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TRANSIENT SURF ZONE CIRCULATION INDUCED BY RHYTHMIC SWASH ZONE AT A REFLECTIVE BEACH

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Abstract

The influence of cuspate swash dynamics on transient surf zone circulation is investigated using both field observation at the low-tide terraced Grand Popo beach and wave-phase resolving numerical simulations. The ability of the model to describing low-tide terrace beach hydrodynamic is tested, and the model is further applied to investigate the role of wave reflection over a rhythmic swash zone pattern on surf zone wave and current. In the numerical simulations, these mechanisms drive higher surf zone irregularities with beach cusps than for an alongshore-uniform swash zone morphology. Rhythmic swash-based reflection generates a standing wave pattern visible in current and wave fields. The positive feedback of reflection on incoming waves drives occasional strong flash rips occurring with different frequencies than individual waves or groups. The so called breakpoint-swash system is thought to pulse with its own temporal characteristics, which depends on wave forcing but also on surf zone terrace and cuspate morphology.

Key words: Nearshore, beach cusps, reflection, standing wave, surf-swash interactions, low-tide terraced beach, SWASH, Radon transform, flash rip

1. Introduction

At steep beaches, the swash zone can become very energetic with strong reflection. This reflection was observed to have a striking influence on surf zone hydrodynamics, such return flow and waves (e.g. breaking), even at incoming-band frequency, which can even form quasi standing waves (Almar et al., 2016; Martin et al., 2016). On the upper part of these beaches, a cuspate rhythmic pattern often develops and induces an alongshore variability of reflection and strong offshore-oriented jets in cusp bays.

Steep beaches are often terraced, showing commonly the activity of rip currents that are transient in both time and space, referred to as flash or transient rips (Johnson and Pattiaratchi, 2004) which have received far less attention than bathymetrically-controlled rip currents (Castelle et al., 2016). The lack of understanding is partly due to the difficulty of measuring flash rips in the field. Previous results suggest that at the low-tide terraced Grand Popo beach, Benin (Castelle et al., 2014; Scott et al., 2016; Mabiala-Boutoto et al., 2017) surf-zone circulation is dominated by hydrodynamically-controlled flash rips at low tide. Despite tentative numerical modelling suggest that these rips were driven by shear instabilities of the longshore current (Feddersen et al., 2014; Marchesiello et al., 2016), field evidence shows that these flash rips were driven by short-scale vorticity evolving freely as migrating surf-zone eddies (Feddersen et al., 2014) because flash rip activity was maximized for shore-normal incidence. In contrast, at mid to high tide for a well-developed cuspate morphology, flash rip activity disappeared with swash rips becoming dominant during the range of wave conditions of the field experiment (Castelle et al., 2014). Swash rips had a short life-span (typically less than 2 minutes) with their cross-shore extension varying substantially. The mechanisms controlling these swash-rips and their variability are not well documented, in particular the role of swash-based reflection (recently addressed in one dimension by Martin et al., 2017) over rhythmic cuspate pattern and how these reflected waves generate irregular surf zone conditions of waves and current remained out of the scope of

