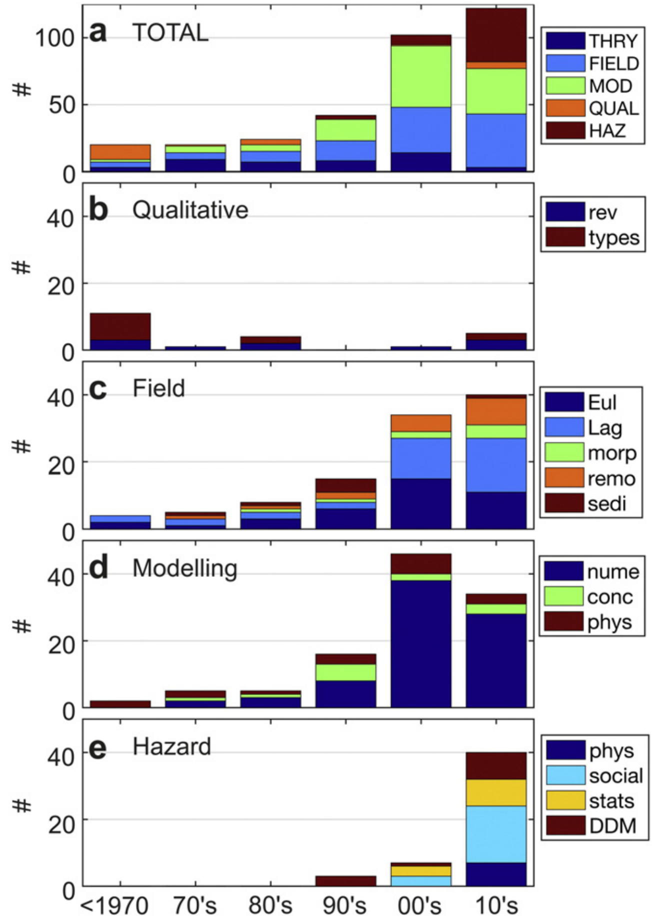


Fig. 2. Temporal patterns in the number of rip current publications in international refereed journals from 1925 to 2016 by theme and sub-themes: (a) Total publications by theme where THRY = theory; FIELD = field measurements; MOD = modelling; QUAL = qualitative; HAZ = hazard; (b) 'qualitative' papers divided into rev = review and types; (c) 'field' papers split into: Eul = Eulerian; Lag = Lagrangian; morp = morphology; remo = remote sensing; sedi = sediment transport; (d) 'modelling' papers split into num = numerical modelling; conc = conceptual; phys = physical laboratory; (e) 'hazard' papers split into phys = physical; social; stats = statistical and DDM = data-driven models/forecasts.

beach safety strategy of swimming parallel to the beach to escape a rip current (Brander and MacMahan, 2011).

As evident from Fig. 2 there has been a recent and rapid increase in Lagrangian rip current flow measurements. The development of low-cost global positioning system (GPS) devices attached to surf zone drifters (Johnson et al., 2003; Schmidt et al., 2003; Johnson and Pattiaratchi, 2004; MacMahan et al., 2009) has enabled fleets of drifters to be deployed in the surf zone providing greater spatial and temporal coverage of rip current system circulation, often supported by improved measurements of surf zone bathymetry (MacMahan, 2001). Similar advances in understanding Lagrangian flow behaviour in rip currents have been made in the physical laboratory (e.g. Kennedy and Thomas, 2004; Castelle et al., 2010) and through improved numerical modelling techniques (e.g. Reniers et al., 2009). Importantly, these advances have challenged the traditional view of rip current circulation shown in Fig. 3a. Recent field studies using GPS drifters at beaches in California, the UK, and France (Austin et al., 2010; MacMahan et al., 2010a) indicated that rather than exiting the surf zone continuously, rip current flow can be confined primarily within the surf zone in semi-enclosed vortices with approximately 20% of drifters per hour exhibiting surf zone exits in episodic bursts (Fig. 3b). From a hazard perspective, MacMahan et al. (2010a) also suggested that instead of swimming parallel to the beach to escape a rip current, bathers might be better off treading water and floating, as the re-circulation would transport them to shallower shoals on the order of minutes, allowing them to conserve their energy. Similarly, as evident from Fig. 3b, the swim parallel escape strategy may result in swimming against an alongshore-directed component of the circulation cell (MacMahan et al., 2010a).

While these new findings generated a certain degree of debate within both the scientific and beach safety community (Brander and MacMahan, 2011; Miloshis and Stephenson, 2011), a growing number of subsequent Lagrangian GPS drifter field studies (Fig. 2e; Houser et al., 2013; McCarroll et al., 2014a, 2014b; Scott et al., 2014; Winter et al., 2014) have shown that the degree of surf zone rip current recirculation can be quite variable with reported surf-zone exit rates per hour varying from 0 to 100%. Importantly, much of this variability is associated with the different types of rip currents that can exist along beaches.

1.2. Rip current systems

Rip currents are inherently complex natural systems that can: i) exist on both planar beaches and those with alongshore three-dimensional morphology; ii) lack morphologic expression, occupy distinct deeper channels or flow against hard structures; iii) be both transient or persistent in occurrence and location; iv) exhibit both mean and unsteady flows; v) vary depending on the angle of wave approach; and vi) can be confined within the surf zone or extend well beyond the breakers. As shown in Fig. 4, the variability in rip current types is fundamentally dictated by a range of physical forcing mechanisms, controls and system feedback relationships which act in concert to generate concentrated offshore flows in the surf zone.

From both a scientific and hazard perspective, it is important to note that different types of rip currents can exist simultaneously on the same beach, often in close proximity and with similar offshore wave energy forcing conditions. The degree of nearshore wave shoaling and breaking is modified by offshore and/or nearshore morphology controls and the presence of rigid boundaries (Fig. 4), such as natural headlands or rock outcrops, or anthropogenic structures such as groynes, jetties and piers. These modifications largely determine the spatial and temporal variability of wave breaking and subsequent rip current system flow circulation and behaviour, all of which are modulated by changing water depths associated with varying tidal levels (on tidal beaches). Resulting rip current flow may also alter nearshore morphology and wave breaking patterns (Fig. 4).

While several attempts have been made to describe the different types of rip currents that exist (Short, 1985, 2007; Dalrymple et al., 2011; Leatherman, 2013), they have sometimes used different terminologies to describe what is often the same type of rip current, which can potentially lead to confusion and misinterpretation. No formal classification presently exists that has been universally adopted in the coastal scientific literature or by beach safety practitioners. This poses a potential problem for public rip current education efforts in terms of communicating correct understanding of different rip current behaviours.

The purpose of this review is to present a classification of the different types of rip currents that exist on beaches based on their physical forcing mechanisms, which control rip flow behaviour. It incorporates results from the many recent field, laboratory and modelling efforts (Fig. 2) that have provided valuable new information on rip current circulation behaviour in varied environments, but have yet to be fully synthesized in relation to the rip current hazard. It is hoped that the classification will serve as a resource for coastal scientists and non-specialists with an interest in the rip current hazard and will serve as a platform for future rip current studies.

2. Background on wave-driven vortical motions in the nearshore

As previously described, rip current flow is driven by alongshore variations in breaking wave height (Bowen, 1969), but the simple rip

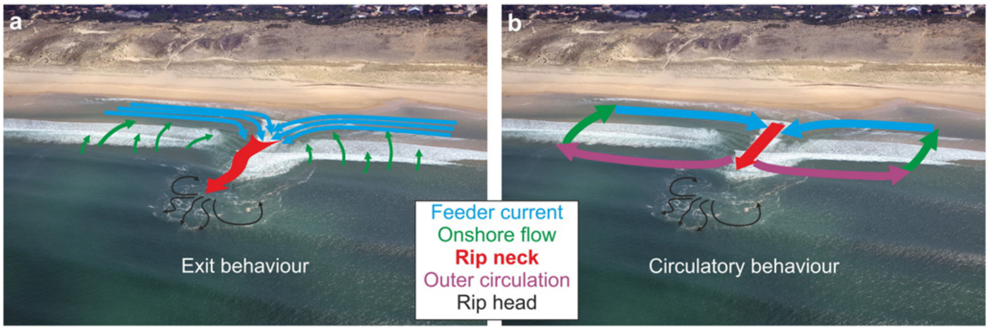


Fig. 3. (a) Traditional view of rip current circulation regime, hereafter referred to as "exit flow", based on early field measurements; (b) the 2010's revision identifies a rip current circulation regime, hereafter referred to as "circulatory flow". In both panels, colours indicate the main structural components of the rip current system (photo Y. Lavigne).

current structure shown in Fig. 3 masks the fact that this alongshore variability, and hence resulting rip current flow behaviour, can arise from a number of different causes. Here the primary forcing mechanisms responsible for rip current flow are described in order to provide the basis for discriminating rip current types in Section 3. Alongshore variability in time-averaged breaking wave energy dissipation can arise from a number of causes: (1) alongshore-variable surf-zone bathymetry; (2) wave energy focusing enforced by wave refraction over offshore bathymetric anomalies; and (3) wave shadowing by a rigid boundary. This is important as these causes, to some degree, all contribute to the existence of different rip current types.

Wave breaking is the main driving force in surf-zone hydrodynamics as wave energy loss through breaking transfers momentum that forces water in the direction of wave propagation. Breaking waves therefore create a reduction in the wave momentum flux, or radiation stress (Longuet-Higgins and Stewart, 1964), and force water onshore causing the mean water level to 'set-up' (Bowen et al., 1968). Alongshore variations in wave height and wave breaking create spatial variations in radiation stress that manifest as regions of higher wave 'set-up' (higher waves, more intense breaking) and lower 'set-up' (lower waves, less intense breaking). It is the imbalance between the breaking wave force and the spatial pressure gradients (e.g. Haller et al., 2002) that

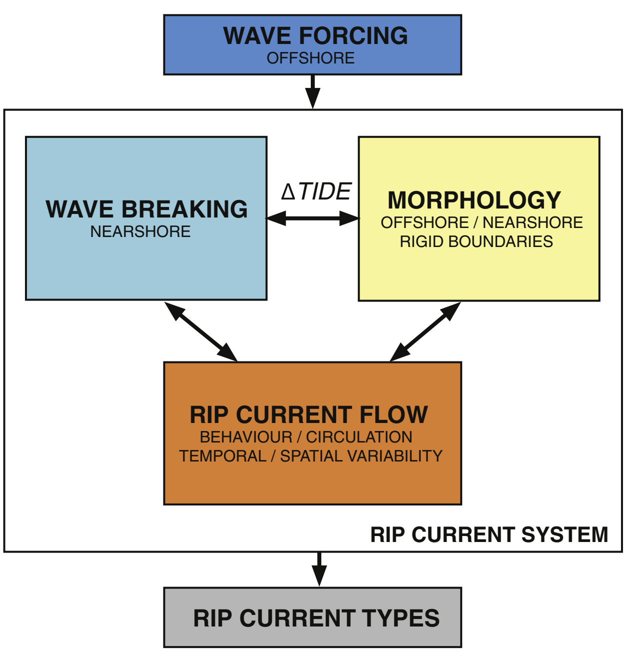


Fig. 4. System diagram highlighting interactions between hydrodynamic forcing, morphology and resultant rip system flow response. Each element within the system provides feedback to the other, generating a variety of rip current behaviours in both space and time.

result in rip current flow (Fig. 5). In the case of obliquely incident waves, the wave-driven forcing also drives a longshore current causing a dominant feeder current and an obliquely offshore-flowing rip current.

Based on general theoretical analysis of wave-driven currents and vortex dynamics due to dissipating waves (Buhler, 2000; Buhler and Jacobson, 2001), Bruneau et al. (2011) derived the depth-integrated and time-averaged momentum equations to directly link alongshore variability in breaking wave height to the existence of vortices in the surf zone. They segregated the rotational forcing term, which is not possible using the radiation stress approach. The alongshore gradient in depth-induced wave breaking dissipation was found to be responsible for a vorticity forcing term (Fig. 5), which is similar to the imbalance between breaking wave force and pressure gradients (see Fig. 10 in Castelle et al., 2012). Accordingly, the alongshore gradients in breaking wave energy dissipation determine both the strength and sign of the time-averaged wave-driven circulation rotational nature (Bruneau et al., 2011) and are a key element to the generation of rip currents.

