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Response of the Bight of Benin (Gulf of Guinea, West Africa) coastline to anthropogenic and natural forcing, Part1: Wave climate variability and impacts on the longshore sediment transport

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ABSTRACT

The short, medium and long-term evolution of the sandy coastline of the Bight of Benin in the Gulf of Guinea, West Africa, has become a major regional focal point due to the rapid socio-economic development that is occurring in the region, including rapid urbanization and a sharp increase in harbor-based trade. Harbors have a significant impact on the present evolution of this coast, notably by affecting longshore sediment transport. However, little is known of the environmental drivers, notably the wave climate, that governs longshore sediment transport and the ensuing pattern of shoreline evolution of this coastal zone. This article aims to address this important knowledge gap by providing a general overview of coastal evolution in the Bight of Benin and the physical processes that control this evolution.

Here, the 1979–2012 ERA-Interim hindcast is used to understand the temporal dynamics of longshore sediment transport. Oblique waves (annual average $H_s = 1.36$ m, $T_p = 9.6$ s, S-SW incidence) drive an eastward drift of approximately 500,000 m^3/yr. The waves driving this large longshore transport can be separated into two components with distinct origins and behavior: wind waves generated locally in the Gulf of Guinea and swell waves generated in the southern hemisphere sub- (30–35°S), and extra-tropics (45–60°S). The analysis undertaken here shows that the contribution to the gross annual longshore transport from swell wave-driven longshore currents is an order of magnitude larger than the local wind wave-driven longshore currents. Swell waves are dominantly generated by westerlies in the 40–60°S zone and to a lesser extent by trade winds at 30–35°S. The longshore sediment drift decay (−5% over 1979–2012) is found to be linked with a decrease in the intensity of westerly winds associated with their southward shift, in addition to a strengthening of the trade winds, which reduces the eastward sediment transport potential. The equatorial fluctuation of the Inter-Tropical Convergence Zone (ITCZ) is found to explain most of the variability in transport induced by wind waves, while the Southern Annular Mode (SAM), an extra-tropical mode, has a predominant influence on transport induced by swell waves. The ITCZ and SAM have, respectively, a negative and positive trend over the period 1979–2012 that explains the decrease in both wind- and swell-wave-induced transport. For future scenarii, General Circulation Models (GCMs) predict a stabilization of the SAM, and, thus, a non-substantial or weak change in longshore sediment transport can be expected on the coast of the Bight of Benin.

1. Introduction

The vulnerability of tropical coastlines is currently increasing under the growing twin pressures of environmental hazards and

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human activities. This situation is aggravated in developing countries where rapid economic development is associated with strongly increasing demographic pressure, especially on coasts, and with uncontrolled exploitation of resources (e.g. sand mining and river dams). The available literature regarding the coastal processes that affect tropical coastlines is scarce in general (Short, 2012), and literature on potential impacts of climate change on tropical coastlines, other than those of islands, is practically non-existent. There is, therefore, a pressing need for a better understanding of the present dynamics and future evolution of tropical coasts related to global climate change (ALOC-GG, 2011 report; global warming impact IPCC, 2014 report; Stive, 2004).

This article focuses on the Bight of Benin coast, much of which comprises low-lying barrier-lagoon systems and river deltas (Anthony, 1995) and concentrates about 80% of the regional economic activity in this African sub-region (UEMOA report, 2009). Over 70% of the population of the West African countries bordering the Bight of Benin (Côte d'Ivoire, Ghana, Togo, Benin, and Nigeria, Fig. 1a) lives in the coastal zone. This open sandy bight coast faces a narrow and irregular continental shelf, and is exposed to a wave climate characterized by energetic swell from the South Atlantic and locally-generated short-crested waves (Davies, 1980; Degbe et al., 2010; Yao et al., 2010). The longshore sediment transport (or littoral drift) has been reported to be one of the largest in the world, variably estimated at between 400,000 and 1,000,000 m^3 /yr and directed eastward. These estimates are based on various approaches, including empirical formulae and measurement of sand volumes trapped in the lee of port breakwaters (Tastet et al., 1985; Blivi, 1993; Anthony and Blivi, 1999; WL|Delft Hydraulics, 1990). The morpho-sedimentary evolution of the Bight of Benin coast is controlled by this strong longshore sediment transport, resulting in a so called'drift-aligned' coastline (Anthony, 1995; Anthony and Blivi, 1999; Laibi et al., 2014; Anthony, 2015), in the sense of Davies (1980). Although large stretches of the Gulf of Guinea coast, especially the Bight of Benin (Fig. 1), are considered to be in morpho-sedimentary equilibrium (alongshore sand inputs are compensated by alongshore sand outputs at any point) (Anthony, 1995; Anthony et al., 2002; Laibi et al., 2014) with a coastline that is more or less stable over the long-term (10^2–10^3 yr), given the magnitude of the longshore sediment transport rates, any temporary and even minor alongshore disequilibrium in such rates can result in massive local erosion or accretion (Rossi, 1989). Local areas of disequilibrium have been generated over the last few decades especially following the construction of deep-water harbour breakwaters, fundamental to the growing commercial exchanges of the region, and hydropower dams. Even though the impacts of this socio-economic development are manifest in terms of coastal erosion and accretion, the spatial and temporal functioning of the drift system they perturb remains poorly known. This poor state of knowledge has a negative feedback effect on development inasmuch as decision-makers do not appreciate the importance of the medium-tem (order of years) coastal sediment balance and its relationship to current and future development projects. Because the four countries in the Bight of Benin are facing the same vulnerability to erosion, this problem is rapidly becoming a major regional issue (Appeaning Addo, 2009, 2011; Anthony, 2015; Convention d'Abidjan-Mission d'Observation du Littoral Ouest Africain (MOLOA) first report, MOLOA, 2013).

