Modelling the alongshore variability of optimum rip current escape strategies on a multiple rip-channelled beach

Bruno Castelle, R. Jak Mccarroll, Robert Brander, Timothy Scott, Benjamin Dubarbier

Modelling the alongshore variability of optimum rip current escape strategies on a multiple rip-channelled beach

Bruno Castelle[1], R. Jak McCarroll[2], Robert W. Brander[2], Timothy Scott[3], Benjamin Dubarbier[1]

[1]Univ. Bordeaux, CNRS, UMR EPOC 5805, 33615 Pessac, France

[2]School of Biological, Earth and Environmental Sciences, UNSW Australia, Sydney, NSW, Australia

[3]School of Marine Science and Engineering, Plymouth University, Drake Circus, Plymouth PL4 8AA, UK

Abstract: Rip currents are a leading cause of drowning on beaches worldwide. How bathers caught in a rip current should attempt to escape has been a subject of recent debate. A numerical model of human bathers escaping from a rip current flow field is applied to a 2-km long section of the open beach of Biscarrosse, SW France. The study area comprises 4 rip channels that visually appear similar from the beach, but exhibit different morphologies. Simulations are run for 2 representative hazardous summer wave conditions. Results show that small changes in the bar/rip morphology have a large impact on the rip flow field, and in turn on the alongshore variability of the optimal rip current escape strategy. The overall flow regime (dominant surf-zone exits versus dominant recirculation), which is found to be influenced by the alongshore dimensions of the sand bars adjacent to the rip channel, is more important to rip current escape strategy than rip velocity. Flow regime was found to dictate the success of the stay afloat strategy, with greater success for recirculating flow. By comparison, the dominant longshore feeder current and rip-neck orientation determined the best direction to swim parallel toward. For obliquely incident waves, swim parallel downdrift then swim onshore with breaking waves was highly successful and can become a simple safety message for beach safety practitioners to communicate to the general public. However, in SW France where rip spacing is large (∼400 m), surf-zone eddies have large spatial scales of the order of 100+ m, requiring a large distance (100+ m) to swim to reach safety, therefore requiring good swimming ability. This also shows that in addition to rip current intensity, rip flow regime and the depth of adjacent sand bars, rip spacing is important for defining rip current hazard and the best safety message. Our results also indicate that for normal to near-normal wave incidence, rip current hazard and best rip current escape strategy are highly variable alongshore due to subtle differences in bar/rip morphology from one rip system to another. These findings challenge the objective of developing a universal rip current escape strategy message on open rip-channelled beaches exposed to normal to near-normal wave incidence, even for seemingly similar rip channels. //

Keywords: Rip current; beach safety; escape strategy; alongshore variability; rip channel morphology; rip flow regime

1 Introduction

Surf-zone rip currents are intense and narrow wave-driven seaward-flowing jets of water that originate near the shoreline and sometimes extend beyond the breakers (MacMahan et al, 2006; Dalrymple et al, 2011). Although rip currents can be hazardous during extreme storms causing localized beach and dune erosion (Thornton et al, 2007; Loureiro et al, 2012; Castelle et al, 2015), they are arguably best known for the hazard they represent to beach users (Scott et al, 2011; Brander et al, 2013). Rip currents are hazardous to beach users because of their ability to carry unsuspecting bathers of all swimming abilities offshore into deeper water (Drozdzewski et al, 2012), each year causing hundreds of drowning deaths and tens of thousands rescues worldwide (e.g. Gensini and Ashley, 2009; Brewster, 2010; Brighton et al, 2013; Arozanera et al, 2015).

Rip currents can be transient in occurrence in space and time when hydrodynamically controlled (e.g. Ozkan-Haller and Kirby, 1999; Feddersen, 2014). Rip currents can also be relatively persistent in space and time when morphologically controlled. For instance, rip currents can be found against natural or anthropogenic rigid structures (e.g. Pattiaratchi et al, 2009; Castelle and Coco, 2013; McCarroll et al, 2014a). More commonly, rip currents are driven by the alongshore variability in breaking wave height (Bowen, 1969) arising from different causes. In this paper we focus on rip currents flowing on rip-channelled beaches, which are driven by alongshore variability in breaking wave height owing to the alongshore variability in depth due to shallow bars and deeper rip channels (Haller et al, 2002; Bonneton et al, 2010; Bruneau et al, 2011). This rip current type is very common worldwide as it is a key element of intermediate beaches (Wright and Short, 1984), also known as rip-dominated intermediate beaches (Short, 2007).

Rip current hazard is influenced by rip current velocity, with beach users being carried offshore more rapidly with increasing rip current intensity. However, rip current flow regime is an additional critical parameter. Rip currents have long been perceived as strong and narrow flows extending well beyond the surf zone (e.g. Shepard et al, 1941; Inman et al, 1971), a flow regime hereafter referred to as *exit flow*. As a result, 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. Instead, the recent development and increasing worldwide use of GPS-equipped surf-zone drifters (e.g. Johnson et al, 2004; Schmidt et al, 2003; MacMahan et al, 2009) challenged this early understanding. MacMahan et al (2010) suggested that rip flow patterns on rip-channelled beaches consist of quasi-steady semi-enclosed vortices, a flow regime hereafter referred to as *recirculating flow*, that retain floating material within the surf zone with full circulation taking roughly 5-10 minutes to complete. Based on this new perception of rip current flow behaviour, MacMahan et al (2010) proposed an alternative stay afloat rip current escape strategy to minimize bather energy expenditure as the recirculation would carry bathers to shallower and safer depths on the order of minutes. Of note, this dichotomous discrimination between recirculating and exit flows masks a considerable variability evident by many recent field, numerical and laboratory studies that show a large variability in the ability of rip currents to flush out the surf zone (Austin et al, 2010, 2013; Castelle et al, 2010; Houser et al, 2013; Castelle et al, 2014; McCarroll et al, 2014a; Winter et al, 2014; Scott et al, 2014).

Field studies on rip current escape strategies are scarce and limited to a small number of swimmers (e.g. Miloshis and Stephenson, 2011). The first intensive field testing of the different bather strategies was performed by McCarroll et al (2014b) at Shelly Beach, NSW, Australia, in 3 rip currents over 3 days in varying wave conditions. Surf-zone capable swimmers were deployed in the surf zone, under the supervision of lifeguard and lifesaving personnel. While floating was found to be a longer duration and more variable escape strategy than swimming parallel, neither scenario was 100% fool proof. Float failures mostly related to exit flows while failures in swimming parallel mostly resulted from swimming against longshore-directed currents of the rip current circulation cell. Using field data on another NSW beach, Van Leeuwen et al (in press) showed that the morphology and depth of the sand bars adjacent to the rip current was an additional important parameter to the optimal rip current escape strategy. However, due to logistical and ethical concerns, the number of swimmers used during these experiments was very limited, therefore there has been minimal examination of how bathers caught in rip currents should attempt to escape. To overcome this issue, McCarroll et al (2015) developed the first numerical model of bathers escaping from a rip current, with application to a single rip current system on an Australian beach. The simulations suggested that slow sustainable swimming may be a preferable escape action to floating, and that optimal swim direction varied with start location, from onshore (near the shoreline), parallel to shore (mid-rip channel) and diagonally onshore (outer rip channel). McCarroll et al (2015) also performed a sensitivity analysis of swimmer speed and height, with changes to human parameters showing predictable results as time to safety was found to decrease for taller bathers with greater swim speeds. However, these findings were specific to a given rip channel on a given beach for a limited range of wave-tide conditions, resulting in the analysis of only 2 contrasting rip flow patterns. This is an important limitation because many studies show that rip currents are highly variable in both space and time (e.g. MacMahan et al, 2010; Bruneau et al, 2011; Scott et al, 2014; McCarroll et al, 2014a). McCarroll et al (2015) concluded that the model should be applied to additional surf zone rip current morphologies and wave-tide inputs, with a goal of determining generalised rip escape principles that may be communicated to the general public.

Most studies dealing with rip-current-related drowning deaths and rescues have been performed in the United States, Australia and England, but little is known on the ocean-wave-exposed SW coast of France. However, rips are ubiquitous along beaches of SW France (Bruneau et al, 2009b). Deep rip channels with an apparently similar morphology cut the sand bar approximately every 400 m along 200+ km of almost uninterrupted open beaches, resulting in 500+ hazardous rip currents flowing every summer day along this coast. Recently, Tellier (2014) showed on a 110-km section of the SW coast of France that, on average, approximately only 5 drowning deaths related to rip currents occur between April and September each year, which masks the thousands of rescues by on-duty lifeguards. Results also show that most of the drowning deaths occur on unpatrolled beaches, highlighting the need to both broaden lifeguard protection

(Branche and Stewart, 2001) and better understand and communicate on rip current hazard and escape strategies.

In this paper, we build on the modelling work of McCarroll et al (2015) who addressed in detail the influence of bather height and swim speed on escape outcome in a single rip current system. Here, by comparison, here we address multiple rip current systems along an open beach for 2 representative wave conditions, implying a broad range of rip current flow behaviours. The alongshore variability of the hazard posed by multiple rip currents is addressed numerically, with an overreaching goal of determining generalised rip escape principles that may be communicated to the general public. In Section 2, the general settings of SW France open beaches and the main characteristics of the rip currents are given. The numerical modelling approach and model set-up are described in Section 3. The results are presented in Section 4 and further discussed in Section 5 before conclusions are drawn in Section 6. We show that, for obliquely incident waves, swim parallel downdrift then swim onshore with breaking waves is systematically highly successful. In contrast, we also show that for near shore-normal incident waves subtle differences in bar/rip morphology have a profound impact on the rip flow field and resulting best rip current escape strategies. This suggests that, even for open-coast beaches where the rip current systems seemingly replicate multiple times alongshore with consistent characteristics, rip current hazard is in fact highly variable alongshore.

2 Field site

2.1 General settings

Biscarrosse beach, SW France, is located approximately 10 km south of the Arcachon Lagoon entrance (Fig. 1) and is representative of most of the open-coast sandy beaches of SW France. Beaches are meso- to macro-tidal with an annual mean spring tidal range and a maximum tidal range of approximately 3.7 m and 5 m, respectively. The strongly seasonally dominated wave climate is energetic, with a dominant W to NW incidence (Butel et al, 2002) resulting in a dominant southerly longshore drift (Idier et al, 2013). The 2-month-averaged significant wave height H_s ranges from about 1.2 m in summer to about 2.5 m in winter with common 7+m high storm wave events (Castelle et al, 2015). The mean grain size is about 0.35 - 0.4 mm although there is a large spatial variability related to the morphological variability (Gallagher et al, 2011).

2.2 Beach morphology

Beaches are mostly intermediate double-barred (Castelle et al, 2007). The outer bar is most of the time crescentic. The inner bar is modally rip-channelled and can go through all the states within the intermediate classification, with a dominant transverse bar and rip state (Sénéchal et al, 2009). Mean rip spacing of the inner and outer bars is about 400 m and 700 m, respectively, along the Gironde coast, with mean spacing increasing southward (Lafon et al, 2005; Castelle et al, 2015). Because the outer bar is deep (about 3-7 m below mean sea level) and located far offshore (about 400-500 m from the beach), outer-bar rip currents are generally inactive during the summer months and do not pose a hazard to beach users. Instead, inner-bar rip currents are ubiquitous throughout summer.

The traditional perception of the inner-bar and rip morphology in SW France is that shown in Fig. 2a-d. The morphology is often assumed as an alongshore inner bar cut by regularly spaced and southward-oriented deep channels. However, the inner-bar rip channels are often irregularly spaced with considerable variability in orientation and shape along the beach (Fig. 2g, see also Castelle et al, 2006; Bruneau et al, 2009b; Almar et al, 2010). During summers, the inner-bar morphology slowly evolves (mean southerly migration of about 2 m/day Lafon et al, 2002), with occasional merging and splitting, as a result of low-energy wave conditions and large rip-spacing. However, rapid morphological changes can be driven by rare summer storms.

