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A LARGE-SCALE LABORATORY EXPERIMENT OF RIP CURRENT CIRCULATIONS OVER A MOVEABLE BED: DRIFTER MEASUREMENTS

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Abstract

The present paper presents a laboratory experiment of rip current circulations over a moveable bed. The rip current characteristics over four distinct beach morphologies, exhibiting more or less developed nature-like bar-rip morphology, were investigated. For each video run, the same offshore shore-normal waves were generated by the wavemaker with the same mean water level in order to study the sensitivity of the rip current characteristics as a function of the beach morphology only. In each case, a 1-hour video run was used to track a large number (~30) of drifters released within the surf zone. Image coordinates were then rectified to still water level Cartesian coordinates to compute drifter velocities, mean characteristics and surf zone retention rates. Results show the presence of classic rip current patterns with counter-rotating cells and a relatively narrow offshore-directed jet with, for three of the situations, a reasonably symmetric shape. Non-surprisingly, it was found that rip current intensity increases with increasing relative depth of the rip channel. The wave-driven circulations were strongly unstable. Computed standard deviation in flow intensity and direction provides high resolution information on the spatial variability of the rip current instabilities with, for instance, highly-pulsating and weakly directionally variable offshore-directed flow in the rip channel. Conversely to what was previously hypothesized in the literature, there was hardly trace of vortices being shed offshore and drifters exiting the surf zone compartment were not systematically caught by a pulsating jet. The cause for drifter exiting the semi-enclosed surf zone compartment remains, however, elusive and deserves further investigations. The computed surf zone retention rates (~90%) were of the order of those previously observed in the field, with no clear relationship with the mean rip current velocity or relative depth of the rip channel. Further video-runs will have to be analyzed to explore potential explanations.

Key words: Rip current circulation, Laboratory experiment, Drifters, Surf zone retention, Mean circulations

1. Introduction

Rip currents are narrow, intense seaward flowing jets that originate within the surf zone and broaden outside the breaking zone which, in recent years, have received increasing interest (MacMahan et al., 2006). They are associated with cell circulations, also known as rip current circulations, which permanently interact with the surf zone sandbars and shoreline rhythms. Rip current systems often result in erosion features known as mega-cusps (Short and Hesp, 1982; Thornton et al., 2007). Therefore, understanding and predicting rip current dynamics is relevant for shoreline evolution and localized beach and dune erosion during storms (Thornton et al., 2007). In addition, rip currents are known to be a major hazard to beach users as they are the cause of the majority of rescues and fatalities within the beach environment (Short, 1999; Scott et al., 2009). Therefore, rip currents also have significant implications from the perspective of beach safety and life-guarding.

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Rip current circulations are driven by longshore variations of wave-induced radiation stress (Longuet-Higgins and Stewart, 1964). These gradients can be due to spatial variability of the incident wave field due to wave groups (Dalrymple, 1975), wave-current interactions (Dalrymple and Lozano, 1978), wave field interaction with lower-frequency waves such as edge waves (Symonds and Ranasinghe, 2000) or local topographic variations (Bowen, 1969). The latter is called 'topographically-controlled rip current', while the three other ones refer to 'transient rip currents' (Johnson and Pattiaratchi, 2004). In this paper, we are essentially dealing with topographically-controlled rip current systems, that is, rip current circulations that are guided and constrained by the surf zone sandbar morphology.

Within the last decade, a significant number of field rip current investigations have been made (Aagaard et al., 1997; Brander, 1999; Brander and Short, 2000, 2001; MacMahan et al., 2004a,b, 2005, 2008, in press; Bruneau et al., in press). Among other findings, it was shown that rip currents may be strongly influenced by tidal elevation with, generally, rip current activity around low tide and maximum rip current velocities at low tide in micro-tidal (Brander, 1999), meso-tidal (Brander and Short, 1999) and macro-tidal (Austin et al., 2009) wave-dominated beaches. Conversely, on the meso- macro-tidal high-energy Aquitanian Coast beaches (SW France), Bruneau et al. (in press) found that maximum rip current velocities shifted toward higher tides with increasing offshore wave height, corroborating earlier numerical exercises in Castelle et al. (2006) and Castelle and Bonneton (2006) on this stretch of coastline. Accordingly, an in-depth investigation of rip current circulations as a function of wave forcing and beach morphology is a challenging task in the field due to the persistent change in tidal elevation and wave conditions. For these reasons the rip current flow, often quantified through the Froude number Fr, has mostly been investigated as a function of the dimensionless variable H/h (offshore wave height / water depth on the sandbar) which is considered as a measure of the forcing intensity. Non-surprisingly, it was found that rip velocities increase with increasing wave height and decreasing water elevation. Conversely, the sensitivity of rip velocities to the relative depth of the rip channel $h_{rip\text{-}channel}/h_{bar}$ for a given offshore wave conditions and tidal elevation has barely been touched upon (Nielsen et al., 2001).

A substantial number of laboratory experiments, all performed with a fixed bed, have been undertaken to more easily grasp topographically-controlled rip current circulation information than on natural beaches. Eulerian measurements (Hamm, 1992; Haller and Dalrymple, 2001; Haas and Svendsen, 2002) and, more recently, lagrangian techniques (Kennedy and Thomas, 2004) have been used to investigate rip current systems. The latter, when a sufficient number of drifters are released during a sufficient duration, can be transformed into a horizontal mean circulation field. The same drifter deployment strategy was recently attempted in the field by Schmidt et al. (2005), Austin et al. (2009) and MacMahan et al. (in press). In addition to the mean circulation information, MacMahan et al. (in press) introduced new thoughts of rip current behaviors, suggesting that rip currents retain more floating material within the surf zone as opposed to transporting floating material offshore, as only ~10% of the drifters that entered a rip current exited the surf zone over the course of the experiment when caught by a pulsing jet. On the field, such a technique requires small tidal ranges, a large number of investigators on the field devoted to this task. Therefore, undertaking an extensive study comprising a large number of seabed morphologies and wave conditions is difficult on the field. Most importantly, it is realistically impossible to accurately assess the sensitivity of the rip current circulation and surf zone retention to the beach morphology for a given wave condition and tidal elevation. In this paper, we use laboratory data to pave these knowledge gaps.

A limitation of the existing laboratory experiments of rip current circulations is the studied beach morphology itself. While most field observations of rip current were undertaken on incised rip channels in shore-connected shoals or depressions on near-planar beaches (MacMahan et al., 2006), all laboratory measurements have been done with an alongshore bar-trough beach cut by a rip channel, except in Hamm (1992) for an incised-channel on a planar beach. The resulting man-made beach shape in laboratory resulted in rather unrealistic or very scarcely observed rip-channel morphologies. For instance, the relative depth of the rip channel is in general deeper in laboratory (2.5 - 5) compared to the field (1.2 – 2.7, see the review of MacMahan et al., 2006). This issue is addressed in the present study.

Here we present (section 2) a laboratory experiment of drifter observations over a moveable bed in the presence of rip current circulations and nature-like bedform features. In section 3, we present the results obtained on the mean characteristics of the rip current system and surf zone retention. In section 4 we discuss the results which, among other findings, bring new thoughts about surf zone retention.

