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Response of the Bight of Benin (Gulf of Guinea, West Africa) coastline to anthropogenic and natural forcing, Part 2: Sources and patterns of sediment supply, sediment cells, and recent shoreline change

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ABSTRACT

The Bight of Benin in the Gulf of Guinea, West Africa, forms an embayment between the Volta River delta in the west (Ghana) and the Niger River delta (Nigeria) in the east. The bight coast comprises sandy beaches backed by Holocene beach-ridge barriers. Incident swell waves, beachface gradient and the unidirectional longshore sand transport from west to east are intimately linked, generating a classic example of a strongly wave-dominated drift-aligned coast. The stability of this coast, which hosts several major cities in addition to three large international deepwater ports, has been strongly affected by human activities. We analyzed shoreline mobility and coastal area change over the period 1990–2015. Our results show how the stability of this coast has been strongly affected by the three ports therein, and by natural and human-altered shoreline dynamics related to the Volta River delta and to distributaries at the northwestern flank of the Niger delta. The combination of these factors has impacted alongshore sediment redistribution by segmenting the previously unrestrained longshore transport of sand that prevailed along this open coast. The result is a mixture of natural and artificial sediment cells increasingly dominated by shoreline stretches subject to erosion, endangering parts of the rapidly expanding port cities of Lomé (Togo), Cotonou (Benin) and Lagos (Nigeria), coastal roads and infrastructure, and numerous villages. Post-2000, the entire bight shoreline has undergone a significant decrease in accretion, which is here attributed to an overall diminution of sand supply via the longshore transport system. We attribute this diminution to the progressive depletion of sand-sized bedload supplied to the coast through the main Volta river channel downstream of the Akosombo dam, built between 1961 and 1965. Sand mining to cater for urban construction in Lomé, Cotonou and Lagos has also contributed locally to beach sediment budget depletion. Although alongshore sediment supply from the Volta River has been the dominant source of sand for the stability or progradation of the Bight of Benin coast, potential sand supply from the shoreface, and the future impacts of sea-level rise on this increasingly vulnerable coast are also important. The continued operation of the three ports and of existing river dams, and sea-level rise, will lead to sustained shoreline erosion along the Bight of Benin in the coming decades.

1. Introduction

The ubiquity of shoreline erosion on long open coasts is often matched by a lack of understanding of the context, processes, and embedded spatial and temporal scales over which the sediment redistribution processes that shape the coast occur. In addition to the

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ambient long-term (post-mid-Holocene, i.e., last ~ 6 ka) large-scale adjustments of the shoreline and shoreface profile to sediment supply from rivers and coastal erosion updrift, and to eventual cross-shore sediment movement from the nearshore zone, the world's shorelines are also increasingly impacted by the effects of climate change and human activities (Pilkey and Cooper, 2014; Ranasinghe, 2016; Anthony, 2017). Understanding the links between shoreline change, natural sediment supply and transport processes, human activities, and climate change is by no means easy, but is an important pre-requisite for establishing effective coastal management frameworks in the face of increasingly intensive occupation of the coast in a rapidly changing world (Ranasinghe and Stive, 2009; Jongejan et al., 2016).

Tropical coasts are largely located in developing countries where the effects of increasing population pressures are exacerbated by the impacts of climate change and generally low adaptive capacity (Duong et al., 2016; Ranasinghe, 2016). In a vast number of situations in developing countries, urbanization or management activities (e.g. port construction) at small segments of high-value coasts can have large-scale impacts that are not always well understood or anticipated. This is very much the case along the Gulf of Guinea coast in West Africa (Giardino et al., 2018; Ndour et al., 2018), the focus of this study (Fig. 1).

This quasi-continuous barrier-lagoon coast, spanning over 1000 km, concentrates 80% of the regional economic activity of this African sub-region (WAEMU West African Economic and Monetary Union, 2012). Over 70% of the population of the West African countries bordering the Gulf of Guinea (Côte d'Ivoire, Ghana, Togo, Benin, and Nigeria) is concentrated within the coastal zone, and pressures on the coast are increasing, notably through continued growth of the main/capital coastal cities. The Bight of Benin coast between the mouth of the Volta River and the western approaches to the Niger River delta (Fig. 1) hosts several major cities: Cotonou (economic capital of Benin, population: 1.2 million), Lomé (administrative capital of Togo, population: 1 million), and Lagos, (economic capital of Nigeria, population: 10 million). There are also numerous rapidly growing small towns and fishing villages throughout this coast, especially in Nigeria. The aforementioned three major cities are each served by a deepwater port built directly on the coast in the 1950s (Lagos, 1957) and 1960s (Cotonou, 1962, Lomé, 1967). These structures are protected by breakwaters that have been periodically extended to ensure that the ports are not silted to a level where they become inoperational, but also to cater for increasing maritime traffic. These ports have had a significant impact on sediment transport along the coast with several studies showing that their breakwaters intercept sand transported alongshore, resulting in the classic updrift accumulation and downdrift erosion on either side of these structures (Anthony and Blivi, 1999; Laibi et al., 2014; Ozer et al., 2017; Giardino et al., 2018).

Using European Re-Analysis (ERA-Interim) wave hindcast data from 1979 to 2012, Almar et al. (2015) identified the origin and temporal dynamics of the wave climate affecting this coast, calculated the sand volumes transported alongshore by waves, and estimated the potential influence of climate change on the wave regime and on longshore sediment transport. The present article is a companion to Almar et al. (2015). The aim of this study is to investigate recent (1990–2015) shoreline change along the Bight of Benin coast and its relationship to longshore sediment transport, and the ways in which the latter has been impacted upon by human activities. Given the overwhelming importance of sand supply by the Volta River and the strong unidirectional longshore sediment transport in the study area, changes in the shoreline patterns are further assessed within the framework of sediment cells identified in this study. The cell notion is not only particularly pertinent to coastal zone management issues (e.g., Bray et al., 1995; Van Rijn, 2011), but is also an important concept with respect to long-term shoreline accretion or erosion, because of the relevance of cell

