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

5

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19

20 **ABSTRACT**

21 The Bight of Benin in the Gulf of Guinea, West Africa, forms an embayment between the Volta
22 River delta in the west (Ghana) and the Niger River delta (Nigeria) in the east. The bight coast
23 comprises sandy beaches backed by Holocene beach-ridge barriers. Incident swell waves, beachface
24 gradient and the unidirectional longshore sand transport from west to east are intimately linked,
25 generating a classic example of a strongly wave-dominated drift-aligned coast. The stability of this
26 coast, which hosts several major cities in addition to three large international deepwater ports, has
27 been strongly affected by human activities. We analyzed shoreline mobility and coastal area change
28 over the period 1990-2015. Our results show how the stability of this coast has been strongly
29 affected by the three ports therein, and by natural and human-altered shoreline dynamics related to
30 the Volta River delta and to distributaries at the northwestern flank of the Niger delta. The
31 combination of these factors has impacted alongshore sediment redistribution by segmenting the
32 previously unrestrained longshore transport of sand that prevailed along this open coast. The result is
33 a mixture of natural and artificial sediment cells increasingly dominated by shoreline stretches
34 subject to erosion, endangering parts of the rapidly expanding port cities of Lomé (Togo), Cotonou
35 (Benin) and Lagos (Nigeria), coastal roads and infrastructure, and numerous villages. Post-2000, the

36 entire bight shoreline has undergone a significant decrease in accretion, which is here attributed to
37 an overall diminution of sand supply via the longshore transport system. We attribute this diminution
38 to the progressive depletion of sand-sized bedload supplied to the coast through the main Volta river
39 channel downstream of the Akosombo dam, built between 1961 and 1965. Sand mining to cater for
40 urban construction in Lomé, Cotonou and Lagos has also contributed locally to beach sediment
41 budget depletion. Although alongshore sediment supply from the Volta River has been the dominant
42 source of sand for the stability or progradation of the Bight of Benin coast, potential sand supply from
43 the shoreface, and the future impacts sea-level rise on this increasingly vulnerable coast are also
44 important. The continued operation of the three ports and of existing river dams, and sea-level rise,
45 will lead to sustained shoreline erosion along the Bight of Benin in the coming decades.

46

47 **Keywords:** Bight of Benin, coastal erosion, coastal sediment cells, longshore sediment transport,
48 shoreface sand supply, river dams, Volta delta, Niger delta.

49

50 **1. Introduction**

51 The ubiquity of shoreline erosion on long open coasts is often matched by a lack of
52 understanding of the context, processes, and embedded spatial and temporal scales over which the
53 sediment redistribution processes that shape the coast occur. In addition to the ambient long-term
54 (post-mid-Holocene, i.e., last ~6 ka) large-scale adjustments of the shoreline and shoreface profile to
55 sediment supply from rivers and coastal erosion updrift, and to eventual cross-shore sediment
56 movement from the nearshore zone, the world's shorelines are also increasingly impacted by the
57 effects of climate change and human activities (Pilkey and Cooper, 2014; Ranasinghe, 2016; Anthony,
58 2017). Understanding the links between shoreline change, natural sediment supply and transport
59 processes, human activities, and climate change is by no means easy, but is an important pre-
60 requisite for establishing effective coastal management frameworks in the face of increasingly
61 intensive occupation of the coast in a rapidly changing world (Ranasinghe and Stive, 2009; Jongejan
62 et al., 2016).

63 Tropical coasts are largely located in developing countries where the effects of increasing
64 population pressures are exacerbated by the impacts of climate change and generally low adaptive
65 capacity (Doung et al., 2016; Ranasinghe, 2016). In a vast number of situations in developing

66 countries, urbanization or management activities (e.g. port construction) at small segments of high-
67 value coasts can have large-scale impacts that are not always well understood or anticipated. This is
68 very much the case along the Gulf of Guinea coast in West Africa (Giardino et al., 2018; Ndour et al.,
69 2018), the focus of this study (Fig. 1).

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

87 Using European Re-Analysis (ERA-Interim) wave hindcast data from 1979 to 2012, Almar et al.
88 (2015) identified the origin and temporal dynamics of the wave climate affecting this coast,
89 calculated the sand volumes transported alongshore by waves, and estimated the potential influence
90 of climate change on the wave regime and on longshore sediment transport. The present article is a
91 companion to Almar et al. (2015). The aim of this study is to investigate recent (1990-2015) shoreline
92 change along the Bight of Benin coast and its relationship to longshore sediment transport, and the
93 ways in which the latter has been impacted upon by human activities. Given the overwhelming
94 importance of sand supply by the Volta River and the strong unidirectional longshore sediment
95 transport in the study area, changes in the shoreline patterns are further assessed within the

96 framework of sediment cells identified in this study. The cell notion is not only particularly pertinent
97 to coastal zone management issues (e.g., Bray et al., 1995; van Rijn, 2011), but is also an important
98 concept with respect to long-term shoreline accretion or erosion, because of the relevance of cell
99 boundaries to alongshore sediment flux (Carter, 1988; Cowell et al., 2003).

100

101 **2. The Bight of Benin coast**

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

115 Tides here are semi-diurnal with a mean spring tidal range that varies from 1.5 to 1.9 m. Almar
116 et al. (2015) showed that the constant S to SW waves impinging on the Bight of Benin coast had a
117 mean 33-year averaged significant height (H_s) of 1.36 m and a peak period (T_p) of 9.6 s, and they
118 computed, for Cotonou, in the centre of the bight (Fig. 1), a net mean eastward sand transport
119 volume of $514 \times 10^3 \text{ m}^3/\text{yr}$ (Fig. 2). Wave forcing was shown to comprise two components with
120 distinct origins and behaviour: wind waves generated locally in the Gulf of Guinea and swell waves
121 generated in subtropical, mid-to high latitudes. Almar et al. (2015) also demonstrated that longshore
122 sediment transport due to swell waves is an order of magnitude larger than that due to wind waves,
123 which corresponds well with the cyclone-free ‘West Coast Swell Environment’ defined by Davies
124 (1980).