2. Experimental setup

2.1. *Laboratory experiment*

The large scale laboratory experiment has been undertaken over a moveable bed, during a 5-week period from November 10 to December 12 2008. The tests were conducted in the multidirectional wave basin at the SOGREAH (LHF facility, France) extending 30 m in both cross-shore and alongshore directions with basin's wall facing the beach constituted of 60 independently-controlled piston-type wavemakers (Figure 1).

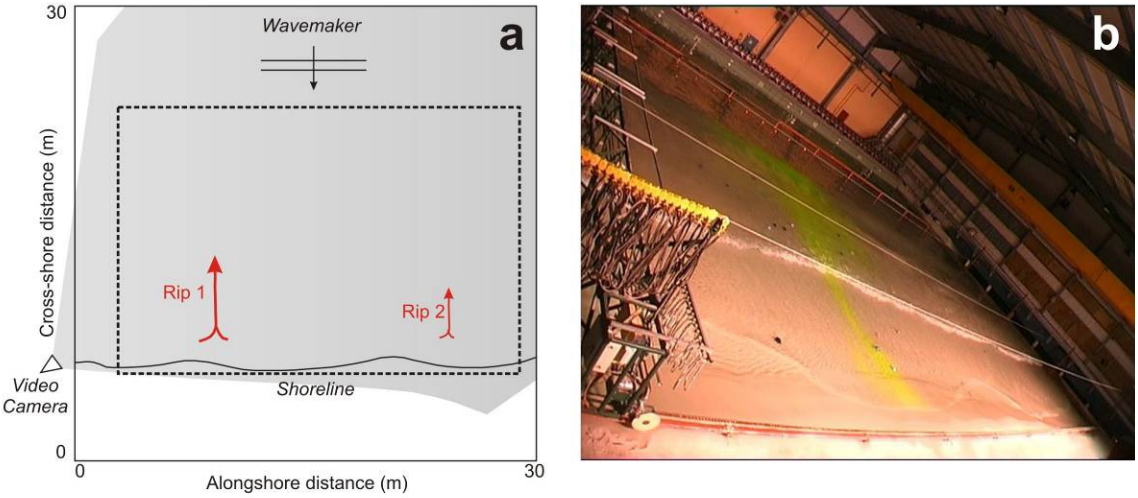

Figure 1. (a) Schematic of setup for the laboratory experiments with approximate location of the two rip current systems, delimitations of the bathymetric survey area (dashed box), location of the video camera and corresponding covering area. (b) Sample of capture video image with drifters during Run1. The rip current system (rip 1 in (a)) is highlighted by the dye trajectory, about one minute after it was released in the feeder.

Only shore-normal waves were used here to favor the formation of rip channel(s) during the experiment. Each run presented in this study consisted of 1-hour period of irregular waves complying to a JONSWAP spectrum with Hs = 18 cm and Tp = 3.5 s, for a constant water level. The moveable bed consisted in fine sediment with d_{50} = 164 µm. Accurate bathymetric surveys were undertaken every day. The beach morphology appeared to be strongly variable during the experiment, ranging from an alongshore-uniform geometry to a well-developed bar-rip morphology, favoring a large range of rip current systems.

2.2. *Beach morphologies*

For the present study, only 4 beach morphologies were used to assess the rip current circulation and surf zone retention as a function of the rip channel geometry. Figure 2 shows these 4 beach surveys undertaken immediately after the video runs, denoted Run1, Run2, Run3 and Run4. These beach morphologies were not shaped by the investigators but formed through the positive feedback between flow (waves and currents) sediment transport and the evolving morphology (that is, self-organization) starting earlier during the experiment from and alongshore-uniform beach geometry. Following the convenient morphodynamic framework of Wright and Short (1984), this morphological sequence clearly appears as a down-state sequence from a well-developed bar-rip morphology (Fig. 2a) to a terrace-like feature with very weakly-developed channels (the observed morphological evolutions during the experiment will be explored elsewhere). An outer bar with a crescentic shape was welded to this bar-rip morphology. Conversely to earlier laboratory experiments, the morphologies were characterized by incised rip channels in shore-connected shoals typical of the morphologies observed in previous field rip current studies. For these four morphologies, two distinct rip channels were observed at the longshore position x = 10 m and x = 22 m. In the following, we will focus on the rip current system at x = 10 m (denoted rip1 in Figure 1a) which was the most intense throughout the experiment.

To have a better idea of the rip channel characteristics, Figure 3 shows the alongshore lines of the seabed at the cross-shore location *y* = 11 m. The rip channel (Rip1) did not migrate in the alongshore direction and progressively infilled from Run1 to Run4. The rip channel characteristics for the four runs are summarized in Table 1. As indicated in this Table, the relative depth of the rip channel $h_{rip\text{-}channel}/h_{bar}$ during the experiment is within the range of values of existing field rip current studies, conversely to earlier laboratory rip current experiments. Figure 3 also reveals the presence of small scale variations of the seabed elevation which are related to the presence of ripples that were observed throughout the experiment (see also Figure 2e). Conversely to Rip1 the secondary, less-developed, rip channel (Rip2) migrated in the alongshore direction (about 3 m migration between Run1 and Run4).