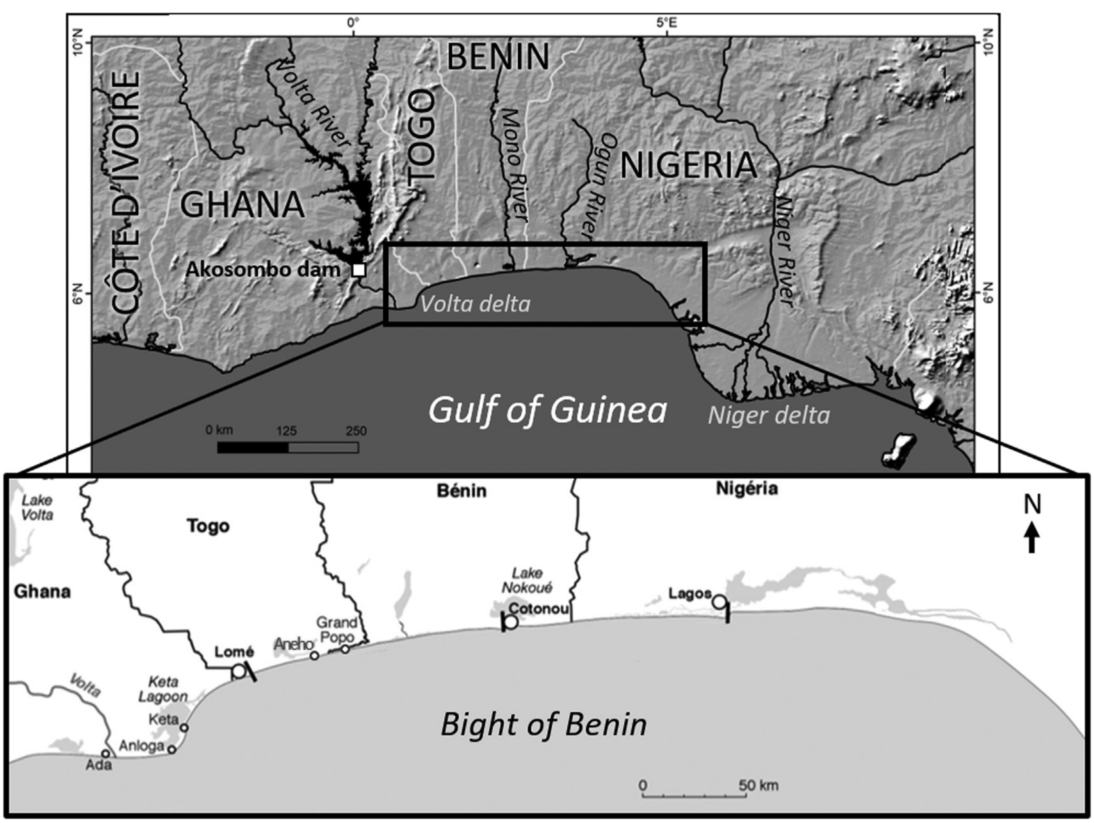

Fig. 1. The Bight of Benin in the Gulf of Guinea. The bight coast stretches from the mouth of the Volta River delta in Ghana to the western confines of the Niger River delta in Nigeria. This microtidal, wave-dominated coast is under the influence of long and regular swell and shorter-fetch trade-wind waves that generate strong wave-induced longshore drift from west to east. The three main cities on the bight coast, Lagos, Cotonou, and Lomé, each have their deepwater port.

boundaries to alongshore sediment flux (Carter, 1988; Cowell et al., 2003).

2. The Bight of Benin coast

The Bight of Benin (Fig. 1) comprises a wave-dominated coast formed of sandy beach-ridge barriers and lagoons (Anthony and Blivi, 1999; Anthony, 2015a). The mildly embayed shoreline is a classic example of a strongly drift-aligned coast (Anthony, 1995) in the sense of Davies (1980). In this configuration, the plan-view coastal morphology that developed over the timescale of the mid- to late-Holocene (since ~6 ka BP) has been influenced by strong alongshore sand transport. The sand barriers have a relatively complex history, aspects of which have been summarized by Anthony and Blivi (1999). Much of the coast shows a prograded single or double barrier. These deposits are composed essentially of medium to coarse (0.4–1 mm) quartz sand, with variable minor fractions of feldspars (up to 10%), shelly debris (5–15%) and heavy minerals (1–5%). The Volta River has been identified as the single most important fluvial sediment source for much of the sand barrier system of the Bight of Benin (Anthony and Blivi, 1999). The alignments of the multiple beach ridges characterizing the barriers have been largely obliterated by human modifications of these deposits, especially through plantations, but can still be identified in places on aerial photographs.

Tides here are semi-diurnal with a mean spring tidal range that varies from 1.5 to 1.9 m. Almar et al. (2015) showed that the constant S to SW waves impinging on the Bight of Benin coast had a mean 33-year averaged significant height (H_s) of 1.36 m and a peak period (T_p) of 9.6 s, and they computed, for Cotonou, in the centre of the bight (Fig. 1), a net mean eastward sand transport volume of 514 × 10^3 m^3/yr (Fig. 2). Wave forcing was shown to comprise two components with distinct origins and behaviour: wind waves generated locally in the Gulf of Guinea and swell waves generated in subtropical, mid-to high latitudes. Almar et al. (2015) also demonstrated that longshore sediment transport due to swell waves is an order of magnitude larger than that due to wind waves, which corresponds well with the cyclone-free 'West Coast Swell Environment' defined by Davies (1980).

The two river deltas bounding the bight, the Niger and the Volta (Fig. 1), are among the three largest deltas in West Africa. The Volta delta, situated entirely in Ghana (Boateng et al., 2018), covers an area of about 5000 km^2 at the outlet of a large river catchment of 397,000 km^2. Prior to the commissioning of the Akosombo dam (Fig. 1), built between 1961 and 1965 across the lower reaches of the Volta River (~100 km upstream from the sea), the river's water discharge varied between a low of 1000 m^3/s in the dry season and a high of over 6000 m^3/s in the wet season. A smaller dam was constructed at Kpong, 24 km downstream of the Akosombo dam, between 1977 and 1982. The mean discharge downstream of the dams is presently about 1260 m^3/s, and has undergone a significant reduction due to the decrease in rainfall in the Sahel since 1975 (Oguntunde et al., 2006). Global climate-change modelling by Jin et al. (2018) suggests, however, that the outflow from Lake Volta downstream of the Akosombo dam will increase by 1% in the 2050s and 5% in the 2090s. About 90% of the total sediment yield of the river is intercepted by this dam, which blocks 95% of the total catchment (Boateng et al., 2012). These authors estimated a reduction in solid discharge downstream of the dam, following its construction, from about 71 million m^3/yr to about 7 million m^3/yr. The sand load supplied annually by the river to its delta prior to dam construction is only a small fraction of the total solid discharge, and has been estimated at about 1 million m^3 (Delft Hydraulics, 1990). Much of this sand was injected into the longshore drift system via a single delta river mouth. The Niger delta, situated in Nigeria, is much larger, covering an area of 19,135 km^2 (Coleman and Huh, 2004). The influence of the Niger delta has been limited essentially to the eastern confines of the Bight of Benin coast. The only other river on the rest of the bight coast that supplies sand directly to the sea is the Mono, in Benin (Fig. 1). The estimated 100,000 m^3 of sand supplied by the Mono River during the wet-season months supplement the massive sand load transported by longshore drift from the Ghana and Togo coasts, but the Nangbéto dam, built 180 km upstream on the Mono in 1987 has also affected the hydrology of this river (Ago et al., 2005) and its sand supply to the coast (Laibi et al., 2014). The other smaller rivers, such as the Ogun in Nigeria (Fig. 1), debouch into still infilling lagoons behind the coastal sand barriers. These lagoons are linked to the sea via three inlets: an inlet at Aneho, an artificial inlet in Cotonou cut in 1888 to alleviate flooding, and the Lagos inlet (Fig. 1), all fixed by engineering structures.

3. Methods

3.1. Shoreline change (1990–2015)

In this study, we used available satellite images that offer not only large individual coverage, given the length of the Bight of Benin coast (> 400 km), but also robust and accurate determinations of shoreline change rates. In total, 15 LANDSAT 4–8 images were used. Three images for each of the years 1990, 2000, 2005, 2010, and 2015 were downloaded from the USGS data portal EarthExplorer. The analysis involved using panchromatic (10 m resolution) and a customized combination of bands maximizing land-water contrast (30 m) to derive the shoreline. We used the most recent images in the time series, and with minimal cloudiness, checked for easy landmarks on those where these could be traced back through time, and georeferenced these using coordinates from Google Earth, from the most recent to the oldest image. The accuracy was typically around 1 pixel (30 × 30 m). From the four individual periods of analysis covered by the images (1990–2000, 2000–2005, 2005–2010 and 2010–2015) we constructed a Hovmöller diagram of spatiotemporal shoreline change.