125 The two river deltas bounding the bight, the Niger and the Volta (Fig. 1), are among the three
126 largest deltas in West Africa. The Volta delta, situated entirely in Ghana (Boateng et al., 2018), covers
127 an area of about 5000 km² at the outlet of a large river catchment of 397,000 km². Prior to the
128 commissioning of the Akosombo dam (Fig. 1), built between 1961 and 1965 across the lower reaches
129 of the Volta River (~100 km upstream from the sea), the river's water discharge varied between a low
130 of 1000 m³/s in the dry season and a high of over 6000 m³/s in the wet season. A smaller dam was
131 constructed at Kpong, 24 km downstream of the Akosombo dam, between 1977 and 1982. The mean
132 discharge downstream of the dams is presently about 1260 m³/s, and has undergone a significant
133 reduction due to the decrease in rainfall in the Sahel since 1975 (Oguntunde et al., 2006). Global
134 climate-change modelling by Jin et al. (2018) suggests, however, that the outflow from Lake Volta
135 downstream of the Akosombo dam will increase by 1% in the 2050s and 5% in the 2090s. About 90%
136 of the total sediment yield of the river is intercepted by this dam, which blocks 95% of the total
137 catchment (Boateng et al., 2012). These authors estimated a reduction in solid discharge downstream
138 of the dam, following its construction, from about 71 million m³/yr to about 7 million m³/yr. The sand
139 load supplied annually by the river to its delta prior to dam construction is only a small fraction of the
140 total solid discharge, and has been estimated at about 1 million m³ (Delft Hydraulics, 1990). Much of
141 this sand was injected into the longshore drift system via a single delta river mouth. The Niger delta,
142 situated in Nigeria, is much larger, covering an area of 19,135 km² (Coleman and Huh, 2004). The
143 influence of the Niger delta has been limited essentially to the eastern confines of the Bight of Benin
144 coast. The only other river on the rest of the bight coast that supplies sand directly to the sea is the
145 Mono, in Benin (Fig. 1). The estimated 100,000 m³ of sand supplied by the Mono River during the
146 wet-season months supplement the massive sand load transported by longshore drift from the
147 Ghana and Togo coasts, but the Nangbéto dam, built 180 km upstream on the Mono in 1987 has also
148 affected the hydrology of this river (Ago et al., 2005) and its sand supply to the coast (Laibi et al.,
149 2014). The other smaller rivers, such as the Ogun in Nigeria (Fig. 1), debouch into still infilling lagoons
150 behind the coastal sand barriers. These lagoons are linked to the sea via three inlets: an inlet at
151 Aneho, an artificial inlet in Cotonou cut in 1888 to alleviate flooding, and the Lagos inlet (Fig. 1), all
152 fixed by engineering structures.

153

154 **3. Methods**

155 3.1 Shoreline change (1990-2015)

156 In this study, we used available satellite images that offer not only large individual coverage,
157 given the length of the Bight of Benin coast (>400 km), but also robust and accurate determinations
158 of shoreline change rates. In total, 15 LANDSAT 4-8 images were used. Three images for each of the
159 years 1990, 2000, 2005, 2010, and 2015 were downloaded from the USGS data portal EarthExplorer.
160 The analysis involved using panchromatic (10 m resolution) and a customized combination of bands
161 maximizing land-water contrast (30 m) to derive the shoreline. We used the most recent images in
162 the time series, and with minimal cloudiness, checked for easy landmarks on those where these could
163 be traced back through time, and georeferenced these using coordinates from Google Earth, from
164 the most recent to the oldest image. The accuracy was typically around 1 pixel (30 x 30 m). From the
165 four individual periods of analysis covered by the images (1990-2000, 2000-2005, 2005-2010 and
166 2010-2015) we constructed a Hovmöller diagram of spatiotemporal shoreline change.

167 To compute rates of change in shoreline position, we used the ArcMap extension module
168 Digital Shoreline Analysis System (DSAS), version 4.3 (Thieler et al., 2009), coupled with ArcGIS®10.
169 The brush/plantation fringe could be used as a robust shoreline marker on this sandy coast
170 characterized by beaches throughout. The shore-normal distance of the vegetation line to a base line
171 was established at 100-m alongshore spacing for the earliest and most recent images. This distance,
172 chosen as a compromise between quality of the interpretation and the total length of analysed
173 shoreline (410 km) was then divided by the time in years between the two dates to generate a
174 shoreline change rate, i.e. the End Point Rate in DSAS 4.3. A total of 4100 change rates, each
175 corresponding to a DSAS transect, were thus determined. The annual error (E) of shoreline change
176 rate, which sums up image rectification, extraction of the shoreline, and operator digitization in
177 delimiting the shoreline, was computed from:

178

$$179 \quad E = \sqrt{d1^2 + d2^2} / T$$

180

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

184 Rates of shore-normal shoreline change along transects are useful in indicating the degree of

185 shoreline mobility. An equally important metric, however, is that of change in areas lost or gained (in
186 km²). Area change was analyzed for the 410 km of bight coast in ArcGIS by vectorizing polygons that
187 comprise of the shoreline and a distance up to two hundred metres inland to account for any losses
188 or gains in coastal area. Surface area differentials were statistically estimated from one period of
189 analysis to the next and an annual rate of evolution of the polygon area representing the coast
190 calculated for each period.

191

192 3.2. Coastal sediment cells

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

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

215

216 **4. Results**

217 The Bight of Benin coast shows overall net advance (accretion) when averaged over the 25-
218 year period of analysis, but also a varying alongshore pattern of shoreline change (Fig. 3). We
219 identified five main sectors, four of which (S1 to S4) correspond with major sediment cells. The
220 identified sectors and their associated cells are built on the cell structure identified by Laibi et al.
221 (2014). Sector S1 (cell 1), associated with the Volta delta, and sector S5 (unidentified multiple cells),
222 along the westernmost flank of the Niger delta, are dominated by natural shoreline change patterns
223 inherent to large deltas (Anthony, 2015b; Anthony et al., 2016; Dada et al., 2016, 2018), whereas the
224 remaining sectors S2-S4 (cells 2-4) between these deltas are dominated by the effects of port
225 engineering structures (Fig. 4), but S3 is also impacted by the mouth of the Mono River and the
226 Aneho inlet.

227 The Volta delta spit (Fig. 4) in S1 appears to be a relatively recent feature (post 1880?)
228 resulting from adjustments among sediment supply from the river, delta dynamics and the strong
229 longshore sand transport on this coast (Anthony et al., 2016). The spit has accreted in its distal sector,
230 increasingly with a convex plan-view shape due to the formation of successive beach ridges, but with
231 restricted longshore growth of its tip. S2 marks the delta transition with the rest of the bight coast.
232 Erosion has prevailed in this transition area since the mid-1880s (Kumapley, 1989), predating the
233 construction of the Akosombo dam (Ly, 1980), as a result of sand sequestering by the Volta spit. This
234 erosion threatens settlements, notably the old trading post of Keta (Fig. 4). This updrift zone of S2
235 corresponds to what was initially a natural drift 'pulse', no doubt characterised by the highest
236 potential longshore transport rate in the Bight of Benin (in excess of 1 million m³/yr (Anthony and
237 Blivi, 1999)) as a result of the shoreline orientation relative to the SW swell waves. A drift pulse is
238 expressed by acceleration of the longshore transport potential caused by a relatively sharp change in
239 wave angle incidence relative to the shoreline (Carter, 1988). The amount of sand bypassing the Volta
240 spit (leakage from S1 to S2) has not been sufficient to balance the strong longshore sand transport
241 potential in this drift pulse zone, hence the strong and chronic erosion in the Keta area. Sector S3,
242 corresponding to a cell with the artificial boundaries imposed by the ports of Lomé (west) and
243 Cotonou (east), has been sourced by sand bypassing the Volta spit trap and by sand released by
244 shoreline erosion in the Keta drift pulse zone. Sector 4 corresponds to another cell with artificial