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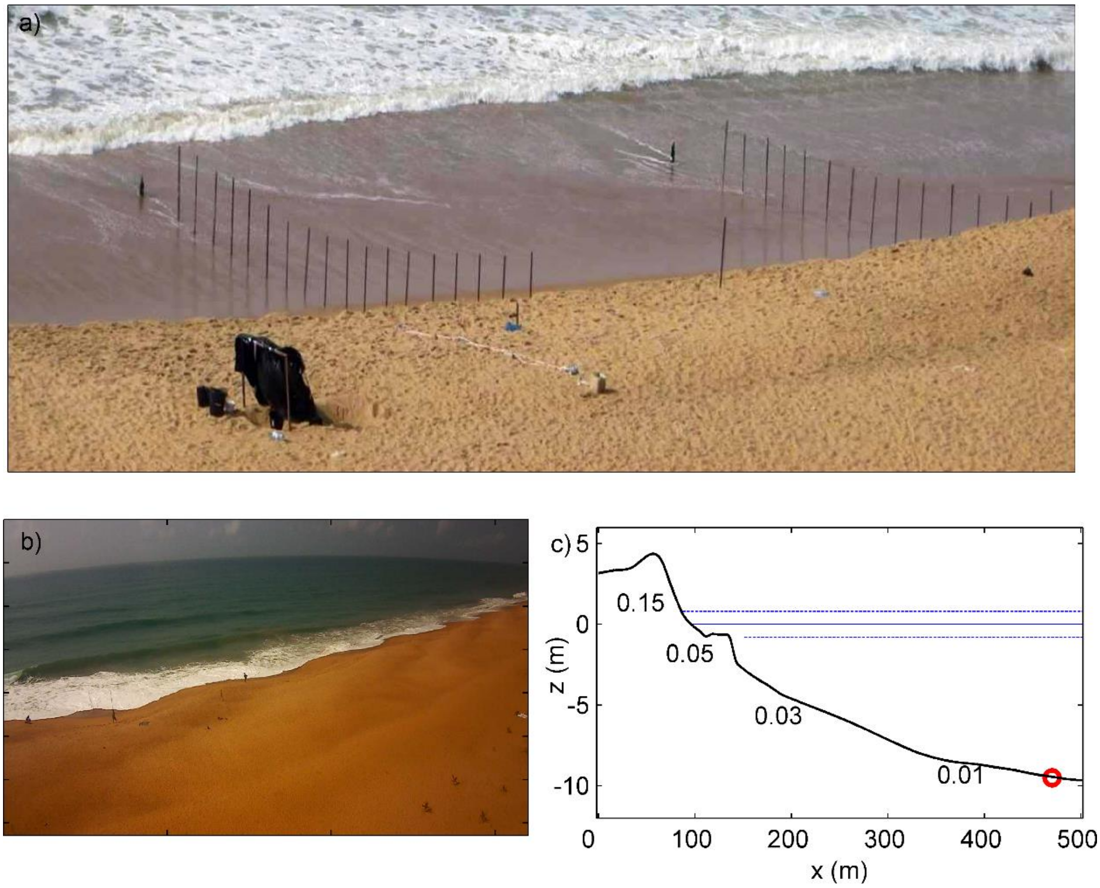

Figure 1. Study site, Grand Popo, Benin. a) deployment setup on the terrace with cusp bay and horn instrumented cross-shore lines, b) Snapshot from video system showing clearly cuspate pattern and c) surveyed bathymetric profile with low tide terrace.

most studies. This is partly attributed to the lack of suited tool which can be overcome by separating incoming and reflected waves on numerical simulations using the Radon Transform (Almar et al., 2014).

From field observations at the low-tide terraced Grand Popo beach and wave-phase resolving numerical simulations, we investigate the influence of cuspate swash dynamics on transient surf zone dynamics. Field data and numerical simulations are first presented. In the results section, the model ability to describe the low-tide terrace beach hydrodynamics is addressed. The model is subsequently used to assess the role of the steep rhythmic swash zone morphology and resulting reflection on the surf current and wave fields. The swash zone morphology is varied, from no cusps to realistic amplitude.

2. Data and methods

An intensive field experiment was conducted during March 2014 at Grand Popo, Benin (Gulf of Guinea, West Africa), a sandy coast exposed to South Atlantic long swells (Almar et al., 2014). Grand Popo is an intermediate-reflective (Ω>2), micro-tidal, wave-dominated (annual mean, *Hs*=1.4 m, *Tp*=9.4 s, oblique incidence from SW), medium grain-sized *D50*=0.6 mm beach with an alongshore-uniform terraced surf zone morphology (Figure 1). A well-developed cuspate morphology is commonly observed at the high tide mark. Measurements included both sea and beach morphological surveys with Differential GPS and bathymetric sonar. Offshore forcing (waves and tide) was characterized using an Acoustic Doppler Current Profiler (ADCP) moored at 10-m depth while wave transformation over the terrace was measured using a Pressure Transducer.

