Rip currents and circulation on a high-energy low-tide-terraced beach (Grand Popo, Benin, West Africa)

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ABSTRACT

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Rip currents are wave-driven intense seaward-flowing jets of water that are important to both beach morphodynamics and the overall ecosystem. Rip currents are also the leading deadly hazard to recreational beach users worldwide. More specifically, the African region is reported to have the highest rates of drowning in the world, yet both the occurrence and the type of rips developing along the African beaches are unknown. In February 2013, a 12-day field experiment was performed at the high-energy low-tide-terraced sandy beach of Grand Popo beach (Benin, West Africa). Human drifter data and video imagery are combined to address wave-driven circulation and rip current activity. Results show two prevailing rip current types. (1) Low-energy (~ 0.2-0.4 m/s) swash rips, with short life-spans of about 1 minute, extend about 5-10 m offshore and occur preferably at mid to high tide at fixed locations in the center of beach cusps. (2) Higher-energy (0.2 – 0.8 m/s) surfzone flash rips become active with the onset of intense wave breaking across the low-tide terrace. They tend to migrate downdrift with a longer time-span of about 2-5 minutes. The relatively weak longshore current (0.2 – 0.55 m/s) measured during the experiment suggests that flash rips were driven by vorticity generated by wave breaking rather than shear instabilities of the longshore current. Swash rips and flash rips are common at Grand Popo and often co-exist. We propose a conceptual model of both flash and swash rip activity on this stretch of the West African coast.

ADDITIONAL INDEX WORDS: *Flash rips, swash rips, longshore current, drifters, video monitoring, beach safety.*

INTRODUCTION

Rip currents are unsteady concentrated flows of water jetting offshore at $O(1\ \mathrm{m/s})$ which are ubiquitous along wave-dominated sandy beaches (Dalrymple *et al.*, 2011). Rip currents are important in the transport and dispersal of pollutants, nutrients and biological species in mixed nearshore waters (Shanks *et al.*, 2010) as well as in offshore sediment transport (Aagaard *et al.*, 1997), short-term (from days to weeks) sandy beach morphodynamics (Michallet *et al.*, 2013) and localized beach and dune erosion during storms (Thornton *et al.*, 2007; Birrien *et al.*, 2013).

Rip currents are also one of the most dangerous natural hazards in the world, and arguably the leading deadly hazard to recreational beach users (*e.g.* Scott *et al.*, 2011; Brander *et al.*, 2013). In high-income countries (HICs) such as the United States and Australia, rip current hazard assessment, lifesaving services and community education programs have been performed for a long time. Yet, fatal drownings at beaches still occur with about 100 reported in the United States (United States Lifesaving Association, 2011) and 29 in Australia (Surf Life Saving Australia, 2011) in 2011. Worldwide, 96% of all unintentional drowning deaths occur in low- and middle-income countries (LMICs; WHO, 2010), which are mostly situated in tropical and subtropical regions with long stretches of coastline exposed to high-energy ocean wave conditions (Hammerton *et al.*, 2013). For instance, the African region is reported to have the highest rates of drowning in the world (Peden and McGee, 2003; WHO, 2010), although there is a wide range of uncertainty around the estimate of global drowning deaths (Hammerton *et al.*, 2013). A necessary step to overcome these tragic statics is to assess both the occurrence and the type of rips developing along the African beaches.

There are many causes of rip current and a wide range of rip types (Dalrymple *et al.*, 2011). One can distinguish (1) rips that are fixed at a given location and (2) those that are episodic and