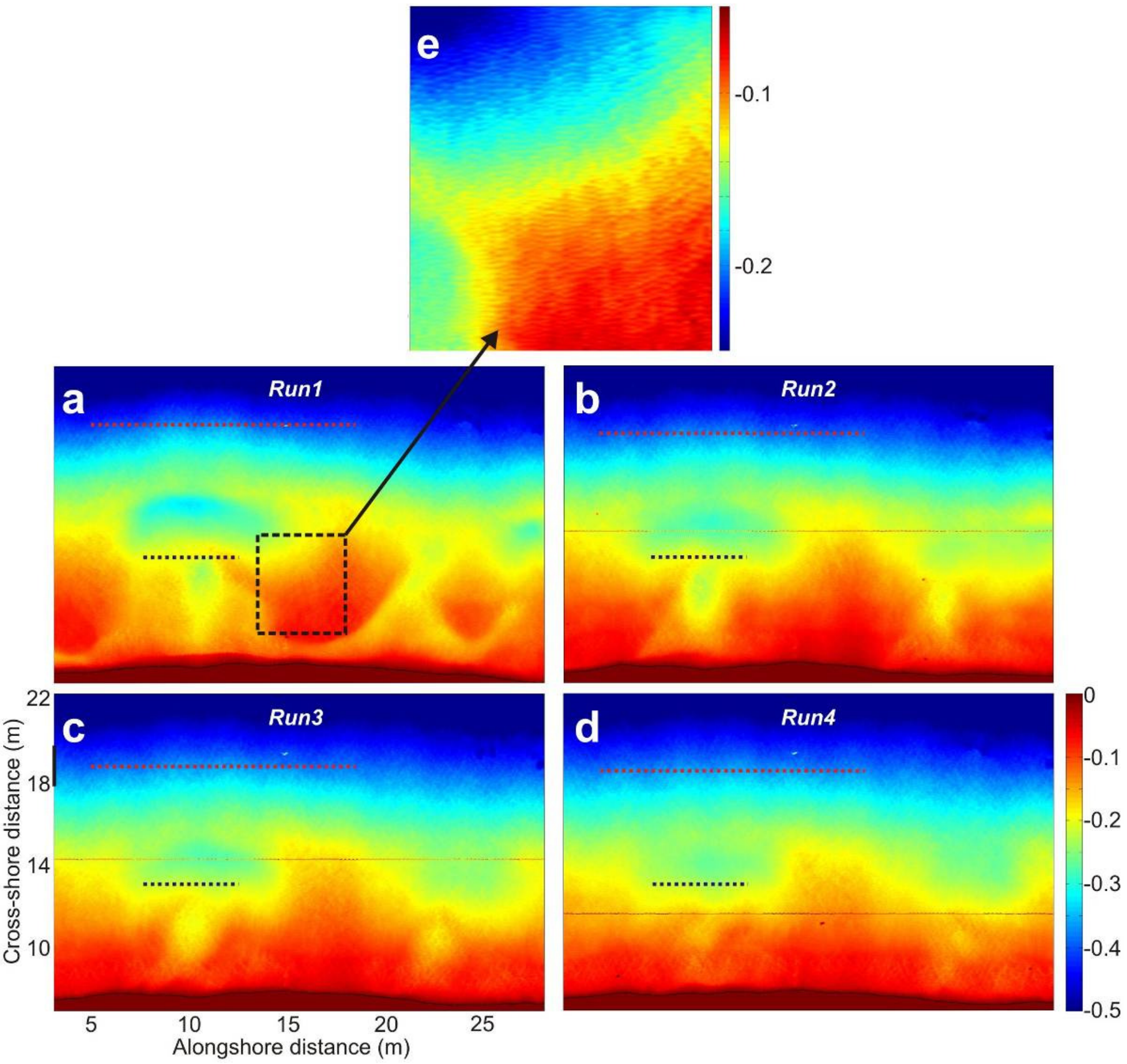

Figure 2. Accurately surveyed beach morphologies corresponding to (a) Run1, (b) Run2, (c) Run3 and (d) Run4, with (e) a zoom revealing the presence of ripples. Colorbar and solid black line indicate the seabed elevation in meter and the shoreline position, respectively. In (a), (b), (c) and (d) the blue dotted line indicate the cross-section of the rip used for computing the number of drifters caught in the rip and the red dotted line indicates the cross-section delimiting the semi-enclosed surf zone domain (1.25*Xs*) used to detect the number of drifters exiting the surf zone.

Table 1. Rip channel characteristics for the four runs.

	Run1	Run2	Run3	Run4
$h_{rip\text{-}channel}$ (cm)	20.	22.	20.	16.
h_{bar} (cm)	9.	12.	13.	13.
$h_{rip\text{-}channel}/h_{bar}$ (cm)	2.22	2.	1.54	1.23

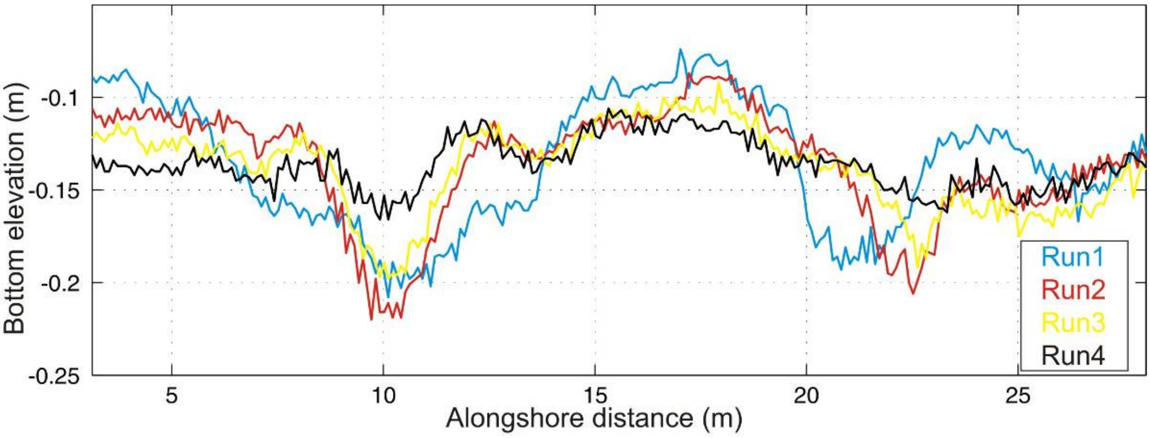

Figure 3. Alongshore lines of the seabed elevation for Run1, Run2, Run3 and Run4 at the cross-shore location y = 11 m.

2.3. *Drifter observations*

In addition to eulerian measurements, drifters were deployed in the surf zone for each run over a 1-hour duration. A few drifter designs and shapes were tested prior to the experiment. Ironically, the best drifter design was a simple balloon filled of water (with a diameter between 5 and 10 cm). Preliminary tests showed that broken and near-breaking waves passing over the drifters did not significantly push the drifters ashore (i.e., “surfing”). Drifters followed gross water motion in the top 5-10 cm of the water column, except for brief periods when the drifters would sink, caught in a plunging breaker, and follow deeper portions of the water column. Drifters were tracked using captured images from a shore-mounted video camera. Image coordinates were then rectified to still water level Cartesian coordinates. Figure 1b shows an example of a captured image, with drifters and a dye release during Run1.

The image rectification to Cartesian coordinates was done using a 3-dimensional direct linear transformation, the transformation coefficients being calculated by a least square method on 29 ground control points. The lens optical distortion (radial) is also taken into account. The procedure mean error applied on the control points position is 0.11 m, with a maximum error of 0.26 m.

Drifters were tracked using a semi-automatic method in order to avoid difficulties and errors induced by a full automatic method. For each drifter, and every 6 seconds, the drifter position is indicated manually by mouse clicking on the original video, and then the position is rectified on the fly automatically. Cross-shore and alongshore velocities were estimated from a 1st order polynomial interpolation in position and time of each sequential position of the drifter position at a 1 second time step. The study area was further divided into 0.5 m by 0.5 m bins in which, according to the drifter position information, the velocity data was sorted into the appropriate bin. Only bins with 5 or more velocity measurements were used for the data processing, which results in statistically confident results (Spydell et al., 2006). When a sufficient number of velocity measurements were available for a given bin and a required duration, mean current vectors and standard deviations in current angle and intensity were computed to grasp information on the spatial variability of the rip current system instabilities.

Because surf zone retention has implication from the perspective of both beach safety and mixing, we computed the surf zone retention for the 4 video-runs. For this, we had to accurately define what a drifter entering in the rip is, as it was not previously detailed in the literature. Therefore, we counted by automatically detecting drifter paths crossing the alongshore section of the rip channel shown in Figure 2. To estimate the surf zone compartment, at first we estimated the seaward extent of the surf zone by the most seaward location where the ratio of the offshore significant wave height to the local water depth reached 0.78. Given that the shoreline position is known with the bathymetric surveys, the surf zone width *Xs* was estimated for each video-run. According to MacMahan et al. (in press) the observed distance 1.25 surf zone widths (1.25*Xs*) is hypothesized to be the seaward boundary for a normal semi-enclosed rip current system, that is, material and fluid that remain within this seaward boundary will re-enter the surf zone. Therefore, we computed the number of escaped drifters by automatically detecting the drifters crossing the 1.25*Xs* boundary (see Figure 2).