The phase-resolving non-hydrostatic wave model (SWASH, Zijlema et al. 2011) is a vertical multi-layered model based on non-linear shallow water equations (NLSW) including non-hydrostatic pressure. It provides

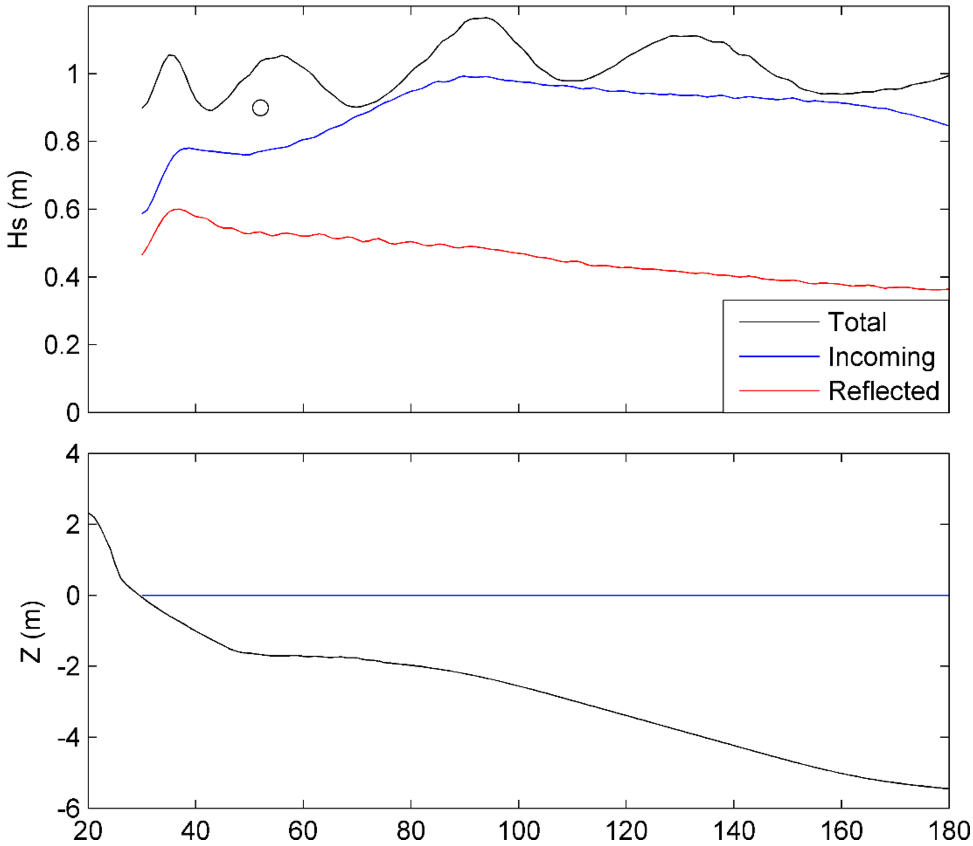

Figure 2. In upper panel, cross-shore profile of average wave height *Hs* (simulated total in black) compared to pressure transducer measurements (cf. Figure 1, black circle). Blue and red lines stand for RT-separated incoming and reflected components, respectively. Bathymetry (black) and water level (blue) are shown in lower panel.

a general basis for describing complex changes in rapidly varying flows and is considered as a valuable tool to reproduce wave propagation, wave breaking, energy dissipation and energy transfer from the incident frequency band to the infragravity band (Smit et al., 2013, Rijnsdorp et al., 2014).
SWASH is now currently used in studies focusing on runup, infragravity wave dissipation, wave-driven circulation and dissipation due to wave breaking in the nearshore area. Most of these studies were validated with flume experiments (Ruju et al., 2014, Rijnsdorp et al., 2014) or for a schematic 1D profile (Torres–Freyermuth et al., 2012; De Bakker et al., 2014). Only recently did the model was applied to real cases in 2D or 3D (multilayered mode, e.g. Guimarães et al., 2015, Gomes et al., 2016, Nicolae Lerma et al., 2017).

In this study, we used the SWASH model in a multilayered (2 vertical layers) 2D mode with periodic lateral boundaries. The simulation time for each case is set to 15 min, with a 5 minutes spin-up, and outputs were stored every second. Wave breaking was parametrized using HFA (Hydrostatic Front Approximation) (e.g., Kennedy et al., 2000; Tonnelli and Petti, 2012) using default parameters as recommended by Smit et al. (2013). The computation domain extends 1.2 km and 0.5 km in the cross-shore and longshore, respectively, with the offshore boundary in 10-m depth and a 1-m resolution. Wave conditions at the offshore boundary was forced using observed water level elevation time series provided by the ADCP derived time series. A reference 10-min simulation is used with waves (*Hs*=1.2 m *Tp*=10s, shore-normal, no directional spread) corresponding to the 13 March during high tide waves, when cusps are the most active.