While the above description addresses the time-averaged hydrodynamics, and by association the large-scale ($O(100\text{ m})$) quasi-steady vortices, the instantaneous forcing is actually composed of individual breaking waves that are often short-crested owing to the directional spread of the wave field (Longuet-Higgins, 1957). Short-crested breaking wave vorticity forcing is due to along-crest variation in wave energy dissipation (Peregrine, 1998) where adjacent regions of breaking and non-breaking wave crests are assumed to form a large differential in forcing (Fig. 6). These changes in vorticity with the passage of individual short-crested breaking waves were recently observed by Clark et al. (2012) at 10+ m length scales. Following a basic principle of 2D turbulence that eddy energy cascades to longer length scales through nonlinear interactions, vorticity injected with the passage of individual short-crested breaking waves can evolve to longer length scales and create a wide range of larger-scale ($O(100\text{ m})$) migrating surf-zone eddies (Feddersen, 2014).

The alongshore variability in breaking wave energy dissipation, from time scales of seconds (individual waves) to tens of minutes, is therefore a key driving mechanism for rip current flow in the nearshore. In between these two time scales, surf-zone vorticity forcing also occurs at the time scale of wave groups (25 s and longer). Accordingly, rip flow kinematics can be partitioned into mean, infragravity (25–250 s) and very low frequency (4–30 min, VLF) components, with the tide further modulating rip flow velocity (MacMahan et al., 2006; Austin et al., 2010; Bruneau et al., 2009). However, although alongshore variability in breaking wave energy dissipation is crucial to rip current generation, other mechanisms can generate vortices and rip currents in the nearshore.

Nearshore vortices can also be generated by the instability of intensely sheared currents (e.g. Oltman-Shay et al., 1989; Ozkan-Haller and Kirby, 1999; Noyes et al., 2004). For instance, shear instabilities of the longshore current involve the strengthening, weakening and interactions of vortices with vortex pairs frequently being shed offshore (Ozkan-Haller and Kirby, 1999). Finally, longshore currents generated by oblique waves may be physically deflected seaward when they collide with a rigid boundary (e.g. headland, groynes) or an opposite longshore current, therefore forming a seaward-oriented jet.

3. Surf-zone rip current type classification based on physical forcing mechanism

In this section we define common and generic rip current types based on an understanding and interpretation of the different fundamental mechanisms involved in driving rip current flow. Recently, rip currents have been differentiated based on whether they occur on open coast or embayed beaches, with the former being far away from permanent topographic features such as headlands or coastal structures (MacMahan et al., 2010a; Dalrymple et al., 2011; Scott et al., 2014). In reality, this distinction is misleading as many embayed beaches support rip currents that are not adjacent to physical boundaries and exhibit the same characteristics as open coast rip currents. Similarly the terms 'fixed' and 'permanent' have been used both formally and informally to describe channelized rips (e.g. Short, 2007; Brander and MacMahan, 2011), but in reality all rips can vary in size and location. Of note, rip currents driven by swash processes are not described in this review because of their limited importance on coastal hazards. These small-scale rips, sometimes referred to as mini-rips (e.g. Russell and McIntire, 1965) or swash rips (e.g. Dalrymple et al., 2011), flow through the centre of O(10 m) spaced cusps on steep beaches (Fig. 7) as wave uprush diverges at the cusp horns driving concentrated backwash streams (Masselink and Pattiaratchi, 1998).

Here we seek to avoid terminology ambiguity by describing three broad categories of surf-zone rip currents based on the dominant controlling forcing mechanism. While it is important to note that all rip current types are driven by hydrodynamics: i) purely *hydrodynamic rips* exist solely due to hydrodynamic forcing mechanisms in the absence of any morphologic control whatsoever and are spatially and temporally variable in occurrence; ii) *bathymetric rips* are driven by hydrodynamic processes strongly influenced by natural variability in alongshore three-dimensional (vertical) morphology in both the surf zone and inner shelf zone; and iii) *boundary rips* are dominated by the influence of rigid lateral boundaries, such as natural headlands or anthropogenic structures (groynes, piers), on their hydrodynamic forcing. Each category is characterized by different rip current types that are now described in detail.

3.1. Hydrodynamically-controlled rip currents

Controlled solely by hydrodynamic forcing, these rip currents differ from all other rip types and are restricted to featureless (alongshore-uniform) beaches, or planar sections of beaches (e.g. low tide terraces, seaward slopes of sandbars). They are transient in occurrence in space and time and are therefore very unpredictable. Hydrodynamically-controlled rip currents have been studied for some time (e.g. Bowen, 1969), but debate exists regarding their exact driving mechanisms (Dalrymple and Lozano, 1978; Sasaki and Horikawa, 1978; Dalrymple, 1975; Bowen and Holman, 1989). Only recently has the pioneering work of Feddersen (2014) shed light on hydrodynamic rip generation, allowing a clear discrimination of two different driving mechanisms and, as a result, two different hydrodynamically-controlled rip current types (Fig. 8).

3.1.1. Flash rips

On alongshore-uniform open beaches, changes in vorticity at 10 + m length scales with the passage of individual short-crested breaking waves (Peregrine, 1998; Clark et al., 2012) result from the natural directionally spread wave field (Cavaleri et al., 2007). A fraction of this short-scale vorticity is dissipated through bottom friction and another fraction cascades to larger length scales (Spydell and Feddersen, 2009a, 2009b), evolving into a wide range of larger-scale (O(100 m)) migrating surf-zone eddies (Feddersen, 2014). *Flash rips*, are the episodic and unpredictable bursts of water jetting offshore associated with these transient surf-zone eddies (Fig. 8a, b). While our understanding of the dynamics and primary driving mechanisms of flash rip currents and surf zone eddies on alongshore-uniform open beaches has improved recently (Johnson and Pattiaratchi, 2006; Spydell and Feddersen, 2009a, 2009b; Clark et al., 2010, 2011; Feddersen, 2014), their frequency of occurrence and associated wave conditions (e.g. wave height, period, angle of incidence and directional spread) remains poorly understood. This is partly due to the lack of existing field data spanning a wide range of wave and morphological conditions (Murray et al., 2013; Castelle et al., 2014a) owing to their unpredictable nature. However, in general, flash rips have been found (Murray et al., 2013; Castelle et al., 2014a) to: (1) have a relatively short lifespan (2–5 min); (2) tend to migrate downdrift; and (3) occur

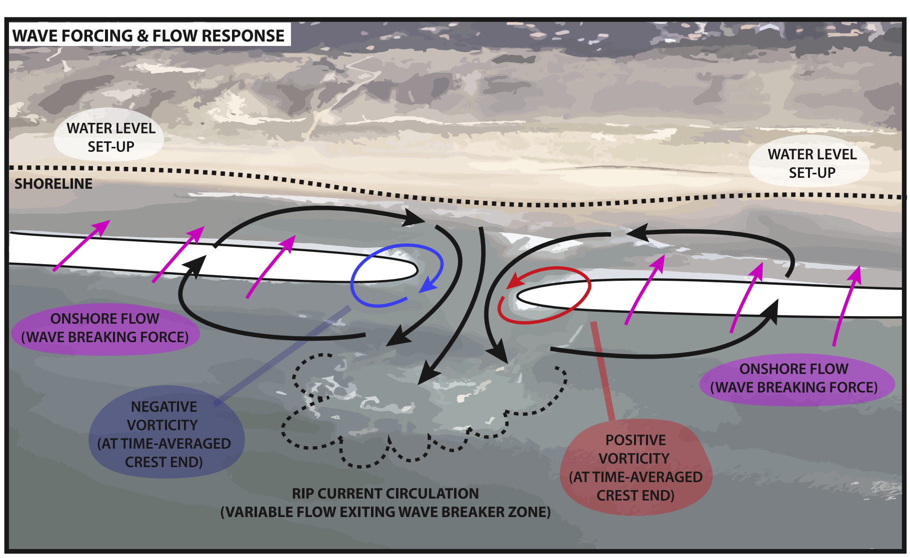


Fig. 5. Conceptualized time-averaged vortical flow driven in the nearshore by alongshore variation in breaking wave height.

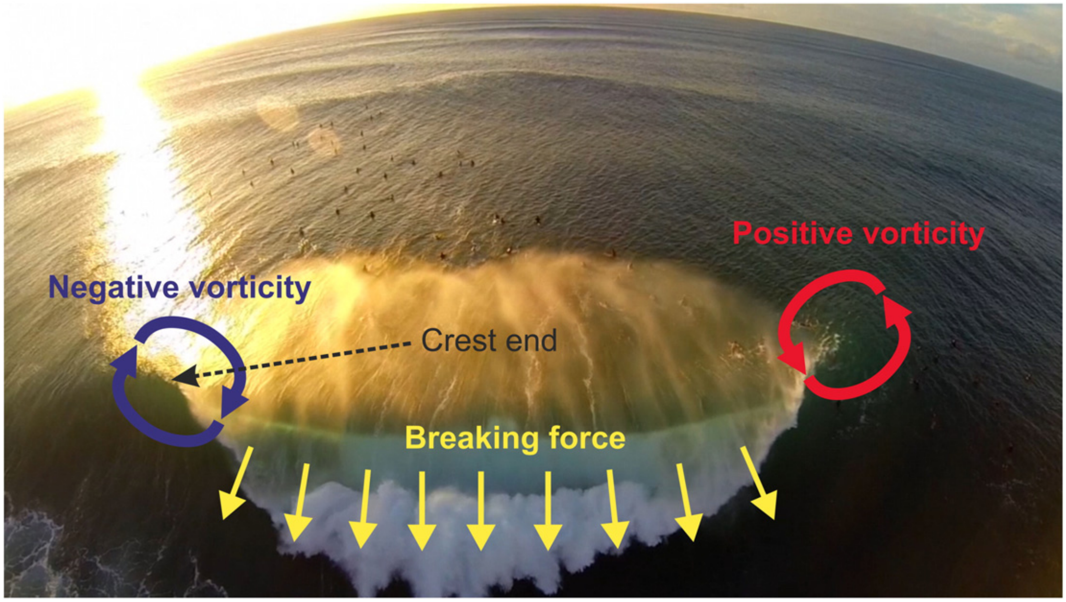


Fig. 6. Definition of short crested breaking wave vorticity (photo Eric Sterman, after Clark et al., 2012).

preferably on alongshore-uniform terraced beaches with dominant plunging breakers and near-normal wave incidence.

3.1.2. Shear instability rips

On alongshore-uniform open beaches, obliquely incident waves drive alongshore surf zone currents. It is well established that longshore currents can be unstable as they may experience shearing in the cross-shore direction (Oltman-Shay et al., 1989; Bowen and Holman, 1989; Dodd and Thornton, 1990; Putrevu and Svendsen, 1992; Feddersen, 1998). Subsequent detailed process-based modelling studies (Ozkan-Haller and Kirby, 1999) showed that shear instabilities of the longshore current exhibit unsteady longshore progressive vortices (shear or vorticity waves) with timescales of $O(100\ \text{s})$ and length scales of $O(100\ \text{m})$ with vortex pairs being frequently shed offshore. These shear instabilities are also associated with locally strong and narrow offshore flowing currents migrating downdrift, hereafter referred to as *shear instability rips* (Fig. 8c, d).

While shear instabilities of the longshore current have long been thought to be the only driving mechanism for non-fixed rip currents, their expected prominent role in the generation of migrating surf zone eddies has been recently challenged. Using state-of-the-art numerical modelling, Feddersen (2014) investigated the relative importance of shear instabilities of the longshore current and breaking wave vorticity in forcing surf zone eddy generation. Feddersen (2014) concluded that in most natural surf zones the shear instability eddy mechanism is negligible compared to breaking wave vorticity dynamics, except in the rare case of very narrow-banded, highly-oblique and high-energy waves (Fig. 8d). The field study presented in Castelle et al. (2014a) showing decreasing non-fixed rip activity with increasing longshore current intensity (up to 0.65 m/s) is in agreement with the numerical results of Feddersen (2014). Accordingly, based on existing knowledge, it can be assumed that shear instability rips are uncommon and only occur on alongshore-uniform beaches when exposed to highly obliquely incident ocean swells.