245 boundaries, bounded to the east by the port of Lagos (Fig. 4). Sector 5 is bounded westward,
246 immediately downdrift of the port of Lagos, by an important landfill structure, Eko Atlantic, an urban
247 complex launched in 2007. East of this landfill, which comprises commercial, financial and residential
248 estates, the multiple cells associated with sector S5 along the Nigerian coast (Fig. 3) comprise natural
249 convergent (shoreline accretion) or divergent (shoreline erosion) cell boundaries, albeit with a sand
250 budget that has no doubt been impacted by the large port of Lagos. In this sector, the several small
251 distributary mouths that are part of the Niger delta tend to favour a highly segmented multi-cell
252 structure. Each cell corresponds to a sand barrier with beach-ridge sets characterized by updrift
253 erosion and downdrift spit recurves associated with accumulation (Allen, 1965; Anthony, 2015b).
254 Downdrift deflection of the distributary mouths by longshore currents is very limited, and each of
255 these short cells probably acts as a depocentre for fluvial and shoreface-derived sand (Anthony,
256 2015b).

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

264 When the apparently reassuring pattern of overall advance is broken down into intervals, a
265 somewhat alarming trend of decreasing shoreline advance appears, with erosion even becoming
266 dominant over the period 2010-2015 at the scale of the entire bight. Figures 5 and 6 show shoreline
267 change for the four discrete periods of analysis (1990-2000, 200-2005, 2005-2010, and 2010-2015)
268 together with the associated gains and losses in coastal area for each of the five identified sectors (S1
269 to S5). These results depict a trend of net advance over the decade 1990-2000, followed by a sharp
270 decline in the advance between 2000 and 2005, and a further decline up to 2010. It is interesting to
271 note that although S1 incorporates the Volta delta shoreline and river mouth, and therefore
272 corresponds to the main source area for sand supply to the bight shoreline, the advance recorded in
273 this sector over the period 1990-2000 was much lower than that of sectors S3 to S5 (Fig. 5b). S2
274 similarly exhibited only mild accretion between 1990 and 2000 (Fig. 5b), whereas the other three

275 sectors accreted significantly over this interval. Since 2000, all sectors have fluctuated more or less
276 markedly, but the interval 2010-2015 has been characterized by retreat in S4 and especially S5.

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

282

283 **5. Discussion**

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

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

303 In order to highlight spatial and temporal structure from the patterns of shoreline change,
304 and, subsequently to further investigate causative factors, we undertook an Empirical Orthogonal

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

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

334 The relatively moderate advance recorded in S1, which includes the main Volta mouth source

335 for sand supply to the bight shoreline, compared to sectors S2 to S5 over the period 1990-2000 (Fig.
336 5b), suggests the operation of efficient longshore transport eastward towards the rest of the bight
337 shoreline. Erosion and accretion have largely alternated in this sector since 1990 (Fig. 8), probably in
338 response to variations in sand supply from the Volta River and in wave conditions that are discussed
339 later. Changes in shoreline orientation associated with spit development, and with an eastward shift
340 of 12 km of the mouth of the Volta since the commissioning of the Akosombo dam (Boateng et al.,
341 2018) may also have had an impact on alongshore variations in accretion and erosion. S2 has been
342 impacted both by drift acceleration in the Keta area (discussed below) and by the Aneho inlet, an
343 erosion hotspot (Fig. 3). The infilling Aneho lagoon captures sand transported alongshore. Groynes
344 were emplaced in this area in 1988 to protect the town of Aneho and a nearby phosphate export
345 facility threatened by erosion (Anthony and Blivi, 1999). Significant accretion in S3 in the interval
346 1990-2000 was likely favoured by additional sand supply by the Mono River (Laibi et al., 2014). This
347 sector has fluctuated since, probably in response to a diminution in sand supply downstream of the
348 Nangbeto dam on the Mono, and fluctuations in river discharge combined with periodic engineered
349 breaching of the sand spit diverting the mouth of the river eastward (Ndour et al., 2018). Erosion has
350 been dominant in S4 which is far downdrift of the Volta source and not associated with any direct
351 river sand inputs. The marked changes that have affected S5, excluding the Lagos city expansion
352 landfill (Fig. 5), and the clear shift to dominant erosion, may reflect the joint impacts, on fluvial sand
353 supply to the coast, of river dams in the Niger catchment and of fluctuations in the hydrology of the
354 Niger and its delta (Dada et al., 2018).

355 The temporal trend of shoreline change is in agreement with the findings of Ozer et al. (2017)
356 for Togo and Benin, where, between 2000 and 2015, 52% of an analysed shoreline length of 170 km
357 was eroding, 34% stable, and only 14% still advancing. A dominantly erosive trend from 2007 to 2013
358 was also highlighted by Addo (2015) for the Volta delta shoreline corresponding to our sectors S1 and
359 S2 (Fig. 8). We consider that the large-scale shift, since about 2000, and especially since 2010, to a
360 dominantly erosional bight shoreline and increasing losses in coastal area (Figs. 5, 6) is due to an
361 overall diminution of sand supply via the longshore transport system, although the bight-averaged
362 erosion between 2010 and 2015 is largely accounted for by the net retreat in S5 in eastern Nigeria
363 (Fig. 5b), impacted not only by interception of alongshore sand supply from the west by the large
364 port of Lagos, but also by Niger delta distributaries.

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

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

390 An additional moderating influence on the alongshore sediment supply has been identified by
391 Almar et al. (2015) who highlighted an eastward longshore transport decay of -5% over the 1979-
392 2012 period of analysis of the ERA wave dataset (Fig. 2). The authors linked this to a decrease in the
393 intensity of westerly winds associated with the southward shift of pressure centres, and a
394 strengthening of the trade winds, both of which reduce the eastward sediment transport potential.

395 The equatorial fluctuation of the Inter-Tropical Convergence Zone (ITCZ) was found to explain most of
396 the variability in transport induced by wind waves, while the Southern Annular Mode (SAM), an
397 extra-tropical mode, had a predominant influence on transport induced by swell waves (Almar et al.,
398 2015). The ITCZ and SAM had, respectively, a negative and positive trend over the period 1979-2012
399 that explain the decrease in both wind- and swell-wave-induced transport. The effect of this slight
400 drop in transport may also have contributed to the attenuation of transport gradients in the Bight of
401 Benin since it goes along with either a slight drop in wave energy or a slight decrease in wave
402 approach angle.