3. Results

The skills of SWASH for representing wave breaking and transformation over the terrace was investigated. Simulated *Hs* and alongshore current are used here for comparison with measurements. Figure 2 shows *Hs* along cusp horn and bay cross-shore transects. Breaking extends over the terrace width, and *Hs* is well retrieved at the PT location on the terrace. The model is able to generate a standing wave, generated by the interaction between incoming and outgoing waves, with an amplitude decreasing offshore and

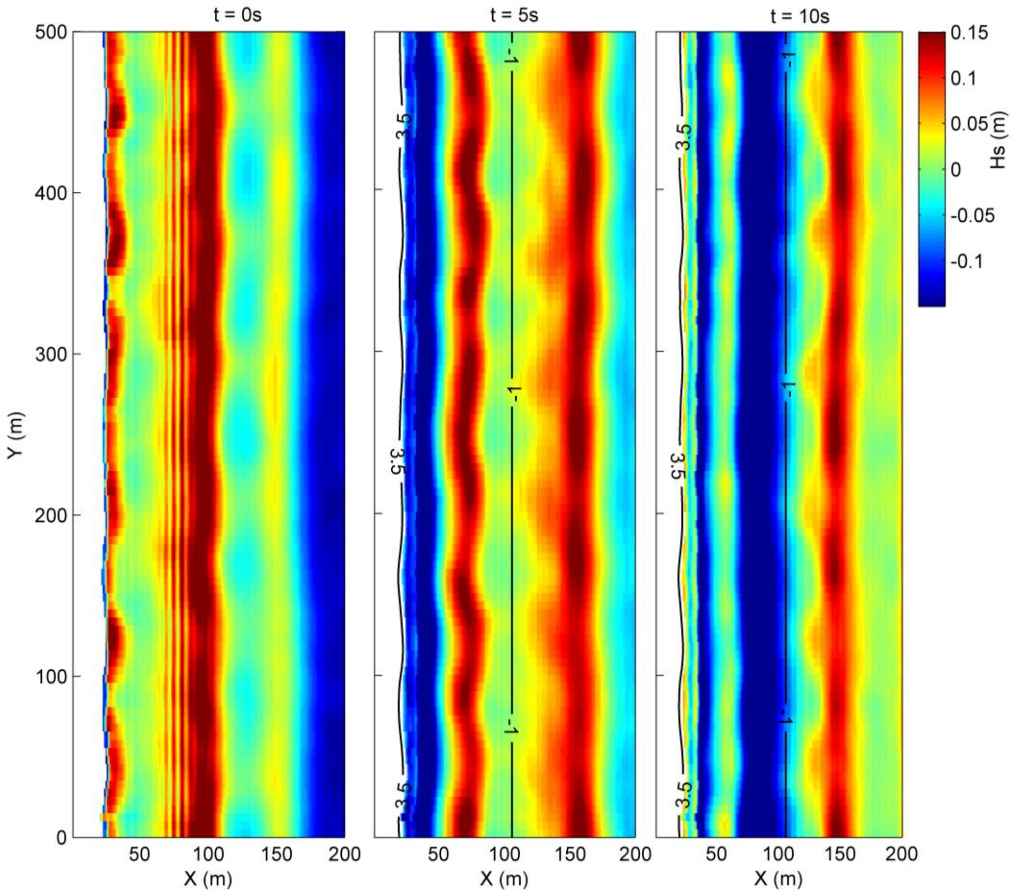

Figure 3. Illustration of simulated reflected surface elevation waves field, separated using the RT, and showing the rhythmic pattern induced by cusps. Black lines show isobaths.

characterized by nodes and antinodes (as previously shown in Almar et al., (2016) using a unidirectional phase-resolving model at Grand Popo). But here we investigate in two-dimensions the interaction of incoming swash flow with the cuspate pattern that generates an irregular reflected wave field. As an illustration, a short sequence of reflected wave propagation, separated using the RT, is illustrated in Figure 3. The rhythmicity of reflected wave crests, both in amplitude and phase, is conserved while they propagate offshore. Average *Hs* is shown in Figure 4. Cases with realistic cuspate morphology and no-cusps alongshore-uniform are shown. No clear irregularity is observed in the no-cusps cases, while a clear rhythmic pattern is visible for the cuspate case. Irregularity are observed in the longshore and cross-shore direction and extends offshore of the breaking zone (materialized by the terrace). It is not clear whether if *Hs* is larger in the surf in front of cusps bays or horns and is variable, depending on cusp length. The presence of nodes and anti-nodes highlight the presence of standing waves. This is caused by irregular reflected pattern. Reflected fields show the signature of cusps wavelength in the surf zone, but longshore wavelength of the reflected irregularities increases offshore, certainly due to wave directional spreading.

