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CONTRIBUTION OF MULTISENSOR SPACE OBSERVATION IN THE STUDY OF THE HYDRODYNAMIC FUNCTIONING OF THE IVORIAN COASTLINE

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ABSTRACT

The Ivorian coastline is the focal point of the Ivorian economy by the presence of its two harbors which are Abidjan and San-Pedro. This role of the coastline has led to an increase in anthropogenic pressure which makes it increasingly vulnerable to coastal erosion. Combating this phenomenon requires better understanding of the physical processes (wave, tide and sea level rise) at its origin. The general objective of this study is to contribute to the understanding of the causes of coastal erosion on the Ivorian coastline. We used altimetry and reanalysis data to investigate the physical processes, and Landsat imagery to analyze shoreline evolution. The results obtained showed that the west coast is stable as a whole and the rest of the coastline is largely eroded. However, this erosive trend has decreased. We then showed that the significant wave heights (on average 1.5 m over the entire coastline) increased from 1993 to 2007 and decreased from 2008 to 2018. The potential sediment transport showed a decreasing trend on the west (630,000 to 540,000 m^3/year) and central coasts (210,000 to 150,000 m^3/year). On the east coast, it showed an increase (100,000 to 260,000 m^3/year) with short periods of decrease. The tide is semi-diurnal with diurnal inequality and an average tidal range of 0.75 m along the coast. Sea level rise showed an upward trend over the study period with a speed of 3.1 mm/year. Thus, shoreline changes along the Ivorian coast are primarily driven by wave dynamics, with the reduced erosion rate likely linked to lower wave heights and decreased sediment transport. This study shows that coastal management policies must take into account changing ocean and climatic conditions, particularly wave dynamics. This can be achieved through enhanced marine monitoring and the implementation of early warning and preventive measures, which will mitigate the risks of medium- and long-term erosion.

Keywords : *coastal erosion, satellite imagery, altimetry, hydrodynamic forcing, Ivorian coastline.*

RÉSUMÉ

Contribution de l'observation spatiale multi-capteurs à l'étude du fonctionnement hydrodynamique du littoral ivoirien

Le littoral ivoirien est au cœur de l'économie du pays grâce à ses deux ports que sont les Ports Autonomes d'Abidjan et de San-Pedro. Ce rôle a entraîné une augmentation de la pression anthropique, rendant le littoral de plus en plus vulnérable à l'érosion côtière. La lutte contre ce phénomène nécessite une meilleure compréhension des processus physiques (vagues, marée et élévation du niveau de la mer) à l'origine de l'érosion. L'objectif général de cette étude est de contribuer à la compréhension des causes de l'érosion côtière sur le littoral ivoirien. Nous avons utilisé des données altimétriques et de réanalyse pour étudier les processus physiques, ainsi que des images Landsat pour analyser l'évolution du trait de côte. Les résultats obtenus montrent que la côte Ouest est globalement stable, tandis que le reste du littoral est largement érodé. Toutefois, cette tendance érosive a diminué. Nous avons ensuite montré que les hauteurs de vagues significatives, qui s'élevaient en moyenne à 1,5 m sur l'ensemble du littoral, avaient augmenté entre 1993 et 2007, puis avaient diminué entre 2008 et 2018. Le transport potentiel de sédiments a quant à lui montré une tendance à la baisse sur les côtes Ouest (de 630 000 à 540 000 m^3/an) et centrale (de 210 000 à 150 000 m^3/an). Sur la côte Est, il a augmenté (de 100 000 à 260 000 m^3/an), avec de courtes périodes de diminution. Nous montrons également que la marée est semi-diurne, avec une inégalité diurne et un marnage moyen de 0,75 m le long de la côte. L'élévation du niveau de la mer a montré une tendance à la hausse sur la période d'étude, avec une vitesse de 3,1 mm par an. Ainsi, sur le littoral ivoirien, la dynamique du trait de côte est étroitement liée à celle de la houle, et la baisse du taux d'érosion s'expliquerait par la diminution de la hauteur des vagues et du transport sédimentaire côtier.