To compute rates of change in shoreline position, we used the ArcMap extension module Digital Shoreline Analysis System (DSAS), version 4.3 (Thieler et al., 2009), coupled with ArcGIS®10. The brush/plantation fringe could be used as a robust shoreline marker on this

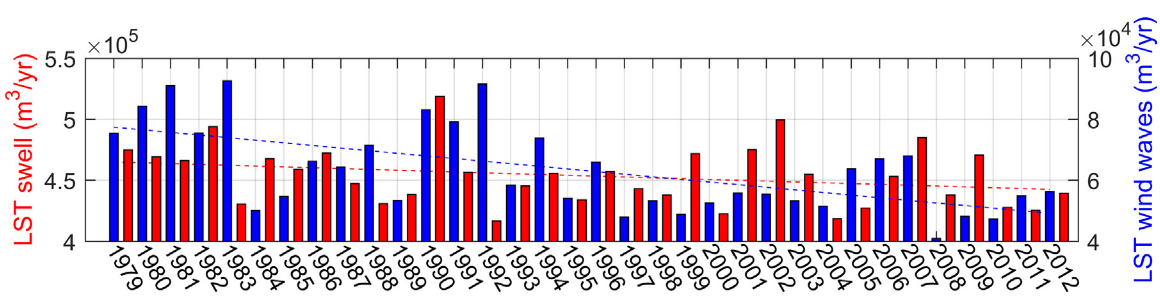

Fig. 2. Interannual variation of the net annual longshore sediment transport, in the centre of the Bight of Benin at Cotonou, induced by swell (red) and wind waves (blue) from 1978 to 2012. Dashed lines show a decrease in transport over the period. Note the two different vertical axes for the two types of waves (from Almar et al., 2015).

sandy coast characterized by beaches throughout. The shore-normal distance of the vegetation line to a base line was established at 100-m alongshore spacing for the earliest and most recent images. This distance, chosen as a compromise between quality of the interpretation and the total length of analyzed shoreline (410 km) was then divided by the time in years between the two dates to generate a shoreline change rate, i.e. the End Point Rate in DSAS 4.3. A total of 4100 change rates, each corresponding to a DSAS transect, were thus determined. The annual error (E) of shoreline change rate, which sums up image rectification, extraction of the shoreline, and operator digitization in delimiting the shoreline, was computed from:

$$E = \sqrt{(d1^2 + d2^2)/T}$$

where d1 and d2 are the uncertainty estimates for successive sets of images and T is time in years between image sets (Hapke et al., 2006). The confidence of the annual change rate is 0.28. We obtained an error of ± 2.4 m/yr between 1990 and 2015.

Rates of shore-normal shoreline change along transects are useful in indicating the degree of shoreline mobility. An equally important metric, however, is that of change in areas lost or gained (in km^2). Area change was analyzed for the 410 km of bight coast in ArcGIS by vectorizing polygons that comprise of the shoreline and a distance up to two hundred metres inland to account for any losses or gains in coastal area. Surface area differentials were statistically estimated from one period of analysis to the next and an annual rate of evolution of the polygon area representing the coast calculated for each period.

3.2. Coastal sediment cells

Wave-driven longshore sediment transport commonly operates within the framework of one or several sediment cells with natural or artificial boundaries (Carter, 1988). The operation of a sediment cell is fundamentally determined, on open beaches, by alongshore wave-energy gradients coupled with the availability of sediment. The shoreface retreats (erosion) under conditions of a negative longshore sediment balance, and advances (accretion) when the sediment balance is positive. The concept has commonly been used in a purely sediment budgetary framework in which individual morphodynamic processes may be ignored, with the emphasis being on the definition of each coastal cell and on net gains and losses of sediment within each cell (Van Rijn, 2011). This approach is valid and useful on coasts where cell boundaries and their spatial and temporal changes are readily constrained, which is commonly the case on open, unbounded, wave-dominated, microtidal coasts, such as the Bight of Benin coast (Fig. 1).

Laibi et al. (2014) identified four key coastal cells (see Results) on the bight coast between the Volta delta and Lagos based on the perceived effects of engineering structures on longshore sand transport. Here, we refine this scheme by coupling cell identification with shoreline changes observed between 1990 and 2015, and field-based reconnaissance coupled with empirical knowledge of recent patterns of shoreline evolution, especially in the vicinity of the mouth of the Volta delta where complex change patterns have been documented (Anthony et al., 2016). No analysis of intra-cell longshore variability is considered here because, for the purposes of this study, the Bight of Benin is assumed to be dominated by an essentially alongshore-uniform wave climate (Almar et al., 2015), and has a plan shape with very little alongshore variability, with the exception of: (1) the afore-mentioned Volta delta, (2) zones influenced by the three ports, and (3) the eastern confines of the bight influenced by the Niger delta.

4. Results

The Bight of Benin coast shows overall net advance (accretion) when averaged over the 25-year period of analysis, but also a varying alongshore pattern of shoreline change (Fig. 3). We identified five main sectors, four of which (S1 to S4) correspond with major sediment cells. The identified sectors and their associated cells are built on the cell structure identified by Laibi et al. (2014). Sector S1 (cell 1), associated with the Volta delta, and sector S5 (unidentified multiple cells), along the westernmost flank of the Niger delta, are dominated by natural shoreline change patterns inherent to large deltas (Anthony, 2015b; Anthony et al., 2016; Dada et al., 2016, 2018), whereas the remaining sectors S2-S4 (cells 2–4) between these deltas are dominated by the effects of port engineering structures (Fig. 4), but S3 is also impacted by the mouth of the Mono River and the Aneho inlet.

The Volta delta spit (Fig. 4) in S1 appears to be a relatively recent feature (post 1880?) resulting from adjustments among sediment supply from the river, delta dynamics and the strong longshore sand transport on this coast (Anthony et al., 2016). The spit has accreted in its distal sector, increasingly with a convex plan-view shape due to the formation of successive beach ridges, but with restricted longshore growth of its tip. S2 marks the delta transition with the rest of the bight coast. Erosion has prevailed in this transition area since the mid-1880s (Kumapley, 1989), predating the construction of the Akosombo dam (Ly, 1980), as a result of sand sequestering by the Volta spit. This erosion threatens settlements, notably the old trading post of Keta (Fig. 4). This updrift zone of S2 corresponds to what was initially a natural drift 'pulse', no doubt characterized by the highest potential longshore transport rate in the Bight of Benin (in excess of 1 million m^3/yr (Anthony and Blivi, 1999)) as a result of the shoreline orientation relative to the SW swell waves. A drift pulse is expressed by acceleration of the longshore transport potential caused by a relatively sharp change in wave angle incidence relative to the shoreline (Carter, 1988). The amount of sand bypassing the Volta spit (leakage from S1 to S2) has not been sufficient to balance the strong longshore sand transport potential in this drift pulse zone, hence the strong and chronic erosion in the Keta area. Sector S3, corresponding to a cell with the artificial boundaries imposed by the ports of Lomé (west) and Cotonou (east), has been sourced by sand bypassing the Volta spit trap and by sand released by shoreline erosion in the Keta drift pulse zone. Sector 4 corresponds to another cell with artificial boundaries, bounded to the east by the port of Lagos (Fig. 4). Sector 5 is bounded westward, immediately downdrift of the port of Lagos, by an important landfill structure, Eko Atlantic, an urban complex launched in 2007. East of this landfill, which comprises commercial, financial and residential estates, the multiple cells associated with sector S5 along the Nigerian coast (Fig. 3) comprise natural convergent (shoreline accretion) or divergent (shoreline erosion) cell boundaries, albeit with a sand budget that has no doubt been impacted by the large port of Lagos. In this sector, the several small distributary mouths that are part of the Niger delta tend to favour a highly segmented multi-cell structure. Each cell corresponds to a sand barrier with beach-ridge sets characterized by updrift erosion and downdrift spit recurves associated with accumulation (Allen, 1965; Anthony, 2015b). Downdrift deflection of the distributary mouths by longshore currents is very limited, and each of these short cells probably acts as a depocentre for fluvial and shoreface-derived sand (Anthony, 2015b).

