The Grand Popo beach 2013 experiment, Benin, West Africa: from short timescale processes to their integrated impact over long-term coastal evolution

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ABSTRACT


The first large nearshore field experiment in the Gulf of Guinea was conducted at Grand Popo Beach, Benin, in February 2013, on an open wave-dominated micro- to meso-tidal coast, located mid-way between Cotonou and Lome harbours. The overall project aims at understanding at multi-scale (from event to interannual) the causes of the dramatic erosion observed throughout the Bight of Benin, and caused by the interaction of a large littoral drift with human engineering works. Grand Popo 2013 experiment was designed to measure the processes over the short term and to test the ability of an installed video system to monitor the evolution of this stretch of coast over the longer term. The beach, characterized by a low-tide terrace and a high tide reflective part, experiences a long swell (Hs=1.6 m, Tp=16 s, oblique incidence ~15-20°). Topographic surveys showed a double beach cusp system interaction and repeated surf-zone drifter runs revealed high flash and swash rip activity driven by wave dissipation over the terrace and energetic swash dynamics at the upper reflective beach. Swash was measured over a cusp system at two locations using video poles. Wave reanalyses (ERAInterim) were used to determine the wave climate and its variability, and to quantify sediment transport. This robust methodology is thought to be replicated elsewhere in different coastal environments in West Africa, in particular with the objective to monitor various sites within the framework of the new West African Coastal Observatory.

ADDITIONAL INDEX WORDS: low-tide terrace, long swell, micro-meso tidal environment, beach cusps, energetic swash, wave reflection, littoral drift, Gulf of Guinea, erosion

INTRODUCTION

Multi-scale coastal evolution is poorly known, mainly due to lack of observational datasets, and this is even more pertinent on tropical coasts. Understanding the processes responsible for coastal evolution at different timescales is crucial for socio-economic development, especially in the present context of vulnerability to climate change. 80 % of the economic activity of the Gulf of Guinea countries is concentrated along the coast, together with large population densities (main cities: Abidjan,
Accra, Lomé, Cotonou, Lagos). Erosion in Cotonou currently reaches 10 m/year (Dossou and Glehouenou-Dossou, 2007) due to recent coastal constructions (i.e. harbour jetty, see Addo et al., 2011, Angnuureng et al., 2013; Laïbii et al., this issue). It is important to move towards more integrated coastal zone management, and a first step is to adequately characterize the natural coastal system, the prevailing processes and their integrated effects. In this framework, an international project has been designed to better understand the processes responsible for the observed erosion and monitor the long-term evolution of this stretch of coast.

We believe that our observations are crucial, not only to understand the causes of erosion in the Gulf of Guinea (Anthony and Blivi, 1999; Blivi et al., 2002; Blivi and Adjoussi, 2004), but to improve our fundamental knowledge on the morphodynamics of low-tide terrace beaches (Wright and Short, 1984). These beaches are mostly described in the literature for micro-tidal and fairly low energetic waves and remain poorly documented in energetic swell-wave dominated environments. As such, our project has the following specific objectives:

1) **Describe nearshore wave-driven circulation (scale L~10 m, T~hour).** This is conducted through the characterization of both alongshore currents and more variable cross-shore currents (e.g. flash and cusp rips), the influence of relative tide, wave conditions, and interactions between swash and surf zone processes.

2) **Explore the small-scale swash zone hydro-morphodynamics (L~metre, T~second).** How is wave energy transferred to lower frequencies, and energy dissipated and reflected in the swash zone (see the current research challenges proposed by Broccolini and Baldock, 2008)? This includes the study of individual swash and swash-to-swash interactions and the influence of tide in generating beach slope changes in the course of the tidal excursion. The objective is also to be able to monitor bed evolution at the swash event scale, and wave groups, and link these events to longer-term beach profile evolution.

3) **Characterize beach cups dynamics and beach profile evolution (L~10 m, T~hour to day).** Routine field observations show that the Gulf of Guinea beaches remain most of the time in the Low Tide Terrace state, following the beach morphodynamic classification of Wright and Short (1984) and the dominant variability is due to the upper beach alternating from rather alongshore-uniform to a periodically steep morphology. The conditions for these transitions and the mechanisms involved are still poorly known, as well as the influence of antecedent morphology; this includes, for instance mechanisms involved in the construction and interaction of stacked beach cusp systems (Vousdoukas, 2013).