Mots-clés : *érosion côtière, imagerie satellitaire, altimétrie, forçage hydrodynamique, littoral ivoirien.*

I - INTRODUCTION

A littoral zone is a border of two different environments, where intense interactions of land and marine physical processes are observed [1]. These processes evolve at different spatio-temporal scales up to the close interactions that exist between the fluid and the sediment [2]. Coastal erosion, the result of these interactions, is nowadays a threat to all sandy coasts [3]. Indeed, sandy foreshores are dynamic systems that can be stable, undergo erosion, or tend to accrete according to natural [4] and anthropogenic forcing [5] to which they are subjected. In the Gulf of Guinea (~ 2.35 million km²), the effect of these forcing is clearly visible on the sandy coasts [6, 7]. Côte d'Ivoire, located in the North of the Gulf of Guinea and 75 % of its coastline is sandy [8], faces the problem of coastal erosion. Research work on coastal dynamics in Côte d'Ivoire has shown an evolution (erosion / accretion) of sensitive sectors such as the coastal zone of Grand-Lahou, Abidjan, Assinie and Grand Bassam [8 - 14]. As the Ivorian coastline presents significant socio-economic interests (ports, industries, more than 8,000,000 people [15], etc.), coastal erosion constitutes a threat that should be taken into account in any coastal management strategy [16]. This management cannot be implemented without in-depth scientific knowledge of the physical processes that lead to coastal erosion, such as coastal hydrodynamic forcing. The most natural way to study this forcing is through in-situ ocean measurements and observations. However, even if the means of observations are more numerous and sophisticated nowadays, their cost remains very high and the implementation of measurements at sea is sometimes difficult. Today, radar altimeters measure the instantaneous height of the ocean surface with centimeter accuracy and regular repetitiveness [17]. As a result, they make a great contribution to knowledge of the oceans. This study is based on the analysis of a time series of altimetric and reanalyze data to characterize natural coastal forcing and explain the causes of coastal erosion in Côte d'Ivoire.

II - MATERIAL AND METHODS

II-1. Study area

The Ivorian coast ***(Figure 1)*** stretches for 566 km, from Cape Palma in the west (Ivorian-Liberian border) to Cape Three Points in the east (Ivorian-Ghanaian border), between latitudes 3.7° and 5.5° north and 3° and longitudes 7.6° west. It is bordered to the north by the coastal road, to the west of Abidjan and the Noé road through Alépé. To the south, it is bordered by the 120 m isobath. Its area is estimated at 23.253 km², or 7 % of the total area of Côte d'Ivoire which is 322.463 km² [18]. The Ivorian coastal area is economically organized around two poles which are the country's port cities: Abidjan (South-East) and San-Pédro (South-West). These ports constitute the heart of the economic development of Côte d'Ivoire [19].

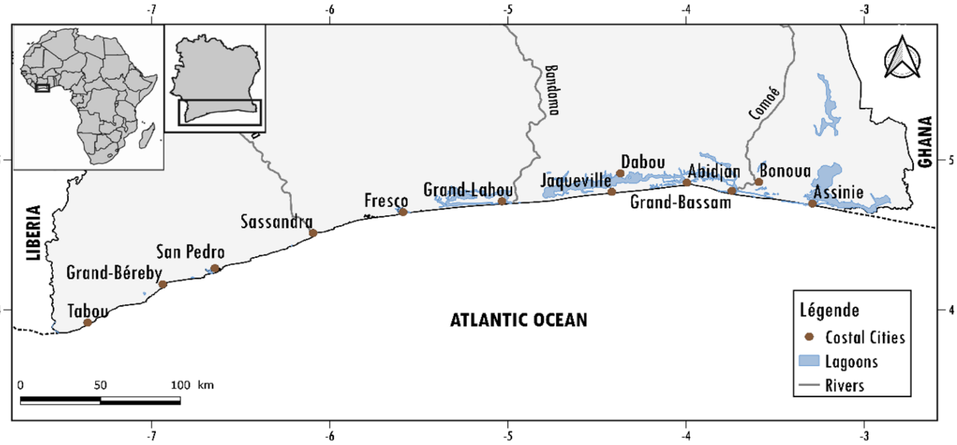

Figure 1 : *Situation map of the Ivorian coast and its different coastal cities*

Two main morphological sectors characterize the Ivorian coast [20]. Between the border of Liberia and Fresco the base comes directly into contact with the sea and forms a relatively low rocky coast. On the East of Fresco the morphology is different. The base is now covered with a sedimentary mantle, the course of the coast becomes rectilinear and a sandy cordon, sometimes several kilometers wide, traps lagoons in communication with the sea when Grau opens. Around Fresco, real living cliffs are cut out of materials dominated by sandy clays. The water system of Côte d'Ivoire has two types of rivers :

1. The large rivers born in the savannah region which cross the country from north to south: from west to east, they are namely, Cavally, Sassandra, Bandama and Comoé.
2. Small coastal rivers or rivers in a forest environment are Tabou, Néro, San Pedro, Bolo, Niouniourou, Boubo, Agnéby, Mé, Bia.