With the exception of the immediate vicinity of the port of Lagos (S4), and the Eko Atlantic landfill where net advance has exceeded 40 m/yr, much of the change shown in Fig. 3, negative or positive, is within 20 m/yr, which is still quite substantial. Net erosion is limited to the proximal segment of the Volta spit near the mouth of the Volta River (S1), the Keta area downdrift of the Volta delta (S2), the Aneho inlet, and segments downdrift of the ports of Lomé (S3), and Cotonou (S4), but is especially prevalent along more important stretches of the Nigerian coast east of Lagos and along the northwestern flank of the Niger delta (S5).

When the apparently reassuring pattern of overall advance is broken down into intervals, a somewhat alarming trend of decreasing shoreline advance appears, with erosion even becoming dominant over the period 2010–2015 at the scale of the entire bight. Figs. 5 and 6 show shoreline

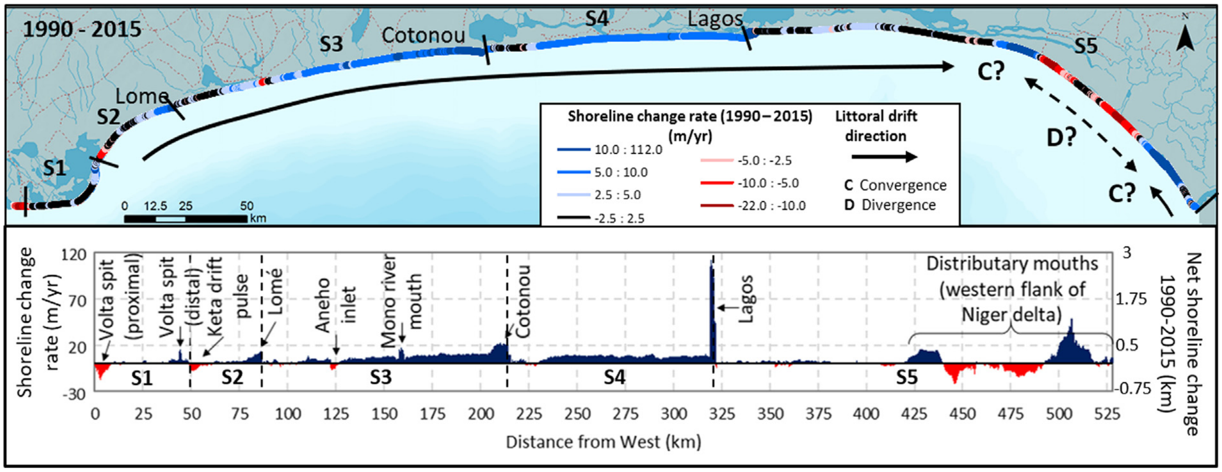

Fig. 3. Shoreline change rates and net change in the Bight of Benin between 1990 and 2015, showing a spiky alongshore pattern. The shoreline has been divided into five sectors (S1 to S5), of which S1 to S4 correspond to individual sediment cells with boundaries. Significant changes are associated with identified features. Arrows show present dominant longshore sediment transport directions (dashed arrows = hypothetical directions).

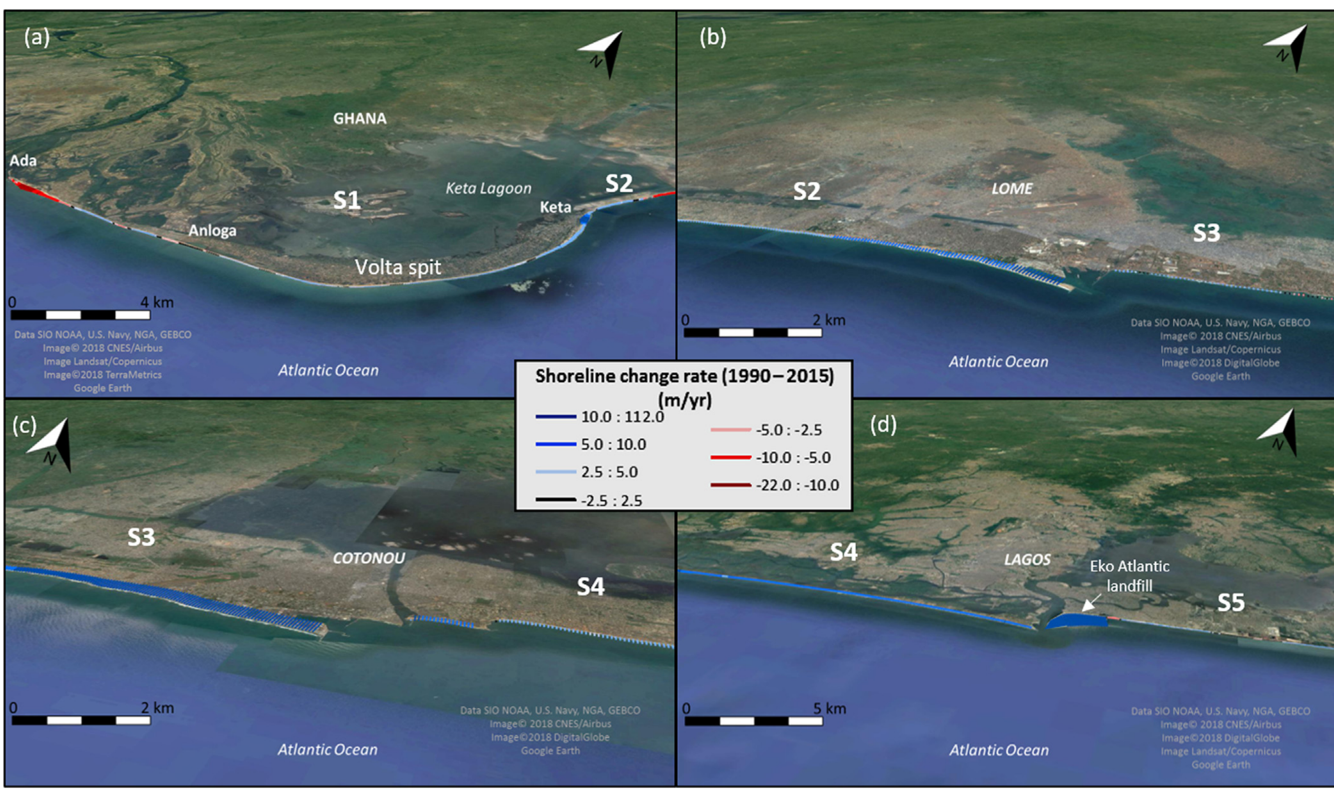

Fig. 4. Google Earth images of sediment cells and their boundaries on the coast of the Bight of Benin: (a) the Volta delta and the former natural cell boundary at Keta, Ghana; (b) artificial cell boundary corresponding to the port of Lomé, Togo; (c) artificial cell boundary corresponding to the port of Cotonou (Benin); (d) artificial cell boundary corresponding to the port of Lagos (Nigeria). The natural cell boundary at Keta corresponded to a drift acceleration zone (drift pulse) where intense erosion has been partially mitigated by the Keta shoreline protection project, a permeable artificial cell boundary.

change for the four discrete periods of analysis (1990–2000, 200–2005, 2005–2010, and 2010–2015) together with the associated gains and losses in coastal area for each of the five identified sectors (S1 to S5). These results depict a trend of net advance over the decade 1990–2000, followed by a sharp decline in the advance between 2000 and 2005, and a further decline up to 2010. It is interesting to note that although S1 incorporates the Volta delta shoreline and river mouth, and therefore corresponds to the main source area for sand supply to the bight shoreline, the advance recorded in this sector over the period 1990–2000 was much lower than that of sectors S3 to S5 (Fig. 5b). S2 similarly exhibited only mild accretion between 1990 and 2000 (Fig. 5b), whereas the other three sectors accreted significantly over this interval. Since 2000, all sectors have fluctuated more or less markedly, but the interval 2010–2015 has been characterized by retreat in S4 and especially S5.