3.2. Bathymetrically-controlled rip currents

Bathymetrically-controlled rip currents are, for a given wave regime and tidal elevation, relatively persistent in space and time. The location and nature of morphologic control leads to different hydrodynamic forcing mechanisms such that two types of bathymetrically-controlled rip currents can occur (Fig. 9): (1) *channel rips* that are forced by

Fig. 7. Swash rips flowing through the centre of beach cusps at Bells Beach, Australia (photo Bruno Castelle).

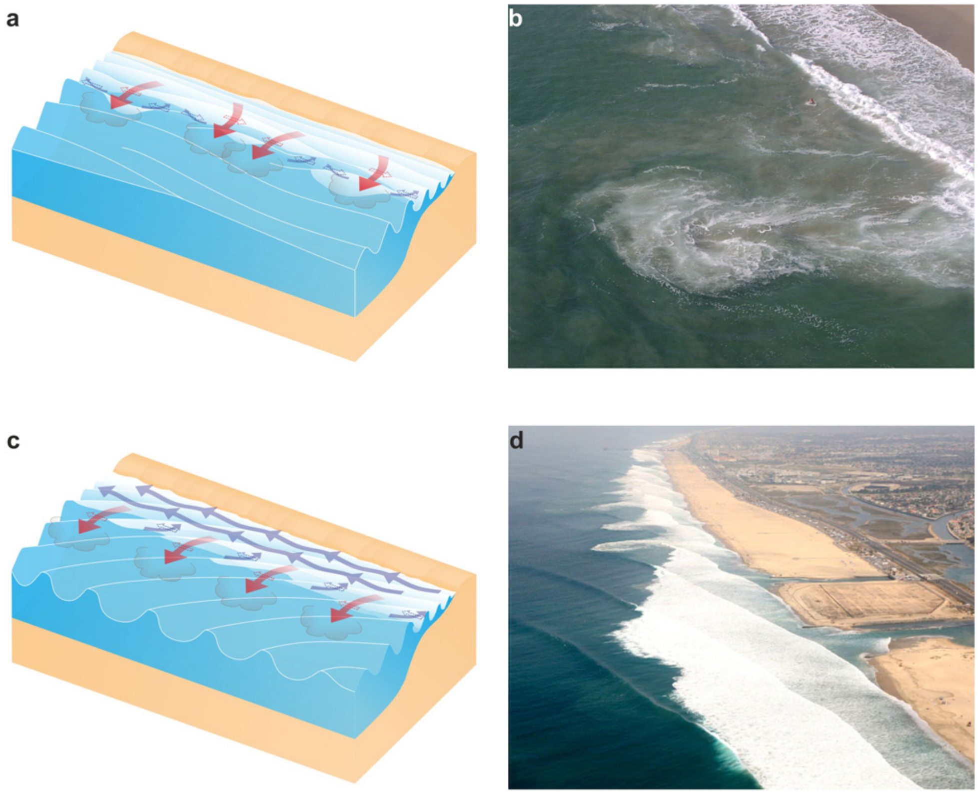


Fig. 8. Examples of hydrodynamically-controlled rip currents: (a) schematic of flash rip currents with predominant shore-normal wave approach; (b) flash rip current at Zuma, California (photo www.fire.lacounty.gov/lifeguard/rip-currents/; (c) shear instability rip currents with obliquely incident narrow-banded waves and strong alongshore current; (d) shear instability rip currents (curved sediment/water plumes past second inlet) at Newport Beach, California (photo Tom Cozad).

three-dimensional morphologic variability in the surf zone; and (2) *focused rips* which are forced by shoaling wave processes determined by morphologic features in the outer surf zone and shoaling zone.

3.2.1. Channel rip currents

Channel rips are the most documented and well understood rip current type given their predictable nature, relative logistic ease of measurement and worldwide ubiquity (Brander and Scott, 2016). They are associated with intermediate beach states (Wright and Short, 1984) and occupy deep channels between surf zone sandbars (Short, 2007; Dalrymple et al., 2011). Surf zone sandbars are ridges of sand, typically found in <10-m water depth along many wave-exposed coasts (e.g. Van Enckevort et al., 2004), that most of the time exhibit quasi-regular undulation in their depth and cross-shore position. They are often incised by rip channels with depth, spacing and width of O(1 m, 100 m and 10 m) respectively (e.g. Short and Brander, 1999; Turner et al., 2007; Thornton et al., 2007; MacMahan et al., 2010a; Gallop et al., 2011). Channel rips are hence driven by alongshore variation in breaking wave energy dissipation due to alongshore variability in water depth (Bowen et al., 1968; Haller et al., 2002; Bruneau et al., 2011) with offshore jets of water occupying deeper channels where depth-induced breaking is less intense or absent (Figs. 3, 9a, b), the primary difference between channel rips and flash rips being the spatial stability and persistence of the short-crested breaking wave forcing.

Channel rips can be relatively stationary in position over temporal periods of days, weeks, and sometimes months. Of note, while most channel rips are associated with mobile sandy bottoms, they can also occur across alongshore-variable shore platforms and fringing reefs through incised channels, in which case they are almost permanent in location. Although these rip currents have sometimes been referred to as 'reef rip currents' (de Leon et al., 2008), their primary driving mechanism is essentially the same as on sandy beaches and are therefore classified as channel rips. Channel rips on mobile substrates are typically formed under near shore-normal incident waves with longer wave periods, but have been observed in wind-sea environments with a large (≈100 m) rip channel width (e.g. Short and Brander, 1999; Winter et al., 2014). A notable characteristic of channel rips is a tidal modulation in flow velocity (see Section 4.2), with channel rips therefore appearing and reappearing in the course of a tidal cycle while maintaining the same location.

3.2.2. Focused rips

Focused rips also occur in fixed locations due to alongshore variability in breaking wave height and breaking wave angle. However, in contrast to channel rips, this variability is caused by the presence of offshore bathymetric anomalies in the outer surf zone or inner shelf (Fig. 9c, d) typically in O(10 m) water depth, meaning that focused rips can occur on featureless (alongshore-uniform) surf zone beaches. Offshore alongshore bathymetric anomalies are typically sorted bedforms (e.g. Cacchione et al., 1984; Coco et al., 2007), transverse ridges (Houser et al., 2011) or may be isolated geologic features such as submarine canyons incising into the nearshore zone (e.g. Belderson and Stride, 1969; Shepard, 1981; Mazieres et al., 2014). On multiple-barred beaches, the alongshore-variable outer (more seaward) bar(s) can also act as bathymetric anomalies (see also Section 3.4.2). Assuming the presence of obliquely incident waves propagating over these features, wave refraction will result in an alongshore variable breaking wave height and angle creating opposing alongshore currents that deflect offshore as a rip current (Fig. 9c). This forcing mechanism is described in more detail by Long and Özkan-Haller (2005, 2016) for focused rip currents generated at La Jolla, California caused by an offshore submarine canyon. Of note, this is the same location as the early Lagrangian rip current studies by Shepard et al. (1941) and Shepard and Inman (1950, 1951), which resulted in the traditional depiction of rip current flow structure shown in Fig. 3.

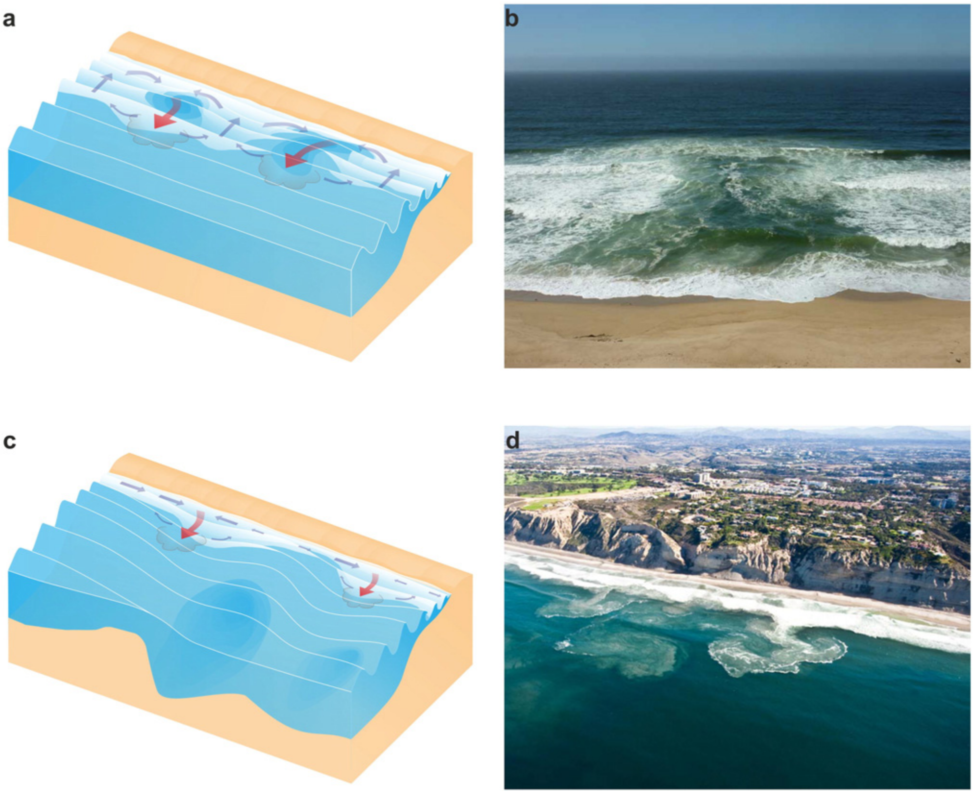


Fig. 9. Examples of bathymetrically-controlled rip currents: (a) schematic of channel rip currents flowing offshore over a rip head bar or through an incised channel between sand bars with predominant shore-normal wave approach; (b) channel rip current at Marina Beach, California (photo Rob Brander); (c) schematic of focused rip currents showing offshore bathymetric hole; (d) focused rip currents (sediment plumes) at Blacks Beach, California (photo Tom Cozad).

Also in contrast to channel rips, focused rips do not necessarily occur where depth-induced wave breaking is less intense (Fig. 9c, d). While they are relatively fixed in location for given tide and wave conditions, they can strongly shift location alongshore with different angles of wave incidence and wave periods. Focused rips are favoured by large bathymetric anomalies close to shore and long period waves that enhance wave refraction and resulting alongshore variability in breaking wave height and angle. Focused rips also tend to disappear with large wave angles as dominant and intense longshore currents tend to overwhelm the surf zone eddies (Long and Özkan-Haller, 2016).

3.3. Boundary controlled rip currents

Many beaches are characterized by the presence of natural rigid features, such as headlands and rock outcrops, and anthropogenic structures, such as groynes, jetties and piers (Short, 1992; Scott et al., 2011a). These physical boundaries effectively exert a lateral bathymetric control on the generation of rip current flow adjacent to them. Two distinctly different forcing mechanisms can be discriminated, depending on which side of the obstacle is considered in relation to incident waves approaching at oblique angles (Fig. 10). *Shadow rips* occur on the down-wave side of a rigid boundary, whereas *deflection rips* occur on the up-wave side of a boundary. However, regardless of the forcing mechanism involved, boundary rip currents are always characterized by rip current flows against the structure, which also makes them persistent in location.

3.3.1. Shadow rips

On alongshore-uniform beaches exposed to obliquely incident waves, the presence of a rigid obstacle results in alongshore variations in wave height and wave energy dissipation due to the wave shadowing effect of the obstacle. (Fig. 10a). The result is an offshore flowing jet occurring against the boundary in the lee of the incident waves (Gourlay, 1974; Pattiaratchi et al., 2009; Castelle and Coco, 2012; Scott et al., 2016). Numerical modelling studies (e.g. Pattiaratchi et al., 2009) have shown that for obliquely incident waves shadow rip activity increases with increasing wave height, period and angle to shore. For normally incident waves, shadow rip activity also increases with increasing directional spreading of the incident wave field (Castelle and Coco, 2012). Because shadow rips are controlled by the geometry of the wave shadowing region, the shape and cross-shore extent of the rigid boundary are crucial to the formation and characteristics of shadow rips. Although shadow rips are ubiquitous along natural rugged and/or trained coasts, detailed field studies of shadow rip flows are scarce, with the notable exceptions of Pattiaratchi et al. (2009) and McCarroll et al. (2014b) in the lee of a groyne and headland, respectively.