Beyond Fresco, towards the east, all the rivers lead into lagoons. There are three openings to the sea; the Grand-Lahou pass, outlet of the Grand-Lahou lagoon, fed by the Boubo and the Bandama; the Vridi canal, built to allow ships to access the Abidjan harbor in the Ébrié lagoon where Agnéby, Mé and Comoé flow; the Assinie pass, outlet of the Aby lagoon and the Bia. The Ivorian continental shelf has a relatively small extension. In the west of the country, off the mouth of the Cavally river, it extends over 22 km. Towards the East, it widens to reach a maximum of 35 km on the border with Ghana. Near Abidjan, the continental shelf is cut by a canyon, the “Bottomless Hole”. The “Bottomless Hole” cuts into the continental shelf from depths of 10 meters. It extends over approximately 200 km then ends in the abyssal plain of Guinea at approximately 5000 m depth [21]. This canyon has a very complex morphology and plays a very important role in the hydro-sedimentary process of the coast. The Ivorian coastal area is washed by Southern Atlantic long wave with a south or southwest direction [22, 23]. The maximum wave height (~2 m) is observed during the Austral winter from May to August. The coast is classified as microtidal because the tide does not reach 1.3 m [24]. The currents that transport sediments are composed of a longshore current, an energetic tidal current, and a weak Guinea current, with a maximum speed (~0.7 m/s), observed during the major upwelling season [24, 25].

II-2. Data and methods

The data collected is limited to the period 1993 - 2018, the aim being to observe the longest time series of altimetric products available. The methodology will consist in identifying the critical erosion areas (erosion hotspots) and observing the behavior of the main hydrodynamic forcing at these zones.

II-2-1. Shoreline evolution

In order to identify the various erosion hotspots along the Ivorian coastline, we used images from the Landsat 5 (30 m resolution), Landsat 7 (30 m resolution) and Landsat 8 (30 m resolution) satellite missions. The images were carefully selected based on the conditions that little or no cloud coverage was present. The images were acquired at Level-1T processing, i.e. in a radiometrically calibrated and geographically referenced form, from the United Stated Geological Survey (USGS) archive (https://earthexplorer.usgs.gov/). The large size and shape of the Ivorian coastline makes it quite challenge for high-resolution satellite sensors to capture the entire coastline in a single pass. As a result, 3 different images captured at a different time (but within the same period/season) were mosaicked in ArcGIS environment. Taking into account the cloud cover and our study period, we downloaded (around the same period of the year) images from the years 1998, 2002, 2008, 2013 and 2018. The analysis of these images is based on four principles:

1. Choice of a reference line

The instantaneous shore line is very often used when working in a microtidal context like that of the Ivory Coast [26, 27]. Thus, the land-water interface is the ideal feature to use as a shoreline position in this study.

2. Radiometric and atmospheric corrections and color composition with the ENVI software (for better visualization of the reference line).
3. Coastline mapping and statistical analysis with ArcGIS software via its DSAS (Digital Shoreline Analysis System) module.

DSAS [28] measures the distances between the intersection points of transects (which it generates) and coastlines, calculates the rates of change along each transect and outputs the results in the form of attribute tables. To understand the temporal evolution of the position of the coastline, we have chosen two indices proposed by DSAS. These are the End Point Rate (EPR) and Linear

Regression Rate (LRR) indices. The EPR index was used to calculate the evolution between two successive periods and the LRR index to calculate the evolution over the long term and over all coastal lines.

4. Estimation of errors

The main sources of estimable inaccuracy when mapping the coastline are those induced by the pixel size and by the digitization of the reference line. In addition to these uncertainties, inequalities in tide levels during image acquisition generate additional errors in the position of the instantaneous shore line. The main source of uncertainty regarding the reference lines resulting from the processing of Landsat images is related to the spatial resolution [29, 30]. On each of the shorelines extracted from the Landsat images, the precision that we consider therefore remains the pixel resolution (30 m), because this cover both the error linked to the tide and that which can be made during digitization. The annualized error for the entire period of study (1998 – 2018) is 1.42 m/yr.