An illustration of a sequence of cross-shore current field is shown in Figure 5 where the development from cusps system to offshore-oriented filaments and vortexes is clearly visible (similar to dye release observations in Marchesiello et al., 2016). Figure 6 shows average anomalies of cross-shore current for the realistic and no-cusp cases. Similar to what is observed for *Hs*, anomalies are generated by the presence of

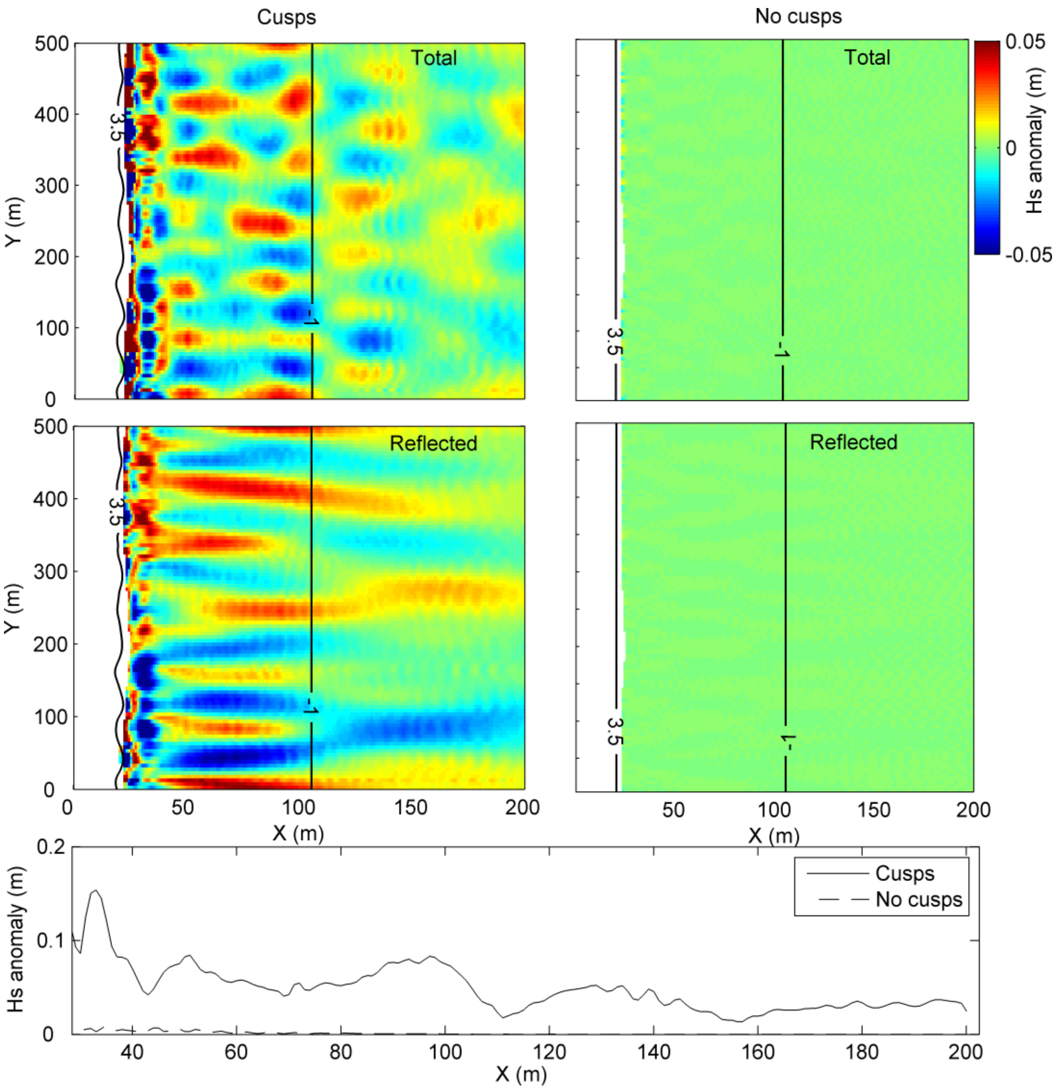

Figure 4. 10-min averages of *Hs* anomaly on realistic (left) and no cusp (right) morphologies, for total waves (incoming and reflected) in upper panels and outgoing waves only in mid panels. Black lines show isobaths. Lower panel shows the amplitude of total *Hs* anomaly in the cross-shore direction, for cusp and no-cusps runs.