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

410 Alongshore sediment transport is fundamental to the stability of many open wave-dominated
411 coastlines, inasmuch as sediment supply for coastal progradation (or to maintain stability) is
412 commonly derived from rivers, which are the main suppliers of sediments to coasts globally (Milliman
413 and Farnsworth, 2011). One unanswered aspect of the sand supply on the Bight of Benin coast is to
414 what extent does outer shoreface/inner shelf sand supply still prevail along this coast? Sand supply
415 from the shelf is thought to have been important in the early phases of barrier progradation as
416 shoreface gradients in West Africa adjusted to the sea-level stillstand (Anthony, 1995). Active sand
417 supply from the shoreface to the coast in wave-dominated settings has been identified on a number
418 of coasts exposed to swell (e.g., Cowell et al., 2003; Stive et al., 2010; Ruggiero et al., 2016).
419 Quantifying sand supply from the shoreface is, however, technically very tricky, and fraught with
420 difficulties (Aagaard, 2014). The Bight of Benin is fronted by a narrow shelf 15 to 33 km wide, and
421 characterised by a fairly uniform, moderately steep shoreface with a gradient of between 1:120 and
422 1:150 down to -15 m, the hypothetical maximum closure depth for significant wave-induced sand
423 transport on this coast (Delft Hydraulics, 1990). This closure depth leaves a significant shoreface zone
424 over which sand stored on the inner shelf can be reworked and driven onshore by the constant SW

425 swell waves impinging on this microtidal coast. The operation of such a potential shoreface sand
426 source needs to be confirmed through high-resolution bathymetric and seismic surveying, but such
427 data are not available. Seaward of the shoreface, the inner shelf forms a low-gradient (1:350-1:400)
428 plain covered by relict transgressive sands (Anthony and Blivi, 1999).

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

436 Regarding climate change, Giardino et al. (2018) anticipate only a minor contribution from
437 change in river hydrology to the stability of the Bight of Benin coast. Two other aspects that need
438 further consideration are: (1) the effects of climate change on the hydrodynamic regime, and (2) sea-
439 level rise. Regarding the influence of climate change on wave climate, General Circulation Models
440 predict a stabilization of the SAM, evoked earlier, and, thus, a non-substantial or weak change in
441 alongshore sediment transport can be expected on the coast of the Bight of Benin (Almar et al.,
442 2015). Over the period 1993-2012, mean sea-level rise in Cotonou has been estimated at 3.2 mm/yr
443 (Melet et al., 2016), a value close to that of the recent global trend (Church et al., 2013). A
444 continuation of this trend in the future will adversely affect the Bight of Benin shoreline as sea-level
445 rise will lead to landward translation of the coastline and an increase in sediment accommodation
446 space on the shoreface. According to the sediment budget model of Giardino et al. (2018), the effect
447 of coastal area loss due to the three ports will be approximately of the same order of magnitude as
448 the effect of coastal retreat due to sea-level rise (SLR) with a SLR scenario of 0.3 m by 2100, but the
449 latter will become the overarching cause of erosion in a SLR scenario of 1.0 m. Given the likelihood of
450 the continued operation of the existing ports, the continued presence of river dams, and ongoing
451 sea-level rise, shoreline erosion will continue to affect the Bight of Benin and the lives and livelihood
452 of its cities and people.

453

454 **6. Conclusion**

455 The morphology of the Bight of Benin coast is an outgrowth of beach-ridge progradation that
456 generated a mildly embayed coast wherein incident wave behaviour, beachface gradient and the
457 longshore sand transport system were intimately linked, representing a classic example of a strongly
458 wave-dominated 'drift-aligned' coast. The patterns of current shoreline change along much of this
459 bight coast have been strongly affected by human activities. The construction of three deepwater
460 ports on a coast exhibiting a high rate of longshore sand drift has resulted in shoreline destabilisation,
461 generating a multiple drift cell system characterized by short updrift sectors of significant accretion
462 but longer downdrift sectors of acute erosion, threatening the safety of large coastal stretches in the
463 strongly growing port cities of Lomé, Cotonou and Lagos; coastal villages; near-coast roads and
464 infrastructure. Analysis of shoreline change undertaken here reveals a significant reduction in
465 accretion from a mean bight-wide value of >10 m/yr over the period 1990-2000 to about 1.1 m/yr in
466 2000-2005, and a clear shift to dominant erosion to the tune of -2.3 m/yr in 2010-2015. We attribute
467 this to a progressively diminishing sand supply from the Volta River downstream of the Akosombo
468 dam. Sea-level rise will adversely affect this coast by leading to landward translation of the coastline
469 and a deeper sediment accommodation space on the shoreface. The continued operation of the
470 three ports and of existing river dams, and sea-level rise, will drive sustained shoreline erosion in the
471 coming decades along the Bight of Benin.

472

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482

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FIGURE CAPTIONS

Figure 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.

Figure 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).

Figure 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).

Figure 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.

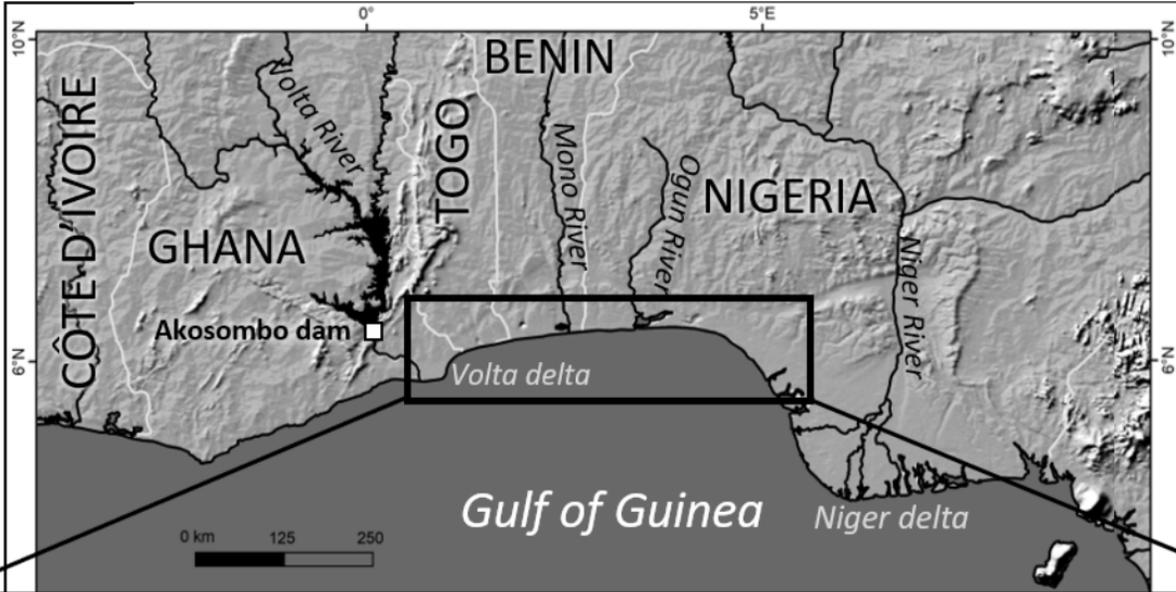
Figure 5. Shoreline change rates in the Bight of Benin over the intervals of analysis between 1990 and 2015, showing the switch in 2010-2015 from net accretion to net erosion across the entire bight shoreline (a), and changes in coastal surface area over these intervals for the five sectors (b). The 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.