3.3.2. Deflection rips

Deflection rips also occur on alongshore-uniform beaches characterized by the presence of a rigid obstacle (Fig. 10b). However, their driving mechanism is very different, as strong alongshore currents generated by oblique waves are physically deflected seaward when they encounter the obstacle (Dalrymple et al., 2011; Castelle and Coco, 2013; Scott et al., 2016). More studies of deflection rips compared to shadow rips exist due to their predictable nature (McCarroll et al., 2014b) and their relatively easier reproduction using physical and numerical models (Wind and Vreugdenhil, 1986; Silva et al., 2010; Scott et al., 2016).

3.4. Other rip current types

3.4.1. Some common mixed rip current types

Although it is easier to describe and classify rip currents as isolated types, in reality many rip currents form through a mixture of driving mechanisms. Rip currents that are associated with small surf-zone bathymetric anomalies (e.g. MacMahan et al., 2008) can incorporate elements of both channel and flash rips. Depending on the respective contribution of time-averaged surf-zone morphology controlled forcing and instantaneous forcing, these mixed channel-flash rips can occur in variable locations in the vicinity of the subtle channel (Fig. 11a). Inner-bar rips are another example of a mixed rip type occurring along double-barred beaches (e.g. Lippmann and Holman, 1990; Aagaard, 1991; Short and Aagaard, 1993; Castelle et al., 2007; Price and Ruessink, 2011; Scott et al., 2011b). In these inner-bar systems, mixed focus-channel rip currents are driven in part by the alongshore variation in breaking wave height due to the alongshore variability in depth of the inner bar, but also due to wave refraction and potentially depth-induced wave breaking across the outer bar(s) (Fig. 11b). As boundary (*deflection* and *shadow*) rips form against natural or anthropogenic structures, they are essentially spatially persistent and under certain conditions can scour a channel against the structure (e.g. Castelle and Coco, 2012; Loureiro et al., 2012a). As a result of this channel deepening, both types of boundary rip current flows can also be driven by the alongshore variability of breaking wave height resulting from the irregular surf zone morphology (Fig. 11c). Accordingly, over mobile sandy substrates, most boundary rips adjacent to natural and anthropogenic structures are typically mixed boundary-channel rips (Short, 1992).

3.4.2. Embayed-cellular rips (channel and embayment boundary)

An important type of rip current resulting from different forcing mechanisms is exclusive to pocket or embayed beaches if the embayment width is narrow compared to surf-zone width. In this case, *cellular rip currents* occur when the rigid boundary dominates circulation within the entire embayment (Short and Masselink, 1999). Cellular rips generally occur at either the centre of the embayment or at one or both ends (Fig. 12), depending on the shape and cross-shore extent of the boundary, wave conditions and beach curvature (Castelle and Coco, 2012). Driving mechanisms responsible for cellular rip formation are a combination of shadowing, deflection and channelization to various degrees, together with the alongshore circulation within the embayment being additionally constrained by the alongshore embayment length. Cellular rips are particularly common during storm wave conditions (e.g. Loureiro et al., 2012b) and have often been named 'mega-rips' due to their large spatial scales (Wright, 1978; Short, 2007). However, embayed-cellular rips can also occur for low- to moderate-energy wave conditions within narrow embayments.

3.5. Rip types summary

Six fundamental surf-zone rip current types have been defined based on the dominant physical driving mechanism. It is important to recognize that these discrete rip types form key elements in a complex spectrum where, in real-world scenarios, the various forcing mechanisms often combine to produce an integrated and dynamic flow response. Therefore, four of the most common mixed rip current types were also defined as examples of the complex reality. Fig. 13 provides a conceptual summary of the rip current types just described, highlighting the principal forcing connections associated with waves, tides and morphology.

Examination of the scientific literature on rip currents between 1925 and 2016 indicates that 236 publications were related directly to one or more of the rip current types described above (see Supplementary Material). As shown in Fig. 14 the vast majority of studies have focused on bathymetrically-controlled rip currents, predominately channel rips (Fig. 14b) largely due to their prevalence, logistical ease of measurement and relatively easier modelling replication (Section 3.2.1). Other rip current types have received significantly less attention over time although a noticeable increase in studies related to boundary (Fig. 14c) and mixed rip current types is evident since 2010 (Fig. 14d). Dedicated studies on hydrodynamically-controlled rip currents remain few,

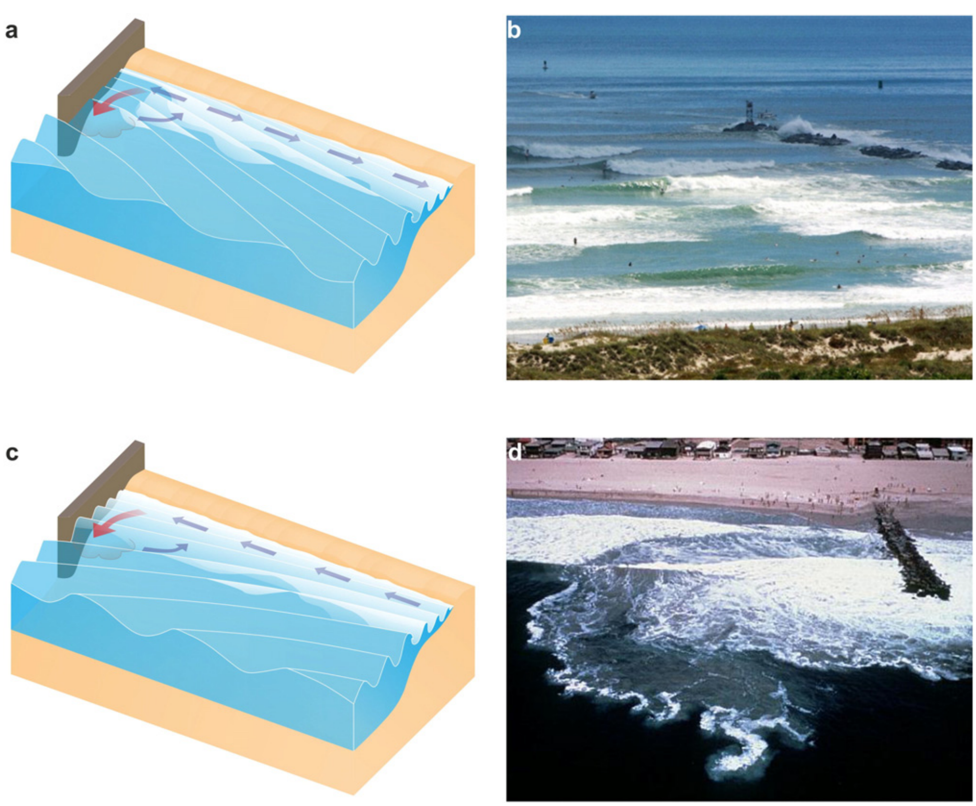


Fig. 10. Examples of boundary rip currents: a) schematic of a shadow rip current in the lee of an obstacle (upwave side); b) shadow rip against Ponce Inlet Jetty, Florida, US (www.bv.com); c) deflection rip current adjacent to obstacle on downwave side of beach; d) deflection rip current at Newport Beach, California, US (http://www.ocregister.com/articles/rip-130324-current-never.html).

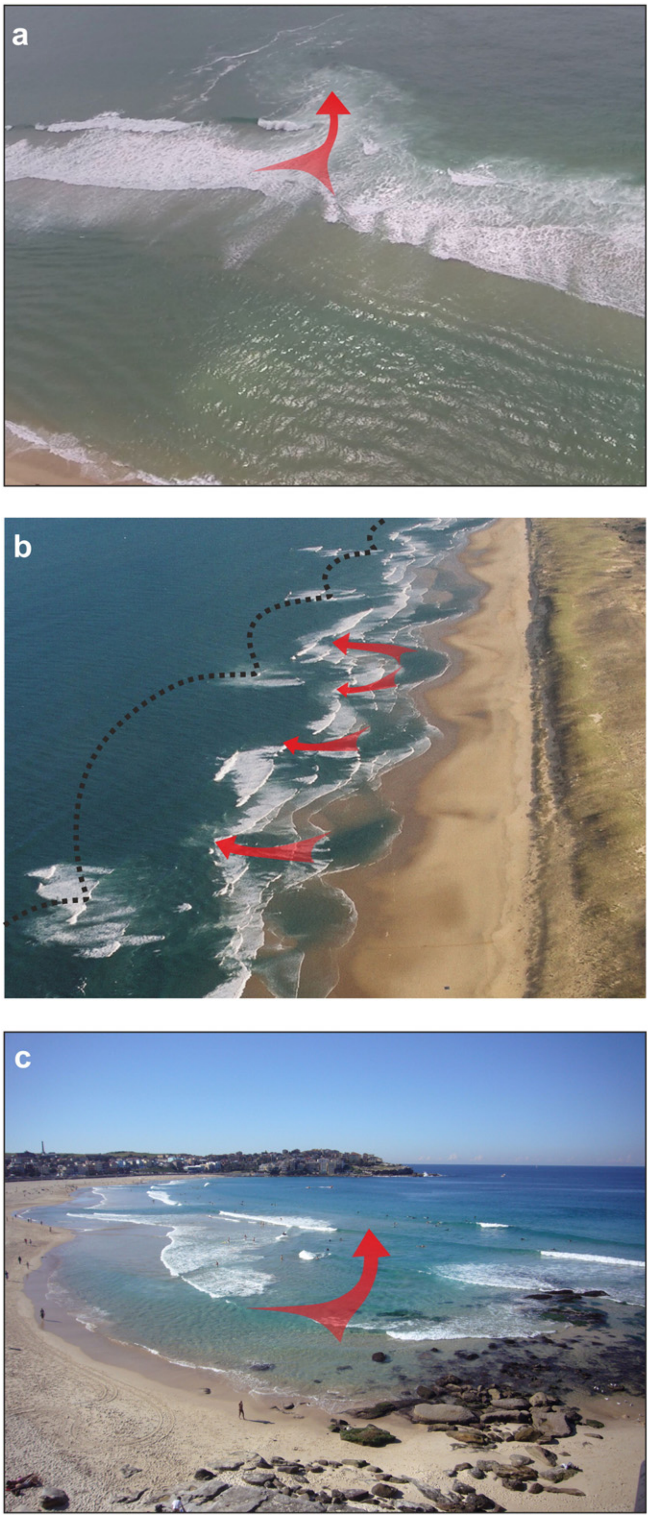


Fig. 11. Examples of mixed rip current types: (a) channel-flash rip occurring through a weakly developed channel in SW France (photo Vincent Marieu); (b) focus-channel rip currents occurring through the inner-bar rip channels on the double-barred sandy beach of Truc Vert, SW France. The dotted line outlines the alongshore variable outer crescentic bar which forces variable alongshore wave breaking on the inner-bar through wave refraction and breaking across shallow bar horns (photo Philippe Larroudé); (c) boundary/channel rip current against a headland flowing through a deep channel at Bondi Beach, Australia (photo Rob Brander).

largely due to the difficulty in measurement, although greater efforts have been made on flash rips in recent years (Fig. 14a).

4. Rip current flow response to variations in forcing

The previous section introduced idealised rip types categorised by primary forcing mechanism. This section examines how these rip types respond to changes in forcing magnitude in terms of spatial and temporal flow response. Forcing mechanisms include waves (height, period, direction, angle, directional spread), morphology (channel spacing, alongshore non-uniformity, boundary dimensions) and tide (water level). Expected rip flow response is described with regard to velocity modulation, circulation regime, and force-response relationships for each major rip type grouping and mixed rip type.

4.1. Hydrodynamically-controlled rips

The key force-response relationships that drive purely hydrodynamic rips on planar beaches are complex and still poorly understood compared to other rip types. While recent field and numerical studies have provided new insight into flash rip behaviour (e.g. Spydell et al., 2014; Feddersen, 2014; Hally-Rosendahl et al., 2014, 2015), shear instability rips have received little attention because of their scarcity.