2.3 Inner-bar rip current dynamics

Inner-bar rip currents are ubiquitous and can be intense (∼1m/s) even for reasonably low wave height (∼1 m, see for instance Fig. 2e, f, and field measurements in Bruneau et al, 2009b). A notable characteristic of inner-bar rips in SW France is their striking tidal modulation owing to the meso- macro-tidal range. Depending on inner-bar morphology and tidal range, rip current activity is generally maximized between low-tide and mid-tide for typical summer wave conditions (e.g. Castelle et al, 2006; Castelle and Bonneton, 2006; Bruneau et al, 2009b, 2011, 2014), with the notable absence of rip currents between mid-tide and high-tide. Between low-tide and mid-tide, rip current intensity is maximized for long-period waves ($T_p \geq 10$ s) and shore-normal wave incidence. Eulerian (Castelle et al, 2006; Bruneau et al, 2009b) and Lagrangian (Bruneau et al, 2009a; MacMahan et al, 2010) measurements are scarce in SW France, and are restricted to only a few days and hours of measurements, respectively. Accordingly, little is known on the ability of inner-bar rip currents to expel bathers offshore on this section of coast.

2.4 Summer wave conditions

18.3 years of modelled wave data calibrated with measurements collected at the Candhis directional buoy (Fig. 1 Castelle et al, 2015) are used to assess the typical summer wave conditions in SW France. When $H_s > 1.5$-2 m, beach users are usually not allowed to enter the water by lifeguards, and the rough seas discourage bathing on unpatrolled beaches. Days when $H_s \approx 1$ m are often the most hazardous (see the detailed assessment of a UK beach in Scott et al, 2014) because (1) beach users of all swimming abilities are likely to bathe in the surf zone and (2) rip currents can be intense (e.g. Bruneau et al, 2009b). Fig. 3 shows the scattered directional plot of measured significant wave height H_s and peak wave period T_p during July, August and September, having a mean H_s of 1.19 m, 1.15 m and 1.35 m, respectively. Fig. 3 shows short-period ($T_p < 8$ s) waves at a wide range of direction from W to NW. In contrast, long-period waves (swells, $T_p \geq 10$ s) are observed at a wide range of direction mostly for $H_s > 1.5$ m. Swell events with $H_s < 1.5$ m are typically observed with normal to near-normally incident waves. Accordingly, in the following modelling exercise, 2 representative common and hazardous summer wave conditions will be used: (1) shore-normal swell waves; (2) oblique NW seas.

3 Numerical model

In this study, the modelling approach developed by McCarroll et al (2015) is used. Below we focus on both the key assumptions of the modelling strategy and the slight differences to the approach of McCarroll et al (2015).

3.1 Hydrodynamic model

The open source model XBeach (Roelvink et al, 2009), Easter 2012 version, is used to simulate waves and wave-driven currents, here switching off sediment transport and bottom changes. XBeach simulates the wave-group forced infragravity (O(1 min)) and very low frequency (O(10 min)) motions which are important to sporadically expel material out of the surf zone through rip pulsation even for dominantly recirculating flow. This model has been widely used to study rip current dynamics (e.g. Reniers et al, 2009, 2010; Castelle et al, 2014) and has been found to be in good agreement with field measurements (e.g. Austin et al, 2013; Winter et al, 2014). The generalized Lagrangian mean flow velocities, i.e. the time-varying surface currents, are further used to carry the numerical bathers.

3.2 Rip escape model

Bathers are initially seeded as points within a given domain of interest with, at each time step Δt, the mean depth $\bar{d}$, the instantaneous wave-driven current $\vec{U}$ and the mean current intensity $\bar{U}$ interpolated at the position x (easting in metres) and y (northing in metres) of each simulated bather. At each time step, a safety condition check is performed with the bather assumed to have reached safety depth if (1) the bather is in a water depth less than a user-defined safe depth ($\bar{d} < d_{safe}$) or (2) if the local hazard rating HR does not exceed a certain threshold HR_{safe} (McCarroll et al, 2015) with:

$$HR = \bar{d}(\bar{U} + 0.5) \tag{1}$$

Time-averaged velocity $\bar{U}$ and depth $\bar{h}$ were used to address safety instead of instantaneous values. This estimated time-averaged local hazard rating was chosen to prevent bathers being alternately safe and unsafe on the sand bar on the timescales of infragravity rip current pulsation. Bathers would therefore be wrongfully set safe in the infragravity-wave trough, while they are likely to be subsequently swept back into the channel at the passage of the infragravity wave crest. At each time step, if a bather is not safe, bather velocity U_{bather} is computed in vectorial form as $\vec{U_{bather}} = \vec{U} + \vec{U_{swim}}$ where $\vec{U_{swim}}$ is swim velocity which can be set to any compass direction. For the stay afloat strategy, U_{swim} is set to 0. Following the work of McCarroll et al (2015), an additional *swim onshore with waves* condition was implemented for any bather located at more than a certain distance alongshore from the rip channel. Such bathers therefore swim onshore at 20° from shore-normal, away from the rip they have been caught in, at a velocity U_{sow}.

These steps are iterated through until a maximum time limit t_{max} is reached. Bathers who have reached safety at any time-step are given a final duration (t_{safe}) and are excluded from further calculations. At the end of the simulation, bathers that have not reached a point of safety are given a duration of t_{max}. For each scenario, failure rate F is computed as the number of bathers with $t_{safe} = t_{max}$ at the end of the simulation expressed as the percentage of the total number of active bathers initially seeded.

3.3 Model set-up

XBeach model was run on the Biscarrosse beach morphology surveyed during the June 2007 experiment (Bruneau et al, 2009b). Fig. 4 shows Biscarrosse beach on June 18, 2007, with the 4 rip current systems addressed in this study highlighted by the absence of breaking waves. These rip current systems are hereafter referred to as *Rip1*, *Rip2*, *Rip3* and *Rip4*. Clearly Rip2, Rip3 and Rip4 have very similar characteristics when observed from the beach (Fig. 4). Fig. 5 shows the surveyed bathymetry comprising 6 rip channels, with Rip1, Rip2, Rip3 and Rip4 in the centre of the domain. One only has to take a quick glance at the bathymetry to realise that the 4 rip systems have different bar/rip morphologies.

The numerical domain extends approximately 1000 m and 2000 m in the cross-shore and alongshore direction, respectively, with a 10 x 10 m resolution grid. Simulations were run for 90 minutes with a time step of 1 s. Only the last 20 minutes of the simulations were used to compute the rip current escape strategies in order to have a dynamically stable non-stationary flow field out of the transition regime. Two XBeach simulations were performed, both representative of summer wave conditions that can be hazardous to beach users of all swimming abilities during lower tides. Both simulations were run between low-tide and mid-tide (0.8 m below mean sea level) with the summer wave conditions discussed in Section 2.4: (1) shore-normal ($\theta = 288°$) swell waves with $H_s = 1$ m, $T_p = 10$ s hereafter referred to as Run1; (2) obliquely-incident NW seas with $H_s = 1$ m; $T_p = 7$ s and $\theta = 308°$ (i.e. 20° N of shore-normal) hereafter referred to as Run2.

McCarroll et al (2014b) performed a detailed sensitivity analysis of swimmer speed and height, as well as statistics on the spatial and temporal variability of each escape strategy on a single rip current system. Here the focus is on the alongshore variability of rip current hazard. Accordingly, average bather/swimmer characteristics were used, corresponding to $d_{safe} = 0.9$ m; $HR_{safe} = 0.6$ m^2/s; $U_{swim} = 0.3$ m/s; $U_{sow} = 0.3$ m/s. This swim speed is suggested as being representative of a moderately experienced surf zone swimmer (McCarroll et al, 2015), however it is important to note that data on non-elite swimmer speeds in the surf zone are extremely limited. The moderate value $U_{swim} = 0.3$ m/s is substantially below the swim speed of professional lifeguards in the surf zone of 0.7-0.9 m/s (Tipton et al, 2008).To prevent edge effects, only the 4 middle rip channels Rip1, Rip2, Rip3 and Rip4 are addressed here. In order not to bias the analysis, all the boundary boxes where escape strategy statistics are performed have the same alongshore length of 170 m. Fig. 5 also shows the boundary boxes away from the rip currents where the bathers are determined to swim onshore with waves. Finally, in contrast with McCarroll et al (2015), here t_{max} is set to 20 min instead of 10 min as the rip current systems at Biscarrosse have larger spatial scales than at Whale beach. Keeping $t_{max} = 10$ min would have strongly limited the number of bathers reaching a safe depth by the end of the simulation. Accordingly, our simulations are underpinned by the premise that rip currents in SW France are more hazardous to beach users than that of Whale beach addressed in McCarroll et al (2015), which will be discussed in Section 5.2.

4 Results

4.1 Mean flow patterns

Simulated wave-driven mean currents are shown in Fig. 6. For Run1 (Fig. 6a), 4 established and alongshore-variable rip current systems are observed along the beach. Rip1 is weak (∼0.4 m/s) with a rather wide and shore-normal exit flow extending a few hundred metres offshore. Rip2 is narrow and reasonably intense (∼0.65 m/s) with the notable absence of south-flowing feeder current. The rip flows slightly southward with a flow regime between exit and recirculating. Rip3, with 2 well-established feeder currents, is reasonably intense (∼0.65 m/s) and flows slightly northward. It is characterized by recirculating flow regime. Rip4 is very different to the 3 other rips as it is reasonably weak (∼0.5 m/s), southward flowing and extends very far offshore (exit flow). Rip4 is also strongly asymmetric with an intense (∼0.85 m/s) north-flowing feeder current and the absence of south-flowing feeder current.

Rip flow patterns are very different for Run2 (Fig. 6b) owing to the obliquely incident waves driving a dominant southerly longshore current. Whilst Rip2 and Rip4 are still clearly flowing offshore, although characterized by a recirculating/meandering flow oriented southward, both Rip1 and Rip3 are overwhelmed by an undulating longshore current with a weak (∼0.2-0.3 m/s) offshore-directed component in the channel.

The inspection of the mean flow fields in Fig. 6 highlights a large alongshore variability in the rip flow field on this open beach for both wave conditions. In addition, it shows that small changes in wave conditions, here the period and angle of incidence, can have a profound impact on the rip flow fields.

4.2 Rip current escape simulations

Fig. 7 and 8 show the spatial distributions of escape simulations for Run1 and Run2, respectively. Histogram summary statistics for the 2 simulations given in Fig. 9 are based only on the active bathers initially seeded in the rip boundary boxes (blue boxes in Fig. 5, 6, 7 and 8).

4.2.1 Stay afloat

In agreement with McCarroll et al (2013), the outcome of the stay afloat strategy (left-hand panels in Fig. 7 and 8) is dictated by the flow regime. For Run1, a large number of bathers are expelled far offshore through Rip1, Rip2 and Rip4 which are mostly characterized by exit flow regime. More surprisingly, and while for Rip1 and Rip2 all the bathers are carried offshore in deep water, for Rip4 there is an additional hazardous zone around the centre of the rip eddy where bathers recirculate multiple times. A similar hazardous zone exists within Rip3 during Run1 which explains a high failure rate (F = 32.2%) for a recirculating flow. Stay afloat is more successful for Run2 for which there is no exit flow regime along the beach. However, there is a large variability of stay afloat outcome as while Rip1 has a failure rate of $F = 51.6\%$ (Fig. 9cc), Rip2 has a very low one ($F = 0.8\%$, Fig. 9u), which is the lowest failure rate of all stay afloat simulations. Overall in Run2, a vast majority of floating bathers caught in the rip reached safe depth on the downdrift shallow sand bar, most of them having to swim onshore with waves when away from the rip (Fig. 8e).