3. Results

3.1. *Detailed Run1 data: mean characteristics*

As indicated in Table 1, the rip channel was the most developed during Run1, resulting in the most intense rip current circulations. In this subsection, we therefore focus on Run1. Figure 4 shows the time-evolution of a cluster of 34 drifters deployed at the beginning of Run1. Between t = 60 s and t = 120 s, most of the drifters enter in the rip with slight spreading, revealing a strongly shore-normal rip current. The initial trajectories within the rip channel are similar, but diverge near (x,y) = (11 m, 15 m) as drifters enter the rip current head (t > 100 s). For t > 140 s, some of the drifters start move shoreward as they are caught by the onshore flow over the shoals, while other exit the surf zone. At t = 220 s, the drifters are spread all over the rip current system.

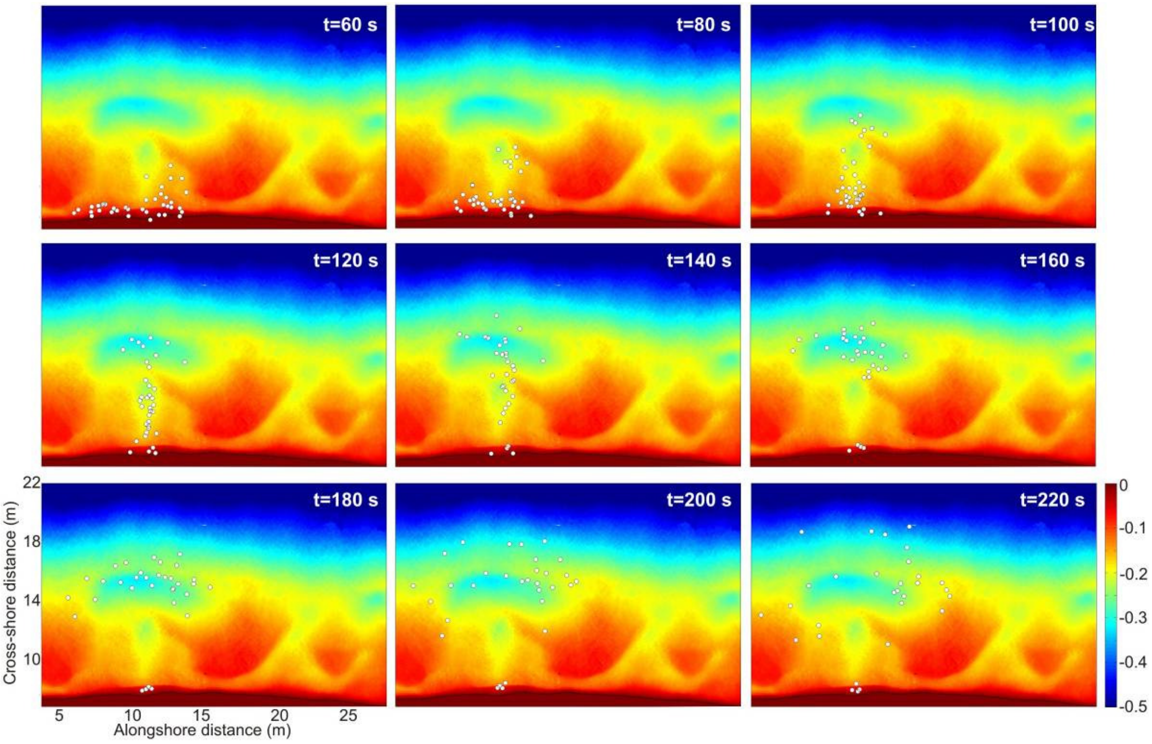

Figure 4. Time evolution of the drifter cluster at the beginning of Run1, from t = 60 s to t = 220 s every 20 s, with superimposed seabed morphology. Colorbar and solid black line indicate the seabed elevation in meter and the shoreline position, respectively.

Figure 5 shows a detailed analysis of 1-hour Run1. As indicated in Figure 5a, numerous drifter velocities were measured covering almost all the domain, with only a few drifter measurements in Rip 2 (Figure 1a). The resulting computed mean current velocity field (Figure 5b) presents a classic rip current pattern with counter-rotating cells and a relatively narrow offshore-directed jet. Rather high mean current velocities are observed, reaching about 11.5 cm/s in the rip neck (narrow offshore-directed jet, Figure 5b and 5d). The most intense mean velocities are observed on the shoal with mean onshore flow velocities reaching 16 cm/s and in the longshore feeder currents with similar magnitude (Figure 5d). Non-surprisingly, most of the drifter observations are located within the circulation cells as drifters were sometimes trapped and hardly escaped as a result of mean current instabilities. Figure 5e and 5f provide interesting information on the rip current system instabilities. Despite mean offshore flows (rip current) are substantially weaker than mean onshore flows, higher standard deviation in velocities is observed in the rip neck, revealing that the pulsating behavior is the most intense in the rip neck. In contrast, the weakest standard deviation in the flow direction is observed in the rip neck. This standard deviation increases in the rip current head, that is, where the rip current broadens. The larger flow angle standard deviation is observed within the circulation cells (Figure 5f). These observations provide high-quality information of the spatial distribution of the mean rip current circulation instabilities.