Hydrodynamic rips are random in time and location, with time-averaged cross-shore currents summing to near-zero within the surf zone (e.g. Spydell et al., 2007) making mean velocity a poor indicator of flow response. A better indicator is low-frequency variability about the mean velocity (e.g. Spydell et al., 2014; MacMahan et al., 2010b), or variability in vorticity (Spydell and Feddersen, 2009a, 2009b). Directional spreading of the incident wave field has been found to impact eddy velocities, although with contrasting conclusions (Spydell and Feddersen, 2009a, 2009b; MacMahan et al., 2008; Suanda and Feddersen, 2015; Spydell et al., 2009). In addition, phase-resolving wave modelling examining the likelihood of flash rip formation from transient eddies (Johnson and Pattiaratchi, 2006) found that wave period, directional spread and beach slope all influenced transient rip formation, velocity and duration. However, these relationships were unclear and require further investigation. A weak positive correlation between wave height and transient eddy velocity has been robustly demonstrated through observations and numerical modelling (MacMahan et al., 2010b). Eddy velocities peak around the mid-surf zone (Suanda and Feddersen, 2015) with flash rip velocities decreasing rapidly outside the surf zone (MacMahan et al., 2010b). Little is known about shear instability rips, but they are expected to increase in intensity with increasing angle of wave incidence, wave height and wave period.

A strong relationship has been modelled between the cross-shore extent of flash rips (relative to surf zone width) and the Iribarren number (Suanda and Feddersen, 2015) indicating that steep beaches with low steepness waves may exhibit flash rips extending many surf zone widths offshore (exit-flow regime). Transient eddies and flash rips are the primary mixing mechanism in the surf zone and near inner-shelf (Feddersen, 2014; Spydell and Feddersen, 2009a, 2009b). Therefore, flash rip dynamics have often been studied through diffusivity (spreading) rates, typically ranging from 0.5–4 m^2/s (Johnson and Pattiaratchi, 2004; Clark et al., 2010; Spydell et al., 2009), mostly during moderate wave forcing. While it is expected that wave height and directional spreading are key drivers, further observations in more variable wave conditions are required to constrain the force-response relationships of flash rips. To our knowledge, circulation regime of shear instability rips has never been addressed although existing simulations and qualitative observation suggest a clear exit-flow circulation regime.

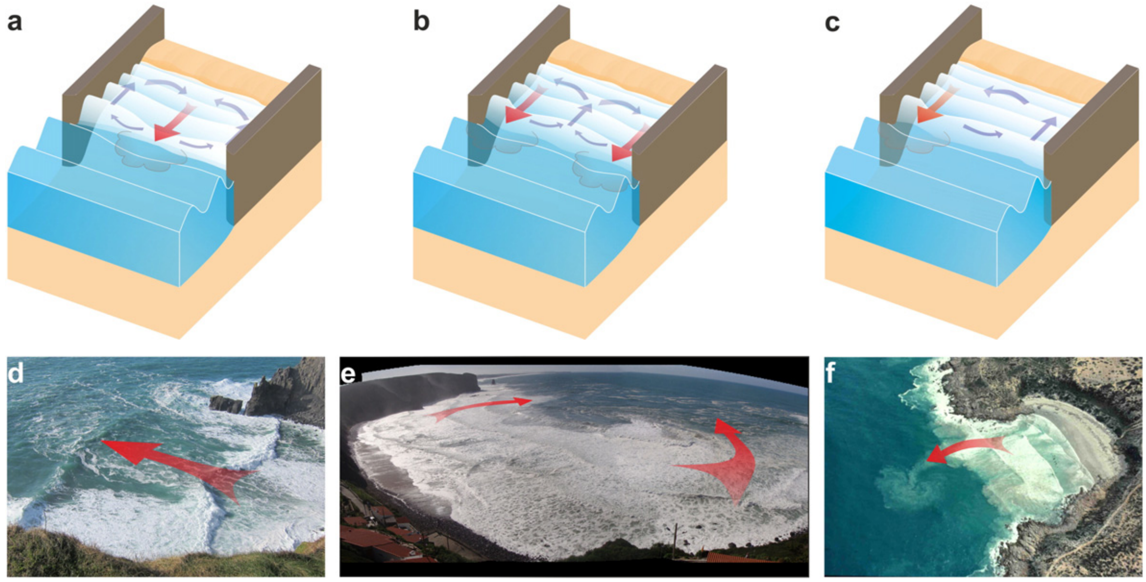


Fig. 12. Schematics (top panels) and examples of cellular rip currents occurring (a, d) at the centre of an embayment at Aileens, County Claire, Ireland (photo Tim Scott); (b, e) at both ends of the embayment at Arrifana, Portugal (photo Carlos Loureiro); and (c, f) at one end of the embayment at Saint James Point, Australia (photo Andrew Short).

4.2. Bathymetrically-controlled rips

Given existing research bias (Fig. 14), channel rip circulation and velocity response is well documented. Numerous field studies (e.g. Brander and Short, 2000, 2001; Castelle and Bonneton, 2006; MacMahan et al., 2006; Austin et al., 2010) have demonstrated that rip flow velocity increases with increasing wave height and/or decreasing water depth (over sandbar crest), modulated by tidal level (hours) or changing beach morphology (month–years). Tidal modulation of rip flow velocity is due to changing breaking wave patterns associated with different water levels (Austin et al., 2010; Scott et al., 2014) with, on sandy beaches, maximum rip current activity tending to occur around low tide (e.g. Aagaard et al., 1997; Brander and Short, 2001; MacMahan et al., 2006; Houser et al., 2013; Austin et al., 2014; Bruneau et al., 2014; Scott et al., 2014). Rip flow velocities have also been well correlated with rip channel morphology (e.g. Brander, 1999; McCarroll et al., 2014b) with rip flow velocity increasing with increasing alongshore variability of surf-zone morphology (Castelle et al., 2010). From a physical perspective, increases in wave height or the relative depth between bar and rip channel will act to increase the alongshore gradient in onshore breaking force, resulting in greater setup onshore of bars and a stronger pressure gradient to drive rip flow. Overall, channel rip flow velocity increases asymptotically under increasing wave height (Fig. 15a, Castelle et al., 2014b) to the point of outer surf zone saturation with reduced alongshore variability of wave breaking. Physically, the alongshore gradient in onshore breaking force is reduced as more waves begin to dissipate in the channel through depth- and current-induced breaking. Channel rip velocity also typically increases with increasing wave period (Castelle et al., 2006). For more information on velocity force-response scaling in channel rips, see Fig. 10 in MacMahan et al. (2006).

Lagrangian drifter measurements in micro- and meso-tidal channel rip systems have shown that under normally incident waves approximately 15–20% of drifters per hour can exit offshore (MacMahan et al., 2010a). However, observed exit rates in channel rips can exhibit a large exit rate variability (0–73%) throughout a range of wave/tide conditions (Houser et al., 2013; McCarroll et al., 2014b; Scott et al., 2014), with very low frequency motions (VLFs) and resulting eddies detaching from the main rip current considered as the primary exit mechanism for circulatory flow behaviour (Reniers et al., 2010; McCarroll et al., 2014b). Reniers et al. (2009) defined an exit parameter for channel rips on a single-barred beach based on modelling and field measurements. Virtual drifter exits were positively correlated with surf zone width and inversely correlated with wave height and period. This relationship was shown to underestimate exit rates when applied to other field datasets (McCarroll et al., 2014b). Based on drifter observations, MacMahan et al. (2010a) hypothesized that a morphodynamic threshold may exist for cross-shore exchange in channel rips where larger waves (breaking further offshore) induce coherent vortices on the order of surf zone dimensions encouraging recirculation and reducing surf zone exits. Scott et al. (2014) observed that drifter exit behaviour at a double barred beach with channel rips scaled inversely with a relative wave energy factor ($H_sT_p/\overline{H_sT_p}$, where $\overline{H_sT_p}$ is the multi-year long-term mean). Scott et al. (2014) determined that wave energy factors below the average (0.5–1) were associated with high exit rates and associated with decreased morphodynamic coupling to a rip system with morphological length scales in equilibrium with the long-term mean wave forcing and circulation. Therefore the surf zone is narrowed as the outer bar is effectively removed from the process domain (Fig. 16). Physically, under lower waves the absence of breaking in the channel reduces onshore forcing through Stokes drift and broken wave bores, allowing a dominating exit flow. For larger waves when intermittent breaking is occurring offshore of the rip channel due to low frequency wave group variability, the latter onshore forcing is increased with flow regime regularly switching between exit and circulatory flow.

Recent laboratory (Castelle et al., 2010) and numerical modelling (Castelle et al., 2014b) studies have revealed how channel spacing also controls circulation regime. Rip channel spacing typically varies between 50 and 500 m on natural beaches (Short and Brander, 1999; MacMahan et al., 2006) and Castelle et al. (2014b) showed that under constant shore-normal moderate wave forcing the ratio of surf zone width X_s to rip spacing λ exerted a significant control on surf zone exit rates. X_s/λ represents a measure of the alongshore constraint of the large-scale vortices associated with the rip currents (Fig. 15a). Below a threshold of about $X_s/\lambda = 1$, increased rip spacing relative to X_s rapidly increased exit rates (Castelle et al., 2014b). This has also been observed in the field by Houser et al. (2013) and McCarroll et al. (2014b). Simulations by Castelle et al. (2014b) also indicated that weak rips appear to flush more floating material out of the surf zone than strong rips (Fig. 15), supporting the field results of Scott et al. (2014).

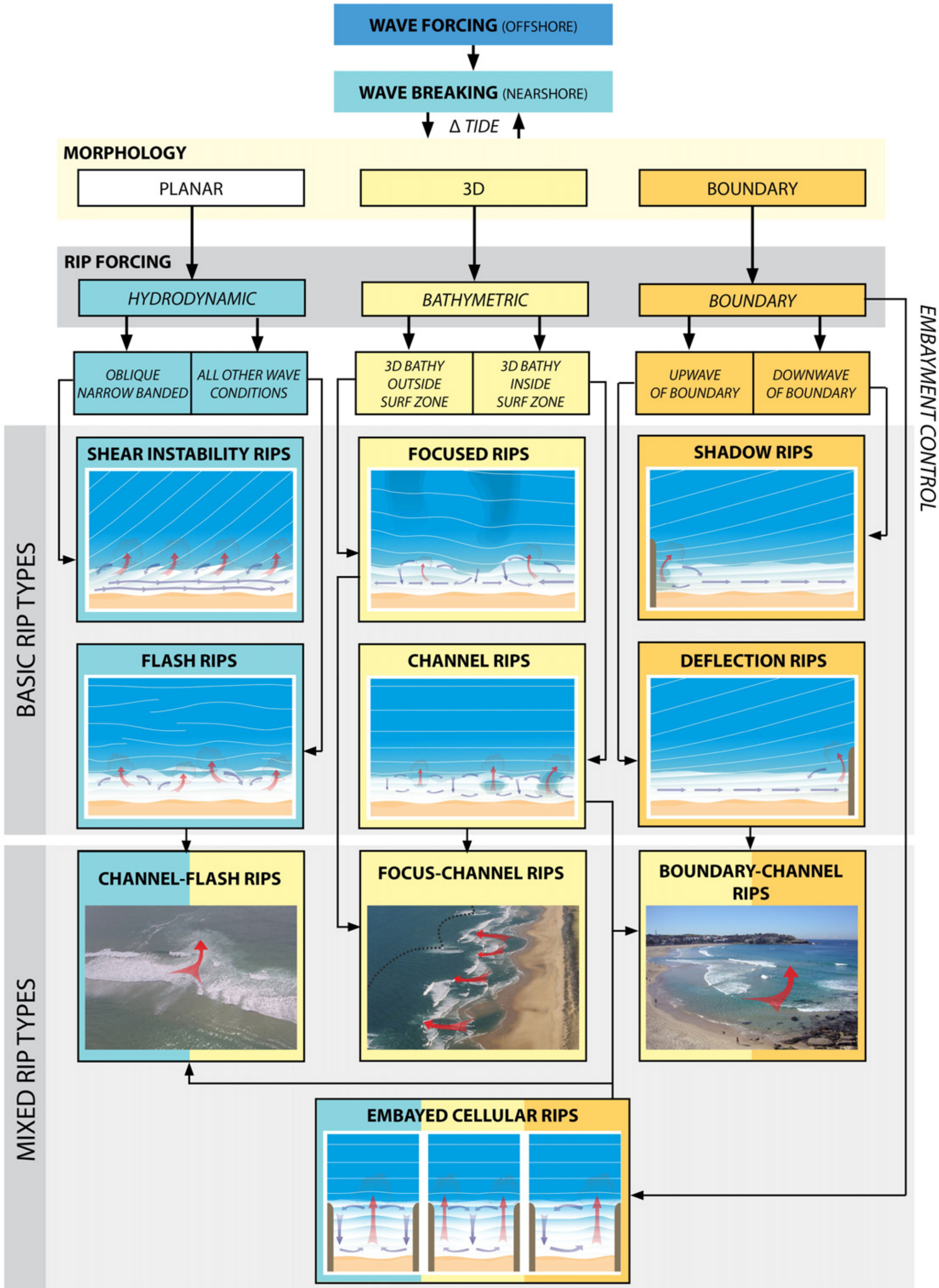


Fig. 13. Summary diagram showing the rip type classification framework.