4) **Establish at a longer timescale the link between wave forcing, littoral drift and morphological evolution (L~10 km, T~month to decades).** The understanding of the integrated effect of short-scale processes is crucial although linking these scales remains a challenging task. To address this aspect, we provide a general description of the Gulf of Guinean morphological system and its wave forcing. This includes an analysis of the strong wave's variability at seasonal and interannual scales, as well as littoral drift.

In this paper we provide an overview of the project, including objectives, field experiment set-up, long term video monitoring system, and main achievements up to now. Closely related to the project are three other papers. The first gives a general overview...
of the Bight of Benin beach system (Laibi et al., this issue), whereas the other two address, respectively, the dynamics of double beach cusps (Senechal et al., this issue) and the occurrence of flash and swash rips (Castelle et al., this issue) at the Grand Popo beach experimental site, described below.

**STUDY SITE**

The field study was conducted in 2013 at Grand Popo beach (6.2°N, 1.7°E, Figure 1) in Benin, Gulf of Guinea, midway (80 km) between Cotonou (Benin) and Lomé (Togo). Like much of the Bight of Benin coast, Grand Popo beach bounds a sand barrier system extending from Ghana to Nigeria (Anthony and Blivi, 1999; Anthony et al., 2002). Grand Popo is representative of the beaches of the Bight of Benin. This bight coast is an open wave-dominated and microtidal environment (from 0.3 m to 1.8 m for neap and spring tidal ranges, respectively) exposed to long period swells (ECMWF 1957-2013 annual wave averages: Hs=1.36 m, Tp=9.4 s, Dir=S-SW) generated at high latitudes in the South Atlantic. The beach (Figures 2 and 3) presents an alongshore-uniform low tide terrace (LTT) and a steep and rather alongshore-uniform lower beachface and persistent upper beachface cuspatate morphology cut into a well-developed berm. The grain size is medium to coarse (D$_{50}$ = 0.6 mm). An eastward littoral drift of 0.8 to 1.5 m/yr has been reported in the literature (Tastet et al., 1985; Anthony and Blivi, 1999; Blivi et al., 2002), driven by persistent oblique long swells year-round.

**DATA**

**Grand Popo beach 2013 experiment**

As a first step in setting up a robust methodology to be replicated, a field experiment was conducted at Grand Popo beach from 17 to 28 February 2013. The experiment was designed both to measure beach changes at the short timescale and to test the applicability of a low-cost video monitoring system. Incident waves were measured with an acoustic Doppler current profiler (ADCP RDI WORKHORSE) moored on the shoreface at a depth of 8 m (Figure 3). Surf zone currents were measured by means of repeated human operators acting as drifters (~10 runs per series) daily, at selected moments, over the entire experiment duration (see Castelle et al., this issue, for a description of the method). Swash was measured over a beach cusp system (~30-m wavelength, Figure 2) along two cross-shore transects, in a cusp bay and horn. This was done using conventional pressure sensors (10 NKE SP2T10-S) and a new technique of dense arrays of poles deployed on the beach. Measurements were conducted daily over daylight hours. Water surface and bed vertical levels were monitored using 2 high frequency video cameras HD (SONY HDR-CX 250, 30 Hz, 1920x1080 pixels, Figure 4). These levels are detected through colour band divergence at the transition between the pole painted in black, the reddish beach sand, and the white-blue water (Figures 4.b, 4.c). A large-scale bathymetric survey was also conducted on the last day of the experiment using an echosounder (GARMIN GPS MAP526S) mounted on a fishing boat. 

**Figure 2.** a) Grand Popo video system and b) a 15-min time-averaged image. Black lines stand for the time stack image locations (2 cross-shore and 1 alongshore), red line is the shoreline automatically detected using method described in Almar et al., 2012a. Pole arrays in the instrumented cusp (horn and bay) are visible in the left part of the image.
boat (Figure 3). Elevations were corrected from the tidal elevations of the ADCP measurements and the Cotonou harbour gauge. Beach surveys were performed daily using a GPS (TOPCON, post-processed using PPP - Precise Point Positioning, see Ebner and Featherstone, 2008). Atmospheric data (wind and pressure) are provided by the Cotonou Airport weather services (http://rp5.ru/).

Offshore wave data
Wave data (Total Swell, wind waves, Hs, Tp and Dir) in deep water were extracted from the ECMWF ERAinterim reanalyses (Dee et al., 2011) from the ECMWF data server (www.ecmwf.int/research/era) which are on a 1x1° grid and based on the WAM model. Data are available from 1979 to the present, with a 6-hr temporal resolution.