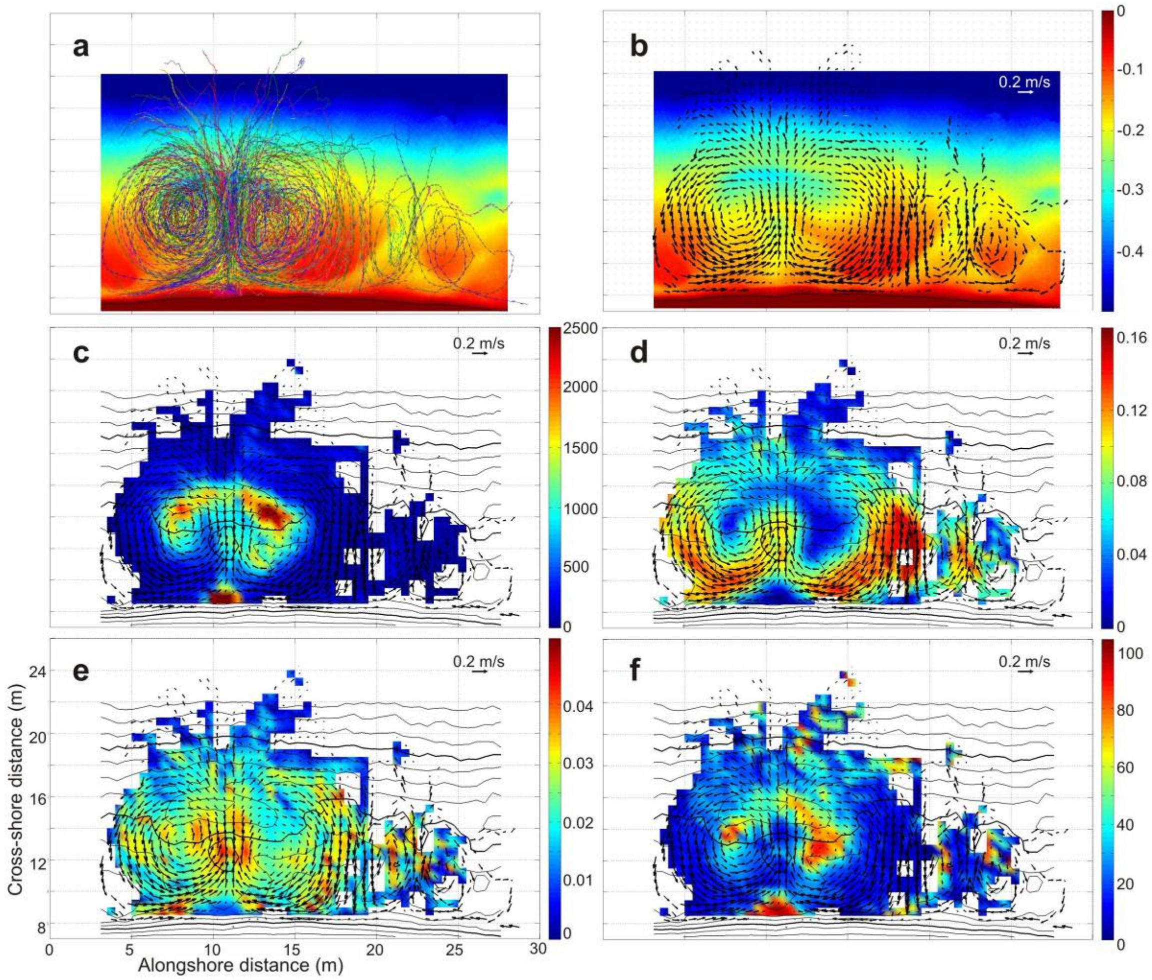

Figure 5. Drifter data gathered during Run1. (a) Superimposition of the measured drifter velocities with beach bathymetry; (b) computed mean current velocities with beach bathymetry (seabed elevation in m); (c) number of drifter observations per m^2; (d) Mean current magnitude in m/s; (e) standard deviation in drifter velocities; (f) standard deviation in drifter velocity angle. In (c,d,e,f) the mean velocity vectors and iso-contours of the bathymetry are superimposed.

3.2. *Sensitivity of the rip current circulations to the beach morphology: mean characteristics*

Computed mean current velocities for the four video runs are given in Figure 6. Rip currents are observed for the four beach morphologies with, non-surprisingly, decreasing rip current velocities with decreasing seabed alongshore non-uniformities. Some of this data are summarized in Table 2. Rip current circulations for the four situations show broad similarities: feeder currents, reasonably intense offshore velocities around the rip channel, strong onshore-directed flow across the shoal, counter-rotating cells to the left and right of the rip channel. However, details differ significantly. For instance in Run3 (Figure 6c), the rip current as it heads offshore is seen to be noticeably asymmetric. Differential breaking caused by alongshore depth variation is hypothesized to be the source of this asymmetry. This is not obvious in the bathymetric data given in Figures 2 and 3 and, therefore, this needs to be explored further through numerical modeling. In addition, from Run1 to Run4, more and more drifters are observed in the right hand circulation cell with the cause, at this stage, remaining elusive. This is particularly intriguing as rip2 is also found to be substantially asymmetric during Run3 (Figure 6c).

Figure 7 reveals that rip current angle standard deviation decreases with decreasing rip current intensity. The spatial variability in the flow angle standard deviation for the four video-runs shows, however, strong similarities. Flow direction appears rather constant in the feeders and over the shoals where strong shoreward currents are observed. This contrasts with the high variable flow direction within the circulation cells.

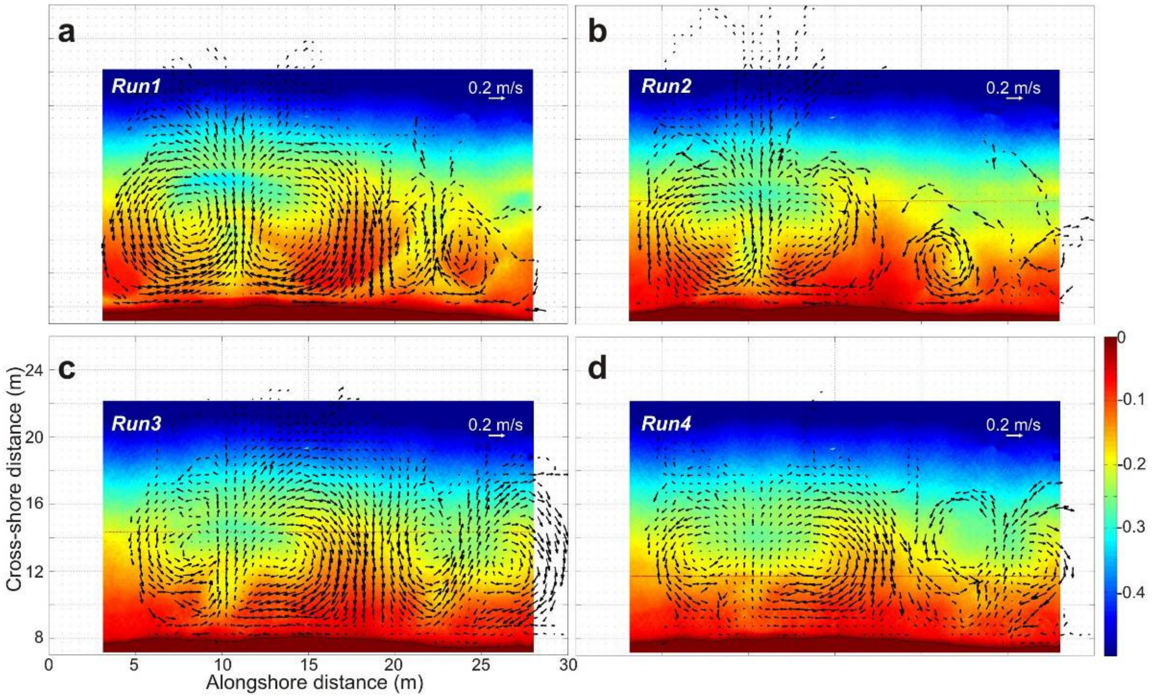

Figure 6. Computed mean current velocity field with superimposed bathymetry (seabed elevation is in m) for (a) Run1, (b) Run2, (c) Run3 and (d) Run4