4.2.2 Swim parallel northward

The outcome of swim parallel northward strategy is more complex. For Run2, the bathers swim against the dominant longshore current, which results in a failure rate larger than 50% for the 4 rip currents (Fig. 9). Even if bathers are not carried far offshore, they systematically swim against the current both inside and at the outer edge of the surf zone. For the shore-normal swell conditions (Run1), the outcome of swim parallel northward is more variable (Fig. 7b, f), but is systematically more successful than stay afloat. Swim parallel northward is less successful for Rip1 ($F = 25.3\%$, Fig. 9z) and Rip4 ($F = 35.7\%$, Fig. 9b), both characterized by exit flow, corresponding to bathers being caught by the rip and swimming northward at the outer edge of the surf zone. These bathers cannot reach safe depth in due time (Fig. 7b, f). Rip2 and Rip3 have more successful outcomes with 75.5% and 62.3% of bathers reaching safety depth within 10 minutes (Fig. 9j, r). However, whilst failure rate is only 3.6% for Rip2, 23.8% of bathers do not reach safe depth within 20 min in Rip3. This corresponds to bathers trapped in a hazardous zone around the centre of the northern rip eddy where bathers recirculate multiple times (Fig. 7b, f).

4.2.3 Swim onshore

The swim onshore strategy is quite successful for Run2 (Fig. 8c, g). For Rip1 ($F = 0$), Rip2 ($F = 1.2\%$) and Rip3 ($F = 0$) almost all the bathers reach safety on the downdrift shallow bar within a reasonably short time, that is, 75.9%, 94.7% and 100% within 10 min (Fig. 9), respectively. Rip4 is more hazardous because a number of bathers recirculate multiple time within the downdrift eddy without reaching safety (Fig. 8c, g). Although the swim onshore strategy is less successful for Run1 than for Run2, a large number of bathers swimming onshore reach safe depth for Run1. Surprisingly enough and in contrast with Run2, Rip4 is now the least hazardous ($F = 5.7\%$). Instead, Rip1 ($F = 34.7\%$), Rip2 ($F = 28.5\%$) and Rip3 ($F = 52.0\%$) are dangerous to bathers swimming onshore with a lot of bathers being stuck in the rip channel when swimming against the rip neck (see red areas in the channels, Fig. 7g). Another interesting characteristic of the swim onshore strategy is that the highest rates of success are simulated at the early stage of the swimming action (third column in Fig. 9).

4.2.4 Swin parallel southward

Swim parallel southward is quite successful for Run2 (Fig. 8d, h) as the bathers rapidly reach safe depth on the downdrift shallow sand bar. However, this strategy is not systematically more successful than swimming onshore as most of the bathers are carried farther offshore and subsequently take more time to reach safety. This is why most hazardous areas are located at the seaward edge of the boundary box (Fig. 8h). The swimming parallel southward strategy is much less efficient for Run1, particular for Rip3 (F = 73.3%, Fig. 9l) that flows northward and, to a lesser extent, Rip2 (F = 47.0%, Fig. 9t) and Rip4 (F = 40.3%, Fig. 9d) which are characterized by strong and dominant northerly feeder currents. As opposed to the swim parallel northward strategy, bathers who do not reach safe depth by the end of the simulation recirculate multiple times within the southern rip eddy (Rip2, Rip3 and Rip4 in Fig. 7d). Overall, for Run1 there is a large alongshore variability in the outcome of swim parallel southward strategy.

5 Discussion

5.1 Alongshore variability of rip current hazard and best rip current escape strategy

The modelling of bather rip current escape strategies on Biscarrosse beach shows a large alongshore variability of rip current hazard and escape strategy outcome. The 4 rip current systems are exposed to the same wave conditions and are morphologically controlled by bar/rip morphologies which, when observed from the beach, are seemingly similar (Fig. 4). However, the 4 rip current systems have in fact subtle morphological differences that result in contrasting rip current escape strategy outcomes. Fig. 10 synthesizes the histograms of t_{safe} for all escape strategies and wave conditions with discrimination of the 4 rip currents. Interestingly enough, combining all the rip current escape strategy outcomes, Rip2 (F = 25.3%) is the least hazardous rip current (F = 35.1%, 34.0% and 39.9% for Rip1, Rip3 and Rip4, respectively) despite Rip2 being the most intense rip current for both Run1 and Run2. This highlights that rip current hazard is not only dictated by the mean flow velocity in the rip neck. Instead, flow regime appears crucial to the degree of hazard posed. Rip2, which is overall the safest, has a clear recirculating flow behaviour for both Run1 and Run2, while Rip4 is the most hazardous rip current system owing to a dominant exit flow regime for Run1.

Modelling studies attempting to understand the hydrodynamic and morphologic factors impacting rip flow regime on rip-channelled beaches are scarce (Reniers et al, 2009; Castelle et al, 2014). Applying the same hydrodynamic model to a large number of idealized rip-channelled bathymetries, Castelle et al (2014) showed that for a given wave forcing, the exit flow character increases with increasing rip spacing. This is qualitatively verified here with the 2 rip currents showing a pronounced exit flow regime (Rip1 and Rip4 in Fig. 6) being those surrounded by long alongshore bars. In contrast, the two closely-spaced rip currents in the centre of the domain (Rip2 and Rip3) exhibit a more recirculating pattern (Fig. 6). This suggests that not only the rip channel morphology, but also the dimensions of the sand bars adjacent to the rip channel are important to the overall rip flow regime.

The alongshore variability in rip current hazard arising from other factors has been scarcely documented. Houser et al (2011) showed on a beach in Florida, US, that rip current hazard variability on lengthscales of approximately 1500 m is enforced by transverse ridges on the inner shelf. These offshore features force wave refraction and focusing at the ridge crests, enforcing a variability in beach state and rip current activity. Van Leeuwen et al (in press) studied two rip currents systems on Cronulla beach, Australia. They showed that one of the rip currents was more hazardous largely because of a lack of adjacent shallow sand bars. Here at Biscarrosse, where energy focussing is negligible and where the 4 rip channels are bounded by shallow shore-connected sand bars, the alongshore variability in rip current hazard in essentially controlled by more subtle differences in bar/rip morphology.

The alongshore variability of rip current hazard also strongly depends on wave conditions. For instance, assuming that the swim onshore strategy is promoted on Biscarrosse beach, Rip3 is the safest for Run2 as 100% of the bathers will have reached safe depth by only 10 min (Fig. 9o). However, for Run1 Rip3 is the most hazardous for bathers swimming onshore with a failure rate of 52.0%. Overall these results show that, on a natural open rip-channelled beach with more or less regularly spaced channels exposed to normal to near-normal incident waves, the alongshore variability of rip current hazard appears overly challenging to predict without using detailed process-based models.

Although it has not been tested here, tide acts as an additional parameter affecting the temporal and alongshore variability of rip current hazard through the modulation of breaker patterns. Not only do tides modulate rip velocity (e.g. Brander and Short, 2001; Austin et al, 2009; Bruneau et al, 2009b; Austin et al, 2014; Scott et al, 2014), but they also affect rip flow regime (Austin et al, 2014; Scott et al, 2014). For instance, both observation and numerical modelling showed on an Australian beach that a change of only tens of centimetres in tide elevation can change an exit flow rip current into a recirculating flow rip (McCarroll et al, 2014a, 2015). On meso- and macro-tidal beaches, the dominant rip flow regime at a given rip current system likely changes over the course of the tide cycle, therefore increasing both the temporal and spatial variability of rip current hazard and optimal rip current escape strategy.

5.2 Assessment of rip current escape strategies: implications for beach safety and limitations

In line with earlier field and numerical works (McCarroll et al, 2014b, 2015; Van Leeuwen et al, in press), no escape option was universally successful. All escape strategies failed for a given summer wave condition and/or for a given rip current system (Fig. 9). Fig. 11 summarizes the histograms of t_{safe} for each escape strategy averaged over all the rip systems and the 2 wave conditions.

Surprisingly enough swim onshore was, *from a physical science perspective*, the most successful strategy across all the scenarios (Fig. 11). Although with a mean fail rate $F = 18.6\%$, more than 19% of bathers on average reach safe depth within only 2 minutes. Failures of the swim onshore strategy occurs in the rip neck when bathers are stuck in the channel when swimming against the offshore-directed flow (Fig. 7c, g). An interesting feature is that the overall rate of success of the swim onshore strategy decreases with time (Fig. 11c). In real life, bathers will not realise they are actually caught in a rip current until it is too late to swim onshore successfully. In addition, here the simulations are for numerical bathers swimming onshore to a fixed compass point. In real life, the situation might not be as clear cut. Bathers in distress who are panicking often adopt a fight or flight response (Brander et al, 2011) which may involve attempting to swim back to the point they entered the water, or simply try to get to the beach at any point. Quantification of such information has not yet been achieved, however, Drozdzewski et al (2012, 2015) describe the actual experiences of people who have been caught in rip currents showing that the onset of panic is partly associated with the need to swim back to safety. Accounting for the onset of panic in the numerical model will be challenging. This statement is also relevant for field studies because of ethical issues. The swimmers involved in the field experiments (McCarroll et al, 2014b; Van Leeuwen et al, in press) know they will be rescued by lifeguard and lifesaving personnel if the escape strategy does not work. They therefore cannot feel the sense of impending drowning that triggers the onset of panic when a bather tries to swim onshore and realizes that he/she makes no progress. Finally, since bathers who realize they are caught in a rip will naturally and instinctively try to swim onshore, it may therefore not be necessary to advocate this strategy as it is a natural response. Instead, it may be that safety messages should focus on alternate escape actions if the initial impulsive reaction to swim towards shore does not work. As such, the findings of this study and others (McCarroll et al, 2014b, 2015; Van Leeuwen et al, in press) which show the advantages of a swim onshore strategy must be considered with extreme caution and should only be communicated in the first instance to beach safety practitioners.

Overall, Swim parallel was highly variable depending if swimming northward (Fig. 11b) or southward (Fig. 11d), but was the overall optimal escape strategy if in the direction of the dominant alongshore flow. During Run2, for which the dominant southerly alongshore flow is obvious owing to the NW obliquely incident waves, swim parallel southward was highly successful ($F = 2.3\%$ averaged across the 4 rip systems, 3 out of the 4 rips with $F = 0$). Accordingly, on open beaches exposed to obliquely incident waves, to swim parallel downdrift then to swim onshore over the bar with breaking waves appears as an optimal and simple escape strategy. However, for normal and near-normal wave incidence, there is no obvious dominant flow. Instead, the dominant alongshore flow can vary from one rip system to another. For instance, during Run1, Rip 1 and Rip2 have a dominant southerly and northerly longshore feeder current, respectively (Fig. 6). Accordingly, swim parallel northward and southward is highly successful for Rip2 and Rip1, respectively, with swimming towards the other direction being a high failure rate action. Determining the dominant longshore feeder currents on open beaches exposed to normal and near-normal wave incidence is something only expert surf-zone users and experienced lifeguards can do. Accordingly, we suspect that open rip-channelled beaches exposed to normal to near-normal wave incidence are highly complex as far as universal rip current escape strategy messaging is concerned.

For the stay afloat strategy, flow regime has a strong influence on outcome. Consistent with observation (McCarroll et al, 2014b), it was the only strategy where bathers are carried far offshore outside of the surf zone (Fig. 7a). Averaged across all scenarios and rip systems, stay afloat is the strategy with the highest rate of failure at our study site ($F = 47.8\%$, Fig. 11a). However, energy expenditure is not accounted for in the simulations which is likely increasingly crucial for weaker and less experienced bathers. As discussed by McCarroll et al (2014b), new data on human surf-zone behaviour, the experiences of people caught in rips, and physiology are needed before accurately comparing the stay afloat strategy with other more active and energy-expending strategies. In addition, because flow regime is critical to stay afloat outcome, more field and numerical studies addressing flow regime as a function of wave and morphological conditions are needed.

