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Surf zone retention in a laboratory rip current

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ABSTRACT

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Field and numerical studies recently challenged the traditional paradigm of rip currents systems that states that rip currents produce a continuous interchange of waters between the surf zone and shelf. Instead it is suggested that rip current flow fields consist of semi-enclosed, large-scale vortices that retain floating material (*e.g.* drifters) at a rate of about 80-90%. In this paper is presented a laboratory rip current experiment over eight contrasting nature-like beach morphologies involving deployment of a large number of drifters. When the rip current was symmetric over a typical bar and rip morphology (4 out of the 8 cases), only about 10% of the drifters entering the rip exited the surf zone, whereas when the mean rip current was asymmetric, more drifters (~30-45%) entering in the rip exited the surf zone compartment. Drifters exiting the surf zone compartment were not systematically caught by a pulsating jet. More frequently, these drifters were likely caught in a vortex being shed offshore, as they often looped track in the vicinity of the rip head before exiting the surfzone compartment. This confirms new thoughts on rip currents that are very important from the perspective of both mixing in the nearshore and beach safety: rip currents systems only sporadically produce intense interchange between the waters of the surf zone and the shelf. Results additionally suggest that asymmetric rip current retain less floating material than symmetric rip currents.

ADITIONAL INDEX WORDS: *Vortex shedding, Drifters, asymmetric rip current*

INTRODUCTION

Rip currents are intense seaward flowing jets that originate within the surf zone and are associated with counter-rotating horizontal circulations (MacMahan *et al.*, 2006). The most commonly observed rip types are topographically-controlled rip current circulations. Topographically-controlled rip current circulations are guided and constrained by the surfzone sandbar morphology, that is, are driven by the alongshore gradients in depth-induced wave breaking dissipation (Bonneton *et al.*, 2010). These ubiquitous flow patterns along wave-dominated beaches have been observed by coastal scientists for many decades and have received increasing attention in recent years (Bruneau *et al.*, 2009; MacMahan *et al.*, 2008, 2010; Austin *et al.*, 2010). One of the reasons is the implications of rip current systems from the perspective of beach safety and lifeguarding, as they are the cause of the majority of rescues and fatalities within the beach environment. Swimmers being caught in a rip current are likely to be rapidly transported off their feet seaward of the surf zone. Accordingly, rip current circulations are also commonly thought to produce a continuous interchange between waters of the surf zone and the shelf, acting as both a distributing mechanism for nutrients and a dispersing mechanism for land runoff.

Recently, Lagrangian techniques have been developed to investigate rip current systems (Kennedy and Thomas, 2004; Schmidt *et al.*, 2005). When a sufficient number of drifters are released during a sufficient duration, Lagrangian velocities can be transformed into a horizontal mean circulation field. In addition to the mean circulation information, MacMahan *et al.* (2010) introduced new thoughts of rip current behaviors that go against the traditional paradigm of rip currents, suggesting that rip currents retain more floating material within the surf zone as opposed to transporting floating material offshore, as only about 10% of the drifters that entered a rip current exited the surf zone over the course of the field experiment. These findings were corroborated by a numerical study by Reniers *et al.* (2010) who assessed the effect of very low frequency pulsations on the ejection of surfzone floating material on a rip-channeled beach through the calculation of Lagrangian coherent structures.

Assessing surf zone retention for a given wave condition and tidal elevation in the field is a challenging task because of persistent changes in tide and wave regimes. Rip currents are known to be significantly tide-modulated (*e.g.* Brander, 1999; Castelle and Bonneton, 2006; Bruneau *et al.*, 2009, Austin *et al.*, 2010) and can be symmetric, asymmetric or rapidly transform into a sinuous alongshore current depending on offshore wave angle to the shore (MacMahan *et al.*, 2010). Field estimation of surf zone retention is also reasonably impossible to achieve without involving a large number of field investigators devoted to drifter release and recovery. Laboratory experiments therefore appear as a suitable alternative solution for investigating surf zone retention of rip current systems.