II-2-2. Tide gauge data

In order to compare the altimetric data with in-situ data, we used a tide gauge from the Global Sea Level Observing System (GLOSS) network situated at Takoradi harbor in Ghana (4.885° N and 1.745° W) about 240 km from Abidjan. These data come from the University of Hawaii Sea Level Center database (https://uhslc.soest.hawaii.edu/). They were recorded every one hour and available for the period 2007 to 2012. This measurement represents sea level (SSH) and was used to compute the sea level anomaly (SLA). The average (SSHavg) calculated over the period 2007 to 2012, i.e. 6 years, was removed from the level measurements to obtain the SLA. The ***Formula*** is given by :

$$SLA = SSH - SSHavg \tag{1}$$

Since these data are collected every one hour, a monthly average of these anomalies was calculated in order to obtain a relatively filtered signal of the effects due to waves, tides etc. The profile obtained is compared with the profile obtained from the altimetric track near Takoradi (track 237). The correlation between these two types of data is calculated from the monthly averages over the 6 years.

II-2-3. Oceanic forcing waves

In order to estimate the wave-induced longshore transport on the Ivorian coast, we used global wave parameters (significant height Hs, peak period Tp and direction both swell and wind wave) derived from retrospective forecast data in the Atlantic Ocean between 1993 and 2018, generated by the European Centre for Medium-Range Weather Forecasts (ECMWF) Wave Atmospheric

Model (WAM). These wave data are part of the ERA Interim dataset, which involves a reanalysis of global meteorological variables [31, 32]. Wave data were extracted from the ECMWF data server (https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/) on 0.125°x0.125° grid and with a 6-hr temporal resolution. The ERA Interim reanalysis is the first in which an ocean wind–wave model is coupled to the atmosphere and the quality of the wave data has been extensively validated against buoy and altimeter data. [32] demonstrated a very good correlation between the ERA Interim data and these sources, except for high waves (significant wave height, Hs >5 m) and low waves (Hs <1m) which tend to be under- and over-estimated, respectively. These extreme wave conditions are not typical of the relatively constant wave regime of the Gulf of Guinea.

II-2-4. Longshore sediment transport

Longshore transport at each hotspot was computed to better appreciate the impact of waves on the coast. There are several formulas for the net sediment flow along the coast which are widely applied in coastal engineering. These are, among others, the formula of [33, 34] and the most recent developed by [1]. There is no general consensus on the choice of a formulation. For our study, we chose that of [1] because of its suitability for sites where data is limited and because it has already been applied to environments similar to our study area [35, 36]. In this ***Formula***, the volume of sediment transported along the coast is calculated as follows :

$$Q = 0.023 h_b^2 V \ [m^3/s] \quad \text{if} \ (h_b^2 V) \ 0.15 \tag{2a}$$

$$Q = 0.00225 + 0.008 h_b^2 V \ [m^3/s] \quad \text{if} \ (h_b^2 V) \ 0.15 \tag{2b}$$

where, h_b is the height of the wave at the breaking point and V is the speed of the coastal current averaged over the entire surf zone.

$$V = 0.25 k_v \sqrt{\gamma g h_b} \ sin2\alpha_b \ [m/s] \tag{3}$$

Where α_b is the angle of the wave at the breaking point, $\gamma = 0.78$ the breaking index, g the gravitational acceleration (m/s^2) and kv an empirical constant. We used kv = 2.9 as suggested by the work of [35, 36] *for wave dominated environments with similar grain size characteristics, around 600 µm, as is the case for the Ivorian coast* [13, 37, 38].

Longshore sediment transport ***Formula*** requires as input the breaking wave parameters, but global wave hindcasts only provide deepwater characteristics. We have used the empirical breaking wave predictor proposed by [39], which directly provides breaking wave height H_b and angle θ_b, given deepwater wave height H_s, period Tp and direction θ_0 :

$$\theta_b = asin(\sqrt{\lambda}\, sin\theta_0)\ ;\ H_b = \gamma h_b$$
$$h_b = \lambda C^2 / 9.81$$
$$\lambda = \Delta[cos\theta_0 / \alpha]^{2/5}$$
$$\Delta = 1 + 0.1649\varepsilon + 0.5948\varepsilon^2 - 1.6787\varepsilon^3 + 2.86\varepsilon^4 \quad (4)$$
$$\varepsilon = (cos\theta_0 / \alpha)^{2/5}\, sin\theta^2$$
$$\alpha = (C.\gamma^2 / C_g)(C/\sqrt{(9.81H_s)})^4$$

where, γ is the ratio between the height of the waves and the depth at the breaking point, $C = 1.56Tp$ and $Cg = C / 2$ are the phase and group celerity respectively; hb the depth at the breaking point. Several research works have been based on this formula [36, 40, 41].