It has been previously demonstrated (McCarroll et al, 2015) that escape times decrease with increased bather height and swim speed, therefore only a single swimmer type was used in this study. Rip current intensity and flow regime, and as a result optimal rip current escape strategy, are highly sensitive to wave conditions, tide elevation and bar/channel morphology. A limited number of rip-channelled morphologies and wave/tide conditions were addressed here. Our results are therefore part of a continuum that can only be thoroughly addressed through a full sensitivity analysis of wave height, period and direction, tide and rip beach morphology. Further improving our model and applying it to other sites with contrasting hydrodynamic conditions and geological settings will provide insight onto this continuum. In addition, all rip current escape studies, including ours, primarily addressed rip currents driven by alongshore variability in breaking wave height owing to the alongshore variability in depth due to shallow bars and deeper rip channels. Although such channelized rips are very common, other rip current types flow along wave-exposed beaches. For instance, topographic rips can flow against permanent topographic features such as headlands or coastal structures (Pattiaratchi et al, 2009; Castelle and Coco, 2013; Scott et al, 2016), flash rips are transient in both time and space (e.g. Ozkan-Haller and Kirby, 1999; Feddersen, 2014; Suanda and Feddersen, 2015) and some rip currents can also be enforced by offshore bathymetric anomalies (Long and Ozkan-Haller, 2005; Castelle et al, 2012). These studies showed unique flow behaviours, suggesting that safety outcomes may contrast with what has been found for existing studies on rip current escape strategies on rip-channelled beaches.

All simulations have been performed using $t_{max} = 20$ min, that is, assuming that a given action fails if the bather does not reach safety within 20 minutes. However, only bathers with good swimming abilities can swim more than 5 minutes at 0.3 m/s in the surf zone. A t_{max} of 20 minutes is also long compared to existing studies based on field measurements (McCarroll et al, 2014b; Van Leeuwen et al, in press) and numerical experiments McCarroll et al (2015), which used $t_{max} = 10$ minutes. In the latter studies rip spacing is on the order of 100-150 m, with a bar crest located some 50 m from the mean sea level shoreline, that is, with similar morphological characteristics to many Lagrangian flow rip current studies (e.g. MacMahan et al, 2005; Houser et al, 2013). In this situation, surf-zone eddies have alongshore scales of the order of 50 m with full circulation taking roughly 5-10 minutes to complete (MacMahan et al, 2010). In SW, France, rip spacing is on average of 400 m and surf-zone eddies have alongshore scales of the order of 100-150 m similar to UK sites (Austin et al, 2010), implying a circulation time longer than 10 minutes. Fig. 12 shows some examples of trajectories for stay afloat action during Run1 zoomed onto Rip2, Rip3 and Rip4. For Rip2 and Rip3, the typical circulation time is roughly 10 minutes although it can vary considerably depending on where the bather has been caught by the rip. For Rip4, which has larger spatial scales, it ranges from about 10 to 20 minutes (Fig. 12). Therefore, whatever the escape strategy used, bathers in SW France will take more time to reach safety than on most of other documented beaches. Accordingly, given the level of swimming ability required to swim during 5-10+ minutes in the surf zone, swimming to reach safety in SW France is a risky message. Overall, this shows that whilst rip current intensity, rip flow regime, the depth of adjacent sand bars and bather characteristic sare important to rip current hazard and best safety message, rip spacing is also important as it influences the lengthscales of surf-zone eddies and, as a result, circulation time and swimming duration to reach safety.

6 Conclusions

A numerical model of humans escaping from a rip current was applied to a 2-km long section of the open rip-channelled beach of Biscarrosse, SW France. 4 distinct bar/rip channel systems with different morphological characteristics were addressed. 4 rip current escape strategies were systematically tested, namely stay afloat, swim parallel northward and southward and swim onshore. Simulations were run for 2 contrasting wave conditions that are representative of hazardous summer wave conditions in SW France. Results were analysed to address physical principles for optimal rip escape methods and their alongshore variability on open rip-channelled beaches worldwide.

Results show that small changes in the bar/rip morphology have a large impact on the rip flow field and in turn on the best rip current escape strategy. The overall flow regime, i.e. exit flow vs recirculating, was found to be more important to rip current escape strategy than rip current velocity. The flow regime is suspected to be influenced by the dimensions of the sand bars adjacent to the rip channel. The flow regime was found to dictate the stay afloat outcome while the dominant longshore feeder current controls the direction towards which to swim parallel. Averaged across all the scenarios tested here, swimming onshore was the most successful strategy, although large failure was found under certain conditions. Given that this strategy can favour the onset of panic and was addressed with some limitations, it is still not a safety message to promote. Instead, for obliquely incident waves, swim parallel downdrift then swim onshore with breaking waves was highly successful and can become a simple safety message for beach safety practitioners to communicate to the general public. However, in SW France where rip spacing is large ($\sim$400 m) and surf-zone eddies have 100+m alongshore scales, this systematically implies large distances to swim in the surf to reach safety. This can become a limiting factor for bathers with limited swimming ability and strengthens the relevance of the stay afloat strategy. These results show that in addition to rip current intensity, rip flow regime and sand bar depth, the spacing of rip current channels is a critical determinant of the rip current hazard and the type of rip current safety message promoted to the general public.

Our results indicate that on open rip-channelled beaches exposed to normal to near-normal wave incidence, rip current hazard and best rip current escape strategy are highly variable alongshore. Subtle differences in bar/rip morphology from one rip system to another can drastically change flow regime and dominant longshore feeder current, which are crucial to rip current escape strategy. The best rip current escape strategy at a given rip current system can be the worst strategy at a nearby one. Accordingly, our study tempers many past rip current studies that have drawn broad implications from an individual rip current system. Here we highlight a fact obvious to expert surf-zone lifeguards, which is that rip currents vary considerably in both time and space and that site-specific studies should not be relied upon as far as universal rip current escape strategy message is concerned. As determining the dominant longshore feeder currents and dominant flow regime under these conditions is something only expert surf-zone users can do, developing a universal, simple and efficient rip current escape strategy message on open rip-channelled beaches exposed to normal to near-normal wave incidence is likely inaccessible. It is also important to note that our modelling study is inherently theoretical in application. More studies that address critical social and psychological elements of how people will actually react to varying rip current conditions are needed before escape strategies can be safely promoted to the general beachgoing public.

This study was performed in the framework of Project DECA (INSU/EC2CO). Additional funding was provided by the Australian Research Council (ARC), Surf Life Saving Australia through Linkage Project LP110200134 and the programme Invited Scholar (Idex, Univ. Bordeaux), the latter funding the stay of RJM and RWB at Univ. Bordeaux. We thank the 3 anonymous reviewers for their comments and constructive criticism

References

Almar R, Castelle B, Ruessink BG, Sénéchal N, Bonneton P, Marieu V (2010) Two- and three-dimensional double-sandbar system behaviour under intense wave forcing and a meso-macro tidal range. Continental Shelf Research 30:781–792

Arozanera I, Houser C, Echeverria AG, Brannstrom C (2015) The rip current hazard in Costa Rica. Natural Hazards 77:753–768

Austin M, Scott TM, Brown JW, Brown JA, MacMahan JH (2009) Macrotidal rip current experiment: circulation and dynamics. Journal of Coastal Research SI 56:24–28

Austin M, Scott TM, Brown JW, Brown JA, MacMahan JH, Masselink G, Russell P (2010) Temporal observations of rip current circulation on a macro-tidal beach. Continental Shelf Research 30:1149–1165

Austin M, Scott TM, Russell PE, Masselink G (2013) Rip Current Prediction: Development, Validation and Evaluation of an Operational Tool. Journal of Coastal Research 29(2):283–300

Austin M, Masselink G, Scott TM, Russell PE (2014) Water-level control on macro-tidal rip currents. Continental Shelf Research 75:28–40

Bonneton P, Bruneau N, Castelle B, Marche F (2010) Large-scale vorticity generation due to dissipating waves in the surf zone. Discrete and Continuous Dynamical Systems - Series B 13(4):729–738, DOI 10.3934/dcdsb.2010.13.729

Bowen AJ (1969) Rip currents: 1. Theoretical investigations. Journal of Geophysical Research 74:5479–5490

Branche CM, Stewart S (2001) Lifeguard effectiveness: A report of the Working Group. Atlanta

Brander RW, Short AD (2001) Flow kinematics of low-energy rip current systems. Journal of Coastal Research 17:468–481

Brander RW, Bradstreet A, Sherker S, MacMahan JH (2011) The behavioural responses of swimmers caught in rip currents: new perspectives on mitigating the global rip current hazard. International Journal of Aquatic Research and Education 5:476–482

Brander RW, Dominey-Howes D, Champion C, Del Vecchio O, Brighton B (2013) A new perspective on the Australian rip current hazard. Natural Hazards and Earth Science System Sciences 13:1687–1690

Brewster BC (2010) Rip current misunderstanding. Natural Hazards 55:161–162

Brighton B, Sherker S, Brander RW, Thompson M, Bradstreet A (2013) Rip current related drowning deaths and rescues in Australia 2004-2011. Natural Hazards and Earth Science System Sciences 13:1069–1075

Bruneau N, Castelle B, Bonneton P, Pedreros R (2009a) Very low frequency motions of a rip current system: observation and modeling. Journal of Coastal Research SI 56:1731–1735

Bruneau N, Castelle B, Bonneton P, Pedreros R, Almar R, Bonneton N, Bretel P, Parisot JP, Sénéchal N (2009b) Field observations of an evolving rip current on a meso-macrotidal well-developed inner bar and rip morphology. Continental Shelf Research 29:1650–1662

Bruneau N, Bonneton P, Castelle B, Pedreros R (2011) Modeling rip current circulations and vorticity in a high-energy meso-macrotidal environment. Journal of Geophysical Research 116(C07026), DOI 10.1029/2010JC006693

Bruneau N, Bertin X, Castelle B, Bonneton P (2014) Tide-induced flow signature in rip currents on a meso-macrotidal beach. Ocean Modelling 74:53–59

Butel R, Dupuis H, Bonneton P (2002) Spatial variability of wave conditions on the French Atlantic coast using in situ data. Journal of Coastal Research Special Issue No 36:96–108

Castelle B, Bonneton P (2006) Modelling of a rip current induced by waves over a ridge and runnel system on the Aquitanian Coast, France. Comptes Rendus Geoscience 338:711–717

Castelle B, Coco G (2013) Surf zone flushing on embayed beaches. Geophysical Research Letters 40:1–5, DOI 10.1002/grl.50485

Castelle B, Bonneton P, Sénéchal N, Dupuis H, Butel R, Michel D (2006) Dynamics of wave-induced currents over an alongshore non-uniform multiple-barred sandy beach on the Aquitanian Coast, France. Continental Shelf Research 26:113–131

Castelle B, Bonneton P, Dupuis H, Sénéchal N (2007) Double bar beach dynamics on the high-energy meso-macrotidal French Aquitanian Coast: a review. Marine Geology 245:141–159

Castelle B, Michallet H, Marieu V, Leckler F, Dubardier B, Lambert A, Berni C, Bonneton P, Barthelémy E, Bouchette F (2010) Laboratory experiment on rip current circulations over a moveable bed: Drifter measurements. Journal of Geophyical Research 115(C12008), DOI 10.1029/2010JC006343

Castelle B, Marieu V, Coco G, Bonneton P, Bruneau N, Ruessink BG (2012) On the impact of an offshore bathymetric anomaly on surfzone rip channels. Journal of Geophysical Research 117(F01038), DOI 10.1029/2011JF002141

Castelle B, Reniers AJHM, MacMahan JH (2014) Bathyemetric control of surf zone retention on a rip-channelled beach. Ocean Dynamics 64:1221–1231

Castelle B, Marieu V, Bujan S, Splinter KD, Robinet A, Senechal N, Ferreira S (2015) Impact of the winter 2013-2014 series of severe Western Europe storms on a double-barred sandy coast: Beach and dune erosion and megacusp embayments. Geomorphology 238:135–148

Dalrymple RA, MacMahan JH, Reniers AJHM, Nelko V (2011) Rip currents. Annual Review of Fluid Mechanics 43:551–581, DOI 10.1146/annurev-fluid-122109-160733