During a recent laboratory rip current experiment, Castelle *et al.* (2010) tracked a large number of drifters released in the surf zone for eight contrasting, essentially nature-like, bar and rip morphologies. While this study was primarily mean-circulation focused, the authors tracked a single drifter and noted that it entered ten times in the rip before exiting the surf zone compartment, which is consistent with MacMahan *et al.* (2010)

and Reniers *et al*. (2010) results. In this paper an in-depth investigation of surf zone retention throughout the experimental period is undertaken.

LABORATORY EXPERIMENT

Experimental set-up

The laboratory experiment was undertaken during a 5-week period in a multidirectional wave basin at the SOGREAH (LHF facility, G-INP, France). An extensive description of the drifter experiment is given in Castelle *et al*. (2010). The basin extended 30 m in both the cross-shore (y axis) and alongshore (x axis) with an offshore wavemaker (Figure 1) generating shore-normal waves throughout the experiment with a significant wave height H_s = 18 cm and a peak period T_p = 3.5 s for all cases presented in this paper. The still water level at the wavemaker was h_0 = 76.5 cm with a mean beach slope of *circa* 1/25.

A moveable bed consisted of fine sand with d_{50} = 164 µm. The seabed morphology was measured with millimeter accuracy using a laser motorized trolley located on a sliding rail (Figure 1). Ambient three-dimension (3D) beach morphologies were not shaped by the investigators but formed through the positive feedback between flow and sediment transport. In this paper we focus on a specific period of the experiment coinciding with both the formation and subsequent disappearance of rip channels, and the deployment of the largest number of drifters to be tracked by the video camera. Figure 2 shows the eight beach morphologies considered herein. The beach initially exhibited a crescentic sandbar feature (Figure 2a) that subsequently migrated shoreward (Figure 2b-c) and attached to the beach (Figure 2d) to form a typical shore-connected bar and rip morphology (Figure 2d-e-f). The beach then tended to an almost featureless terrace-like morphology (Figure 2g-h). Of note, the beach morphologies given in Figure 2 are essentially similar to previously surveyed bar-rip morphologies in the field (*e.g.* Brander and Cowell, 2003) and recently surveyed crescentic sandbars (Almar *et al*., 2010).

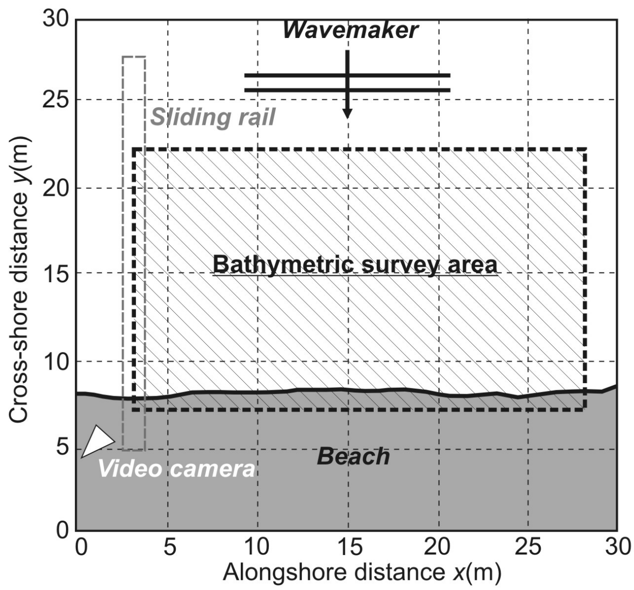

Figure 1. Schematic set-up for the laboratory experiment with delimitations of the bathymetric survey area (dashed box) and location of the video camera that was used to track the drifters.