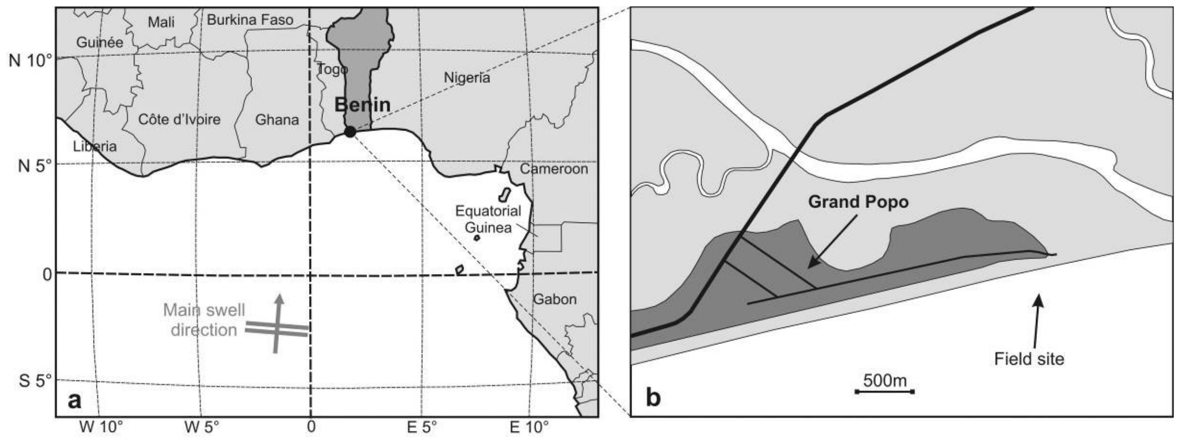

Figure 1.Location of the study site (Grand Popo beach) in Benin, West Africa

tend to migrate alongshore. In the former type, rips driven by alongshore variations in bathymetrically-controlled wave breaking along rip-channeled beaches (Bruneau *et al*., 2011; Austin *et al*., 2013) have been documented for decades (*e.g*. MacMahan *et al*., 2006). Rip currents against headlands, groins or piers (Pattiaratchi *et al*., 2009) are driven by wave shadowing (Castelle and Coco, 2012) or the deflection of the longshore current (Castelle and Coco, 2013) when located at the downwave or upwave side of this fixed rigid boundary, respectively. Nearshore rip currents can also be controlled by offshore bathymetric anomalies such as canyons (Long and Ozkan-Haller, 2005; Castelle *et al*., 2012). Swash rips, often found in the center of beach cusps (Masselink and Pattiaratchi, 1998; Dalrymple *et al*., 2011), are also fixed in location but are not surfzone rip currents in contrast to all the other rips described herein. The second type of rip currents, episodic and migrating alongshore, known as flash rips (also called transient rips; Johnson and Pattiaratchi, 2004; Murray *et al*., 2013) have received far less attention. Whether shear instabilities of the longshore current (Ozkan-Haller and Kirby, 1999) or vorticity generated by wave breaking (Clark *et al*., 2012) is the major driving mechanism for surfzone eddies and flash rips remains an open question. The lack of understanding is partly due to the difficulty of measuring flash rips in the field because of their unpredictable nature. Flash rips are preferably found along alongshore-uniform beaches exposed to groundswells or wind-wave conditions.

Along the high-energy low-tide-terraced beaches of the Benin Coast, which are representative of a lot of beaches in West Africa, rip currents are readily ubiquitous, although nothing is known about the dominant rip current types. In addition, nothing is known about the nature and cause of beach drownings and reliable data on the number of drowning incidents are non-existent. In February 2013, a 12-day field experiment was performed at Grand Popo beach (Almar *et al*., this issue). In this paper we address wave-driven circulation and rip current activity during the experiment using Lagrangian and video data.

METHODS

Study site

Grand Popo beach (6.2°N, 1.7°E ; Figure 1) is located in Benin, West Africa. Grand Popo is representative of the natural undisturbed reflective sandy beaches of the Gulf of Guinea (for an extensive description, see Laibi *et al*., this issue). This is an open wave-dominated and microtidal beach (mean spring tide range: ~1.8 m) exposed to long period swells with a mean significant wave height Hs = 1.36 m and a mean peak wave period Tp = 9.4 s. The combination of the medium to coarse quartz sand (0.4–1 mm, $D50$: 0.6 mm) and dominant groundswell regime generated in the South Atlantic results in a modal intermediate, rather reflective, beach state corresponding to the low-tide terrace classification in