A second gap needing to be addressed, in order to design effective counter-measures for existing and potential future coastal erosion problems, is the severe lack of knowledge (and/or interest) on the climatic drivers (and their potential climate change-driven variations) of wave conditions which, in turn, drive the aforementioned longshore sediment transport. Whereas mid- to high latitude climates are strongly dominated by short-event to seasonal processes, tropical to sub-tropical climates in cyclone-free regions are commonly dominated by longer seasonal to inter-annual fluctuations. Due to limited long-term observations, the link between coastal evolution and regional climatic modes has largely remained outside the scope of coastal studies. Only recently have a number of studies started addressing this key link. Pioneer studies on the US west coast (Inman et al., 2001; Allan and Komar, 2002) showed the effect of the El Nino Pacific mode on storm occurrence and impact on inter-annual coastal evolution, with an observed reversal of the longshore drift. On the east coast of Australia, Ranasinghe et al. (2004) demonstrated the influence of the South Oscillation Index on pocket beach rotation, later supported by work undertaken by Harley et al. (2011a), Splinter et al. (2012) and Short et al. (2012). In Europe, the North Atlantic Oscillation (NAO) has been shown to explain most of the inter-annual wave variability in energy and direction (Charles et al., 2012; Masselink et al., 2014) which influences shoreline evolution, although no clear link has been reported by these authors at longer timescales, suggesting a complex response of the coastal system to these climatic variations. However, a link between coastal evolution, North Atlantic waves, and the NAO has been demonstrated for the muddy wave-exposed mangrove coast of French Guiana (Walcker et al., 2015). The South Atlantic Ocean wave regime has attracted much less attention (Hemer et al., 2010) compared to other ocean basins. This is partly due to sparse in-situ observations of winds and waves, a problem now being tackled by the production of increasingly more accurate model hindcasts and by satellite altimetry (Woolf et al., 2002; Young et al., 2011).

This article, which is part one of a series of two, aims to provide general insights on the contemporary and potential future longshore drift regime in the Bight of Benin and associated wave climate forcing using wave hindcasts and future climate projections.

2. Study area

2.1. The Bight of Benin coastline

The study area, comprises the sandy coast between Ghana and Nigeria that forms the Bight of Benin in the Gulf of Guinea, West Africa (Fig. 1). This coast exhibits a mildly embayed sand barrier system between the western confines of the Niger River delta in the east and the Volta River delta in the west (Anthony and Blivi, 1999; Anthony et al., 2002). It is an open environment exposed to long swell waves that travel far from mid- to high latitudes (45–60°) in the South Atlantic as well as to locally generated short-waves in the tropical band (6°N to 15°S). The mid- to high-latitude wind regime is characterized by strong westerlies whereas the subtropical area (30–35°S) is dominated by south easterly trade winds blowing off the coast of Namibia. The southwesterly swells impinge slightly obliquely (at angles of 10–15°) on the nearly rectilinear west-east oriented Bight of Benin coast, generating the afore-mentioned unidirectional and large longshore drift toward the east. The tidal regime is microtidal (from 0.3 m to 1.8 m for neap and spring tidal ranges, respectively).

The beaches along this coast (Almar et al., 2014; Laibi et al., 2014) are mostly in the 'reflective-to-intermediate' state classes (Gourlay parameter, $\Omega = 1$, following Wright and Short, 1984; Relative Tide Range RTR$\sim$1, Masselink and Short, 1993), and often exhibit an alongshore-uniform low-tide terrace and a steep reflective upper beachface (Fig. 1d). The grain size is medium to coarse with $D_{50} = 0.6$ mm (Anthony and Blivi, 1999).

2.2. South Atlantic climate dynamics

In this section the different modes of climate variability in the South Atlantic that affect winds and waves and subsequently the