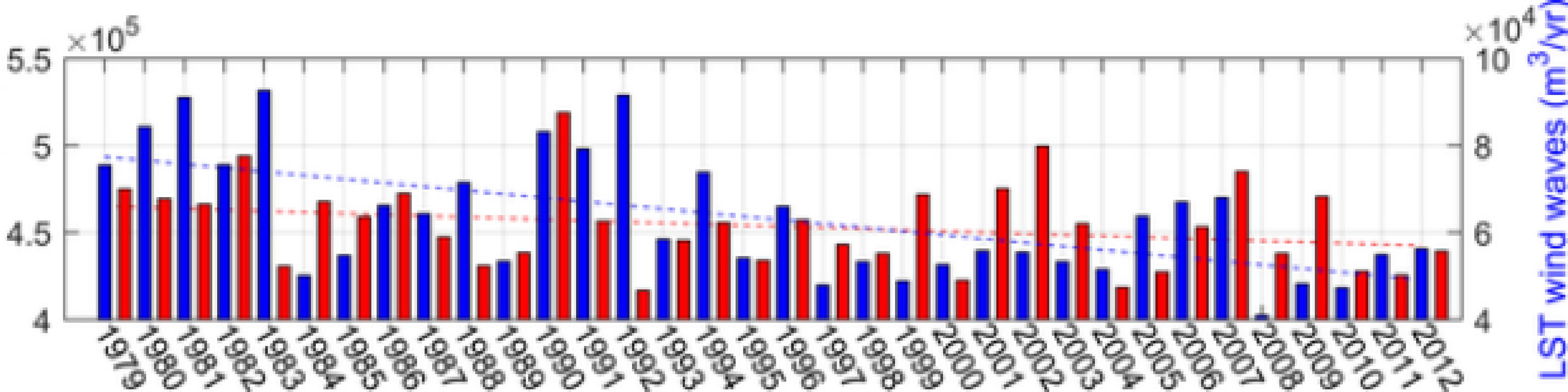
Figure 6. Maps of shoreline change in the Bight of Benin for the four individual intervals of analysis, and Hovmöller diagram of the spatiotemporal change pattern highlighting the increasing tendency towards dominant erosion.

Figure 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.

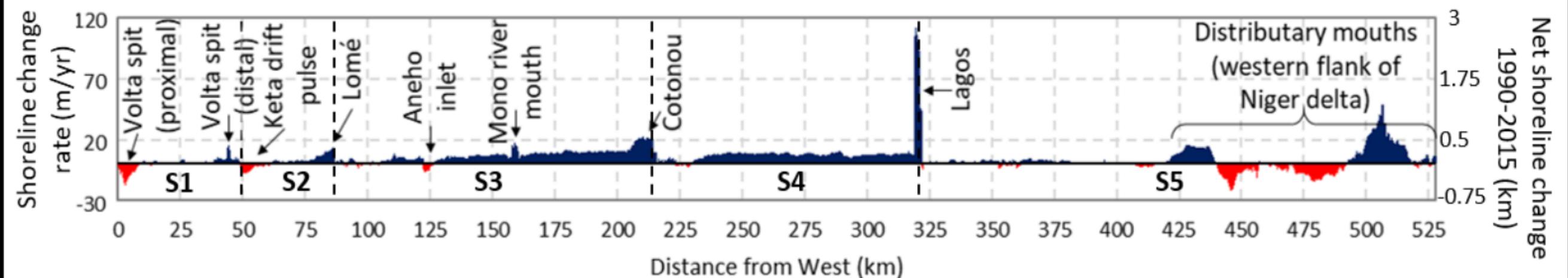
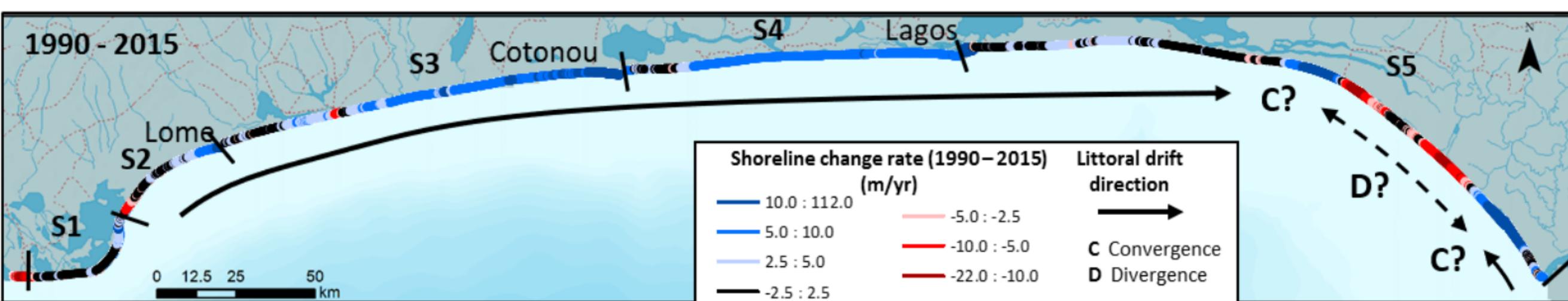
Figure 8. Schematic morphology and cell dynamics downdrift of the mouth of the Volta delta (a), and shoreline changes between 1990 and 2015 (b). A single longshore drift cell is presumed to have existed up to, and after, the 1880s, allowing transport of sand from the mouth of the Volta to the Bight of Benin (Anthony et al., 2016). The current cell (S1) between the delta mouth and Keta has been characterised 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).