II-2-5. Sea level

In order to evaluate the impact of coastal sea level forcing we used different X-TRACK products. X-TRACK is a software that has been developed by CTOH/LEGOS (Centre of Topography of the Oceans and the Hydrosphere/Laboratory of Space Geophysical and Oceanographic Studies) in France to improve and extend the use of altimetry in the coastal zone [42]. We used the sea level (doi 10.6096/CTOH_X-TRACK_2017_02) and tidal constants products (doi 10.6096/CTOH_X-TRACK_Tidal_2018_01) produced by CTOH/LEGOS and distributed by the AVISO + operational center (https://www.aviso.altimetry.fr/index.php?id=3047). The X-TRACK sea level products (Mean SSH, SLA) are based on the combination of Topex / Poseidon, Jason 1, Jason 2 and Jason 3 missions and cover the period of 1993 - 2017. It was used to compare climatologies between altimeter and tide gauge. The X-TRACK tidal constants (amplitude, phase) products are based on the combination of Topex / Poseidon missions, Jason 1, Jason 2 from 1993 to 2015, using harmonic analysis. To observe the trend of sea level anomalies in our study area we used a different dataset: the coastal sea level trends based on X-TRACK/ALES product (doi: 10.5270/esa-sl_cci-xtrack_ales_sla-200206_201805-v1.1-202005) from ESA which cover the period 2002 - 2018 [43]. These new data are better suited for observing trends of SLA and have been evaluated along the Western African coast [44] and applied in different regions of the world [43, 45]. This new processing system called X-TRACK/ALES is detailed in [46]. The SLA and altimetric tidal constant data were extracted at the points closest to the coast (having at least 80 % valid cycle), on the tracks covering the Ivorian coast ***(Figure 2)***. In order to observe the behavior of the variation of the sea level from the open sea to the coast, we extracted sea level trends over the 16-year time (2002 – 2018) span at each 20 Hz (350 m) point for the last 20 km to coast. Knowing the amplitude and phase of the most important tidal components, it is possible to reconstruct the tide signal at any past or future instant, as long as the conformity of the coasts is not significantly different from that existing during the measurement of the data used to perform the harmonic decomposition. We reconstructed the tidal signal over the period 1993 - 2015. The tidal range was calculated by subtracting high water from low water.

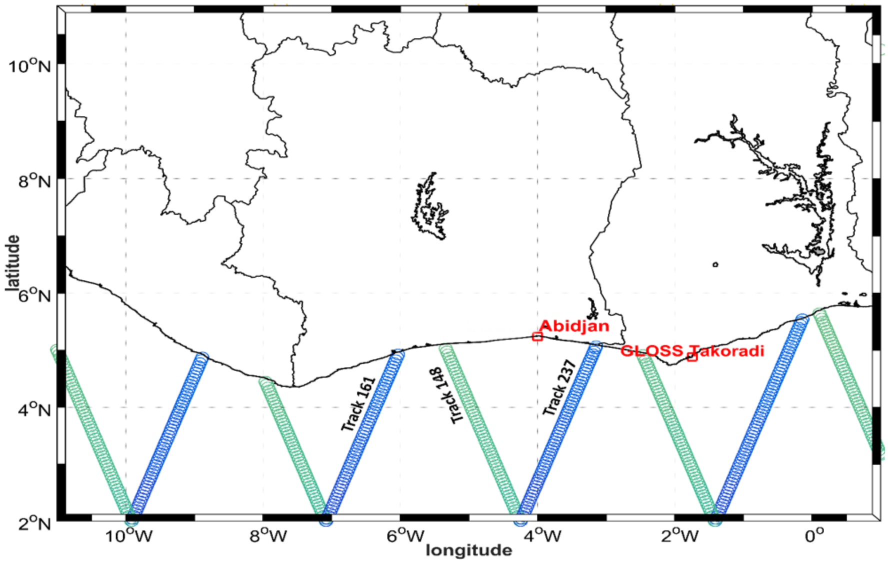

Figure 2 : *Location map of Jason's altimetry tracks (ascending in blue and descending in green) and Gloss tide gauge at Takoradi*

III - RESULTS

III-1. Shoreline evolution on the Ivorian coast

Figure 3 shows the evolution of the shoreline over the period 1998 - 2018 including the years 2002, 2008 and 2013, on the east coast (east of Abidjan to Tiapoum). More than 50 % of this area is eroded. Erosion is more extensive in Abidjan (east of the Vridi canal) and then the city of Grand-Bassam. The city of Bonoua is greatly accreted while; at the city of Adiaké erosion is felt in the municipality of Assinie. As for the city of Tiapoum, there is an alternation of eroded and accreted surface.