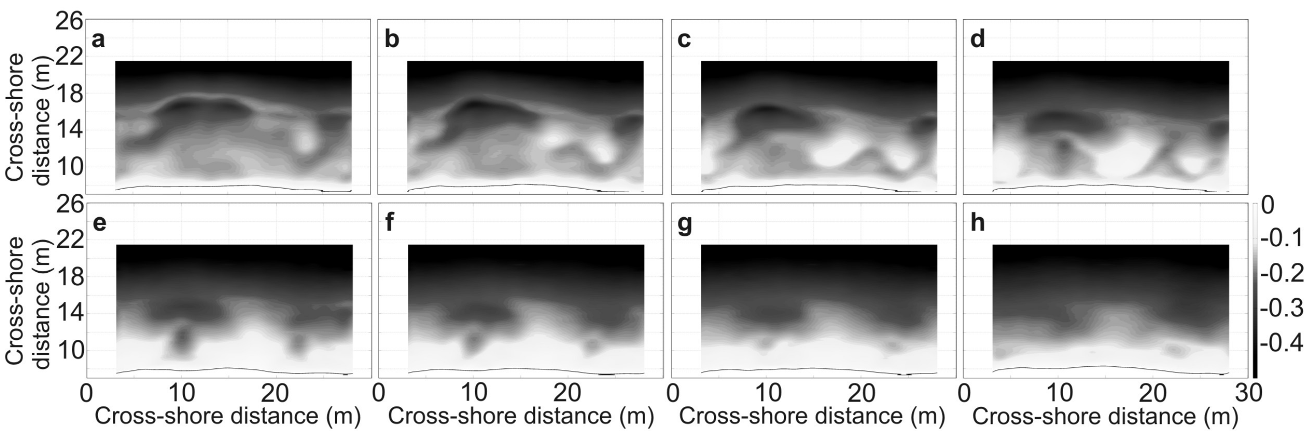

Figure 2. Beach morphologies surveyed with millimeter accuracy corresponding to the eight situations (from runs a to h) described in this paper. Colorbar indicates seabed elevation in meters.

Table 1: Video-run duration and number of drifters deployed for the 8 situations.

	Run a	Run b	Run c	Run d	Run e	Run f	Run g	Run h
Video-run duration (min)	40	30	60	60	60	60	60	40
Number of deployed drifters	22	20	25	37	29	39	32	21

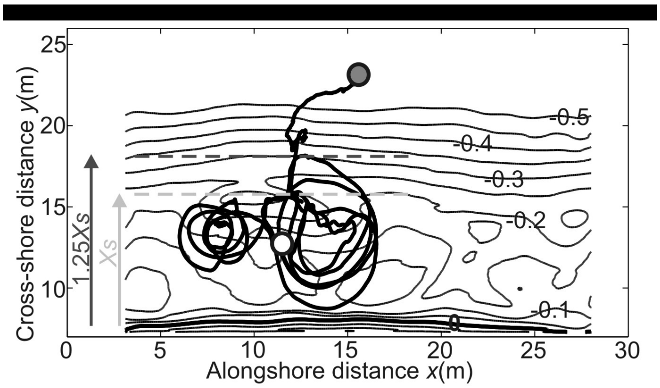

Figure 3. Example of a drifter pathline (thick solid black line) during video run d with the local bottom morphology contoured in the background (solid black lines) and with the white (grey) circle corresponding to the startup (end) of the pathline. The offshore extent of the semi-enclosed surf zone compartment is the dark grey dashed line with *Xs* the surf zone width.

Drifter tracking and surf zone retention computations

For each beach morphology between 20 and 39 drifters were deployed in the surf zone. Drifters were designed so that they were extremely effective in resisting surfing. They were typically manually deployed ashore along the entire domain and were subsequently caught by the feeder currents and then spread within the surf zone by the wave-driven circulations. Drifters were tracked every six seconds using captured images from a shore-mounted video camera with a semi-automatic method. Image coordinates were rectified to still water level Cartesian coordinates. Table 1 lists the video-run conditions, with the eight video runs further denoted run a to run h in this paper.