Focused rips can inhabit a broad range of scales and behaviours dependant of the degree of focusing, wave energy and alongshore length scales involved. The location and strength of rip flows are modulated by wave height, period and angle of incidence where flow velocities typically increase with greater degrees of wave focusing through increased wave period and wave height (Long and Özkan-Haller, 2016). Long and Özkan-Haller (2016) also demonstrate that the direction of offshore waves is the primary parameter controlling the occurrence of focused rips, with waves approaching with large angles of incidence inducing a strong longshore current that dominates the nearshore circulation. Focused rip circulation is typically characterized by exit flow regime with flow extending well beyond the surf zone (Shepard and Inman, 1950; Long and Özkan-Haller, 2005, 2016), although offshore rip flow extension appears to decrease with increasing angle of wave incidence (Long and Özkan-Haller, 2016).

4.3. Boundary-controlled rips

Wave height, wave direction and boundary geometry all play key roles in controlling both rip current flow velocities and circulation

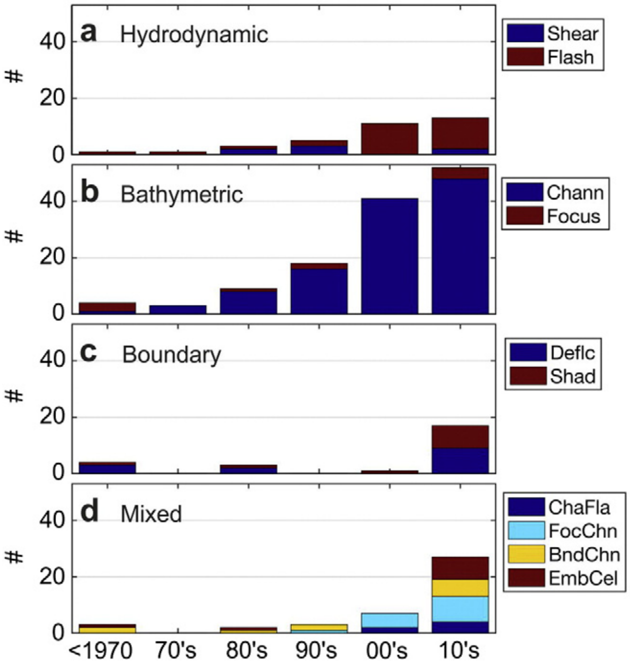


Fig. 14. Temporal progression in the number of publications between 1925 and April 2016 related to the rip current types described in Section 3. Rip type abbreviations: Channel (Chann), Focused (Focus), Deflection (Deflc), Shadow (Shad), Channel-Flash (ChaFla), Focus-Channel (FocChn), Boundary-Channel (BndChn), Embayed-Cellular (EmbCel).

regime of boundary rip currents. In terms of flow velocity, the relationships are reasonably straightforward. For shadow rips, the wave angle to shore normal and boundary geometry itself determine the degree of wave shadowing and therefore the gradient of alongshore wave dissipation driving boundary rip flow circulation (Pattiaratchi et al., 2009). In the case of deflected boundary rips, both breaking wave angle and wave height control longshore current strength and therefore offshore-directed rip current flow velocity. The relative length of the boundary structure (L_g) (e.g. headland or groyne) to surf zone width X_s is a key control on flow dynamics (Scott et al., 2016).

Only recently has boundary rip current circulation been studied in detail (Fig. 14c). Observations and modelling of deflected rip flows around groyne fields by Scott et al. (2016) showed three clear circulation regimes (Fig. 17a): 1) where $0 < L_g/X_s < 0.5$, no significant offshore deflection occurs and rip flow velocity is close to the natural alongshore current velocity; 2) increasing groyne length to $0.5 < L_g/X_s < 1.25$, rip flow velocity is maximized as alongshore flow around the boundary tip is compressed within the surf zone, offshore deflection increases, but typically remains part of meandering alongshore current; and 3) when $L_g/X_s > 1.25$ offshore deflection and exit behaviour rapidly increases and rip flow velocity decreases to a quasi-constant speed as flow is fully deflected and no momentum is exchanged to the downwave embayment. Modelling and laboratory studies (Wind and Vreugdenhil, 1986; Castelle and Coco, 2013) and field experiments in both wind-wave groyne fields (Scott et al., 2016) and swell-dominated headland embayments (McCarroll et al., 2014b) show that deflection rips are typically associated with very high exit rates, often with offshore mean flow pattern extending multiple surf zone widths offshore (Fig. 17b).

In contrast, shadow rips are characterized by strongly (weakly) recirculating rips in energetic swell (low-energy wind) wave environments (Fig. 17b). Maximum exits occur when the active boundary length is greater than the surf zone width ($L_g/X_s > 1$) (Castelle and Coco, 2014; Scott et al., 2016; Fig. 17a). Only two studies have addressed the behaviour of deflection and shadow rips within a single embayment (Castelle and Coco, 2013; McCarroll et al., 2014b) enabling comparison between types under the same wave forcing. Using numerical simulations, Castelle and Coco (2013) found that in embayments dominated by boundary rips, exit rates were greater than channel rips. McCarroll et al. (2014b) also measured two headland boundary rips simultaneously within the same embayment (Fig. 18) and observed >80% exit rates from the downstream deflection rip (typically a concentrated offshore jet with exit flow regime) and only 22% exit rates from the upstream shadow rip, which was dominated by a circulatory flow regime.

4.4. Mixed rip types

In reality, all surf zones exhibit directionally spread, variable wave forcing (MacMahan et al., 2010b), therefore all rip types experience variable breaking wave vortical forcing (Fig. 6). For channel rips, the transient surf zone eddies generated by wave breaking interact with the mean flow and result in variable flow behaviour in the very low frequency (VLF, O(10 min)) band (MacMahan et al., 2010b). The flash-channel continuum can be analysed by examining mean velocity, forced by differential wave breaking, as well as variable velocity and circulation, related to transient eddies. In a laboratory model, Castelle et al. (2010) examined Lagrangian flow across a full downstate transition, from a rhythmic bar to an attached terrace. In this case, higher alongshore bathymetric non-uniformity was associated with higher mean velocities and greater velocity variability through pulsing. By opposition, more planar beach states exhibited lower mean velocities and greater directional variability, which is in line with more recent works (e.g. Murray et al., 2013; McCarroll et al., 2016a).

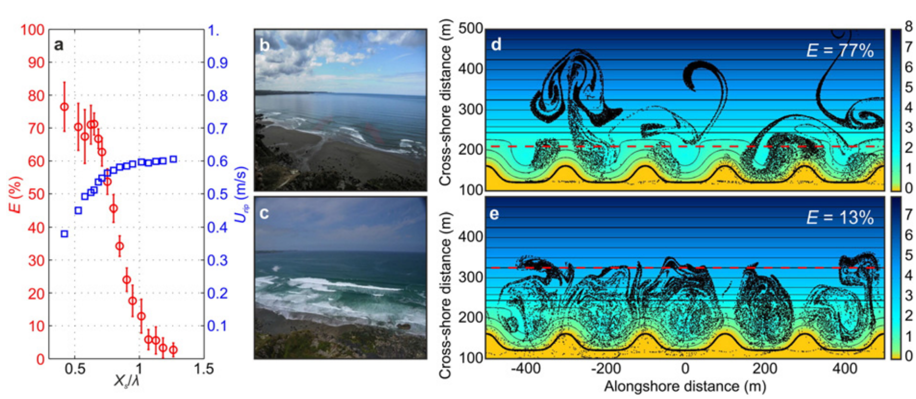


Fig. 15. Relationships between flow response, wave forcing (surf zone width) and rip channel spacing (adapted from Castelle et al., 2014b). Left panel shows modelled response of hourly surf zone exit rate (E) using XBeach model (Roelvink et al., 2009), with variable shore normal wave forcing (surf zone width is X_s) and fixed channel spacing (λ) of 200 m. Exit rate (E) is in red and rip flow velocity (U_{rip}) in blue. Right panel shows synoptic examples of model results with both narrow and wide surf zones. Virtual drifters are black dots and red dashed line is surf zone limit. Middle panel provides real-world example of the simulated behaviour in west Cornwall, UK (photos Timothy Scott).

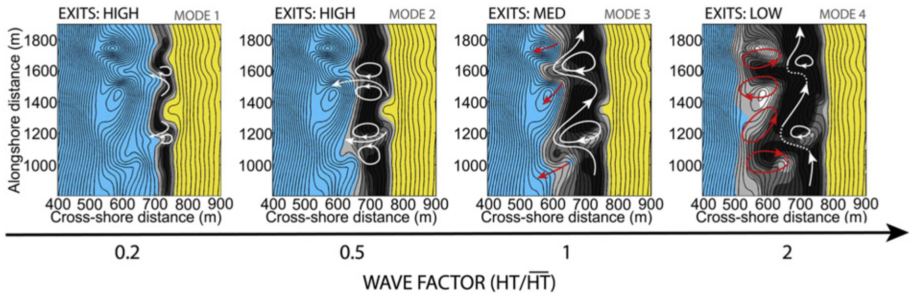


Fig. 16. Synthesis of flow behaviours from validated XBeach model simulations over measured bathymetry at Perranporth Beach in the UK showing how wave forcing ($H_sT_p/\overline{H_sT_p}$) can control circulation regime over a rip-channelled morphology (adapted from Scott et al., 2014). Greyscale is wave dissipation from high (black) to low (light grey).

Concerning mixed focus-channel rips flowing along double-barred beaches Scott et al. (2014) show that with increasing wave height, breaking throughout the outer and rip head bar system can enclose the inner rip system and induce onshore flows (reduced alongshore gradient in wave breaking along outer bar) that can reduce offshore exchange (Fig. 16; Mode 4). Recent studies have also suggested that the combination of channel rips and focused rips, derived from bathymetric anomalies in the inner-shelf, can affect exit rates. Rip circulation cells can extend well beyond the surf zone limit in the lee of the anomaly and between wave focusing hotspots (Castelle et al., 2014b), providing a conduit or barrier for transporting floating material out of the surf zone and into the inner shelf region. Overall, these recent studies highlight that circulation regime of channel rips can be strongly influenced by offshore bathymetric anomalies (e.g. rip head bar, outer bar, canyon), which characterizes mixed focus-channel rip types.

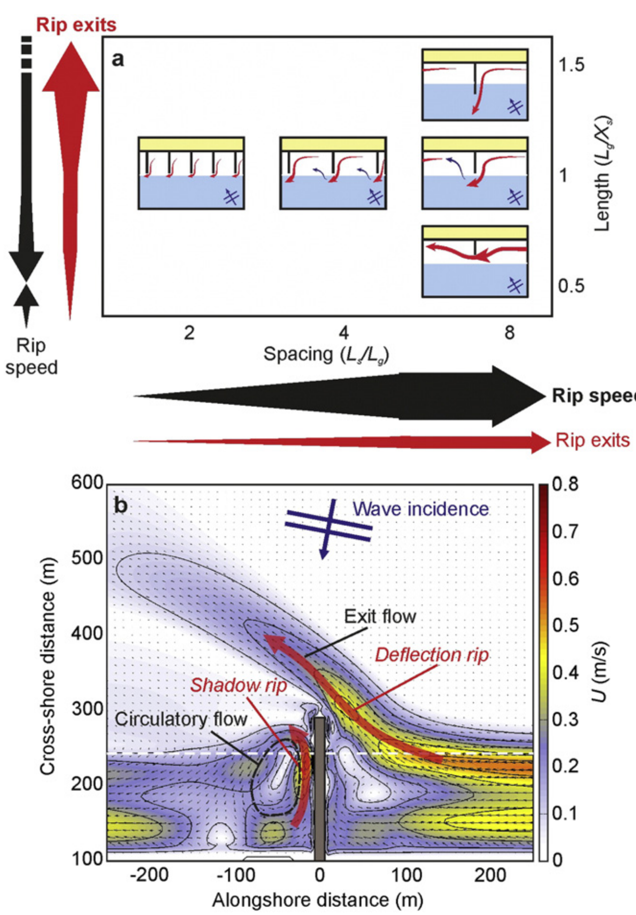


Fig. 17. (a) Summary of force-response relationships of deflection rips at Boscombe beach, UK (adapted from Scott et al., 2016). (b) Simulation of Shadow and deflection rips showing clear circulatory and exit flow regimes, respectively. Surf-zone edge is dashed (adapted from Castelle and Coco, 2014).