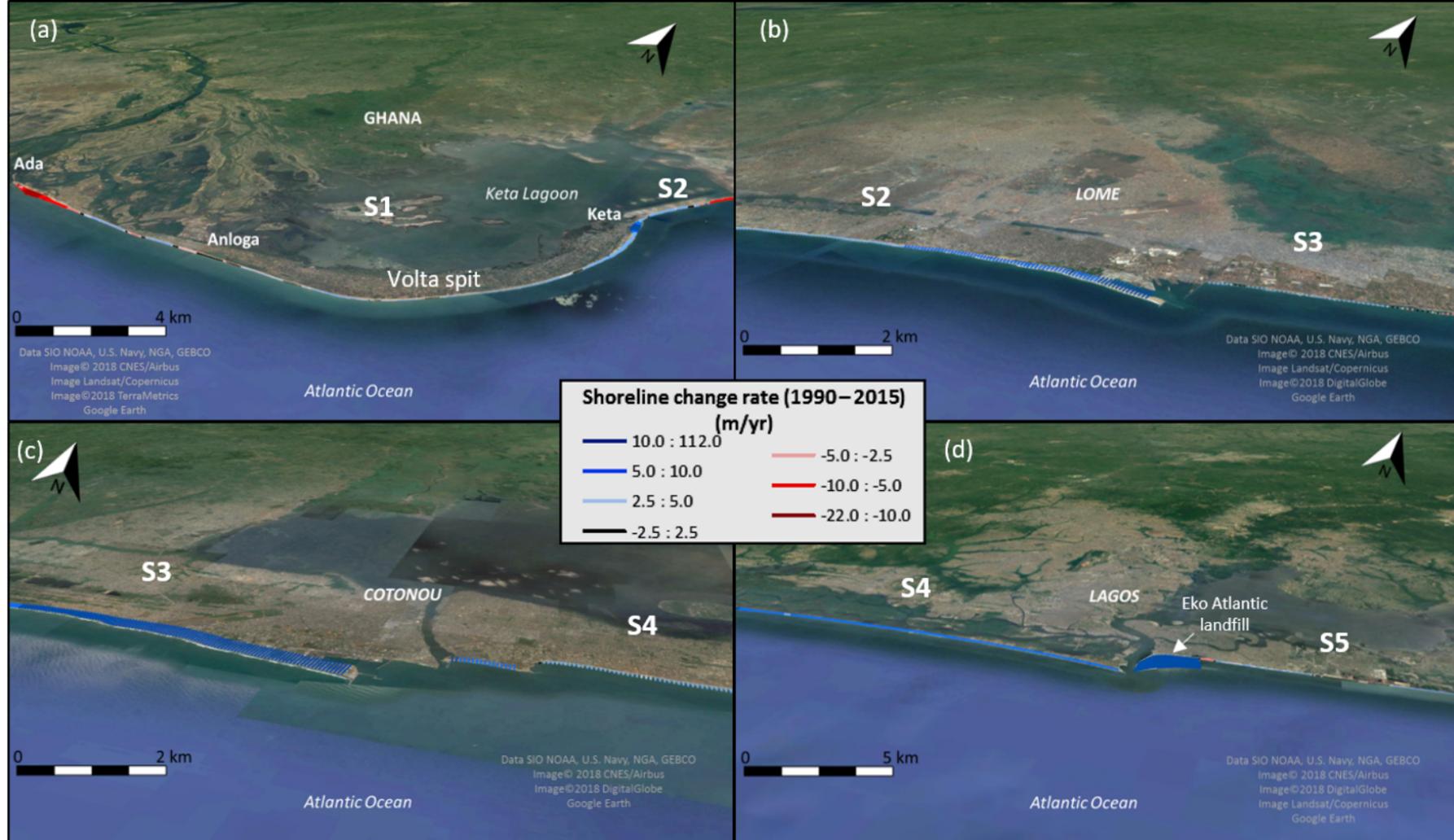


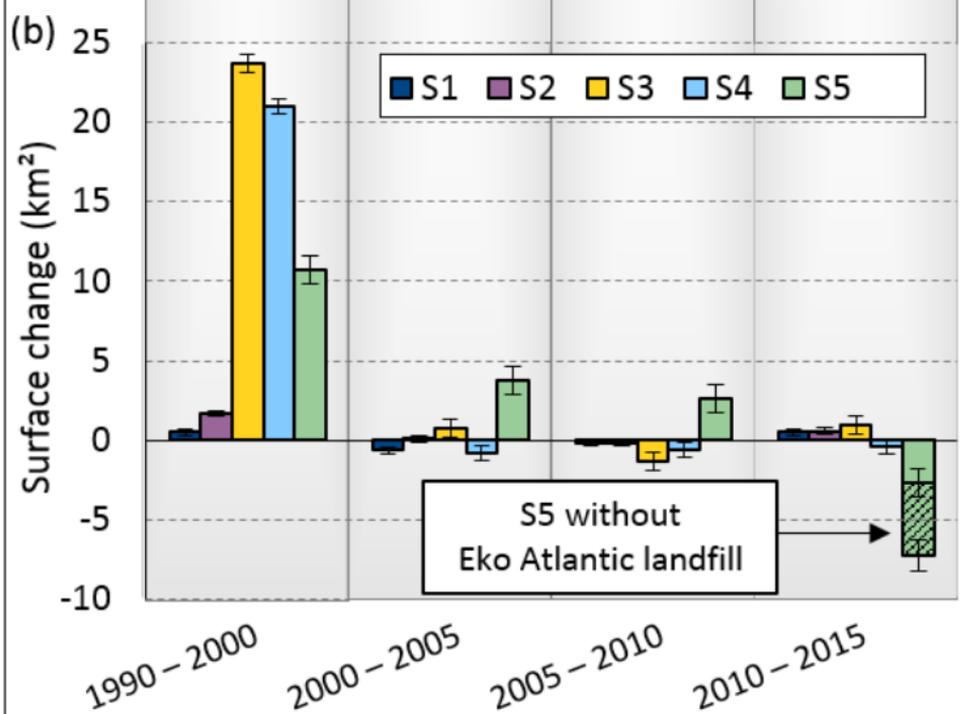
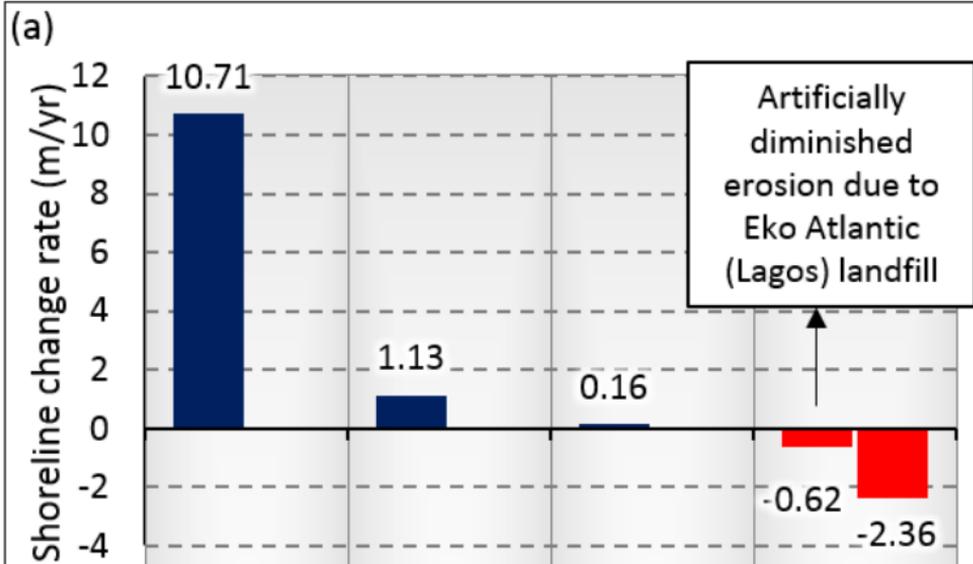
LST swell (m^3/yr)



LST wind waves (m^3/yr)