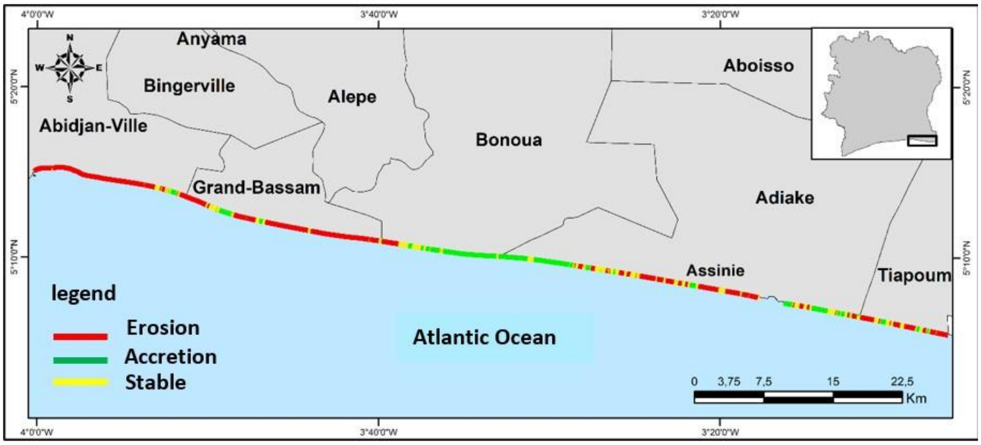

Figure 3 : *Map of shoreline evolution between Abidjan and Tiapoum (East coast)*

Figure 4 shows the evolution of the shoreline at the central coast (west of Abidjan to Fresco). This area is more in accretion than in erosion. The coastline from the city of Abidjan (west side of the Vridi canal) to half of the city of Jacqueville is in accretion. Erosion continues up to a few meters from the east arrow of the estuary of the city of Grand-Lahou where accretion is observed, then extends again from the west arrow to the coastal perimeter of the village of Lahou-Kpanda. Accretion is then observed followed by erosion, and then to the pass of the Ngni lagoon at Fresco where accretion is observed.

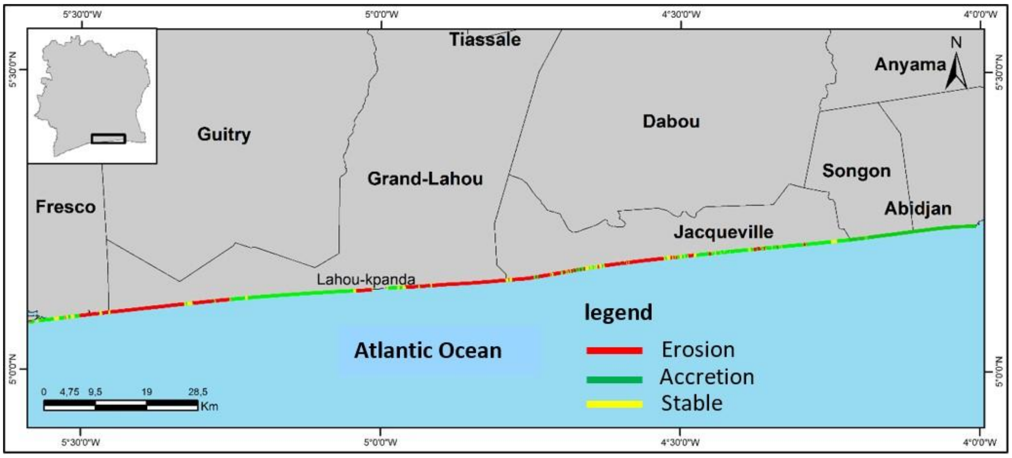

Figure 4 : *Map of shoreline evolution between Abidjan and Fresco (central coast)*

Figure 5 shows the evolution of the shoreline at the west coast (west of Fresco to Tabou). This zone alternates between erosion, accretion and stable surfaces. Erosion and accretion in this area is very low, making this part of the coastline almost stable.