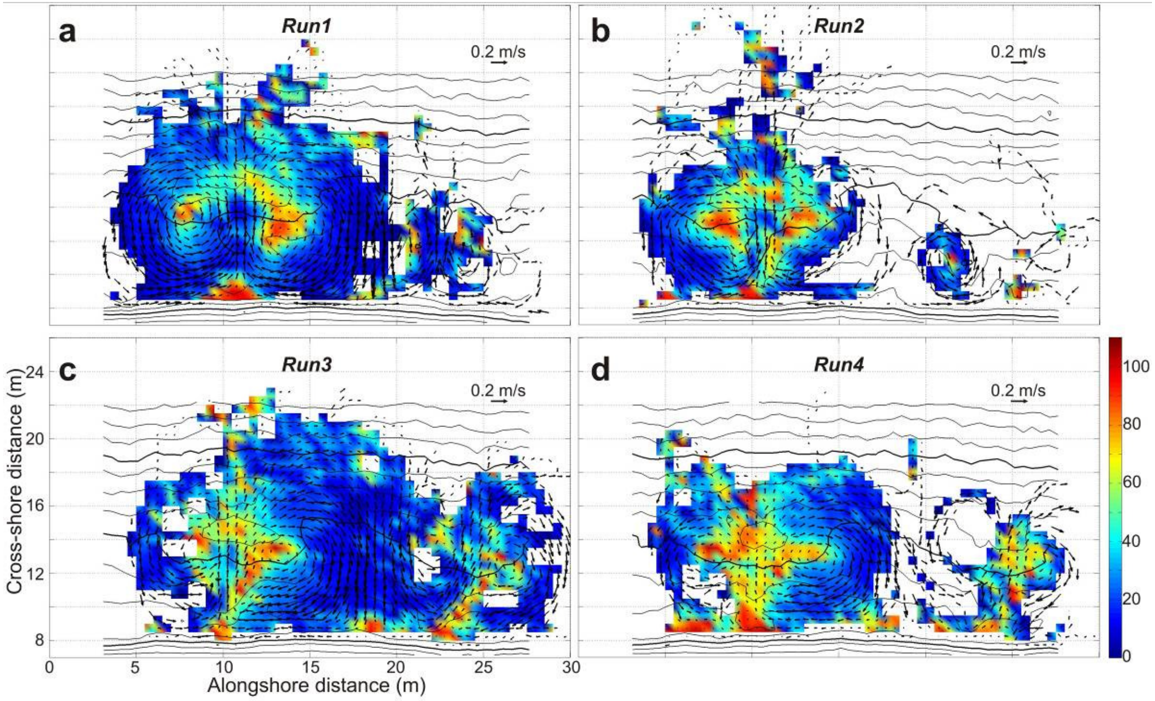

Figure 7. Computed standard deviation (degree) in drifter velocity angle field with superimposed mean current velocity field and iso-contours of the bathymetry (a) Run1, (b) Run2, (c) Run3 and (d) Run4

3.3. *Non-stationary behavior and surf zone retention*

The mean properties of the rip current circulations have been described in the previous subsection. Two of these properties (flow intensity standard deviation and standard deviation in flow direction) show that, non-surprisingly, the wave-induced current patterns were strongly unstable throughout the experiment. The general behavior of the rip current system showed many scales of motion. As indicated by preliminary data analysis of eulerian currentmeters deployed in the laboratory (not presented here), infragravity and far-infragravity motions were captured in all the domain.

Figure 8 presents unsteady properties for Run1 using drifter paths every 2 minutes over a 24-minute duration. The circulation cells can be easily deduced from these drifter paths. As observed in previous laboratory rip current studies, the rip sometimes changes of direction from left to right for no apparent reason. For instance, a significant leftward trend is observed during Run1 at t = 900 s that rapidly changes to a rightward trend at t = 1140 s. The circulation cells do not seem to migrate in the alongshore migration as a result of cellular-scale instabilities, meanwhile significant cross-shore migration of the circulation cells are readily apparent. For instance, the cell centers seem to be located at about y = 15 m at t = 900 s or at t = 2100 s while, most of the time, they appear to be located at about x = 13 m (Figure 8). Interestingly, this seaward migration of the rip current circulation seems to be associated with subsequently events of drifter expulsion from the surf zone compartment (see at t = 1020 s and 2100 s in Figure 8), despite it was not always observed in other expulsion events. Conversely to other laboratory rip current studies, there was hardly trace of vortices (expected to be of O(0.5 – 1 m)) being shed offshore.

Because surf zone retention has implication from the perspective of both beach safety and mixing, we computed the surf zone retention for the 4 video-runs using the method described in section 2.3. Surf zone retention results, as well of the mean characteristics of the rip current, are summarized in Table 2. There does not seem to be a relationship between the relative depth of the rip channel and the surf zone retention rate, whereas rip current intensity increases with increasing relative depth of the rip channel. However, we note that the highest surf zone retention rate is computed for the weakest mean rip current intensities (Run 4).