cusps. Currents are offshore-oriented in the cusp bays and onshore oriented in the front of the horns. These current anomalies peak in cusps bays but extends over the terrace and offshore.

The forcing of these offshore-oriented current intensity is investigated in Figure 7. It is determined whether if incoming wave energy (low-frequency envelope) variability or alongshore waves anomaly induced by reflection have predominant influence. Alongshore-averaged current varies with a rather regular period (~30 s) which is similar to the one obtained for the longshore waves anomaly, whereas incoming alongshore-averaged waves signal has contrasted temporal characteristics. Correlation coefficient is much larger between current intensity and waves longshore anomaly (0.78) than with incoming waves (-0.24) which indicates that current and wave anomalies induced by reflection might be linked to the same mechanism.

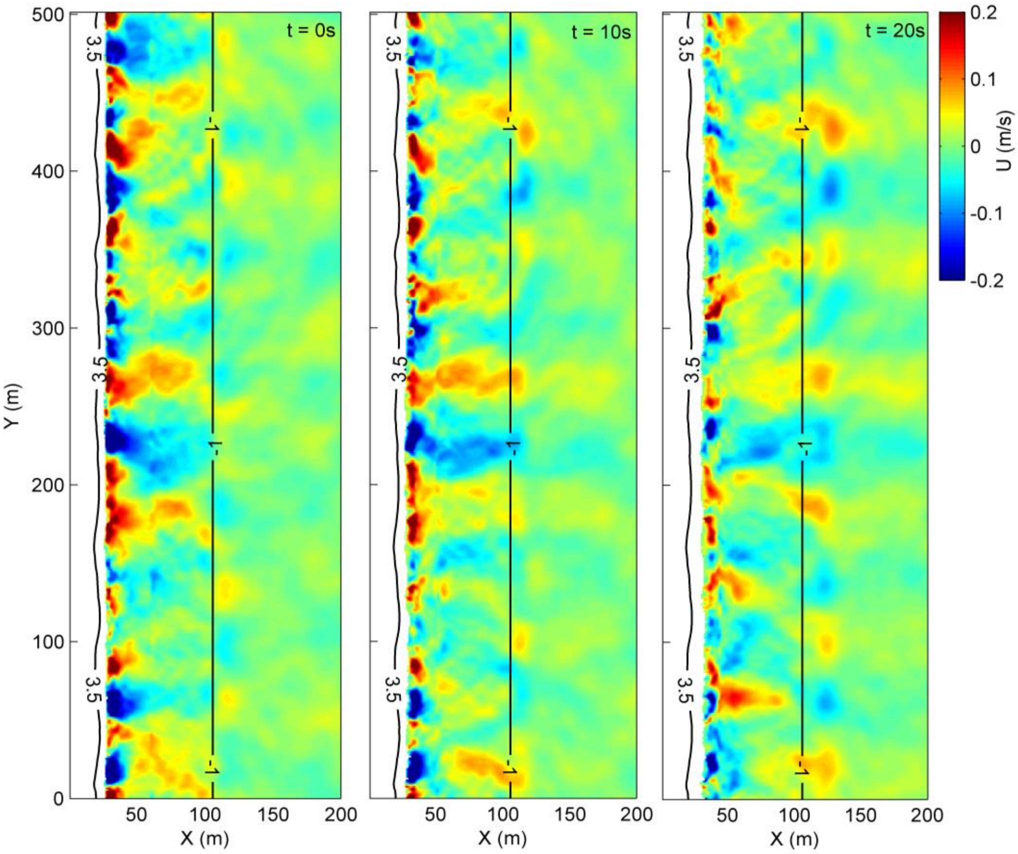

Figure 5. Illustration of simulated current field showing the development of offshore oriented filament generating vortex off the terrace. Black lines show isobaths.