Permanent video system
In parallel, a long-term video station was deployed (camera VIVOTEK IP7361, 1600x1200 pixels, Figure 2.a) on a 15 m-high semaphore belonging to the navy of the Republic of Benin, 80-m distant from the shore (i.e. which is the approximate beach width). This autonomous system is powered by a solar panel. A computer on site processes the raw images and store data. Three types of secondary images are stored: instant, 15-min averages (Figure 2.b, and time stacks (Figure 6). 3 time stacks are generated, 2 across-shore, to cope with alongshore non-uniformity, and 1 alongshore, offshore of the low-tide terrace, at the breaker point (Figure 2). This station gives continuous and long-term information on beach morphological change as well as on waves, tides and currents. During the experiment, 2 Hz raw videos were stored.

Rectification of images from pixels into real world coordinates was accomplished by direct linear transformation using GPS ground survey points (Holland et al., 1997) after a correction of the lens radial distortion (Heikkila and Silven, 1997). Although varying somewhat throughout the field of view, the pixel footprint was less than 0.1 and 0.05 m in the region of interest (surf-swash zones of the instrumented cusp) for cross-shore and alongshore direction, respectively.

Figure 4. Illustration of the high frequency video/poles measurements. a) Camera mounted on a tripod on the berm aligned with a cross-shore transect of poles and results of a 30 Hz vertical time stack (~1 min) on poles located in the lower (b) and upper (c) swash zone.

Figure 5. Average energy spectrum from the ADCP over the experiment duration. Red dashed line is the shore normal direction.
PRELIMINARY RESULTS

Various aspects of the experiment are discussed by Senechal et al., (this issue) and Castelle et al. (this issue). Here, some of the results recorded by the ADCP and obtained from the swash poles are presented.

Figure 7 shows the long swell conditions at Grand Popo beach from 22 to 26 March. A noteworthy element is that the long distance between the swell generation zone in the South Atlantic and Grand Popo beach results in the maximum in peak wave period $T_p$ preceding that of the significant wave height $H_s$ for about 3 days, which is long compared to the lag generally encountered elsewhere in smaller oceanic basins. Another key specificity of this site is that the energy spectrum (Figure 5) reveals a large shore reflection of incoming swell waves energy ($8 < T_p < 20$ s), the swash playing the role of a low-pass filter (see Almar et al., 2012b). A time series (not shown) of this reflection value denotes a large influence of both incoming period and tidal level; the reflection peaking when the swash occurs on the steep upper beachface and when breaking in the surf zone is reduced.

The recently developed method of video pole arrays (Figures 4 and 8, see also Lefebvre et al., this issue, for a description) shows good skills at describing both bed and swash elevation. This set up enables a description of the wave-by-wave impact of breakers on the beach morphology, and swash energy frequency-transfer and reflection. Large variations (of the order of 1 to 10 cm) of the bed level are observed at periods longer than group periods (typically 5 - 10 min), suggesting a substantial morphological control on swash-surf zone dynamics. This will be further investigated.

CONCLUDING REMARKS

The Grand Popo 2013 experiment, the first of such importance to be conducted in the Gulf of Guinea, took place from 17 to 28 February 2013 and involved 17 scientists from 7 institutions in Benin, Ghana and France. The experiment was aimed at describing processes at event scale responsible for observed dramatic erosion in the Gulf of Guinea and placed emphasis on a description of the nearshore circulation (pulsations or rips), morphological interactions between stacked cusp systems, and swash hydro-and morphodynamics including energy dissipation, reflection and bed level change. The experiment also involved the testing of an original video monitoring system. At a larger scale, empirical and quantitative (from ECMWF reanalyzes) results were obtained, allowing a global description of the Bight of Benin wave forcing and coastal behaviour.

It is still too early to draw conclusions on seasonal and interannual patterns of the evolution of this stretch of coast, but the quantitative information obtained from such permanently operating low-cost coastal video systems is key to building long-term robust systems of observation and analysis of beach dynamics and long-term coastal stability in the region. Following the success of this first system, similar video monitoring systems are currently being deployed along the West Africa coast within...
the framework of the recently set up West African Coastal Observatory (MOLOA) and ALOC-GG projects. The current overall project methodology thus provides a basis for replicated elsewhere in West Africa in the next years.

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Figure 8. Illustration of the bed/swash detection at the 6 poles of a cross-shore line (23 feb. 2013). Black and red lines are water and bed levels, respectively.