On embayed beaches, rip flow becomes increasingly embayed-cellular with increasing wave height and decreasing embayment size (Short and Masselink, 1999; Castelle and Coco, 2012). Simulations by Scott et al. (2016) and Castelle and Coco (2012) identified that the prevalence of a downwave deflection rip typically diminishes with reduced embayment width for both groyne fields and headland embayments respectively (see Fig. 17a). Ultimately, circulation becomes cellular (Fig. 12). Higher exit rates occur through the shadow rip, in contrast with traditional shadow rip circulation regime, as the longshore current does not have enough room to develop within the embayment (Castelle and Coco, 2013). Fig. 19 illustrates how overall exit rates within embayments were found to increase with decreasing embayment width L_s in numerical simulations (Castelle and Coco, 2013). Although thresholds in δ have not been systematically verified (McCarroll et al., 2016b), this work demonstrated that embayed beaches have systematically higher exit rates than typical open beach channel rips and that floating material is also more rapidly expelled from the surf zone. Exit flow behaviour is maximized for narrow embayment and large wave height i.e. for embayed-cellular rips and absence of pure boundary and channel rips.

An important characteristic on embayed beaches and boundary rips is their ability to maintain rip circulation under larger wave conditions. The term 'mega-rip' has been used rather loosely to describe rip currents occurring under high-energy or extreme wave conditions (Short, 2007). The term is commonly used to describe large, high-velocity rip flows that occur under high-energy cellular circulatory conditions. These rips are characterized by strong flows extending well beyond the surf zone. Short (2007) and Loureiro et al. (2012b) both argue that mega-rips have high exit rates and are important agents for cross-shore exchange during storms along the Atlantic coast of Portugal and in SE Australia, where mega-rip velocities can reach 3 m/s and extend 1–2 km offshore (Coutts-Smith, 2004). Loureiro et al. (2012b) and McCarroll et al. (2014b) identified characteristic (wide and deep) antecedent rip channel morphologies created by cellular mid-beach mega-rip flows, and hypothesized their role in heightening channel/surf zone width ratios and enhancing rip exit rates in channel rips under lower energy conditions.

4.5. Flow response summary

Table 1 provides a summary of the key force-response relationships described in Section 4. It must be noted that this is an idealised, non-exhaustive representation of a complex, nonlinear reality. For hydrodynamic rip currents, flash rips increase in intensity with increased breaking wave height. However, the correlation between increased wave height and flash rip cross-shore exchange is yet to be verified.

In terms of bathymetric rip currents, low-energy channel rips typically exhibit low velocities, but with higher rates of exchange (exit flow regime), due to narrow surf zones and an absence of breaking in the rip channel (Fig. 15b, d). As wave height and channel depth are

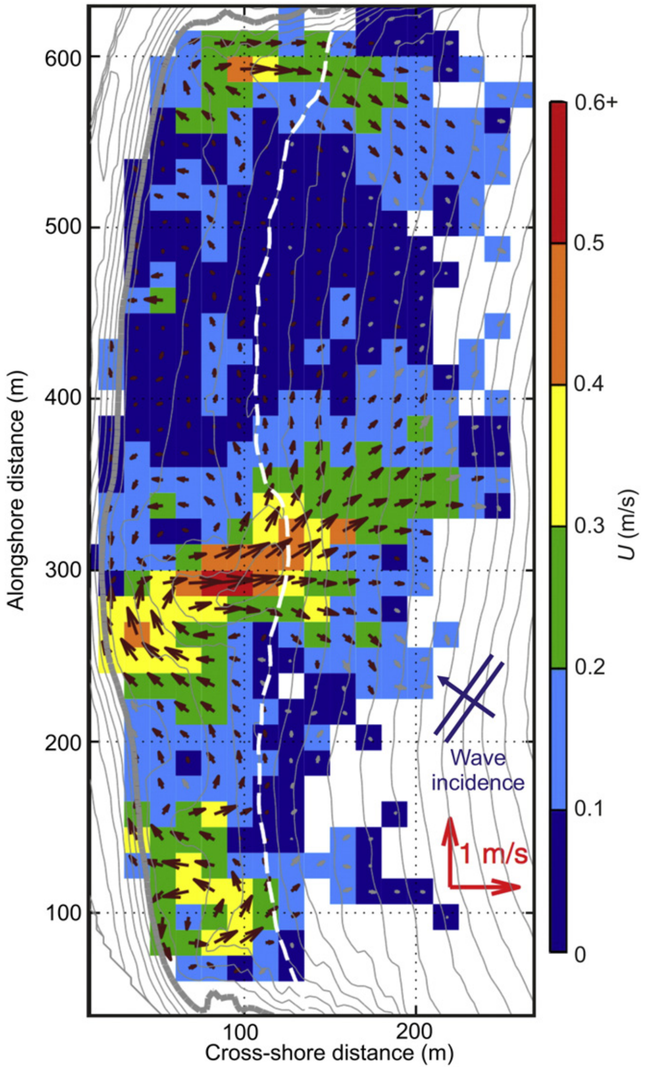


Fig. 18. Synoptic Lagrangian velocity field determined from mean of independent observations for a drifter experiment at the embayed Whale Beach, Australia (shoreline is bold and surf-zone edge is dashed, adapted from McCarroll et al., 2014b).

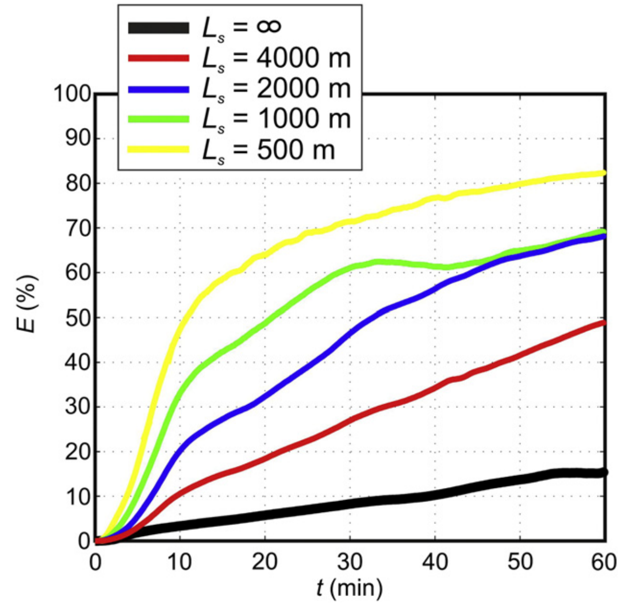


Fig. 19. Time series of surf-zone exit rate for obliquely incident waves and varying embayment width L_s (adapted from Castelle and Coco, 2013).

increased, or water level is decreased, channel rips asymptotically increase in velocity as alongshore wave breaking gradients increase, but asymptotically decrease in cross-shore exchange due to the wider surf zone and possible breaking across the rip channel (Fig. 15a, c). As wave heights increase further saturating the surf zone, or as water level drops to expose sand bars thereby reducing onshore flow over the bars, the alongshore dissipation and pressure gradients required to drive rip flow are reduced, resulting in lower velocities and exchange. Focused rips exhibit higher velocities and cross-shore exchange rates with low wave angle and long wave period.

Finally for boundary rip currents, shadow rips typically have low rates of exchange. Rip flow correlates positively with increases in wave energy and increases in wave angle, though rates of exchange remain low compared to other rip types. For deflection rips, as wave angle, wave height and boundary spacing is increased, the longshore current becomes stronger, leading to increased velocity and exit rates. Additionally, as boundary extent (relative to surf zone width) is increased, exit rates increase.

5. Implications for beach safety hazard

Rip currents each year cause hundreds of drowning deaths and tens of thousands of rescues on beaches worldwide (e.g. Gensini and Ashley, 2009; Brewster, 2010; Brighton et al., 2013; Arozarena et al., 2015) and are the leading deadly hazard to recreational beach users (Brander and Scott, 2016). Accordingly, how bathers caught in a rip should react or attempt to escape is a research question of great societal importance. While rip flow speed clearly relates to how fast rips can carry bathers offshore (Drozdzewski et al., 2012), it is the rip flow circulation regime that ultimately dictates the optimum strategy to escape rips (e.g. McCarroll et al., 2015; Castelle et al., 2016). Because of the traditional exit flow perception (Fig. 3a), early beach safety advice for beach users being caught in a rip was to "swim parallel" to the beach to escape the rip in order to reach safety on an adjacent shallow sand bar, or to just swim out of the rip. In contrast, the concept of circulatory flow regime (Fig. 3b) with typical full recirculation time of 5–10 min supports the "stay afloat" escape strategy to minimize bather energy expenditure as recirculation should carry bathers to shallower and safer depths on the order of minutes (MacMahan et al., 2010a). However, this dichotomy masks the considerable natural variability in morphological and hydrodynamic rip current forcing that blur the best safety message to promote to the general public.

Table 1
Summary of force-response relationships by rip current type. Variables: H – breaking wave height; T – wave period; U – mean velocity; U_rms – RMS velocity; σ_θ – directional spreading; σ_z – bathymetric 3-dimensionality; EXITS – rate of surf zone exits; h – water depth; λ – rip spacing; Ls – alongshore boundary spacing; Lg – cross-shore boundary extent; Xs – surf zone width. Responses with (?) are unconfirmed.

Hydrodynamic	Bathymetric	Boundary
FLASH	CHANNEL Low to moderate energy conditions	SHADOW
Force: ↑ *H*	*Force:* ↑ *H*, σ_z, ↓ *h*, λ	*Force:* ↑ *H*, θ
Response: ↑ U_{rms}, *EXITS*(?)	*Response:* ↑ *U*, ↓ *EXITS*	*Response:* ↑ *U*, ↑ *EXITS*(?)
SHEAR	FOCUSED	DEFLECTION
Force: ↑ *H*, *T*, ↓θ, σ_θ	*Force:* ↑ *H*, *T*, ↓ θ	*Force:* ↑ *H*, θ
Response: ↑ U_{rms}, *EXITS*	*Response:* ↑ *U*, *EXITS*(?)	*Response:* ↑ *U*
		Force: ↑ L_s/L_g
		Response: ↑ *U*, *EXITS*
		Force: ↑ L_g/X_s
		Response: ↑ *EXITS*, ↓ *U*

Recently, intensive experiments on rip current escape strategies involving GPS-equipped drifters and swimmers were conducted by McCarroll et al. (2014b) and Van Leeuwen et al. (2016), with neither the "swim parallel" nor "stay afloat" strategies found to be 100% successful. In order to overcome ethical issues and explore a wider range of wave-tide conditions and bather characteristics, McCarroll et al. (2015) developed the first numerical model of bathers escaping from a rip current applied to a single rip current system. It was shown that time to safety typically decreases for taller bathers with greater swim speeds, and that slow and steady swimming may be more successful than simply staying afloat. The model was subsequently used to address escape strategies at four nearby inner-bar rip current systems in SW France (Castelle et al., 2016). Of note, it was found that for normal to near-normal wave incidence, the optimal rip current escape strategy in a given rip current system can be the worst strategy at a nearby rip system. This is due to subtle differences in bar/rip morphology, which can greatly affect rip flow regime and the resulting optimal escape strategy.

A conceptual model of rip escape outcomes from both the field experiments (McCarroll et al., 2014b; Van Leeuwen et al., 2016) and numerical modelling (McCarroll et al., 2015; Castelle et al., 2016) is presented in Fig. 20, indicating the pros and cons of the "swim parallel" and "stay afloat" strategies in channel rips. Float failures are related to exit flow regime (Fig. 20a), though this strategy is more successful under a circulation flow regime (Fig. 20b). Swim parallel is a successful strategy when the swimmer is moving perpendicular to a cross-shore flow, such as under an exit regime (Fig. 20c). However the swim parallel strategy may fail when the swim trajectory is directed against alongshore feeder currents or the outer alongshore part of the circulation (Fig. 20d).