Drozdzewski D, Shaw W, Dominey-Howes D, Brander RW, Walton T, Gero A, Sherker S, Goff J, Edwick J (2012) Surveying rip current survivors: preliminary insights into the experiences of being caught in rip currents. Natural Hazards and Earth Systems Science 12:1201–1211

Drozdzewski D, Roberts A, Dominey-Howes D, Brander RW (2015) The experiences of weak and non-swimmers caught in rip currents at Australian beaches. Australian Geographer 46:15–32

Feddersen F (2014) The generation of surfzone eddies in a strong alongshore current. Journal of Physical Oceanography 44:600–617

Gallagher EL, MacMahan JH, Reniers A, Brown J, Thornton EB (2011) Grain size variability on a rip-channeled beach. Marine Geology 1-4:43–53

Gensini VA, Ashley WS (2009) An examination of rip current fatalities in the United States. Natural Hazards 54:159–175

Haller MC, Dalrymple RA, Svendsen IA (2002) Experimental study of nearshore dynamics on a barred beach with rip channels. Journal of Geophysical Research 107(C2), DOI 10.1029/2001JC000955

Houser C, Barrett G, Labude D (2011) Alongshore variation in the rip current hazard at Pensacola Beach, Florida. Natural Hazards 57:501–523

Houser C, Arnott R, Ulzhofer S, Barrett G (2013) Nearshore circulation over transverse bar and rip morphology with oblique wave forcing. Earth Surface Processes and Landforms 38:1269–1279

Idier D, Castelle B, Charles E, Mallet C (2013) Longshore sediment flux hindcast: spatio-temporal variability along the SW Atlantic coast of France. Journal of Coastal Research Special Issue No. 65:1785–1790

Inman D, Trait R, Nordstrom C (1971) Mixing in the surf zone. Journal of Geophysical Research 76:3493–3514

Johnson D, Stocker R, Head R, Imberger J, Pattiaratchi C (2004) A compact, low-cost GPS drifter for use in the oceanic nearshore zone, lakes, and estuaries. Journal of Atmospheric and oceanic technology 20(12):1880–1884

Lafon V, Dupuis H, Howa H, Froidefond JM (2002) Determining ridge and runnel longshore morphodynamics using SPOT imagery. Oceanologica Acta 25:149–158

Lafon V, Dupuis H, Butel R, Castelle B, Michel D, Howa H, De Melo Apoluceno D (2005) Morphodynamics of nearshore rhythmic sandbars in a mixed energy environment (SW France): II. Physical forcing analysis. Estuarine, Coastal and Shelf Science 65:449–462

Long JW, Ozkan-Haller HT (2005) Offshore controls on nearshore rip currents. Journal of Geophysical Research 110(C12007), DOI 10.1029/2005JC003018

Loureiro C, Ferreira O, Cooper JAG (2012) Extreme erosion on high-energy embayed beaches: Influence of megarips and storm grouping. Geomorphology 139-140:155–171

MacMahan JH, Thornton EB, Stanton TP, Reniers AJHM (2005) RIPEX-observations of a rip current system. Marine Geology 218:113–134

MacMahan JH, Thornton EB, Reniers AJHM (2006) Rip current review. Coastal Engineering 53:191–208, DOI 10.1016/j.coastaleng.2005.10.009

MacMahan JH, Brown JW, Thornton EB (2009) Low-cost handheld global positioning system for measuring surf-zone currents. Journal of Coastal Research 25:744–754

MacMahan JH, Brown JW, Brown JA, Thornton EB, Reniers AJHM, Stanton TP, Gallagher EL, Morison J, Austin MJ, Scott TM, Senechal N (2010) Mean lagrangian flow behavior on an open coast rip channeled beach: a new perspective. Marine Geology 268:1–15, DOI 10.1016/j.margeo.2009.09.011

McCarroll RJ, Brander RW, MacMahan JH, Turner IL, Reniers AJHM, Brown JA (2013) RIPSAFE: Rip Current Swimmer and Floater Experiments, Shelly Beach, NSW, Australia. Journal of Coastal Research Special Issue No 65:784–789

McCarroll RJ, Brander RW, andH E Power ILT, Mortlock TR (2014a) Lagrangian observations of circulation on an embayed beach with headland rip currents. Marine Geology 355:173–188

McCarroll RJ, Brander RW, MacMahan JH, Turner IL, Reniers AJHM, Brown JA, Bradstreet A, Sherker S (2014b) Evaluation of swimmer-based rip current escape strategies. Natural Hazards 71:1821–1846

McCarroll RJ, Castelle B, Brander RW, Scott T (2015) Modelling rip current flow and bather escape strategies across a transverse bar and rip channel morphology. Geomorphology 246:502–518

Miloshis M, Stephenson WJ (2011) Rip current escape strategies: lessons for swimmers and coastal rescue authorities. Natural Hazards 59:823–832

Ozkan-Haller HT, Kirby JT (1999) Nonlinear shear instabilities of the longshore current: A comparison of observations and computations. Journal of Geophysical Research 104:C11, DOI 10.1029/1999JC900104

Pattiaratchi C, Olson D, Hetzel Y, Lowe R (2009) Wave-driven circulation patterns in the lee of groynes. Continental Shelf Research 29:1961–1974, DOI 10.1016/j.csr.2009.04.011

Reniers AJHM, MacMahan JH, Thornton EB, Stanton TP, Henriquez M, Brown JW, Brown JA, Gallagher E (2009) Surf zone retention on a rip-channeled beach. Journal of Geophysical Research 114, DOI 10.1029/2008JC005153

Reniers AJHM, MacMahan JH, Beron-Vera FJ, Olascoaga MJ (2010) Rip-current pulses tied to lagrangian coherent structures. Geophysical Research Letters 37, DOI 10.1029/2009GL041443

Roelvink JA, Reniers AJHM, van Dongeren A, de Vries JV, McCall R, Lescinski J (2009) Modelling storm impacts on beaches, dunes and barrier islands. Coastal Engineering 56:1133–1152, DOI 10.1016/j.coastaleng.2009.08.006

Schmidt WE, Woodward BT, Millikan KS, Guza RT, Raubenheimer B (2003) A GPS-Tracked Surf Zone Drifter. Journal of Atmospheric and Oceanic Technology 20:1069–1075

Scott T, Austin M, Masselink G, Russell P (2016) Dynamics of rip currents associated with groynes — field measurements, modelling and implications for beach safety. Coastal Engineering 107:53 – 69, DOI http://dx.doi.org/10.1016/j.coastaleng.2015.09.013, URL http://www.sciencedirect.com/science/article/pii/S0378383915001702

Scott TM, Russell PE, Masselink G, Austin MJ, Wills S, Wooler A (2011) Rip current hazards on large-tidal beaches in the United Kingdom. In: Leatherman S, Fletemeyer J (eds) Rip Currents: Beach Safety, Physical Oceanography, and Wave Modelling, CRC Press, pp 225–242

Scott TM, Masselink G, Austin MJ, Russell PE (2014) Controls on macrotidal rip current circulation and hazard. Geomorphology 214:198–215

Sénéchal N, Gouriou T, Castelle B, Parisot JP, Capo S, Bujan S, Howa H (2009) Morphodynamic response of a meso- to macro-tidal intermediate beach based on a long-term dataset. Geomorphology 107:263–274

Shepard FP, Emery KO, La Fond EC (1941) Rip currents: a process of Geological Importance. Journal of Geology 49:337–369

Short AD (2007) Beaches of the New South Wales coast: a guide to their nature, characteristics, surf and safety. Sydney University Press, Sydey, Australia

Suanda SH, Feddersen F (2015) A self-similar scaling for cross-shelf exchange driven by transient rip currents. Geophysical Research Letters 42(13):5427–5434, DOI 10.1002/2015GL063944, URL http://dx.doi.org/10.1002/2015GL063944, 2015GL063944

Tellier E (2014) Noyades sur le littoral océanique girondin: étude rétrospective des conditions de noyade en 2011-2013. PhD thesis, Université de Bordeaux, in French

Thornton EB, MacMahan JH, Sallenger Jr AH (2007) Rip currents, mega-cusps, and eroding dunes. Marine Geology 240:151–167

Tipton M, Reilly T, Rees A, Spray G, Golden F (2008) Swimming performance in surf: the influence of experience. Int J Sports Med 29(11):895–897

Van Leeuwen BR, McCarroll RJ, Brander R, Turner IL, Power HE, Bradstreet AJ (in press) Examining rip current escape strategies in non-traditional beach morphologies. Natural HAzards

Winter G, van Dongeren AR, de Schipper MA, van Thiel de Vries JSM (2014) Rip currents under obliquely incident wind waves and tidal longshore currents. Coastal Engineering 89:106–119

Wright LD, Short AD (1984) Morphodynamic variability of surf zones and beaches: A synthesis. Marine Geology 56:93–118

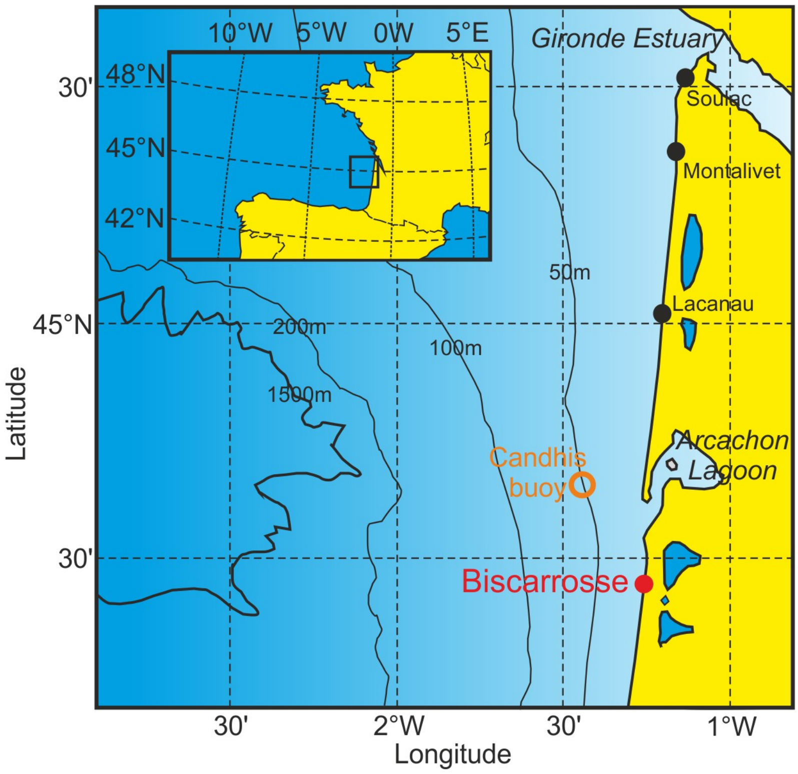

Figure 1: Location map of Biscarrosse beach, SW France, with indication of the Candhis directional wave buoy.