Here we focus on the rip current system that was located at *circa* x = 10 m, as throughout the experiment, both the highest rip current velocities and largest number of drifters were most of the time observed in this region. An automatic method was designed to compute surf zone retention at this rip current system. For this, both drifters entering in the rip and drifters exiting the surf zone compartment had to be defined. For computing the number of drifters entering in the rip during a given video run, we automatically counted the number of drifters crossing the alongshore section joining the two centers of the mean horizontal vortices computed in Castelle *et al.* (2010). The surf zone compartment geometry had to be defined. First was estimated the seaward extent of the surf zone by the alongshore-averaged (along the shoals of the bar and rip morphology) cross-shore position where the ratio of H_s (computed with SWAN model; Booij *et al.*, 1999) to the local water depth h reached the breaker index $\gamma = 0.78$ (*i.e.* h = 0.25 m). Then the surf zone width *Xs* was deduced from shoreline position. According to the approach described in MacMahan *et al.* (2010), the seaward boundary of the semi-enclosed rip current system was defined as 1.25 times the surf zone width (1.25*Xs*). Therefore the number of drifters exiting the surf zone compartment was computed by automatically detecting the drifters crossing the 1.25*Xs* alongshore section seaward of the considered rip current system. Figure 3 shows an example of surf zone compartment with a superimposed single drifter pathline. The drifter was caught about 10 times in the rip current before being subsequently ejected from the 1.25*Xs* surf zone compartment and finally remained almost stationary at a distance from the shore of about 2*Xs*.

RESULTS

Table 2 lists the number of drifters entering in the rip N_r, the number of drifters exiting the surf zone compartment N_e, the resulting surf zone retention rate R together with the mean rip current intensity U_{rip} computed by Castelle *et al.* (2010) for the eight situations. Results show that there is no relationship between rip current intensity of surf zone retention. Corroborating the field study of MacMahan *et al.* (2010), in four out of eight cases the surf zone retention is *circa* 90% (video runs d, e, f and g). Interestingly much lower retention rate of 55-70% are observed for video runs a, b and c for the crescentic sandbar situations and for the video run h when the rip current was almost non-existent (U_{rip} on the order of 2 cm/s).

Figure 4 shows the pathlines of all the drifters exiting the surfzone compartment superimposed to the mean flow patterns computed in Castelle *et al.* (2010). Of note, the three first situations (video runs a, b and c) were characterized by a significantly asymmetric rip current (skewed rightward for both video run a and b, and leftward for video run c). This is also the case for run h for the low-energy rip current. Only for the video run f the ejected drifter pathlines are readily asymmetric together with a high retention rate. For no apparent reason, the mean rip current flow was readily symmetric for this situation (Castelle *et al.*, 2010) which contrasts with the strongly asymmetric ejected drifter pathlines together with the large surf zone retention rate (89.4%, Table 2).

The hypothesis suggesting that drifters that exit the surf zone are caught in a rip current pulsation has been tested as visual observations during the laboratory experiment did not always fit with this explanation. For every drifter caught in the rip, we computed the maximum offshore-directed (alongshore) velocity $\max\{v\}$ ($\max\{|u|\}$) it experienced during its last rotation in the rip current circulation and we further distinguished the drifters subsequently exiting the surf zone compartment from those being retained in the rip current circulations. From this discrimination,

Table 2: For the 8 situations: rip current intensity U_{rip} computed in Castelle *et al.* (2010), number of drifters entering in the rip *Nr*, number of drifters exiting the surf zone compartment *Ne* and resulting surf zone retention rate *R*.