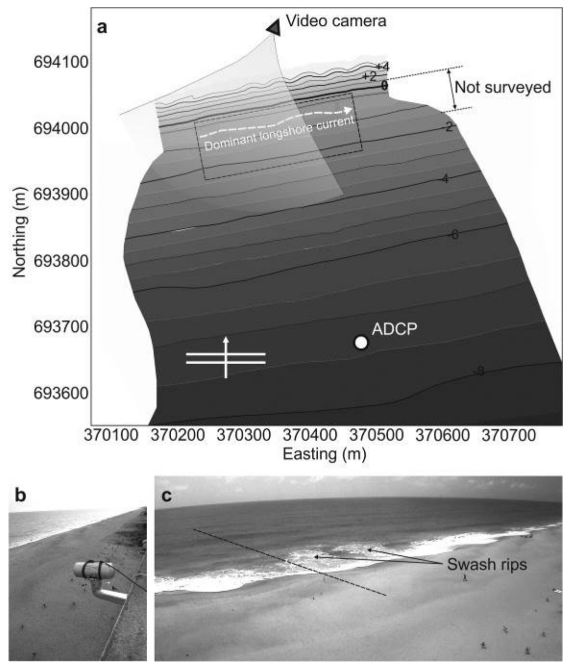

Figure 2. (a) Grand Popo beach bathymetry surveyed in February 2013 (note that the terrace was not surveyed due to breaking waves; the terrace shape is therefore indicated loosely based on observations by the human drifters) with locations of the ADCP and the video camera. (b) Video camera mounted on a 15-m high semaphore located about 80 m from the mean sea water shoreline and (c) example of snapshot showing 2 swash rips with the black line indicating the time stack location.

Wright and Short (1984). The combined effect of persistent S swells throughout the year and the beach steepness results in an intense easterly longshore drift of about $0.8x10^6$ m^3/year (Laïbi *et al.*, this issue).

Field experiment

The field experiment was conducted from February 17 to 28, 2013 (for an extensive field experiment description, see Almar *et al.*, this issue). The experiment was designed both to measure beach changes on short timescales and to test the applicability of a low-cost video monitoring system in such remote environments. Figure 2 shows the measured nearshore bathymetry with the location of the video system and that of the ADCP moored in 8-m depth to obtain the wave and tide conditions throughout the experiment. The beach exhibited an alongshore-uniform low tide terrace, a steep and rather alongshore-uniform lower shoreface and a well-developed cuspate morphology in the high tide zone that were spaced at about 30 m.

During the experiment, shifting from a neap tide (0.4-m range) to a spring tide (1.5-m range) cycle, Grand Popo beach was exposed to 2 successive groundswell regimes from the South with a significant wave height *Hs* peaking at 1.1 m and 1.6 m and a peak wave period peaking at 12 s and 16 s, respectively (see Figure 3). During this experiment, morphological changes were restricted to the beach cusp system (Sénéchal *et al.*, this issue). The dominant swell regime combined with the coastline orientation resulted in a persistent, yet varying in intensity, easterly longshore current throughout the experiment. Wave breaking type was mostly plunging across the terrace and surging across the beach cusp system during low and high tide, respectively.

Data collection

Mostly because of logistic difficulties, it was not possible to deploy traditional PVC GPS-equipped drifters (see for instance MacMahan *et al.*, 2009). Instead we resorted to the use of human operators that drifted with the currents, each equipped with a GPS. This enabled a fair representation of the current structure. In total, 7 human drifter experiments were performed at low tide for about 1-1.5 hours with 2 or 3 operators. Human drifters were released updrift in the video camera view field and willingly went ashore about 250 m downdrift (Figure 2a).

Rip current activity was also identified from the video camera, which was mounted on a 15-m high semaphore located about 80 m from the mean sea water shoreline (Figures 2b, c). The camera recorded continuous video footage at 2 Hz. Timestacks and timex were generated every 15 minutes.

RESULTS

Figure 4 shows the human drifter results for the 7 experiments together with the corresponding directional wave spectra and representative video snapshots. These results are further analyzed in Table 1 with an overall description of both the sea state and wave-driven circulation using Lagrangian data and visual inspection of the video runs.