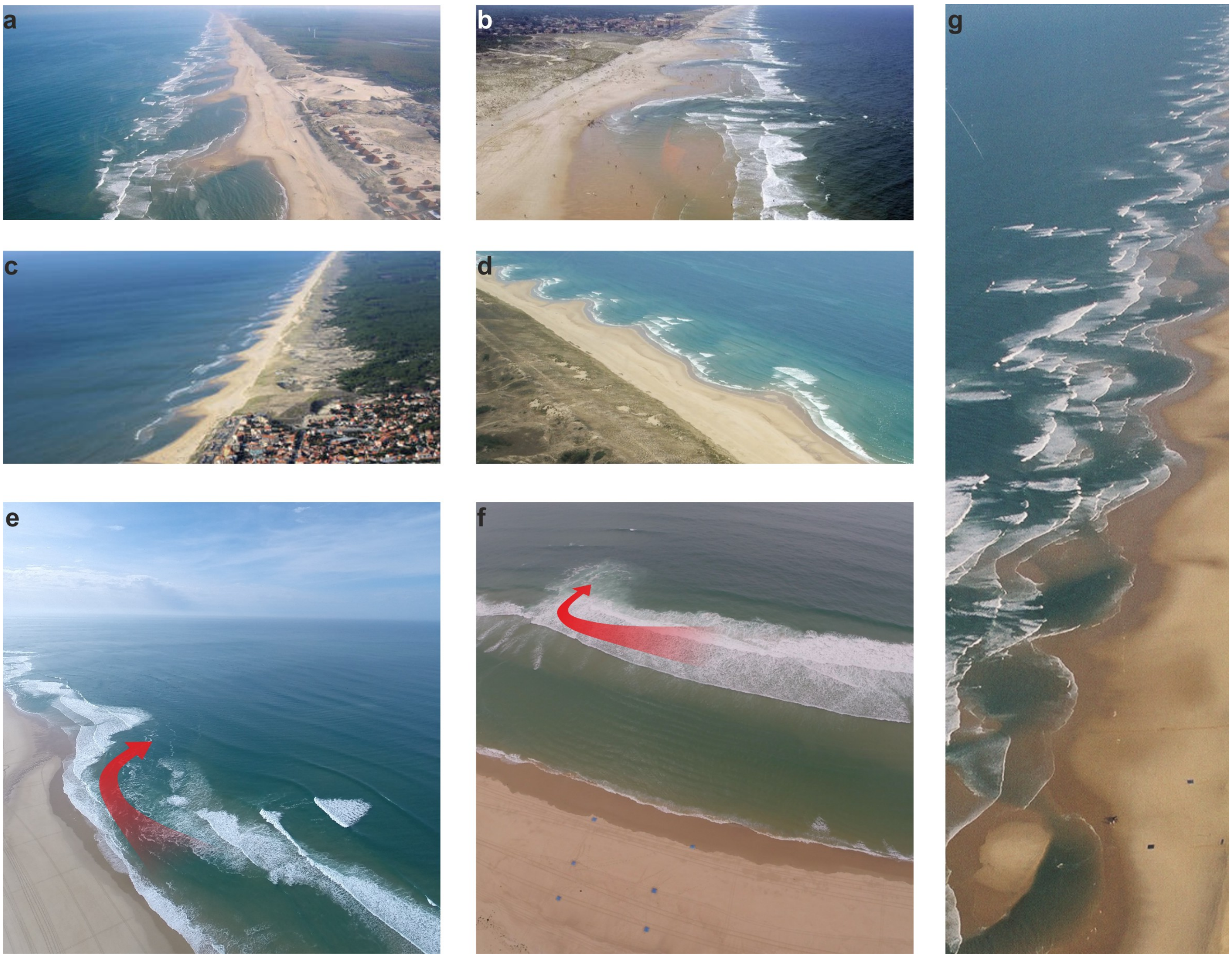

Figure 2: Aerial photographs showing bar and rip morphologies in SW France: (a-d) regularly spaced and southward oriented rip channels as sometimes observed during the summer months (Photos: scr www.mairie-lacanau.com); strong rip currents (red arrows) flowing through (e) deep and (f) shallow rip channels (Photos: V. Marieu); (g) rip channels with random spacing and orientation, which is the modal morphology on most of the SW France beaches (Photo: P. Larroudé).

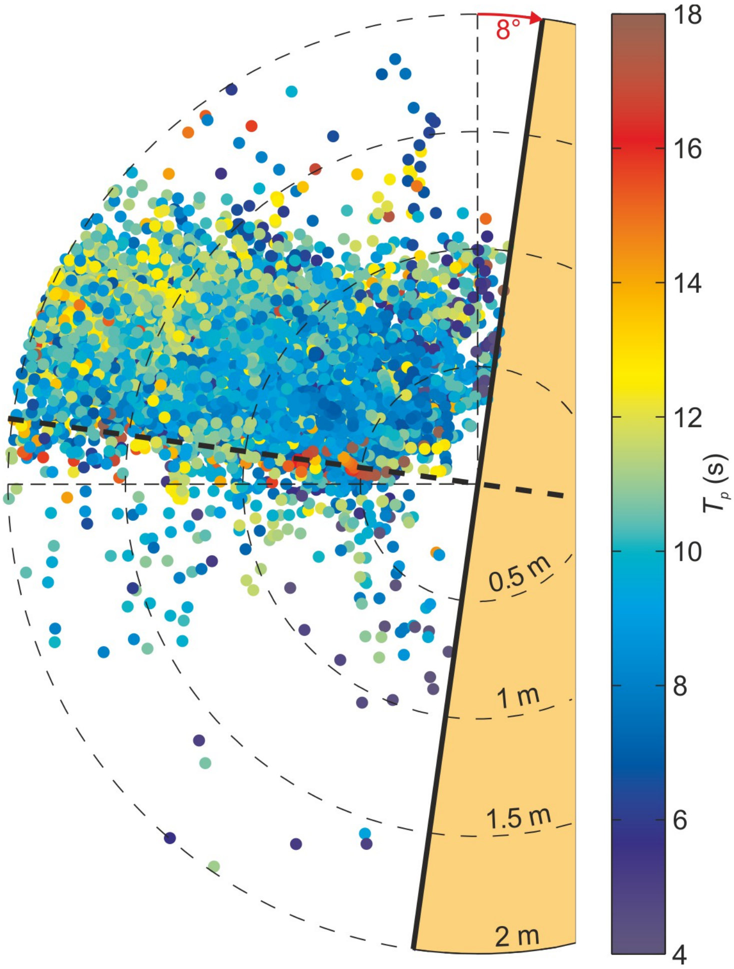

Figure 3: Scattered directional plot of significant wave height H_s measured by the Candhis buoy during July, August and September. The thick solid and dashed black lines indicate mean shoreline orientation and shore-normal incidence at Biscarrosse. The colour bar indicates peak wave period T_p in seconds.

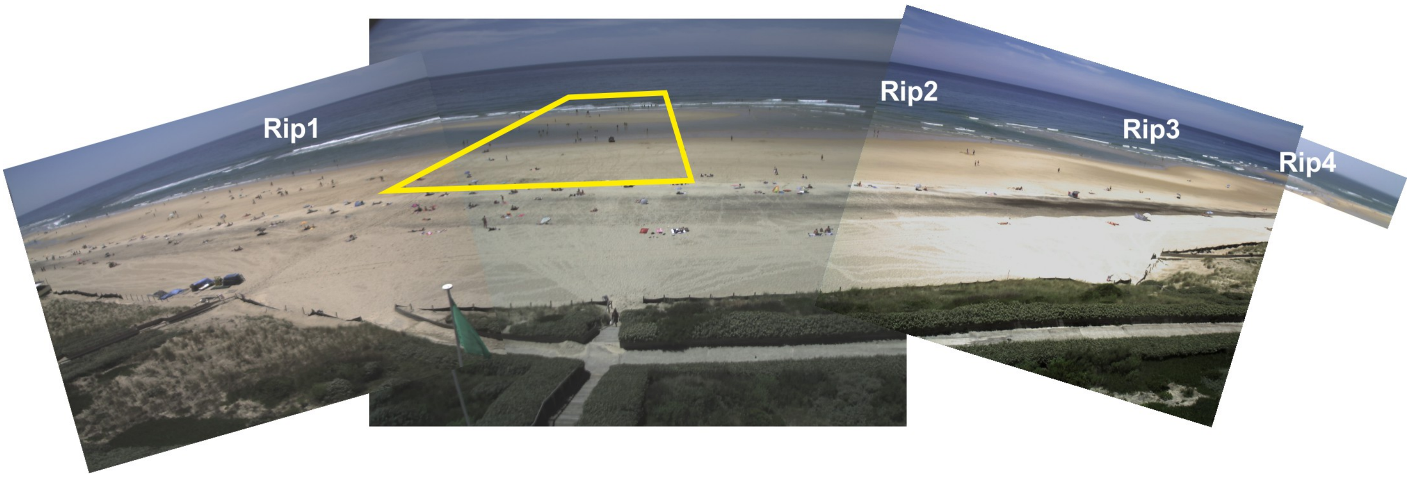

Figure 4: Biscarrosse beach on June 18, 2007. The 4 rip channels (Rip1, Rip2, Rip3 and Rip4) further addressed in the modelling exercise are highlighted by the absence of breaking waves. The yellow box shows the preferred location of the swim between the flag area at Biscarrosse beach during June 2007. Note that from the dune Rip2, Rip3 and Rip4 seemingly have very similar bar/rip morphologies.

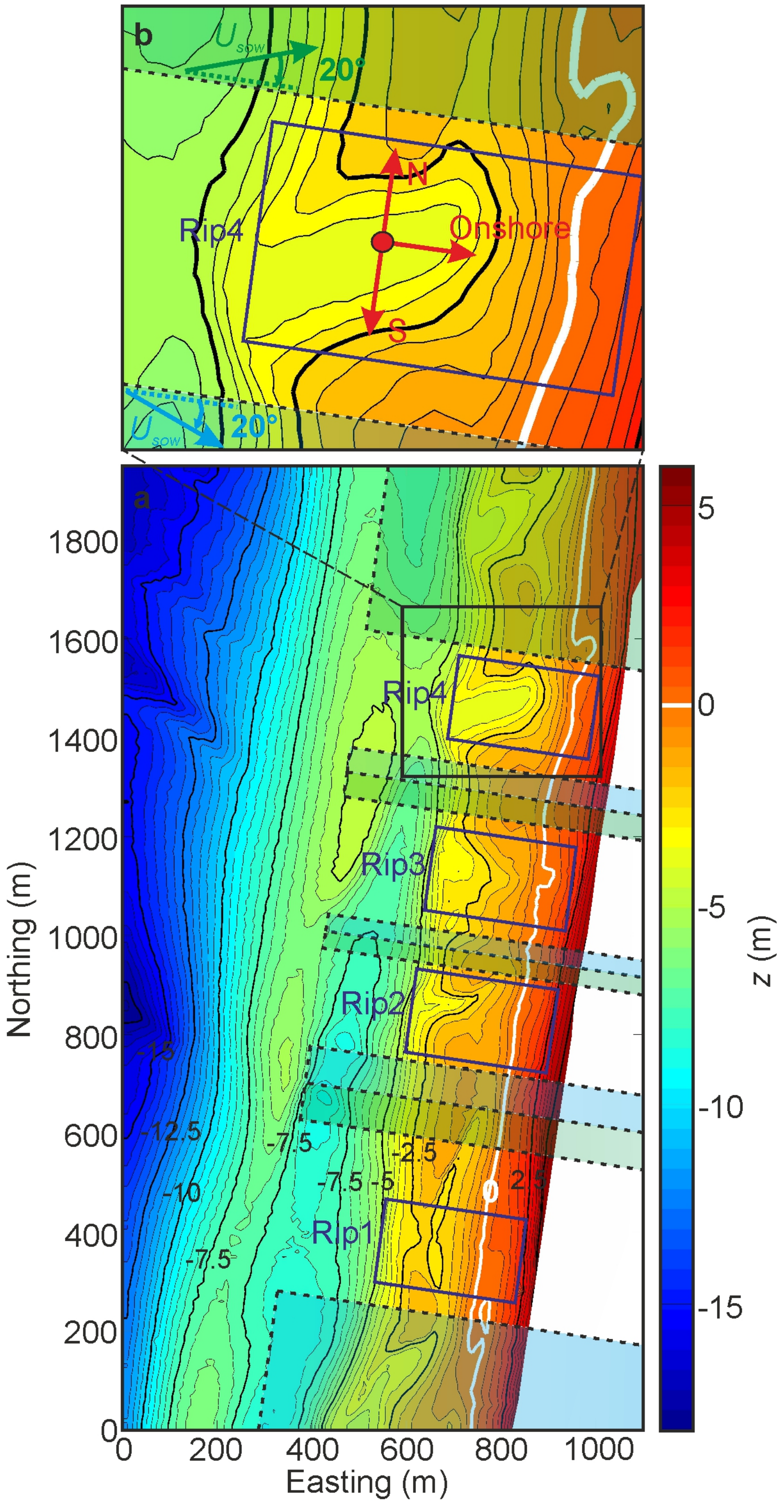

Figure 5: Biscarrosse beach morphology surveyed during the June 13-17, 2007 experiment (Bruneau et al, 2009b). (a) Computational domain with indication of the 4 rip channels addressed here (see also Fig. 4). The colour bar indicates elevation in metres above mean seal level (thick white line), with the bathymetry contoured in the background. (b) Zoom onto Rip4 to define the rip escape model setup and domains. The green and blue transparent areas are where the bathers are determined to swim onshore with waves 20° away from the rip they have been caught in. The blue boundary for starting locations of escape actions (blue box) is used throughout for statistical summaries for each rip current system.