The strong mean erosion trend between 2010 and 2015 calls for two observations: (1) it is largely accounted for by S5, whereas S1 to S3 showed mild recovery, and (2) is offset by the massive Eko Atlantic landfill (Fig. 5). Other accretion spots are associated with the Lomé and Cotonou port breakwaters. Since 2010, long tracts of erosion prevail along much of the bight coast of Ghana, Togo and Benin, and especially in S5 east of Lagos (Fig. 6).

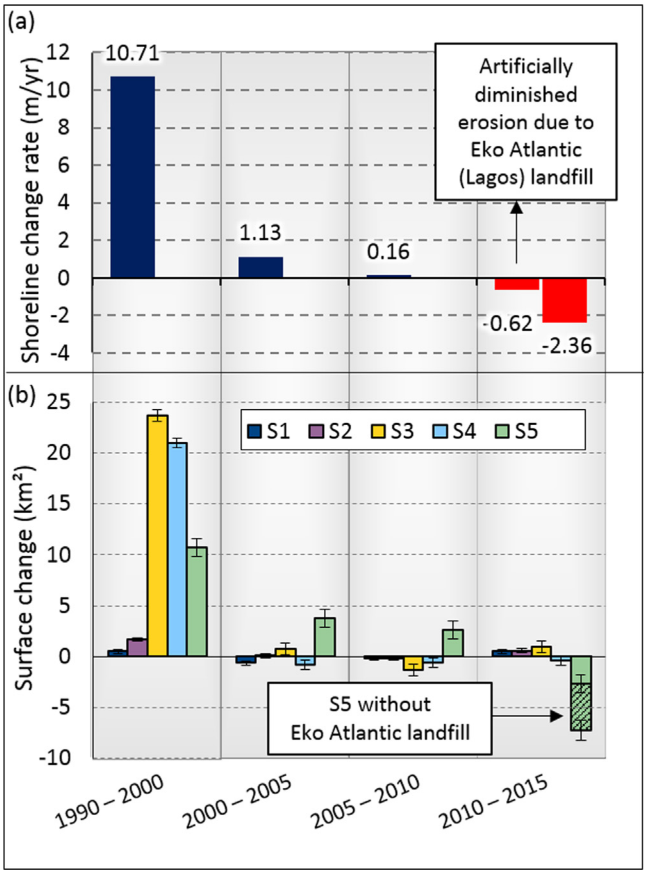

Fig. 5. Shoreline change rates in the Bight of Benin over the intervals of analysis between 1990 and 2015, showing the switch in 2010–2015 from net accretion to net erosion across the entire bight shoreline (a), and changes in coastal surface area over these intervals for the five sectors (b). The two bars representing the 2010–2015 interval (a), and sector S5 (b) show the mitigating effect of artificial landfill near Lagos harbour on shoreline retreat, and the large shoreline retreat rate when this landfill is excluded from the analysis.

5. Discussion

Analysis of shoreline change on the Bight of Benin coast between 1990 and 2015 reveals a: (1) ‘spiky’ and segmented spatial pattern highlighted in five sectors, S1 to S5, largely delimited on the basis of sediment cells with distinct boundaries (Figs. 3 and 4), and (2) three temporal phases: a significant shoreline advance, albeit variable from one sector to the other, between 1990 and 2000, a downswing in accretion at about 2000 that had become more pronounced by 2010, and the dominance of net bight-averaged erosion between 2010 and 2015 (Figs. 5 and 6). Following an analysis of this spatial pattern and the temporal phases, and their relationship to alongshore sand supply, we will briefly discuss the potential effects of sea-level rise on coastal stability and of climate change on wave-generated longshore sediment transport when considering the future state of the bight shoreline.

Sharp gradients in, or interruptions of, longshore sand transport are expressed, as expected, by switches from accretion to erosion, or vice versa, as on either side of each of the three ports (Fig. 3). The (now modified) Volta delta cell bounding S1 evinces a similar effect on shoreline stability in S2 as discussed below. The synchroneity of the changes throughout the bight coast, illustrated by the downward shift in accretion after 2000 (Fig. 5a), suggests, however, the operation of through-drift across the artificial port cell boundaries which are, therefore, permeable. This permeability is also confirmed by the dredging operations to keep the port accesses free of sand transported alongshore (Lihoussou, 2014), and by periodic alarming reports in the regional press on the deleterious effects, on port activity, of inadequate dredging of these accesses.

In order to highlight spatial and temporal structure from the patterns of shoreline change, and, subsequently to further investigate causative factors, we undertook an Empirical Orthogonal Function (EOF) analysis of the generated shoreline change data. EOF analysis, or principal components analysis, is a commonly used technique to analyze spatial and temporal patterns of shoreline change (e.g., Anthony, 1994; Wijnberg and Terwindt, 1995; Kroon et al., 2008; Hapke et al., 2016). The EOF analysis brings out two modes (Fig. 7). Mode 1 accounts for 64% of the variability, and represents small spatial scales associated with relatively sharp local changes in accretion/erosion caused by the three ports and by natural shoreline dynamics, notably associated with distributary mouths debouching from the Niger delta, the Aneho inlet in Togo, and the Volta spit (Fig. 7a). These features explain the spiky pattern of shoreline change between 1990 and 2015 (Fig. 3). From almost 0 in the intervals 1990–2000 and 2000–2005, the intensity expressed by this mode increased clearly in the interval 2005–2010 (Fig. 7b), reflecting the increasingly more segmented and variable shoreline pattern caused by the afore-mentioned features. Mode 2 explains 36% of the variability, and is interpreted as representing a larger scale (Fig. 7a) associated with the gradual regional diminution in accretion over the study period (Fig. 7b). This mode brings out the influence of the two longest sectors, S3 and S5, impacted, respectively, by sand inputs from the Mono River in addition to updrift accretion caused by the port of Cotonou (S3), and the significant fluctuations related to artificial landfill and fluctuations in sediment supply by distributary mouths (S5). Figs. 3 and 7a suggest that, apart from the inordinately large shoreline advance induced by the port of Lagos in S4 and the artificial landfill in S5 (Fig. 5), the effect on shoreline change by river/distributary mouths (Mono in S3 and Niger delta distributaries in S5) has been as important as that of the ports of Lomé and Cotonou.

The spiky pattern of shoreline change highlights, thus, the effect, on longshore sand transport, of artificial and natural cell boundaries, within a context of diminished advance since 2000 (Fig. 6). The alongshore alternations of eroding/stable/advancing sectors occurring along much of the cell segments away from the immediate vicinity of the three ports highlight intra-cell alongshore sand reworking within this context. Diminished shoreline advance has involved a west-east progression of erosion along the Bight of Benin coast, with increasingly longer stretches of eroding shoreline releasing sand that accumulates in shorter segments of accretion. This erosion threatens coastal communities, roads and infrastructure, entailing their successive landward displacements, and generates geopolitical tensions as the erosion wave, recognized in each country as being caused by the port updrift in the neighbouring country, crosses country borders (Ozer et al., 2017).