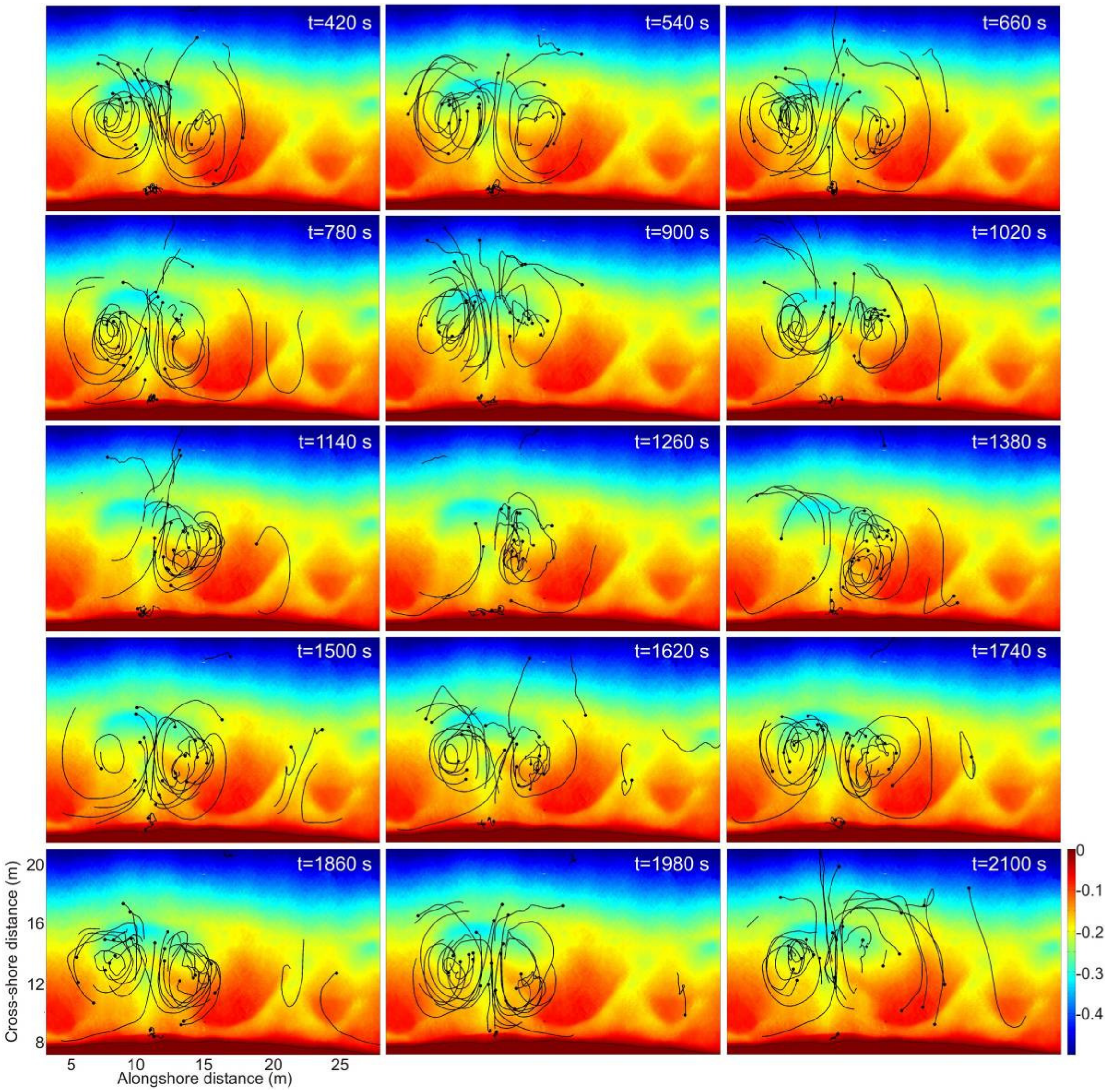

Figure 8. 2-minute drifter tracks over a 24-minute duration during Run1. Dots indicate track endings (sometimes dots are non-existent because the drifter was lost during the 2-minute duration in the darkest areas of the video camera view field). In all the panels, the bathymetry is superimposed (seabed elevation in m).

Table 2. Rip channel characteristics for the four runs together with surf zone retention and rip current information.

	Run1	Run2	Run3	Run4
$h_{rip\text{-}channel}$ (cm)	20.	22.	20.	16.
h_{bar} (cm)	9.	12.	13.	13.
$h_{rip\text{-}channel} / h_{bar}$	2.22	2.	1.54	1.23
Mean rip current velocity (cm/s)	11.48	11.44	8.26	5.14
Maximum rip current velocity (cm/s)	19.86	18.86	16.90	14.99
Standard deviation in rip current velocity (cm/s)	4.52	5.59	4.25	3.18
Number of drifter caught in the rip	276	132	193	142
Number of drifters exiting the surf zone	21	15	25	3
Surf zone retention rate (%)	92.4	88.6	87.0	97.8

The cause leading to drifter escaping the semi-enclosed rip current system was tentatively investigated. 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 velocity it experienced within the rip channel V_{Dmax} as well as its most landward position in the feeder before entering in the rip, Xc. Figure 9 shows V_{Dmax} versus Xc for the four video-runs, with black circles indicating the drifters that exited the semi-enclosed surf zone compartment ($1.25Xs$). Interestingly, the drifters that exited the surf zone compartment were not readily preferably those caught in a pulsating jet as they did not always correspond to the highest V_{Dmax} values, except for Run2 (Figure 9). In addition, V_{Dmax} clearly increases with decreasing Xc which means that, for a given drifter, the most shoreward it will be caught in the feeder the most likely it will experience a high offshore-directed velocity within the rip channel (which does not necessarily means that it will be more likely to exit the surf zone compartment).

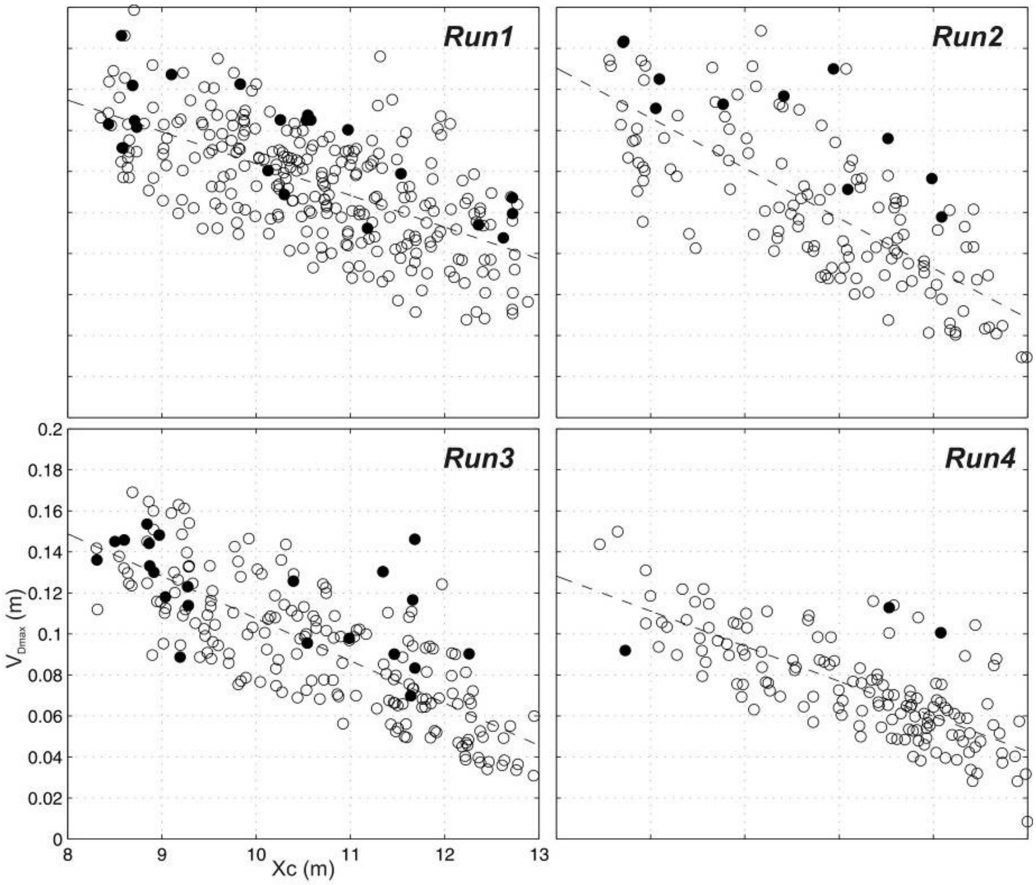

Figure 9. For the four video-runs: maximum drifter offshore-directed velocity within the rip channel V_{Dmax} versus Xc the corresponding most landward position in the feeder before entering in the rip. The white circles and black circles correspond to drifters remaining within the semi-enclosed surf zone compartment and exiting this compartment, respectively

Figure 10 shows the drifter paths when caught in the rip for the four video-runs. There is readily no preferable trajectory for the drifters to exit the surf zone compartment as drifters coming from the left of right circulation cell and from the shoreward or seaward part of the feeder have similar behavior for Run1, Run2 and Run4. In contrast, for Run3 when the rip current was significantly asymmetric, as it was heading rightward, about 50 % of the drifters coming from the left hand circulation cell exited the surf zone compartment. However, it does not seem to have an impact on the overall surf zone retention rate (87 %, similarly to Run2 and Run3).