	Run a	Run b	Run c	Run d	Run e	Run f	Run g	Run h
U_{rip} (m/s)	0.0650	0.1044	0.0975	0.0921	0.0647	0.0595	0.0304	0.0256
Nr	47	74	79	329	135	283	218	40
Ne	12	22	35	27	16	30	10	17
R (%)	74.5	70.3	55.7	91.8	88.1	89.4	95.5	57.5

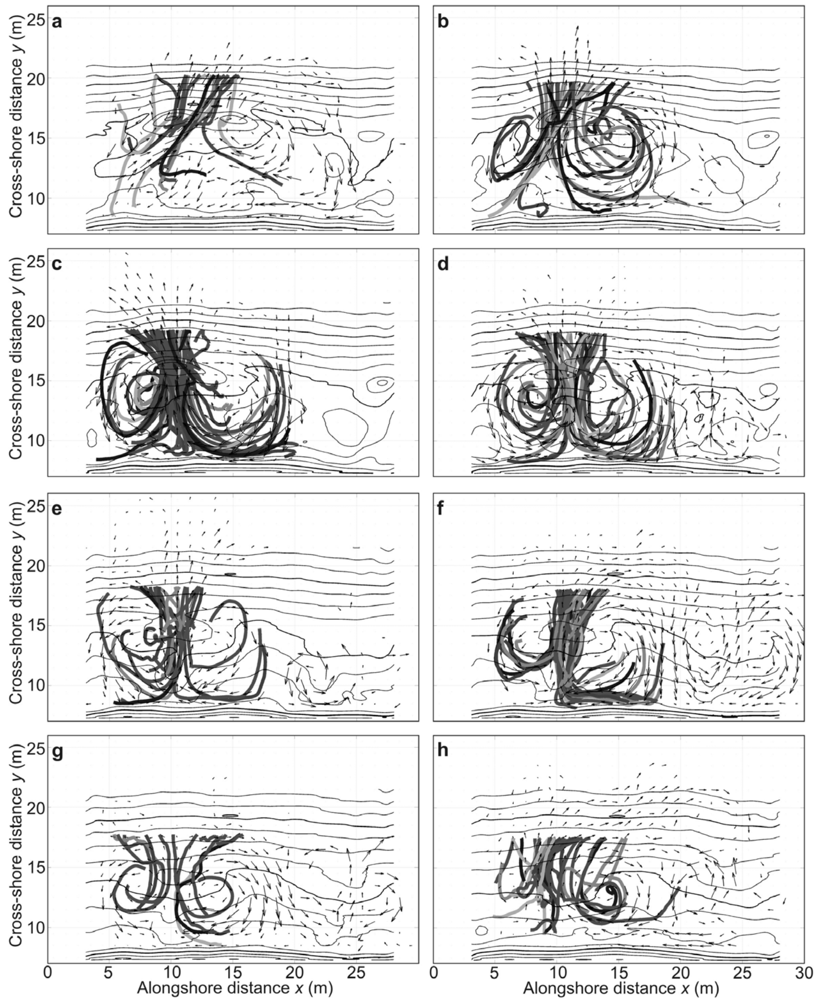

Figure 4. Computed mean flow patterns computed in Castelle *et al*. (2010) with the local bottom morphology contoured in the background for the eight situations from video runs a to h. The pathlines (thick grey lines) of all the drifters exiting the surfzone compartment are superimposed.

Figure 5 shows that the drifters that exited the surf zone compartment were not preferably those caught in a pulsating jet as they did not always correspond to the highest max$\{v\}$ values (nor for max$\{|u|\}$).

In Figure 4 the superimposed drifter pathlines show that a significant number of drifters exiting the surf zone compartment were characterized by a looped track before exiting the surf zone compartment or immediately after (not shown in Figure 4). One of these looped tracks can be seen at *circa* (x = 12 m, y = 18 m) in Figure 3. In addition, drifter expulsion events were often characterized by a cluster of drifters being ejected from the surf zone compartment at about the same time, while the rest of the time all drifters were retained in the rip current circulations. This supports the idea that ejection of drifters, or any surf zone floating material, preferably occurs when surf zone eddies temporarily extend the rip current beyond the surf zone and subsequently detach (Reniers *et al*., 2010), which results in sporadic expulsion events.