The relatively moderate advance recorded in S1, which includes the main Volta mouth source for sand supply to the bight shoreline, compared to sectors S2 to S5 over the period 1990–2000 (Fig. 5b), suggests the operation of efficient longshore transport eastward towards the rest of the bight shoreline. Erosion and accretion have largely alternated in this sector since 1990 (Fig. 8), probably in response to variations in sand supply from the Volta River and in wave conditions that are discussed later. Changes in shoreline orientation associated with spit development, and with an eastward shift of 12 km of the mouth of the Volta since the commissioning of the Akosombo dam (Boateng et al., 2018) may also have had an impact on alongshore variations in accretion and erosion. S2 has been impacted both by drift acceleration in the Keta area (discussed below) and by the Aneho inlet, an erosion hotspot (Fig. 3). The infilling Aneho lagoon captures sand transported alongshore. Groynes were emplaced in this area in 1988 to protect the town of Aneho and a nearby phosphate export facility threatened by erosion (Anthony and Blivi, 1999). Significant accretion in S3 in the interval 1990–2000 was likely favoured by additional sand supply by the Mono River (Laibi et al., 2014). This sector has fluctuated since, probably in response to a diminution in sand supply downstream of the

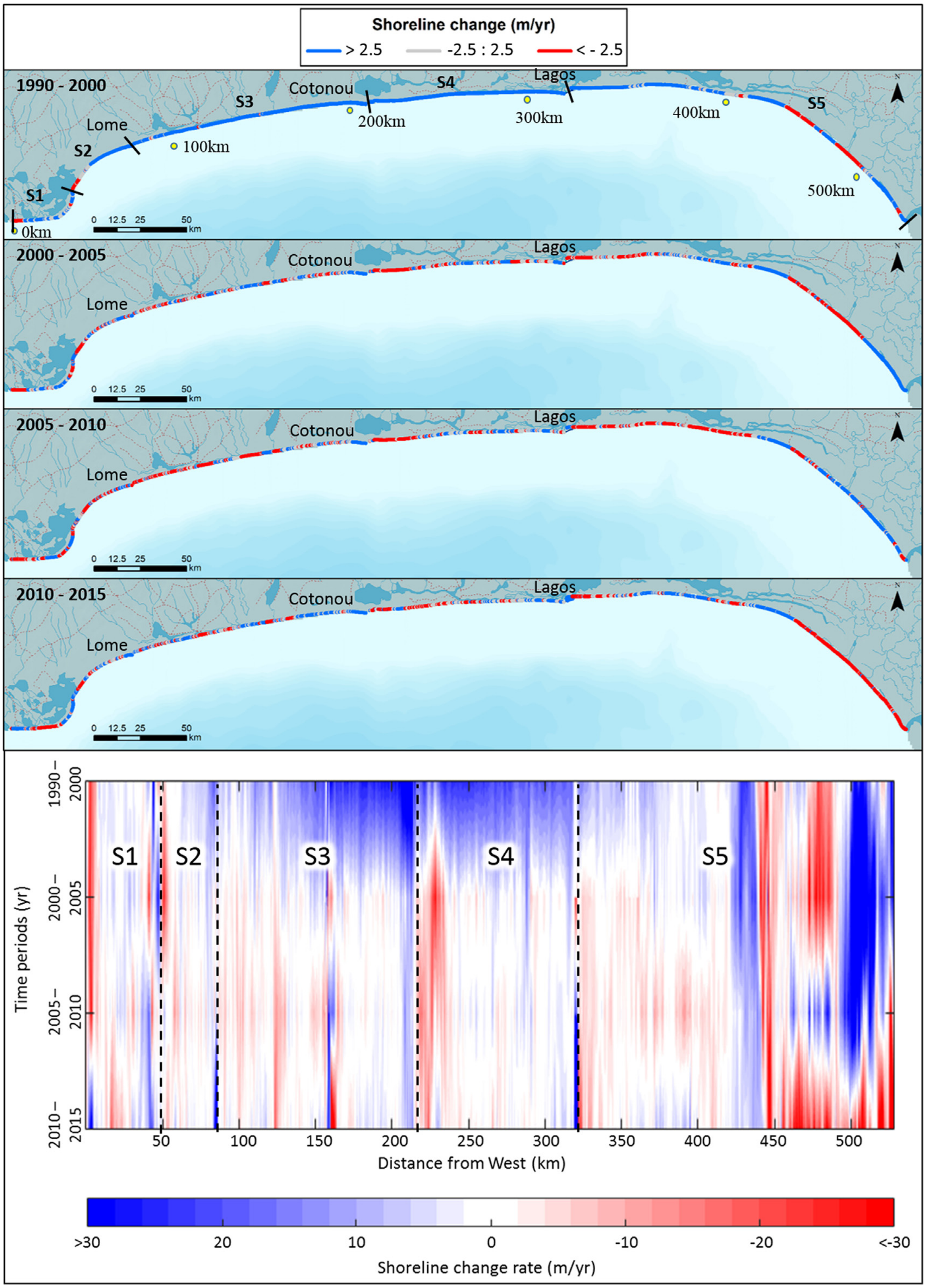

Fig. 6. Maps of shoreline change in the Bight of Benin for the four individual intervals of analysis, and Hovmöller diagram of the spatiotemporal change pattern highlighting the increasing tendency towards dominant erosion.

Nangbeto dam on the Mono, and fluctuations in river discharge combined with periodic engineered breaching of the sand spit diverting the mouth of the river eastward (Ndour et al., 2018). Erosion has been dominant in S4 which is far downdrift of the Volta source and not associated with any direct river sand inputs. The marked changes that have affected S5, excluding the Lagos city expansion landfill (Fig. 5), and the clear shift to dominant erosion, may reflect the joint impacts, on fluvial sand supply to the coast, of river dams in the Niger catchment and of fluctuations in the hydrology of the Niger and its delta (Dada et al., 2018).

The temporal trend of shoreline change is in agreement with the findings of Ozer et al. (2017) for Togo and Benin, where, between 2000 and 2015, 52% of an analyzed shoreline length of 170 km was eroding, 34% stable, and only 14% still advancing. A dominantly erosive trend from 2007 to 2013 was also highlighted by Addo (2015) for the Volta delta shoreline corresponding to our sectors S1 and S2 (Fig. 8). We