Results show a large variability in wave-driven circulation during the experiment although the 2 successive groundswells regimes were not that much contrasted. For both wave regimes, the wave period peaked about 2-3 days before the peak in significant wave height (Figure 2) as waves originate from storm far out to sea in the South Atlantic. In addition, the first pulses of swell typically have a S-SW incidence that progressively shifts to the S as the remote storms tracked W-E. Given that Grand Popo is primarily exposed to long-period swells (*Tp* ~ 10-16 s), wave are strongly refracted which resulted in an overall S incidence that progressively, and slightly, shifted from W to E as *Hs* increased (see for instance February 22 – 25 in Figure 3). Accordingly, for each wave regime the nearshore circulation was initially dominated by a longshore current with the subsequent (within 1 or 2 days) increase in rip current activity as both *Hs* peaked and wave incidence became more shore-normal.

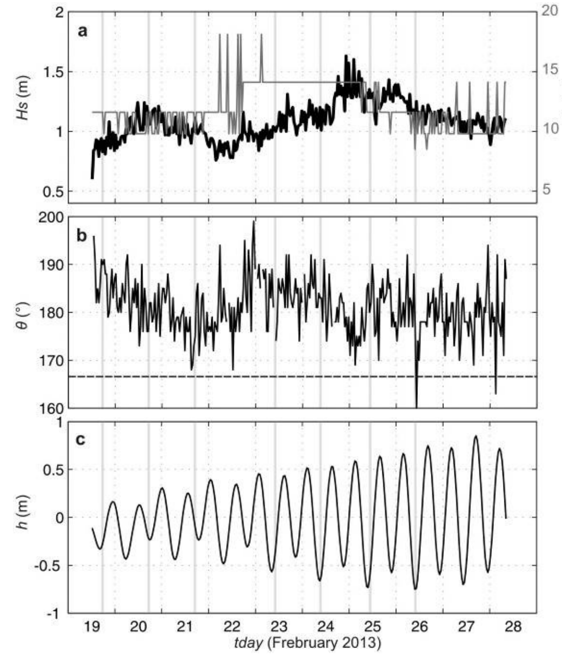

Figure 3. Time series of offshore wave conditions and tides measured by the ADCP (Figure 2) during the field experiment with the indication the performed human drifter experiments (gray vertical lines). (a) Significant wave height *Hs* (black) and peak wave period *Tp* (gray); (b) angle of wave incidence θ with the horizontal dotted black line indicating shore-normal incidence and (c) tide elevation *h*.

We first describe the nearshore circulation during the first swell regime (February 19, 20 and 21). On February 19, the low-energy S groundswell combined with a SW sea resulted in a weak (0.2 m/s) longshore current (Figures 4a, b and c). Low-energy swash rips extending about 5-10 m offshore were observed as the low-tide water level was relatively high because of the neap tidal range. On February 20 (Figures 4d, e and f), the increase in *Hs* combined with a more shore-normal incidence resulted in the formation of both swash and flash rips, with a weak longshore current. Among the 14 human drifter pathlines measured that day, 7 were caught in a flash rip (Figure 4d) with a rip speed of about 0.5 m/s. When these drifters exited the surf zone, they subsequently slowly migrated alongshore. Some of them re-entered the surf zone, before being transported by the alongshore current. A detailed visual inspection of the video runs indicates that flash rips were episodic, characterized by short life-spans of 2-5 minutes, in agreement with the observations of Murray *et al.* (2013) on the Gold Coast (Australia), and tended to migrate slowly downdrift. The next day (February 21, Figures 4g, h and i) the fading S swell combined with the increase in SW sea resulted in a dominant weak longshore current (0.2 m/s) with occasional swash rips.