4. Discussion

These numerical results show that the presence of cusps affects the surf zone due to reflection. At reflective beaches such as Grand Popo, it might be responsible for a large amount of waves and current spatio-temporal variability at specific spatio-temporal scales.

There is still a debate on the cause of surf zone circulation variability, forced or intrinsic. This previously overlooked feedback of waves reflection on swash rhythmic pattern on surf zone was not accounted for by other studies at this site (Scott et al., 2016; Marchesiello et al., 2016; Mabiala-Boutoto et al., 2017) but also more generally (Feddersen, 2014; Castelle et al., 2016), mainly due to the lack of insights in the wave reflected field. Suited tools such as the Radon Transform applied to wave-phase resolving models or dense observations (e.g. LIDAR) now allows to quantify this impact. Recent studies show the key role play by swash-based reflection on surf zone, in particular incoming short waves characteristics such as breaking and asymmetry (Rocha et al., 2017) and wave pattern (Almar et al., 2013; Almar et al., 2016), undertow and current (Martin et al., 2017). Our study reinforces these results and extends this into two-dimensions.

Preliminary analyses show that depending on incoming waves, quasi-standing wave appears with spatio-temporal characteristics controlled by waves (period and incidence angle), terrace width and cusp wavelengths. Spatial and temporal pattern of current and waves anomalies have similar behavior. Their characteristics are close to standing edge waves, earlier described in the formation of beach cusps (Guza and Inman, 1975; Huntley and Bowen, 1978) but recently challenged (Ciriano et al., 2005), in particular due to the issue of having standing waves at open beaches such as Grand Popo. However, in our numerical simulations, current and *Hs* anomalies propagate in two ways along the shore which result in a striking standing edge-wave pattern. This has to be further investigated.