CONCLUSIONS

In this paper was presented a laboratory rip current experiment over eight contrasting nature-like beach morphologies to assess surf zone retention in the presence of shore-normal waves. Results showed that when the rip current was symmetric over a typical bar and rip morphology, only about 10% of the drifters entering in the rip exited the surf zone which is consistent with field results given in MacMahan *et al*. (2010). Expulsion events were characterized by clusters of several drifters being ejected at about the same time. Results also show that when the mean rip current was asymmetric more drifters (~30-45%) entering in the rip exited the surf zone compartment. Drifters exiting the surf zone compartment were not systematically caught by a pulsating jet. More frequently, drifters exiting the surf zone were likely caught in a vortex being shed offshore as they often looped track in the vicinity of the rip head. This paper is therefore an additional contribution to recent field (MacMahan *et al*., 2010) and numerical (Reniers *et al*., 2010) studies that challenge the traditional paradigm of rip currents. Rip currents systems are found to only sporadically produce intense interchange between the waters of the surf zone and the shelf. In this contribution it is additionally suspected that asymmetric rip currents retain less floating material than symmetric rip currents. This motivates further field and numerical studies to verify this hypothesis.

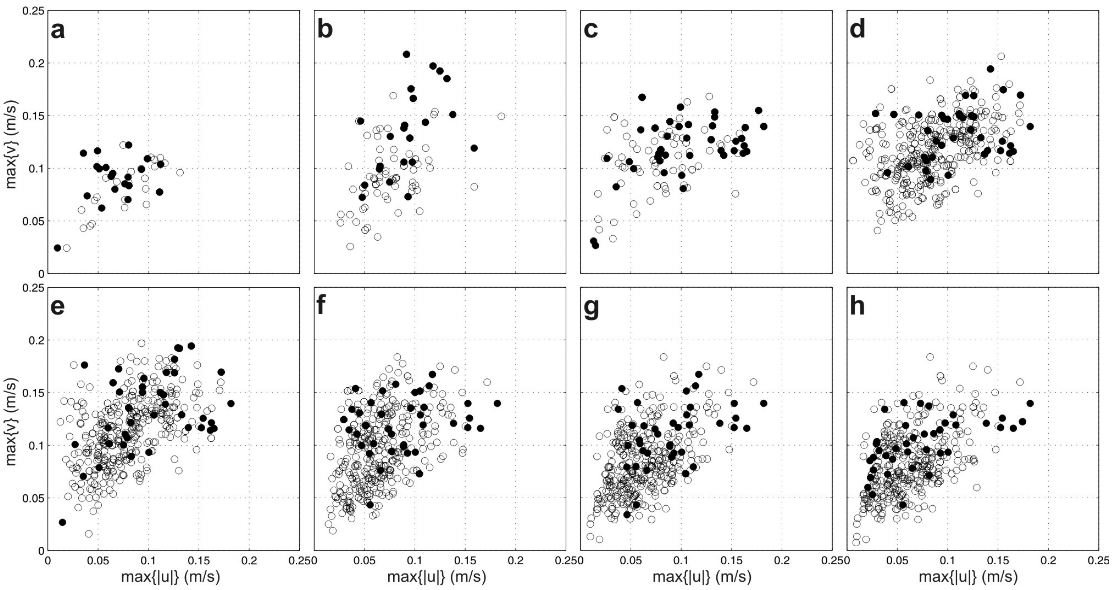

Figure 5. For every drifter, maximum offshore-directed (alongshore) velocity max{|*u*|} (max{*v*} the drifter experienced within the rip current circulation during the single last rotation. For the 8 situations from video runs a to h, drifters subsequently exiting the surf zone compartment (1.25*Xs*) are black circles and those being subsequently retained in the rip current circulations are white circles.

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