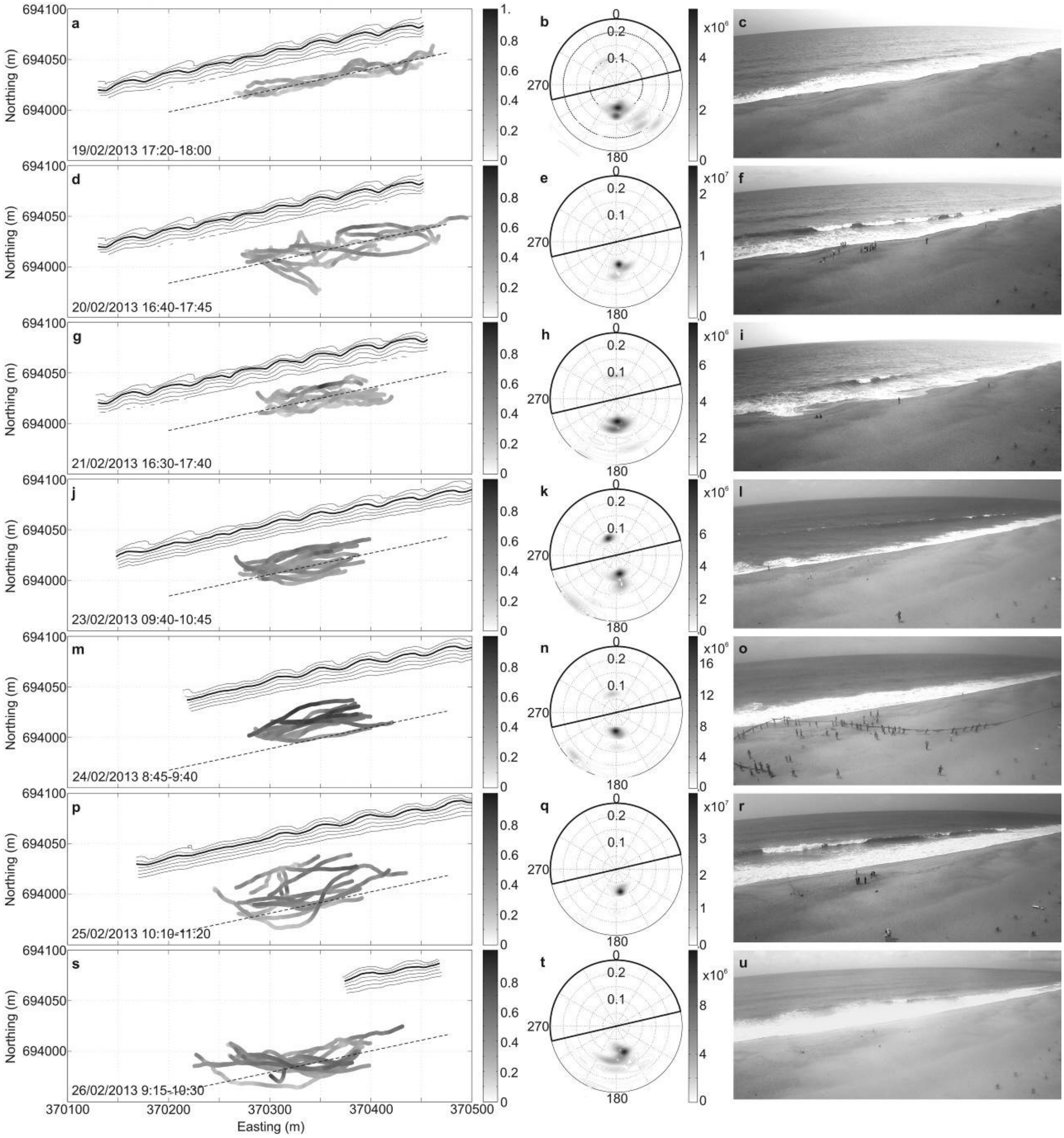

Figure 4. Wave-driven circulation and wave conditions for the 7 human drifter experiments. Left-hand panels: pathlines of the human drifters with color bar and the dashed black line indicating drifter velocity in m/s and the outer edge of the surf zone loosely based on visual observations, respectively. The beach cusp topography is contoured at a 0.5-m interval (the thick contour corresponds to z = 4 m). Middle panels: directional wave spectra measured by the ADCP with color bar indicating energy density in m.Hz$^{-0.5}$.deg$^{-0.5}$. Right-hand panels: snapshot during the corresponding experiment.