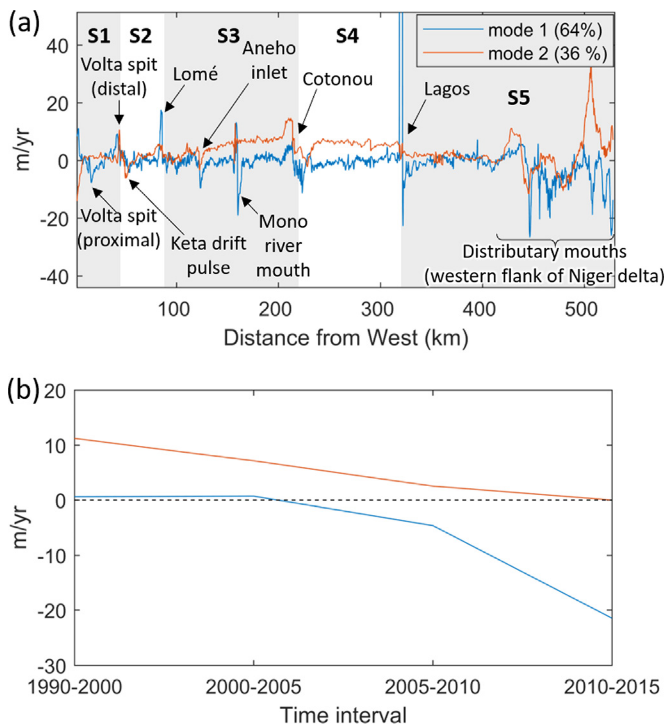

Fig. 7. EOF modes of shoreline change in the Bight of Benin from 1990 to 2015: (a) spatial pattern, showing two modes representing, respectively, the pronounced local influence of features identified in Fig. 3 (mode 1), and the more regional (larger-scale) influence (mode 2) of the two longest two sectors, S3, dominated by the port of Cotonou, and S5, characterized by delta distributary mouths at the western flank of the Niger delta; (b) temporal pattern expressing each of these modes. Note the relatively marked decline expressed by mode 1 at the local level, and the gentler bight-wide decline by mode 2 mitigated by overall accretion in S3 and by two segments of strong accretion in S5 (one of which is the Eko Atlantic landfill), despite longer segments of erosion.

consider that the large-scale shift, since about 2000, and especially since 2010, to a dominantly erosional bight shoreline and increasing losses in coastal area (Figs. 5 and 6) is due to an overall diminution of sand supply via the longshore transport system, although the bight-averaged erosion between 2010 and 2015 is largely accounted for by the net retreat in S5 in eastern Nigeria (Fig. 5b), impacted not only by interception of alongshore sand supply from the west by the large port of Lagos, but also by Niger delta distributaries.

The most likely explanation for the downswing in significant advance in the decade 1990–2000 is an overall diminution of sand supplied by the Volta River. The continuous seaward growth of the large Volta spit (Fig. 4) over several decades (Anthony and Blivi, 1999; Anthony, 2015a; Addo, 2015), the significant accretion throughout the Bight of Benin in the decade 1990–2000, and the downswing in this accretion after 2000 (Fig. 5), including in growth of the Volta spit, all suggest that the negative effect of dams on sediment supply from the Volta River to the Bight of Benin was offset for several decades by the progressive transfer of channel bedload from the ~100 km-long Volta channel downstream of these dams to the delta shoreline. This hypothesis, which concerns the adjustment time and dynamics of the Volta channel downstream of the Akosombo and Kpong dams, will require further research. Petts and Gurnell (2005) showed that river channel adjustment downstream of dams may occur over long periods (decades to centuries).

The changes recorded since 2000 also coincided with enhanced but temporary sand trapping in the Keta drift pulse (Fig. 8) following the completion, in 2004, of a shoreline stabilization project to protect Keta (Nairn and Dibajnia, 2004). This project comprised several groynes, beach nourishment between groynes, a seawall, and landfill. The Keta project generated an artificial but permeable cell boundary that replaced part of the original drift pulse, which has shifted alongshore, resulting in erosion well downdrift of Keta (Fig. 4). Although some interception by the Keta groynes no doubt contributed to a decrease in the volume of sand in transit to the Bight of Benin from the mouth of the Volta after 2000, we do not deem this interception as having played an important role in the decline in shoreline advance along the rest of the bight shoreline because: (1) spaces between these groynes were nourished in the course of the project (Fig. 8) to minimise aggravated downdrift erosion caused by sand trapping by the groynes, (2) erosion has occurred in recent years (2010–2015) in this protected segment of S2, an aspect also reported by Angnuureng et al. (2013) and Addo (2015), and (3) the longshore transport potential impacted by these structures would have been offset, anyway, by erosion of a large updrift segment of S2.

An additional moderating influence on the alongshore sediment supply has been identified by Almar et al. (2015) who highlighted an eastward longshore transport decay of −5% over the 1979–2012 period of analysis of the ERA wave dataset (Fig. 2). The authors linked this to a decrease in the intensity of westerly winds associated with the southward shift of pressure centres, and a strengthening of the trade winds, both of which reduce the eastward sediment transport potential. The equatorial fluctuation of the Inter-Tropical Convergence Zone (ITCZ) was found to explain most of the variability in transport induced by wind waves, while the Southern Annular Mode (SAM), an extra-tropical mode, had a predominant influence on transport induced by swell waves (Almar et al., 2015). The ITCZ and SAM had, respectively, a negative and positive trend over the period 1979–2012 that explain the decrease in both wind- and swell-wave-induced transport. The effect of this slight drop in transport may also have contributed to the attenuation of transport gradients in the Bight of Benin since it goes along with either a slight drop in wave energy or a slight decrease in wave approach angle.

In addition to the deduced foregoing effects on sand supply from the Volta, the sediment budget of the bight coast has also been impacted negatively in the last decades by localized extractions of beach sand to cater for aggregate needs in urban construction (Dossou and Glehouenou-Dossou, 2007; Rutten, 2011; Ozer et al., 2017; Ndour et al., 2018) in all the bight countries, and especially for the cities of Cotonou and Lagos. Although legislation has been passed since 2000 in both Togo (Ayenagbo et al., 2011) and Benin (pers. com. L.M. Oyédé) to regulate and even forbid beach sand extraction, the practice still continues, albeit at an apparently reduced rate.

Alongshore sediment transport is fundamental to the stability of many open wave-dominated coastlines, inasmuch as sediment supply for coastal progradation (or to maintain stability) is commonly derived from rivers, which are the main suppliers of sediments to coasts globally (Milliman and Farnsworth, 2011). One unanswered aspect of the sand supply on the Bight of Benin coast is to what extent does outer shoreface/inner shelf sand supply still prevail along this coast? Sand supply from the shelf is thought to have been important in the early phases of barrier progradation as shoreface gradients in West Africa adjusted to the sea-level still stand (Anthony, 1995). Active sand supply from the shoreface to the coast in wave-dominated settings has been identified on a number of coasts exposed to swell (e.g., Cowell et al., 2003; Stive et al., 2010; Ruggiero et al., 2016). Quantifying sand supply from the shoreface is, however, technically very tricky, and fraught with difficulties (Aagaard, 2014). The Bight of Benin is fronted by a narrow shelf 15–33 km wide, and characterized by a fairly uniform, moderately steep shoreface with a gradient of between 1:120 and 1:150 down to −15 m, the hypothetical maximum closure depth for significant wave-induced sand transport on this coast (Delft Hydraulics, 1990). This closure depth leaves a significant shoreface zone over which sand stored on the inner shelf can be reworked and driven onshore by the constant SW swell waves impinging on this microtidal coast. The operation of such a potential shoreface sand source needs to be