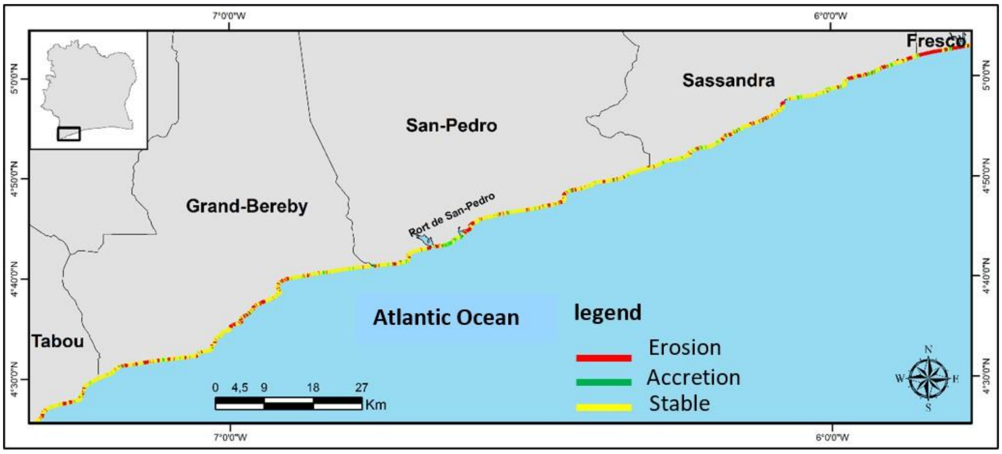

Figure 5 : *Map of shoreline evolution between Fresco and Tabou (West coast)*

Table 1 shows the different hotspots chosen for the rest of the study. Overall, there is an alternation of erosion and accretion years, and a decrease in the erosion rate over the study period. The year 2002 was the most erosive outside the west coast. The port of San-Pedro undergoes an evolution of the erosion rate over 1998 - 2013 then a slight decrease over 2013 - 2018. The village of Lahou-Kpanda experienced an accretion over the period 2008-2018 but still remaineds in erosion over the period 1998-2018. The towns of Port-Bouët and Mondoukou are undergoing a strong erosion trend, this trend decreased from 2013 to 2018. Apart from the exceptional decline in 2002, the Assinie coast suffered a low erosion rate.

Table 1 : *Selected hotspots and summary of the shoreline evolution (m/year)*

	San-Pedro harbor	Lahou-kpanda	Port-bouet (Abidjan)	Mondoukou (Grand-Bassam)	Assinie
1998-2002	-0.97	-2.1	-4.65	-4.8	-4.5
2002-2008	0	-1.59	+1.32	+1.86	+2
2008-2013	-1.27	+0.03	-1.3	-2.99	-0.39
2013-2018	-1.12	+1.9	-0.6	+0.82	-0.14
1998-2018	-0.89	-0.41	-1.02	-0.94	-0.44

III-2. Validation of altimetric data

In this part we compare the SLA from Takoradi (City closest to our study area and the altimetry track 237) tide gauge and that from altimetry because the measurement period of Abidjan tide gauge (1982 - 1988) did not covered the measurement period of altimeter (1993 - 2017). [47] showed that in the northern part of the Gulf of Guinea the variations of SLA are mainly annual and semi-annual with a slight domination of the semi-annual cycle. This is also reflected by our two instruments ***(Figure 6)***. In our study we focus on the climatology of SLA ***(Figure 6)*** to compare altimeter and tide gauge. This comparison shows consistency with in-situ measurements, since the minimum and the maximum are reached during the same months, July and November, respectively. Also, the two curves follow the same evolution everywhere. We can therefore conclude that the two measurements converge. However, it should be noted that the variation in sea level, although similar in the two types of measurements, is slightly higher in the altimetric data (min = -81.7 mm ; max = 131.2 mm) than in the *in-situ* data (min = -94.4 mm; max = 125.2 mm). In order to strengthen our appreciation for these two types of measurement, we performed a statistical analysis of the data. This is the calculation of correlation between the climatology of anomalies over the six years that are common to both types of measurements. We find as a correlation coefficient R = 0.94, which is significantly positive; with a significance test p = 2.74 * 10-6 (< 5 %), which means that the result of the correlation is not due to chance at the risk threshold of 5 %.