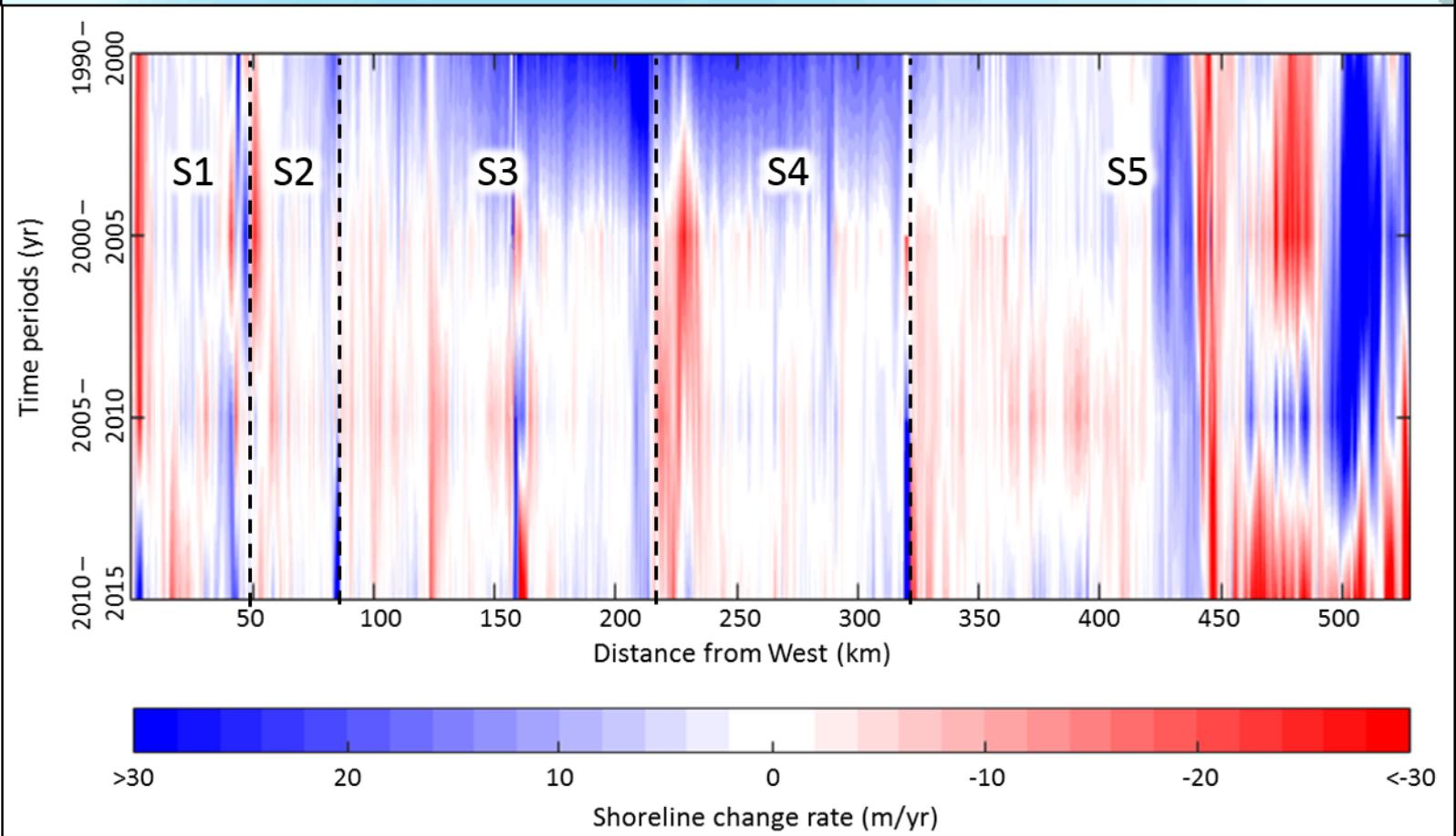
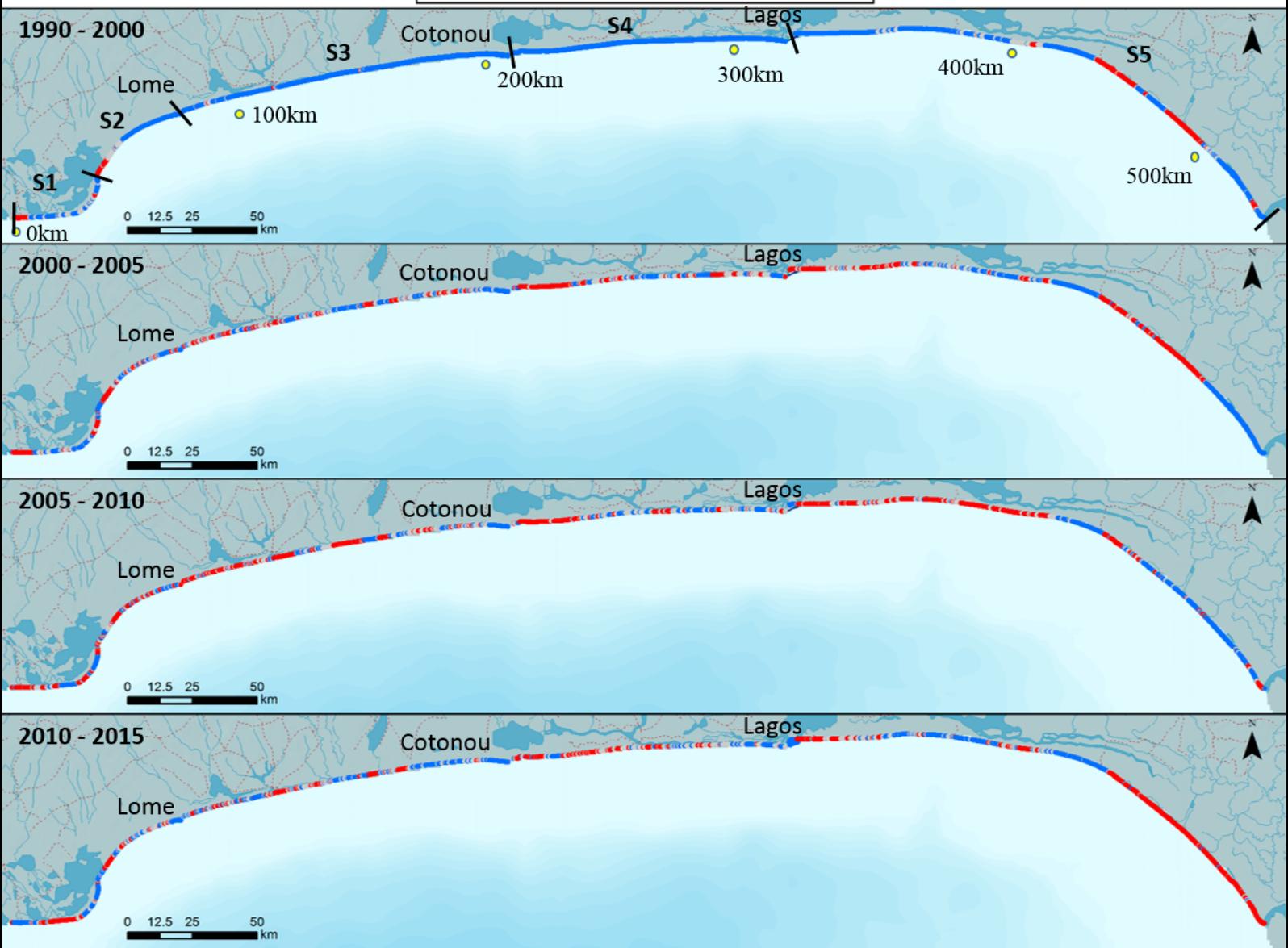