The second swell regime (February 23, 24, 25 and 26) coincided with a progressive shift towards spring tides. Although swash rips were ubiquitous during mid- and high-tide phases, they progressively disappeared during the human drifter experiments which were performed at low tide (-0.7 m < h < -0.4 m). During the first 2 days, the S wave incidence combined with a SW sea resulted in a dominant longshore current increasing in speed (0.35 to 0.55 m/s, see also drifter pathlines in Figure 4). This relatively strong longshore current pulled fishnets nearby and forced the local fisherman to pass over our instrumented site (Figure 4o). On February 25 (Figures 4p, q and r), the fading SW sea and the building S swell (Hs = 1.4 m) with an increasingly shore-normal incidence resulted in ubiquitous flash rips (~0.4 – 0.8 m/s). Yet, a rather small number of human drifters actually exited the surfzone compartment (Figure 4p) as they were mostly transported by the longshore current (~ 0.3 m/s, Table 1). Flash rips remained active the subsequent day (Figures 4s, t and u) with similar characteristics. As for the first swell regime, flash rips were episodic and tended to migrate slowly downdrift.

Table 1. Overview of wave conditions and wave-driven circulation for the 7 human drifter experiments (*Ul* is the mean surface longshore current computed from the Lagrangian data).

Date	*h* (m)	*Hs* (s)	*Tp* (m)	*θ* (°)	*Sea state*	*Circulation description*	*Ul* (m/s)
19/02/2013 17:20-18:00	-0.3	0.9	12	190	Low-energy S swell + SW sea	Dominant weak longshore current, occasional swash rips	0.2
20/02/2013 16:40-17:45	-0.2	1.1	10-12	180	Building S swell + low-energy SW sea	Weak longshore current with flash and swash rips	0.25
21/02/2013 16:30-17:40	-0.1	1.0	12	175	Fading S swell + SW sea	Dominant weak longshore current, occasional flash rips	0.2
23/02/2013 9:40-10:45	-0.4	1.0	14-16	185	Slowly building S swell + low-energy SW sea	Dominant longshore current increasing in speed, rare swash rips	0.35
24/02/2013 8:45-9:40	-0.6	1.1	14	185	Slowly building S swell + SW sea	Dominant longshore current further increasing in speed, rare rips	0.55
25/02/2013 10:10-11:20	-0.6	1.4	12-14	180	S swell peaking + low-energy SW sea	Weak longshore current, active flash rips, no swash rip	0.3
26/02/2013 9:15-10:30	-0.6	1.2	10-12	180	Slowly fading S swell + low-energy SW sea	Weak longshore current, active flash rips, no swash rip	0.3

DISCUSSION AND CONCLUSION

This paper presents the first assessment of rip current activity on a West African beach. Our results indicate that, at Grand Popo beach, there are 2 common types of rips. (1) Low-energy (~0.2 - 0.4 m/s) swash rips extending about 5-10 m offshore (see Figure 2c) occur preferably at mid to high tide in the center of beach cusps with no significant influence of the incoming wave characteristics. Although swash rips are fixed at a given location, they have a very short life-span (typically less than 2 minutes, see for instance the video time stack in Figure 5). (2) Surfzone flash rips, episodic and tending to migrate downdrift, become active with the onset of intense wave breaking across the low-tide terrace. Given that the latter type of rips was observed under relatively low longshore current speeds (< 0.5 m/s), flash rips were not driven by shear instabilities of the longshore current. Instead, vorticity generated by wave breaking was likely the major driving mechanism for surfzone eddies and flash rips at Grand Popo beach. Flash rips were occasionally intense (0.8 m/s) and were preferably observed at low tide during the experiment.

Given the high rate of beach-user drownings in West Africa, assessing the occurrence and the types of rip developing along this stretch of coast was a necessary first step. Figure 6 presents a conceptual model of rip current activity at Grand Popo as a function of wave and tide conditions. All the configurations in the left-hand and middle panels were observed during the experiment. Although the circulations shown in the right-hand panels (*Hs* > 2 m) in Figure 6 were not observed during the experiment, they were based on a detailed visual inspection of the video data from March to November 2013 for which a number of high-energy events were monitored (see Figure 6b, c). Interestingly enough, Grand Popo beach remained low-tide terraced even during storms with *Hs* > 2.5 m, suggesting that the up-state transition towards a bar and rip morphology, for which rips driven by alongshore variations in bathymetrically-controlled wave breaking are ubiquitous (Bruneau *et al.*, 2011), may never be reached.