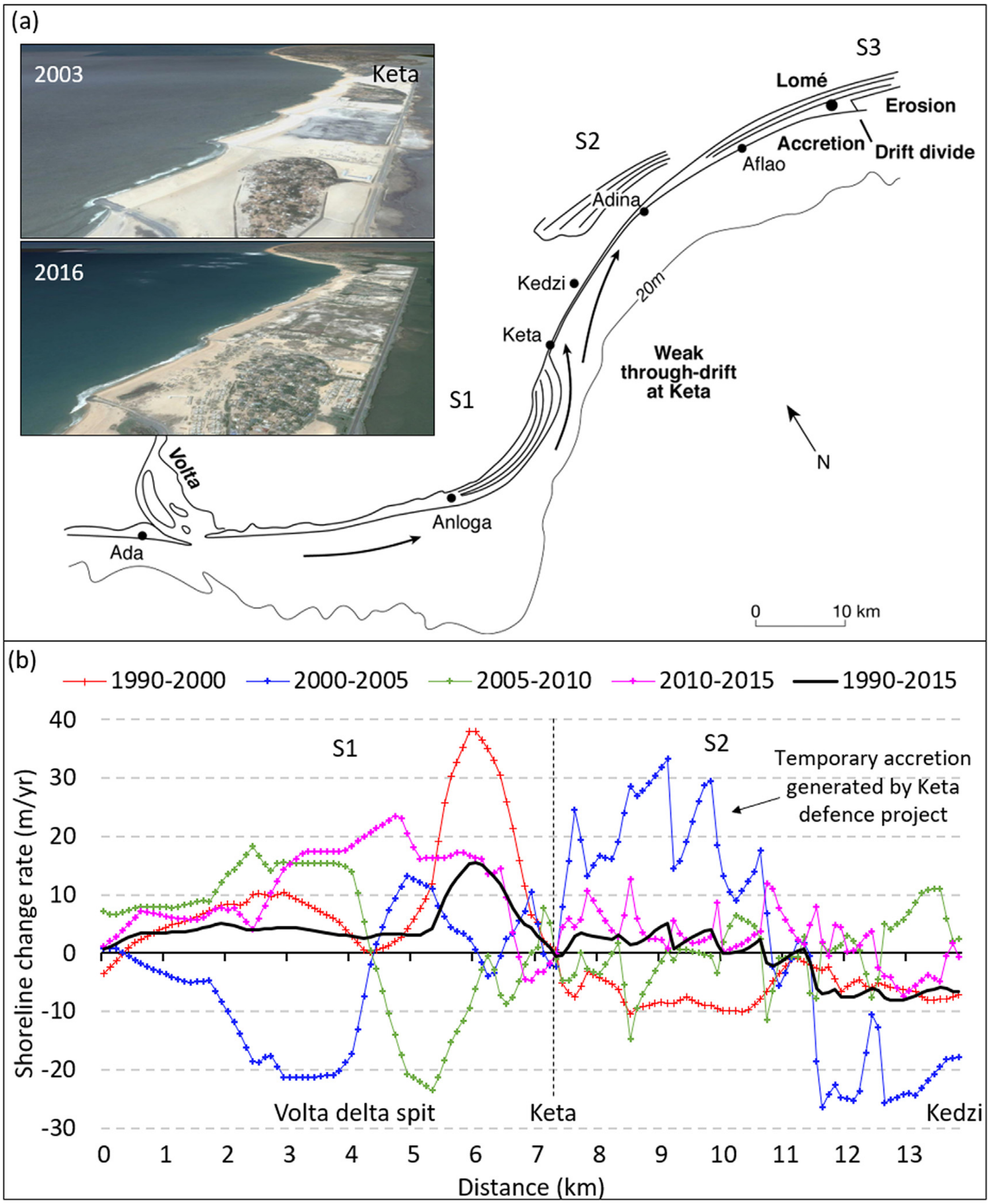

Fig. 8. Schematic morphology and cell dynamics downdrift of the mouth of the Volta delta (a), and shoreline changes between 1990 and 2015 (b). A single longshore drift cell is presumed to have existed up to, and after, the 1880s, allowing transport of sand from the mouth of the Volta to the Bight of Benin (Anthony et al., 2016). The current cell (S1) between the delta mouth and Keta has been characterized by trapping of an unknown proportion of Volta sand by a distinct spit, resulting in the formation of a drift divide in the area of Keta and erosion of the Keta-Kedzi barrier sector downdrift of which occurs a second cell (S2) bounded eastward by the deepwater port of Lomé. The shoreline in this transition zone between S1 and S2 has fluctuated markedly since 1990, especially along the Volta spit. A coastal defence project involving groynes, a seawall, and landfill was implemented in Keta in the early 2000s (2003 and 2016 Google Earth photos inset), resulting in temporary accretion, and transformation of part of the natural Keta drift pulse into a fixed permeable artificial cell boundary accompanied by aggravated erosion downdrift towards Kedzi. Adapted from Anthony et al. (2016).

confirmed through high-resolution bathymetric and seismic surveying, but such data are not available. Seaward of the shoreface, the inner shelf forms a low-gradient (1:350–1:400) plain covered by relict transgressive sands (Anthony and Blivi, 1999).

The extent to which the contemporary dominant erosion will continue to prevail on the Bight of Benin coast in the next decades will depend on: (1) the management choices implemented by the regional governments regarding the construction (likely) or removal (unlikely) of river dams in the future, and (2) climate change (Giardino et al., 2018). Meanwhile, ports, maintained and extended in the pursuit of economic development, will continue to fragment longshore sand transport on this coast, with localized accretion near downdrift sectors adjacent to cell boundaries and increasingly more prevalent erosion along much of the bight coastline.

Regarding climate change, Giardino et al. (2018) anticipate only a minor contribution from change in river hydrology to the stability of the Bight of Benin coast. Two other aspects that need further consideration are: (1) the effects of climate change on the hydrodynamic regime, and (2) sea-level rise. Regarding the influence of climate change on wave climate, General Circulation Models predict a stabilization of the SAM, evoked earlier, and, thus, a non-substantial or weak change in alongshore sediment transport can be expected on the coast of the Bight of Benin (Almar et al., 2015). Over the period 1993–2012, mean sea-level rise in Cotonou has been estimated at 3.2 mm/yr (Melet et al., 2016), a value close to that of the recent global trend (Church et al., 2013). A continuation of this trend in the future will adversely affect the Bight of Benin shoreline as sea-level rise will lead to landward translation of the coastline and an increase in sediment accommodation space on the shoreface. According to the sediment budget model of Giardino et al. (2018), the effect of coastal area loss due to the three ports will be approximately of the same order of magnitude as the effect of coastal retreat due to sea-level rise (SLR) with a SLR scenario of 0.3 m by 2100, but the latter will become the overarching cause of erosion in a SLR scenario of 1.0 m. Given the likelihood of the continued operation of the existing ports, the continued presence of river dams, and ongoing sea-level rise, shoreline erosion will continue to affect the Bight of Benin and the lives and livelihood of its cities and people.

6. Conclusion

The morphology of the Bight of Benin coast is an outgrowth of beach-ridge progradation that generated a mildly embayed coast wherein incident wave behaviour, beachface gradient and the longshore sand transport system were intimately linked, representing a classic example of a strongly wave-dominated ‘drift-aligned’ coast. The patterns of current shoreline change along much of this bight coast have been strongly affected by human activities. The construction of three deepwater ports on a coast exhibiting a high rate of longshore sand drift has resulted in shoreline destabilisation, generating a multiple drift cell system characterized by short updrift sectors of significant accretion but longer downdrift sectors of acute erosion, threatening the safety of large coastal stretches in the strongly growing port cities of Lomé, Cotonou and Lagos; coastal villages; near-coast roads and infrastructure. Analysis of shoreline change undertaken here reveals a significant reduction in accretion from a mean bight-wide value of > 10 m/yr over the period 1990–2000 to about 1.1 m/yr in 2000–2005, and a clear shift to dominant erosion to the tune of -2.3 m/yr in 2010–2015. We attribute this to a progressively diminishing sand supply from the Volta River downstream of the Akosombo dam. Sea-level rise will adversely affect this coast by leading to landward translation of the coastline and a deeper sediment accommodation space on the shoreface. The continued operation of the three ports and of existing river dams, and sea-level rise, will drive sustained shoreline erosion in the coming decades along the Bight of Benin.

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