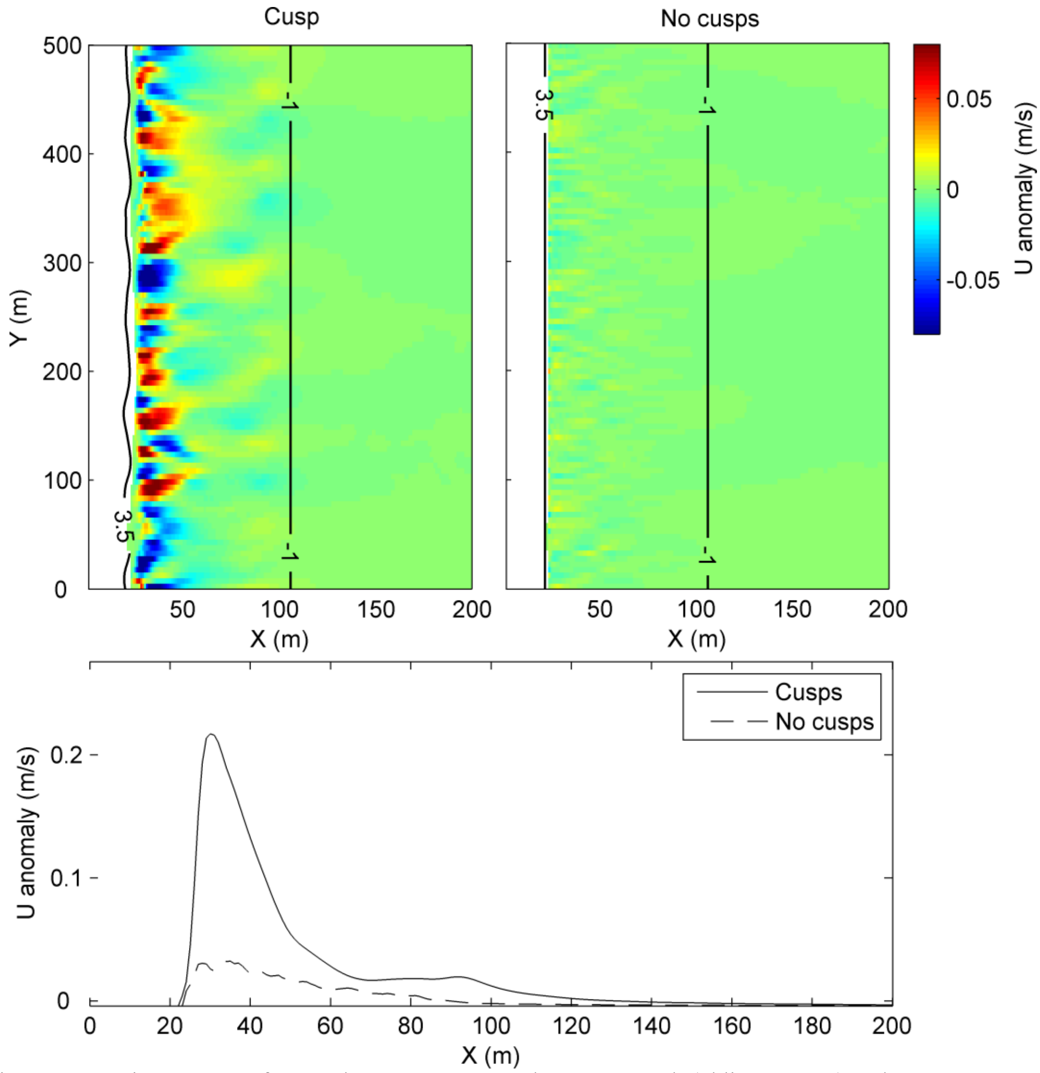

Figure 4. 10-min averages of cross-shore current anomaly on 13 March (oblique waves) and on 14 March (shore-normal waves). Black lines show isobaths. Lower panel shows the amplitude of this anomaly in the cross-shore direction, for cusp and no-cusps runs.

5. Conclusions

From field observations at the low-tide terraced Grand Popo beach and wave-phase resolving numerical simulations, we have investigated the influence of cuspate swash dynamics on transient surf zone. The model SWASH shows good skills in describing low-tide terrace beach hydrodynamic and is applied to investigate the role of rhythmic swash zone pattern and induced wave reflection on wave and current irregularities. Results from numerical simulations show that these mechanisms drive high surf zone variability when a cusp morphology is considered, as compared with no cusps. Interestingly, the positive feedback of wave reflection on surf zone generates a regular waves and current standing pattern and drives occasional strong flash rips occurring with different frequencies than individual waves or groups. The so called breakpoint-swash system is thought to pulse with its own temporal characteristics, which depends on wave forcing but also on surf zone terrace morphology and cuspate morphology.

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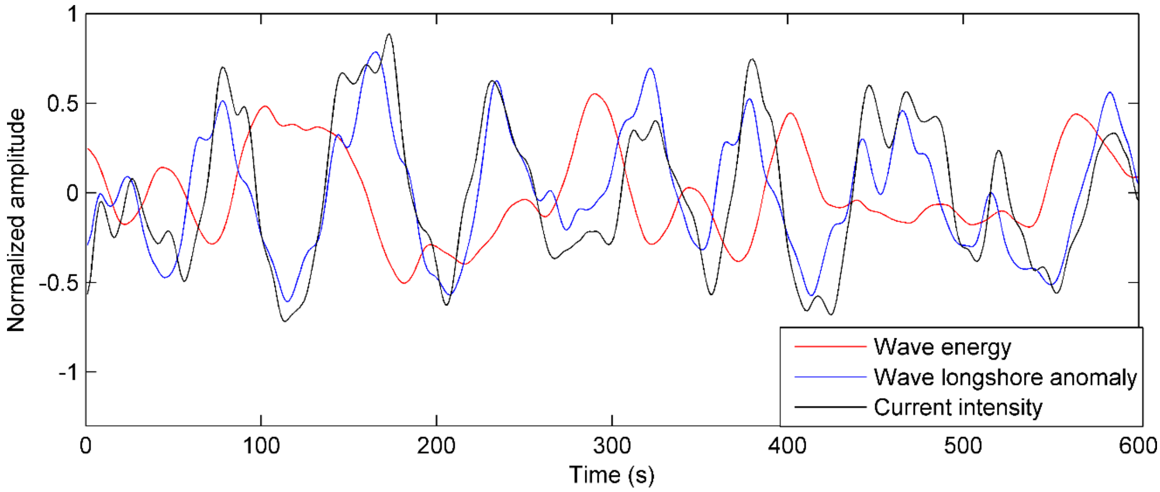

Figure 7. Normalized timeseries of incoming wave energy (red, low frequency envelope), wave energy anomaly (blue, alongshore standard deviation) and offshore-oriented current intensity (black, longshore-averaged).

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