To conclude, this study is the first one on rips in West Africa. Another experiment is planned at Grand Popo in March 2014 for which expected higher-energy waves and the deployment of a large number of PVC GPS-equipped drifters will arguably further increase our understanding of rip current dynamics in West Africa.

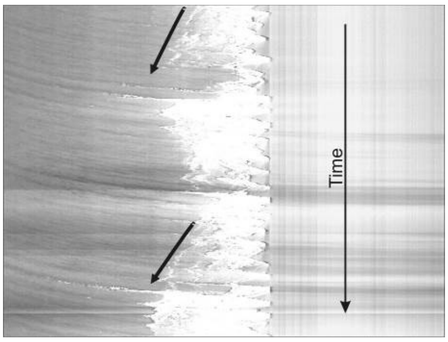

Figure 5. 5-minute timestack showing the occurrence of 2 swash rips identified by the foam streaks migrating seaward. Both swash rips have a life-span of about 1 minute.

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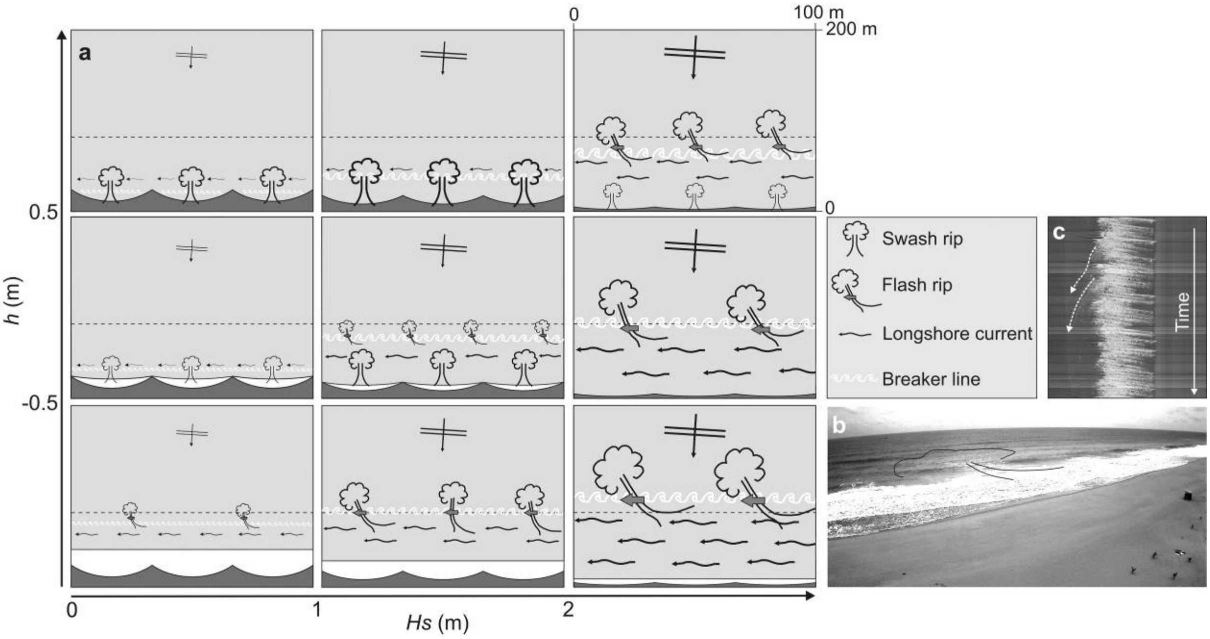

Figure 6. Conceptual model of rip current activity at Grand Popo beach (W Africa) as a function of the significant wave height Hs and tide level h. (b,c) Snapshot and corresponding 10-min time stack of a flash rip for *Hs* > 2 m on May 6, 2013.

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