Both field and modelling results of rip escapes clearly indicate that promotion of a singular and universal 'rip current escape strategy' educational message to beachgoers is not appropriate, or safe. However, for obliquely incident waves "swim parallel" downdrift then swim onshore with breaking waves is found to be highly successful for channel rips (McCarroll et al., 2015; Castelle et al., 2016; Fig. 20d).

In close interaction with beach safety educators and practitioners, the International Life Saving Federation synthesized the studies discussed above and recently endorsed a standard suite of rip current survival safety for beachgoers caught in a rip: (1) Do not panic - conserve your energy and consider your options; (2) Stay Calm and Seek Help – particularly if you are close to a supervised location; (3) Float – go with the rip current and see if you are returned to shallower water; (4) Swim Parallel to the current – across the rip towards areas of breaking waves; (5) Regularly reassess the situation – confirm your decided course of action is working. If not, try an alternative.

Additional field and numerical swimmer experiments are encouraged in rip current types other than channel rips. All the rip current escape studies discussed above essentially address channel rips. However, we show that spatial and temporal rip flow response, which dictates the optimum strategy to escape rips, strongly depends on rip type. Given that flash rips are episodic and unpredictable bursts of water jetting offshore with generally no preferred direction and alongshore migration, the best rip current escape strategy at any given time is likely completely random. For other rip types, the safety advice may be reasonably straightforward to follow for beach goers. For instance, it is expected that swimming parallel away from an obstacle (e.g. groyne, headland) is the optimum strategy to escape boundary rips.

It should be noted, that existing swimmer escape strategy studies, both field or modelling based, do not replicate real world scenarios as they are both conducted in controlled environments and therefore cannot assess the critical social and psychological elements of how people will actually react to being caught in a rip current and the varying rip current types and flow conditions they may encounter. Studies of this nature are clearly needed before any sort of rip current educational strategies can be safely promoted to the general beach-going public. It is therefore encouraging to see the recent increase in social science based rip current studies (Fig. 2e).

6. Summary and conclusions

6.1. Summary

Surf-zone rip currents are narrow wave-driven seaward flowing jets of water originating within the surf zone on beaches along most wave-exposed coasts. However, this broad definition masks considerable temporal and spatial variability in terms of their occurrence, flow characteristics and behaviour. While rip current flow has been widely studied, the circulation patterns, or flow regime, of rip currents has only recently received dedicated scientific attention. This is despite rip circulation being a critical component to the transport and cross-shore mixing of heat, sediments, pollutants, nutrients and biota and of clear importance to beach safety and lifeguarding. Over the last 15 years, a growing body of rip current literature has greatly enhanced our understanding of the formation and dynamics of rip currents, including circulation regime. From a review of recent scientific advances in our understanding of rip currents based on theoretical, numerical, laboratory modelling and field measurement approaches, a comprehensive and robust rip current type classification has been developed, which provides a further framework to understand and predict rip current flow on wave-exposed coasts worldwide.

We have demonstrated that rip currents can be robustly classified into three broad categories based on the dominant controlling forcing mechanism. Each category is further divided into two types owing to different physical driving mechanisms, for a total of six fundamentally different surf-zone rip current types:

- *Hydrodynamically-controlled rips* are transient in both time and space, occur on alongshore-uniform beaches and are essentially driven by hydrodynamic forcing mechanisms: (1) *shear instability rips* form through shear instabilities of strong longshore currents, in contrast to (2) *flash rips* that preferably develop for weak or absent mean longshore current through short-scale vorticity evolving freely as migrating surf-zone eddies.
- *Bathymetrically-controlled rips* occur at relatively fixed locations and are driven by hydrodynamic processes strongly influenced by natural variability in alongshore three-dimensional (vertical) morphology in both the surf zone and inner shelf zone: (3) *channel rips* are driven by alongshore variation in breaking wave energy dissipation due to alongshore variability in water depth and typically occupy deeper channels where depth-induced breaking is weaker or absent while (4) *focused rips* are due to alongshore variability in breaking wave height and breaking wave angle enforced by wave refraction and/or breaking across offshore bathymetric anomalies.
- *Boundary-controlled rips* are dominated by the influence of rigid lateral boundaries, such as natural headlands or anthropogenic structures (groynes, piers) and are therefore fixed in space and time as they flow against them: (5) *deflection rips* occur on the downwave side of the boundary and are driven by the deflection of the longshore current against this obstacle, while (6) *shadow rips* occur on the opposite side of the boundary and are driven by the alongshore variation in breaking wave height owing to wave shadowing effect of the obstacle.

It is important to recognize that in reality, many rip currents form through a mixture of driving mechanisms and that these discrete rip types in fact form key elements in a wide and complex spectrum of rip currents on natural beaches. Four examples of mixed rip types characterized by their worldwide ubiquity have been described: *channel-flash rips*; *focus-channel rips*; *boundary-channel rips* and *embayed cellular rips*. Overall, this rip current type classification (Fig. 13), provides a new conceptual framework to classify these rip

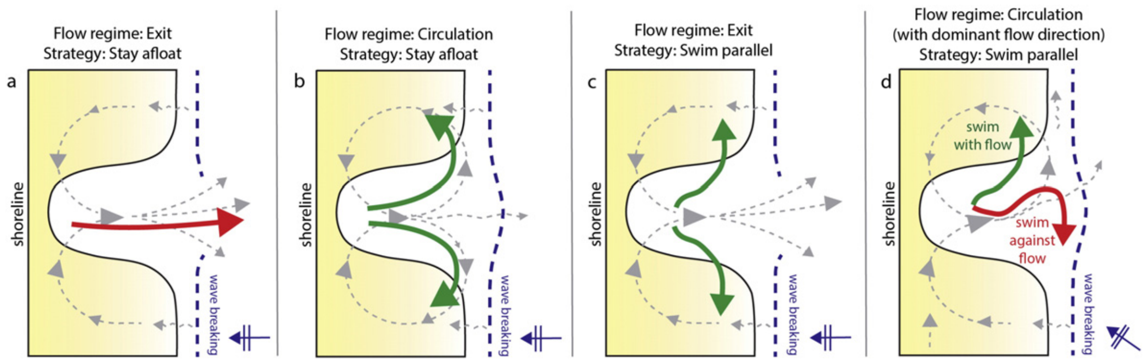


Fig. 20. Channel rip current escape strategies ("Stay afloat" and "Swim parallel") under various flow regimes, with successful escape strategies (green arrows), unsuccessful escape strategies (red arrows) and underlying flow field (grey dashed arrows) indicated.

currents and their driving mechanisms on beaches. This should be of benefit to coastal scientists, non-specialists and beach safety practitioners alike, the latter of which provides the most practical outcome of this classification.

The development in the early 00's and subsequent worldwide use of GPS-equipped surf-zone drifters to address Lagrangian rip current flow behaviour, together with important progress in numerical modelling, has provided unprecedented insight into rip current circulation regimes. Rip currents have long been perceived as narrow offshore-directed flows extending well beyond the breakers and flushing out the surf zone at a high rate ("exit flow" regime). Instead, it has been shown that rip flow patterns sometimes consist of quasi-steady semi-enclosed vortices retaining most of the floating material within the surf zone ("circulatory behaviour"). Recent studies from the early 10's revealed that this dichotomy between circulating and exit flows masks a considerable variability with reported offshore exit rates per hour varying from 0 to 100%. The rip current type classification developed in this review paper provides a relevant framework to understand the primary morphological and hydrodynamic parameters controlling rip current flow regime (see Table 1). For instance, previously referred to simply as "topographic rips", when classified in terms of the forcing mechanism boundary-controlled rips can be discriminated into different types based on wave deflection and shadowing mechanisms. These differences are crucial for understanding and predicting changes in boundary rip flow velocity and circulation regime in response to varying wave and boundary geometry conditions. Overall, greater advances in our understanding of rip current flow regime have been made on channel rips and boundary controlled-rips as they are essentially fixed in location and therefore reasonably easier to measure. However, there are still many unknowns for the other rip types, with the behaviour of mixed rip types being even more uncertain.

6.2. Future research and concluding remarks

The purpose of this review is to present a classification of the different types of rip currents that exist on beaches based on their physical forcing mechanisms, which control rip flow behaviour. It incorporates results from the many recent field, laboratory and modelling efforts (Fig. 2) that have provided valuable new information on rip current circulation behaviour and patterns in varied environments. It is hoped that the classification will serve as a resource for coastal scientists and non-specialists with an interest in the rip current hazard and will serve as a platform for future rip current studies.

Many accomplishments have been achieved, particularly over the last two decades, on rip current dynamics including driving mechanisms and flow response. However, overall, the coastal community is only at an early stage of understanding rip current flow regimes, as evident by the many unknown exit rate trends in Table 1. There is a clear need for additional field measurements of Lagrangian rip flow studies to be undertaken in a wide range of wave-tide-morphology conditions and particular rip current types. Given the amount of surf-zone-swimming-capable scientists and drifters required to collect dense Lagrangian measurements in a single rip current system, inter-institutional and international field campaigns should be encouraged. This is particularly relevant for rip types that have received little attention so far (Table 1), including mixed rip types and channel rips over crescentic bars. In addition, to date there is no universal definition for the outer edge of the surf zone, which is important to further compute flushing rates and to characterize rip flow regime. Such a definition, which must be compatible with the data collected through field and laboratory measurements, remote-sensing and numerical modelling, will be important to provide consistent assessment and comparison of flow circulation regimes and exit rates between rip types.

Collecting Eulerian and particularly Lagrangian data during severe storms is one of the greatest challenges for future rip current research. For obvious ethical and safety reasons, it is challenging to both release and retrieve drifters in these conditions. Instead, deploying GPS-equipped drifters using, for instance, Global System for Mobile Communications (GSM) technology offers capability to monitor and collect the data in real-time and to further retrieve the drifters after the storm. Remote-sensing of nearshore currents also appears as a potential avenue to monitor surface rip current flows, particularly during storms. Optical remote-sensing has already shown encouraging results to monitor surf-zone surface currents (Puleo et al., 2003; Chickadel et al., 2003; Holman and Haller, 2013; Almar et al., 2016), but has never been applied to a rip flow field. Even more promising is the observation of rip currents from X-band radar images (Haller et al., 2014), which has the potential to provide rip current surface flow data at unprecedented spatial and temporal resolution. Because these remotely-sensed techniques cover relatively large spatial areas, they are particularly suitable for hydrodynamically-controlled rips that are transient in occurrence in space and time. Of note, these methods only track surface flow currents, which are critical in carrying bathers offshore. However, measuring and modelling the three-dimensional structure of rip currents will also help improve our understanding of rip current dynamics.

To date, most numerical modelling rip current efforts have been performed by time averaging the phase of gravity waves. However, changes in vorticity with the passage of individual short-crested breaking waves is critical to rip flow dynamics. Recent improvements in phase-resolving models and decrease in computation time has enabled many recent major advances in the understanding of non-stationary rip current flows (e.g. Feddersen, 2014). However, these modelling studies have essentially addressed the dynamics of surf-zone eddies and resulting flash rip activity on planar beaches. In future, this type of model should be used on bathymetries with different degrees of alongshore non-uniformity to explore the mixed channel-flash rip continuum between an idealised planar beach, with pure hydrodynamic control, and deep, well-defined rip channels with strong bathymetric control. This modelling framework should also be applied to other rip types, including boundary-controlled rips, as all natural rips have, to some degree, a component of transient eddy forcing. In addition, the swimmer modules developed in McCarroll et al. (2015) and Castelle et al. (2016) will benefit from the coupling with phase-resolving models to explore the optimum escape strategies for each rip current type within this wide and complex natural spectrum. Finally, other parameters such as inner-shelf water stratification and tidal currents are also expected to affect rip current circulation regime.

Rip currents have long been of strong interest mostly due to the coastal hazard they represent. The recent growing body of rip current literature dealing with beach safety and lifeguarding calls for future interdisciplinary studies at the crossroad of physics, psychology and physiology. It is expected that bringing together coastal and beach safety communities will improve rip current education and awareness, and will eventually meet the challenge of providing optimal safety messages to the general public. From the perspective of hazard to recreational beach users, the rip current type classification developed here also provides a relevant framework to understand and further predict the other coastal hazards and ecosystem modifications related to rip current activity.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2016.09.008.

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