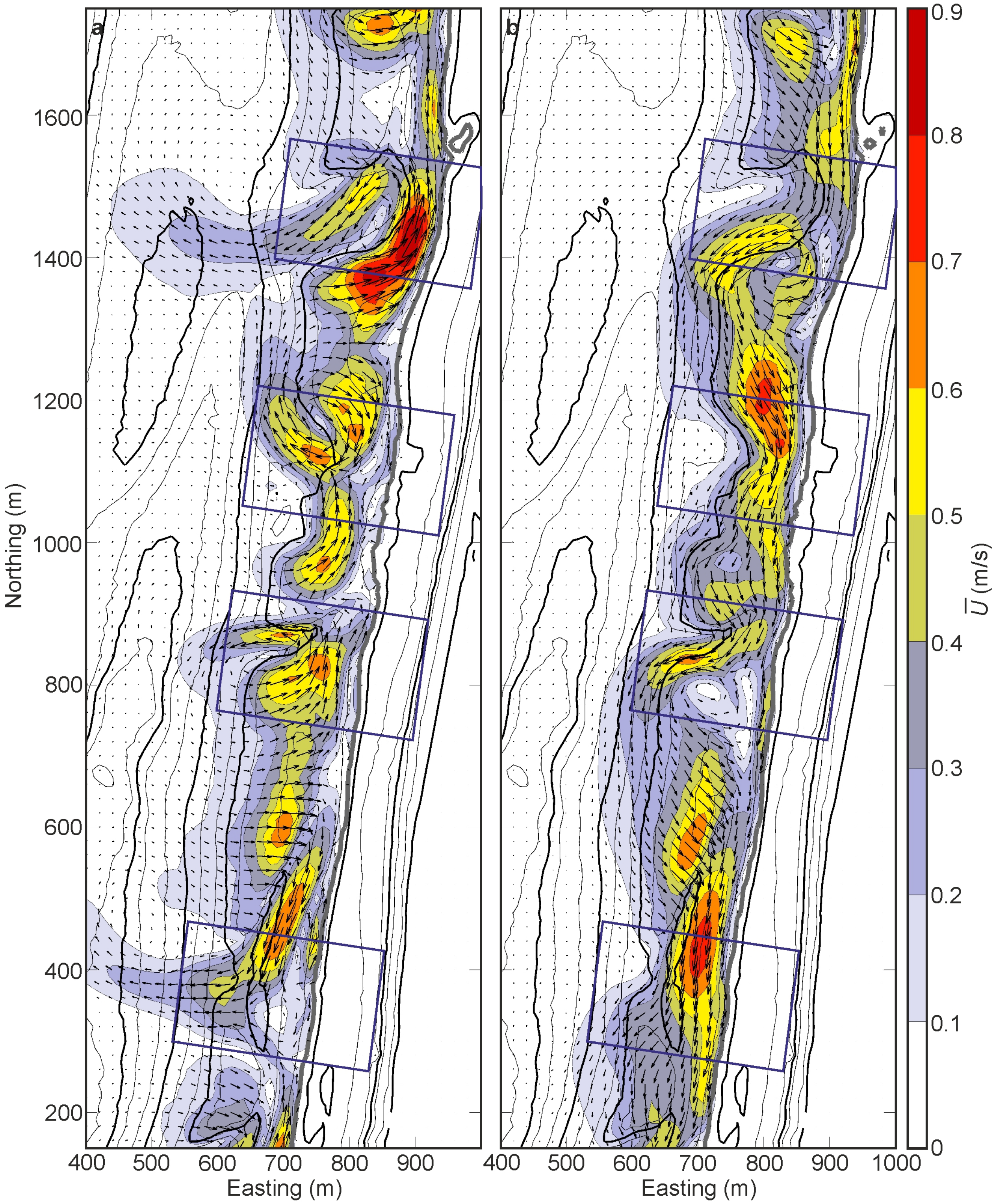

Figure 6: Mean wave-driven circulation at Biscarrosse beach for (a) Run1 with shore-normal swell with $H_s = 1$ m, $T_p = 10$ s and $\theta = 288°$ and (b) obliquely-incident NW short waves with $H_s = 1$ m; $T_p = 7$ s and $\theta = 308°$. In all panels, mean flow velocity is indicated by the colour bar in m/s and black vector arrows (1 out of 4 for clarity), the bathymetry is contoured in the background and the thick grey line is the water-level contour. The blue boxes show the boundary for starting locations of escape strategies for each rip current system.

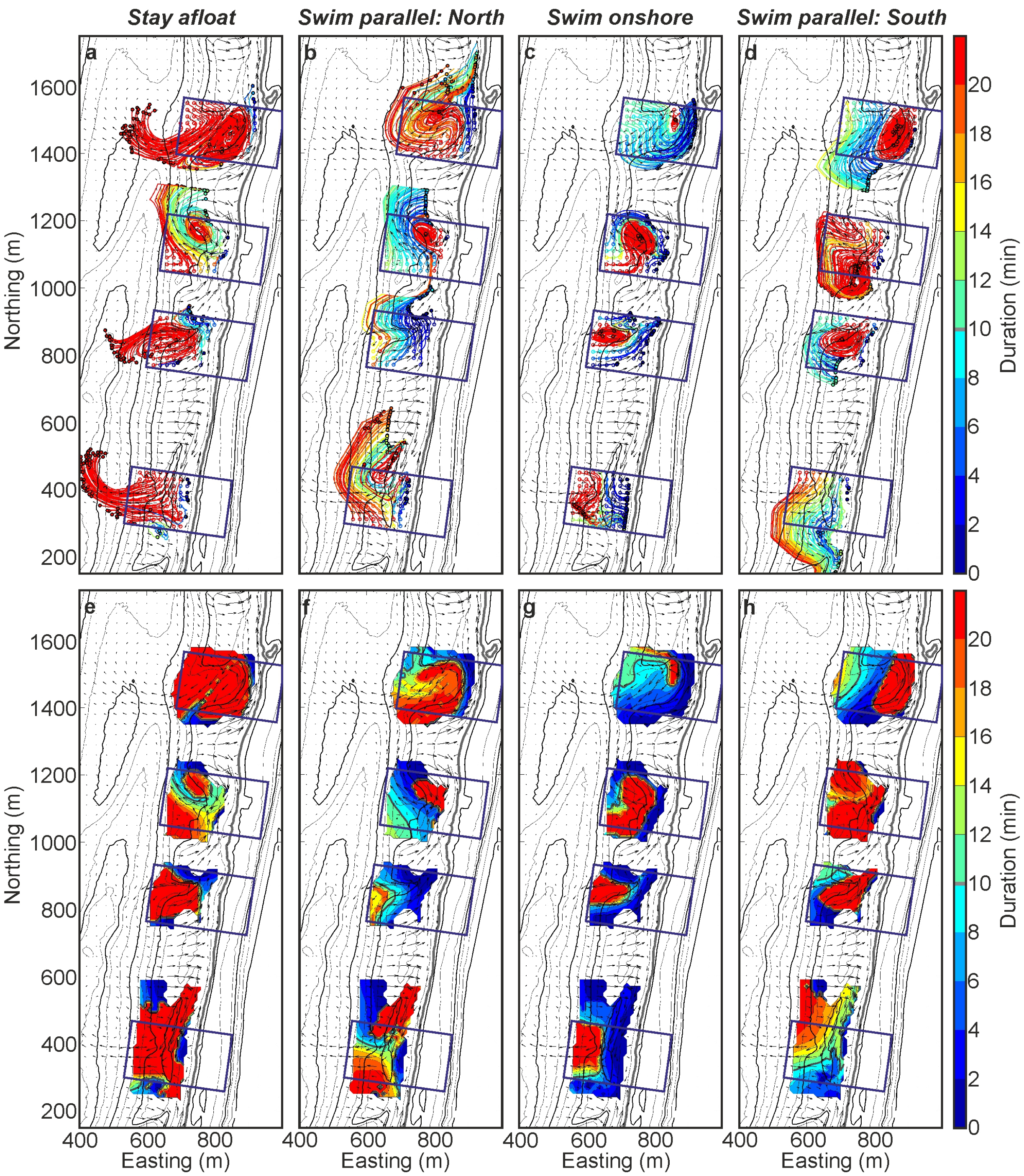

Figure 7: Rip current escape simulations for Run1. Top panels: trajectories of escape actions, open symbols indicate start point, solid symbols are end points. Bottom panels: spatial distribution of time to safety t_{safe} in minutes. In all panels, the colour bar indicates t_{safe} in minutes, the bathymetry is contoured in the background, the thick grey line is the water-level contour and mean flow velocity is indicated by black vector arrows (1 out of 9 for clarity). The blue boxes show the boundary for starting locations of escape strategies for each rip current system.

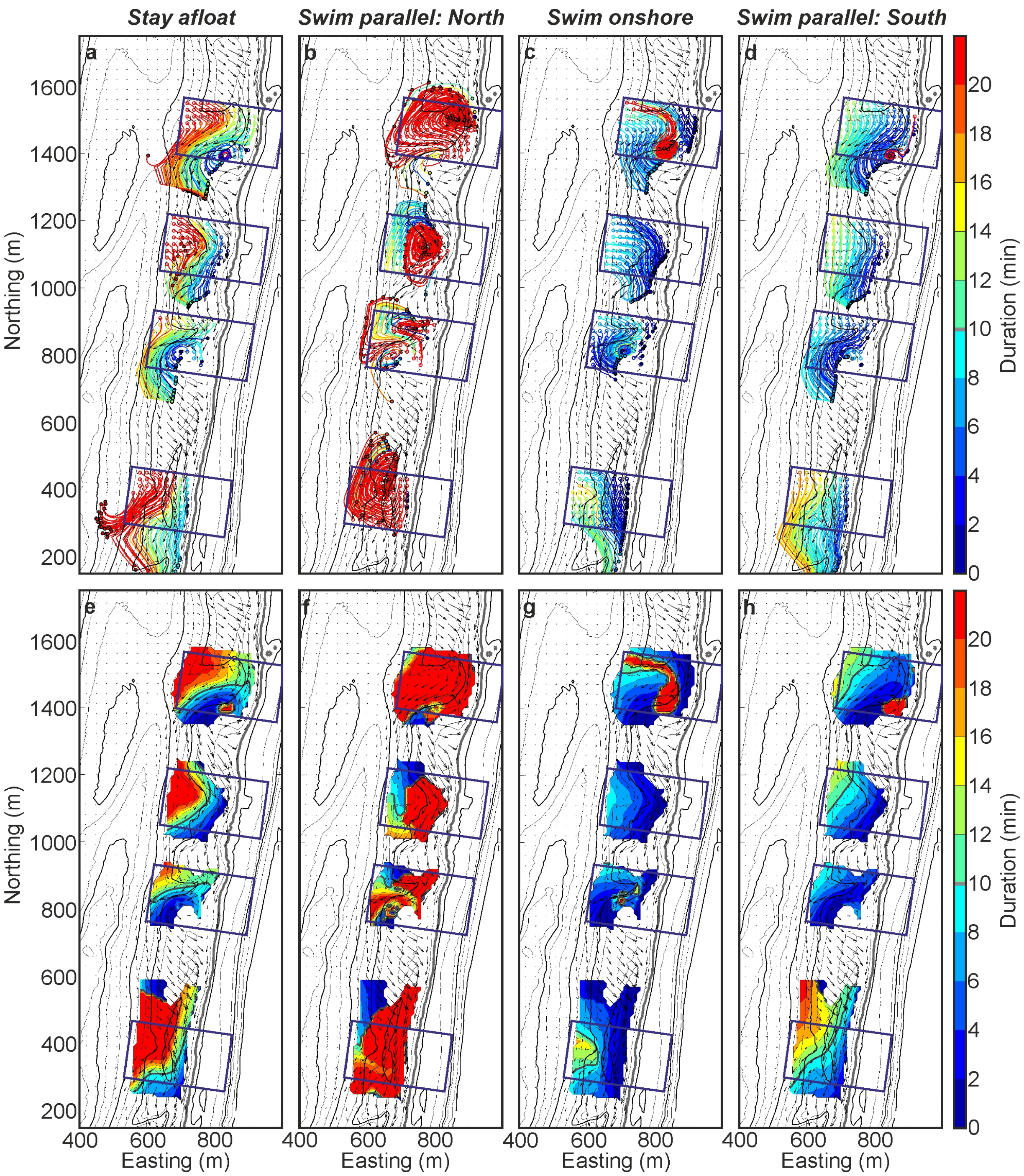

Figure 8: Rip current escape simulations for Run2. Top panels: trajectories of escape actions, open symbols indicate start point, solid symbols are end points. Bottom panels: spatial distribution of time to safety t_{safe} in minutes. In all panels, the colour bar indicates t_{safe} in minutes, the bathymetry is contoured in the background, the thick grey line is the water-level contour and mean flow velocity is indicated by black vector arrows (1 out of 9 for clarity). The blue boxes show the boundary for starting locations of escape strategies for each rip current system.