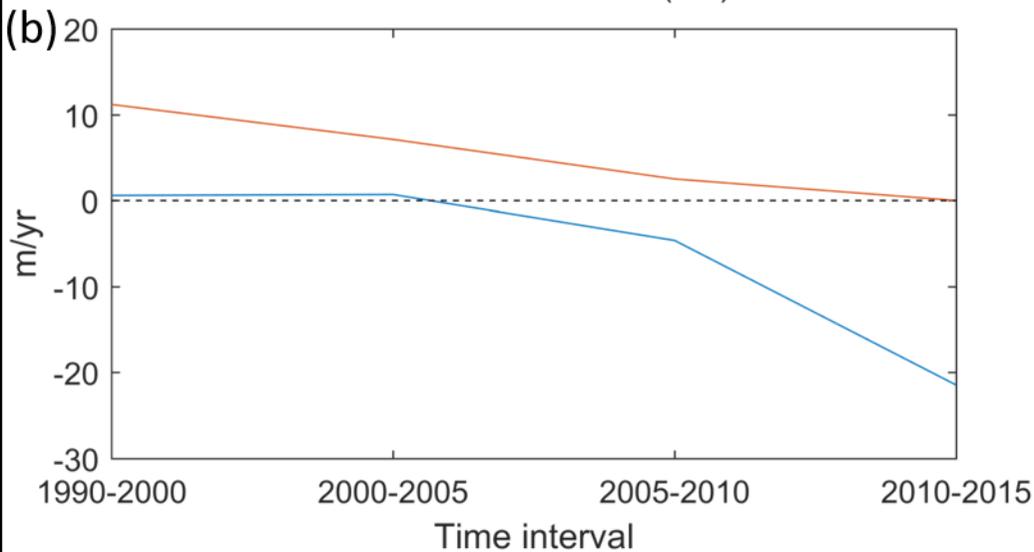
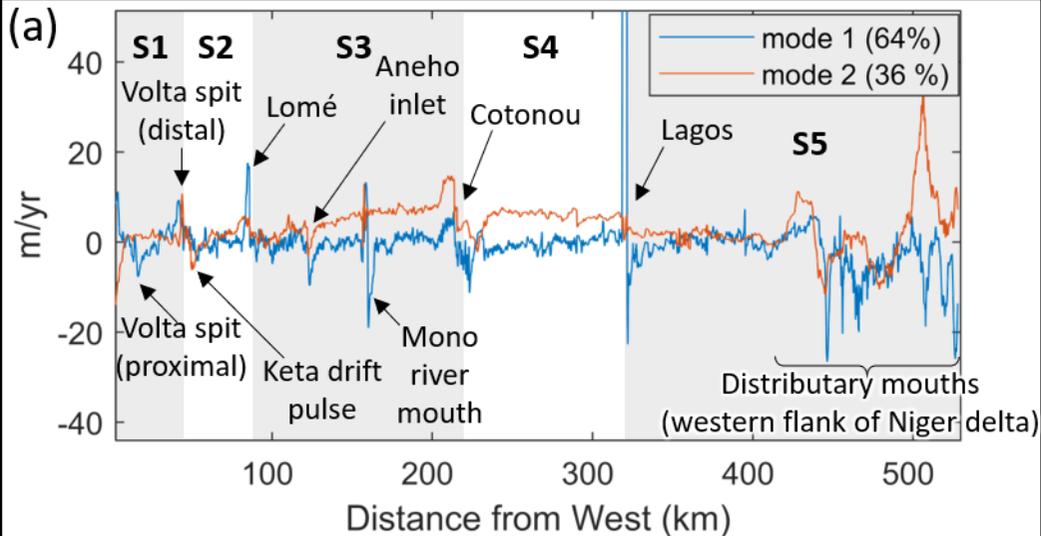




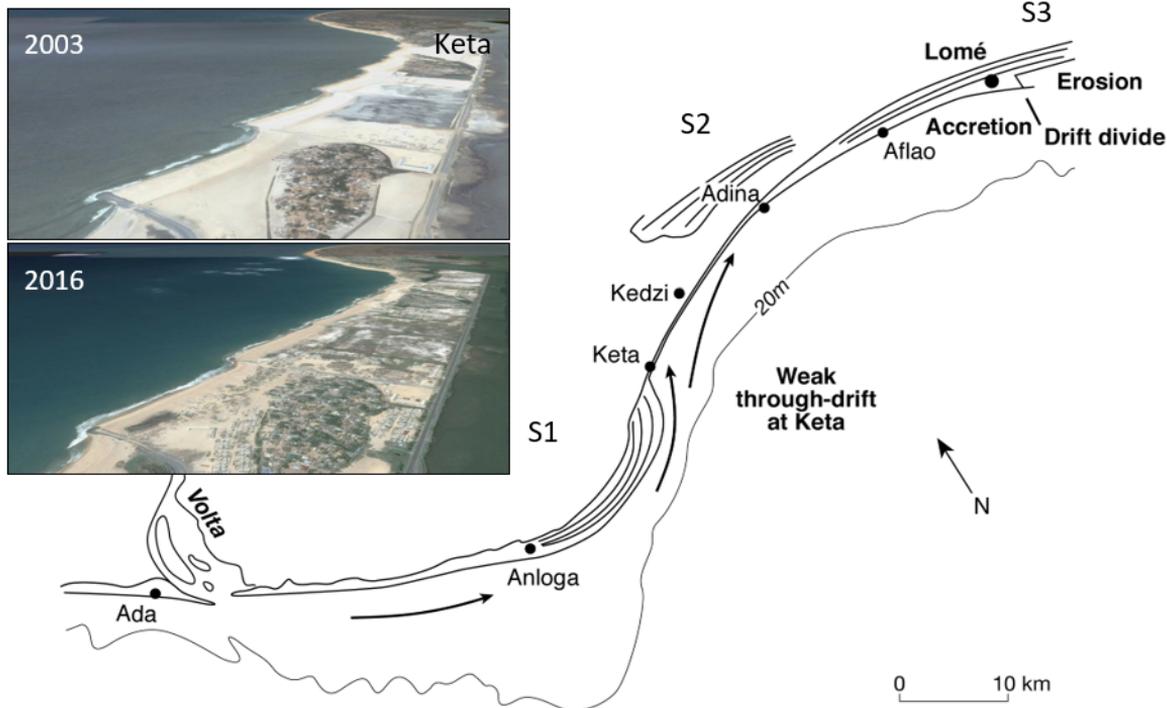
Shoreline change (m/yr)

— > 2.5 — -2.5 : 2.5 — < -2.5





(a)



(b)