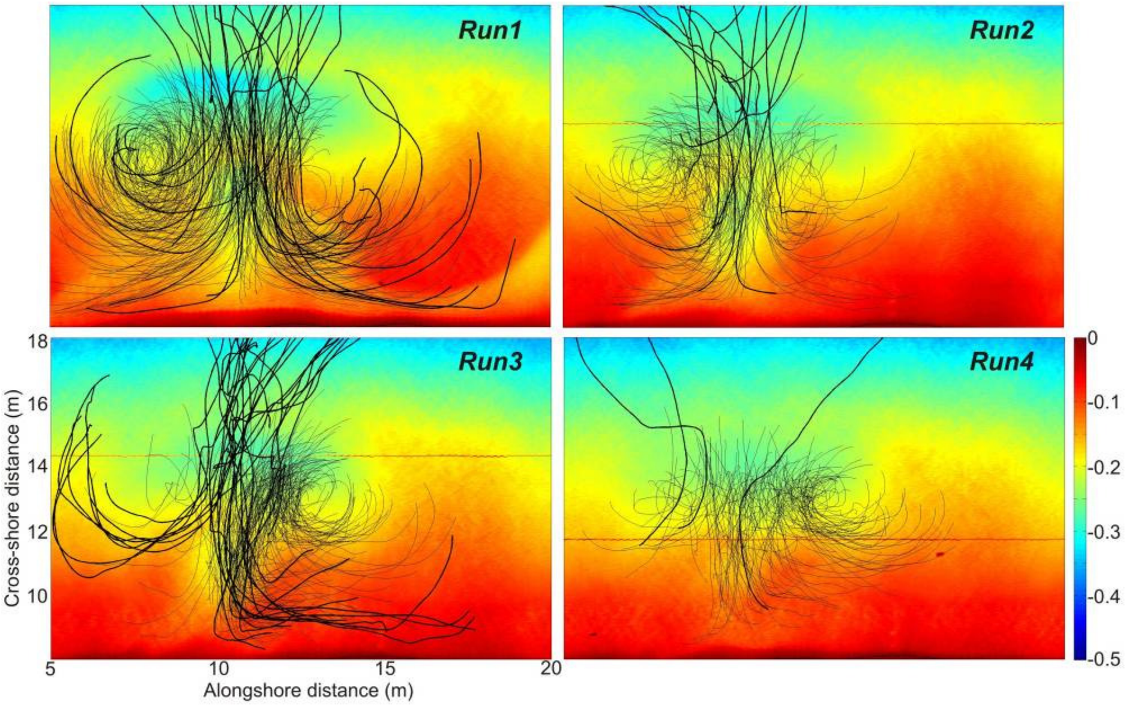

Figure 10. Drifter paths when caught in the rip for the four video-runs. Thin solid lines: drifters that remain in the semi-enclosed surf zone compartment; Thick solid lines: drifters that exit the semi-enclosed surf zone compartment.

4. Discussion and conclusions

In this paper we investigated topographically-controlled rip current circulations using a large number of drifters over four distinct beach morphologies. The bathymetries exhibited more or less developed nature-like bar-rip morphology. Results show the presence of classic rip current patterns with counter-rotating cells and a relatively narrow offshore-directed jet with, for three of the situations, a reasonably symmetric shape. Non-surprisingly, it was found that rip current intensity increases with increasing relative depth of the rip channel. As it has been largely reported in the literature, the wave-driven circulations were strongly unstable and subject to pulsation over a large range of temporal scales (Shepard and Inman, 1950; Sonu, 1972; Smith and Largier, 1995; Haller and Dalrymple, 2001; Callaghan et al., 2004; among other). Computed standard deviation in flow intensity and direction provides high-resolution information on the spatial variability of the rip current circulation variations. For instance, we highlighted highly-pulsating and weakly directionally variable offshore-directed flow in the rip channel which contrasts with weakly-pulsating and highly-directional variable flows within the circulation cells. Despite significant differences in the beach morphologies, rip current circulations for the four situations showed broad similarities: feeder currents, reasonably intense offshore velocities around the rip channel, strong onshore-directed flow across the shoal and counter-rotating cells to the left and right of the rip channel. However, Run3 differed substantially with a rip current noticeably asymmetric. Despite not obvious when looking at the bathymetry, differential breaking caused by alongshore depth variation is hypothesized to be the source of this asymmetry. This needs to be confirmed with numerical modeling.

The computed surf zone retention rates of about 90 % are of the order of those previously observed in the field by Bruneau et al. (2009), involving only a small number of drifters, and MacMahan et al. (in press) with much more numerous measurements. The surf zone retention rate strongly increased for Run4 when a weakly-energetic rip current was observed over a terrace-like beach morphology. For the three other video-runs, when rather well-developed bar-rip morphologies were observed (Figure 2), there was no clear relationship between the surf zone retention rate and the relative depth of the rip channel, the mean rip current velocity or the standard deviation in offshore-directed flow intensity. Further video-runs would provide more information on the possible explanation for the variability in surf zone retention rates.

In addition, and conversely to what was previously hypothesized in the literature (Smith and Largier, 1995; Reniers et al., 2007), drifters exiting the surf zone compartment were not systematically caught by a pulsating jet. Rip current pulsations are very complex and, to date, rather poorly understood. Rip currents are observed to pulsate at various temporal scales, which have different forcing (for more details see MacMahan et al., 2006): they are composed of infragravity motions, modulations of wave group energy, shear instabilities (and tides for field rip current studies). While some of the drifters exiting the surf zone compartment were readily related to a seaward migration of the order of a few meters of the surf zone circulations (Figure 8), this was not always the case. An in-depth investigation of drifter expulsion as a function of wave groups, surf-zone eddies oscillation and shear instability is required.

As shown in Figure 9, it was found that drifters coming from the most shoreward part of the feeder are likely to experience larger offshore-directed flow within the rip channel. To our knowledge, this behavior has never been touched upon in the literature. This has significant implications from the perspective of beach safety and life-guarding as, despite shallow water and shoreline proximity are usually assumed to be synonym of reasonable safety, these results suggest that swimmers who are the closest to the shoreline are, if caught by the feeder current, likely to experience a more rapid and frightening seaward migration. However, they are not more likely to exit the surf zone compartment than when coming from any other area within the surf zone. In Run1, Run2 and Run4 there was indeed no evidence of specific initial drifter location for it to more likely exit the surf zone. In contrast, when the rip current was significantly asymmetric (Run3, heading rightward), about 50 % of the drifters coming from the left hand circulation cell exited the surf zone compartment. Despite it does not seem to have an impact on the overall surf zone retention rate (88.6 %, similarly to Run2 and Run3), this also has significant implications from the perspective of beach safety and life-guarding.

Conversely to other laboratory rip current studies, there was hardly trace of vortices (expected to be of O(0.5 – 1 m) given the offshore significant wave height and rip channel dimensions) being shed offshore (Kennedy and Thomas, 2004; Kennedy et al., 2006). This can be explained by the gently sloping beach morphology observed during this laboratory experiment, similar to existing field rip current studies, which contrasts with the strong abrupt bathymetric changes in Kennedy et al. (2006).

For the first time to date, this laboratory rip current study was undertaken for nature-like beach morphologies, using very dense drifter measurement over a long duration. This study brings new thoughts about rip current systems, particularly on a surf zone retention point of view. Despite, at this stage, the cause for drifters exiting the surf zone compartment remains uncertain, it was found that drifter expulsions were surprisingly not related to a pulsating jet event. Overall, further video-runs involving more contrasting beach morphologies are required for more in-depth investigating the sensitivity of the rip current characteristics to the beach morphology. This analysis is currently in progress and should eventually provide high-quality data for future wave-driven circulation models.

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