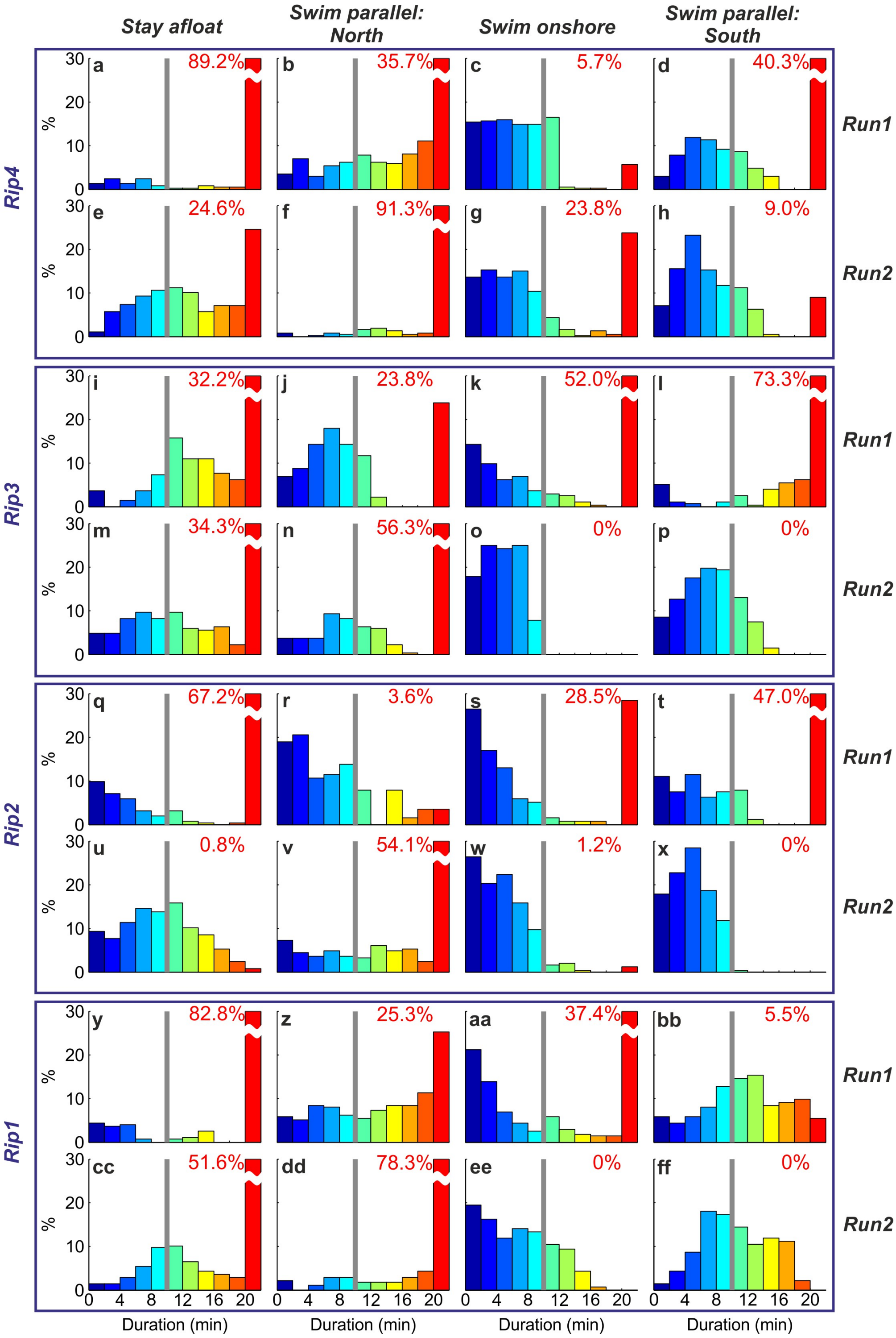

Figure 9: Histograms of t_{safe} for all rip escape strategies for both Run1 and Run2. In each panel, the percentage in red indicates failure rate F.

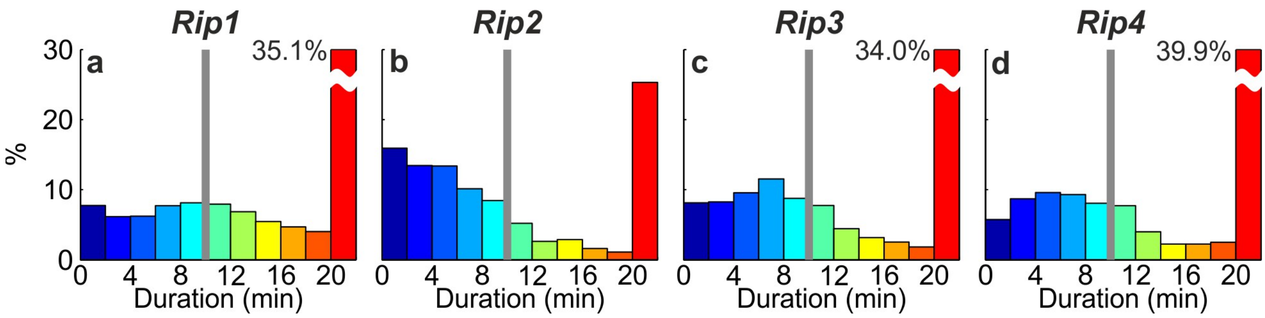

Figure 10: Histograms of mean t_{safe} for each rip current, averaged over Run1 and Run2 and over all rip escape strategies.

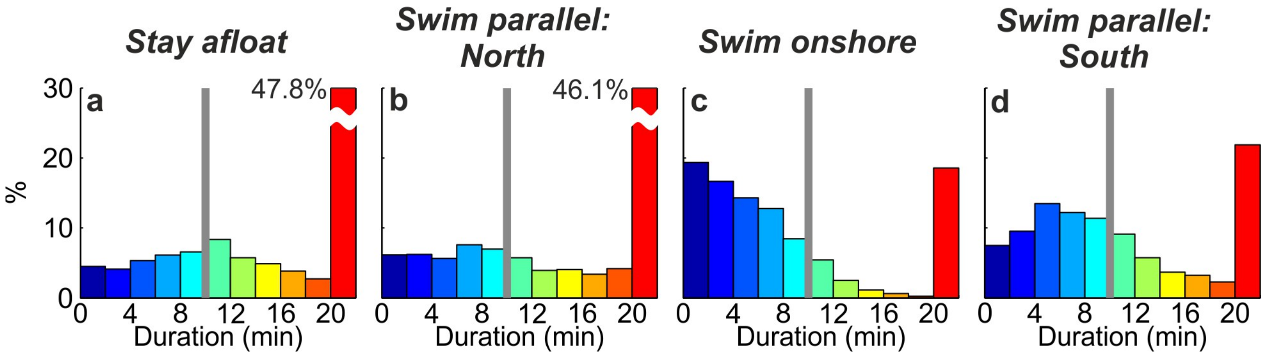

Figure 11: Histograms of mean t_{safe} for each rip escape strategy, averaged over Run1 and Run2 and over all rip current systems.

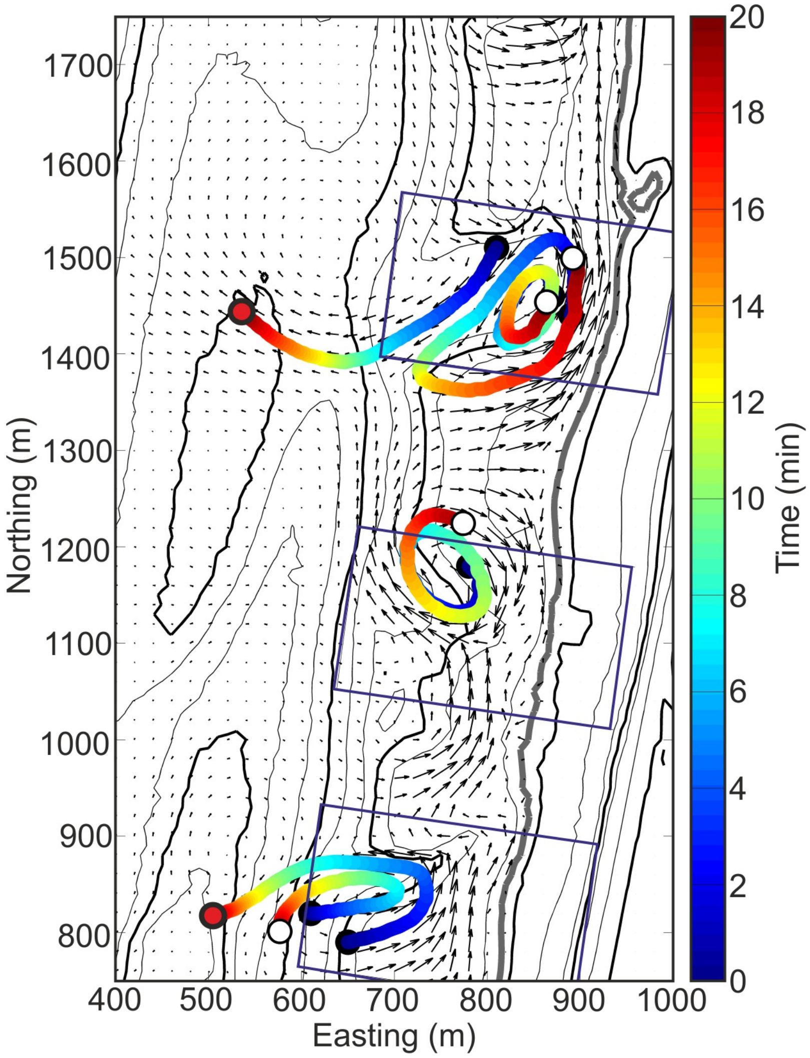

Figure 12: Examples of trajectories for stay afloat action during Run1 zoomed onto Rip2, Rip3 and Rip4 with colour bar indicating time in minutes. Black symbols indicate start point, solid white and red symbols are end points for recirculating and exit flow behaviour, respectively. The bathymetry is contoured in the background, the thick grey line is the water-level contour and mean flow velocity is indicated by black vector arrows (1 out of 4 for clarity). The blue boxes show the boundary for starting locations of escape strategies for each rip current system.