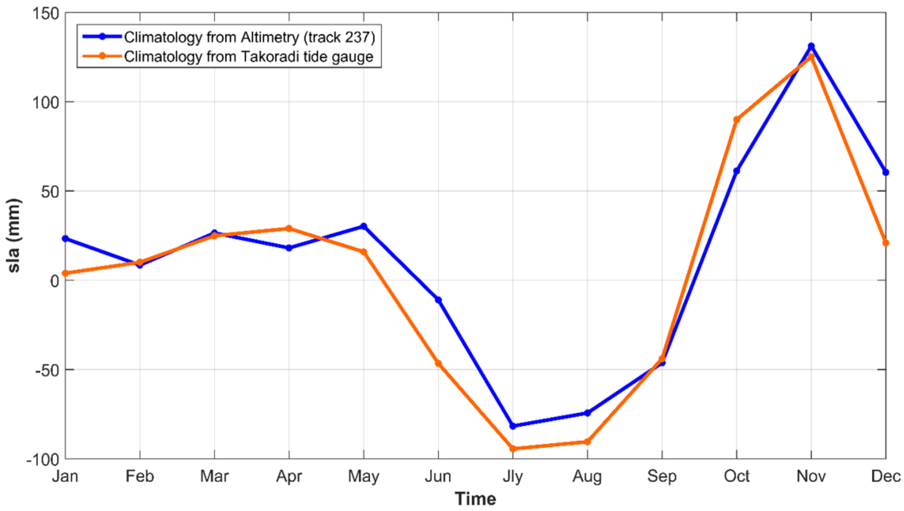

Figure 6 : *Comparison of SLA from altimetry (in blue) and SLA from Takoradi tide gauge (in orange color). The SLA from altimetry has extracted at the point of track 237 closest to the coast*

III-3. Variability and trends in the waves, longshore transport and sea level

Figure 7 shows the areas (sensitive to erosion) where the hydrodynamic forcing is observed and analyzed. These are the port areas of San Pedro, Lahou-Kpanda in Grand-Lahou, Port-Bouet in Abidjan, Mondoukou in Grand-Bassam and Assinie.

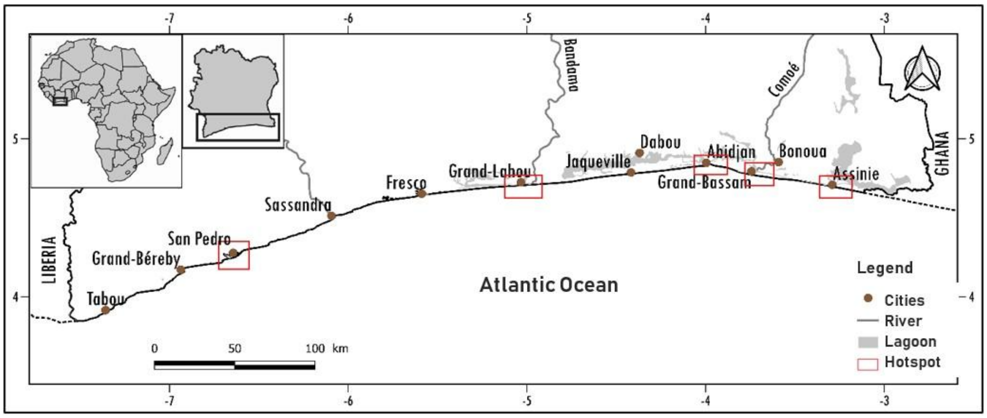

Figure 7 : *Location map of hotspots erosion on the Ivorian coast (area framed in red)*

III-3-1. Significant wave heights

Figure 8 presents the interannual variation (from 1993 to 2018) of the significant height (Hs) of the waves at the 5 hotspots. On the whole, we observe an upward trend over the period of 1993 - 2007 and a downward trend over the period of 2007 - 2018. At San-Pedro (SP) the Hs ranges from 1.56 m to 1.68 m with an average of 1.61 m; in Grand-Lahou (GL) it ranges from 1.47 m to 1.58 m with an average of 1.53 m; in Abidjan (Ab) it ranges from 1.52 m to 1.63 m with an average of 1.57 m; in Grand-Bassam (GB) it goes from 1.48 m to 1.59 m with an average of 1.54 m and in Assinie (As) it goes from 1.47 m to 1.58 m with an average of 1.53 m.

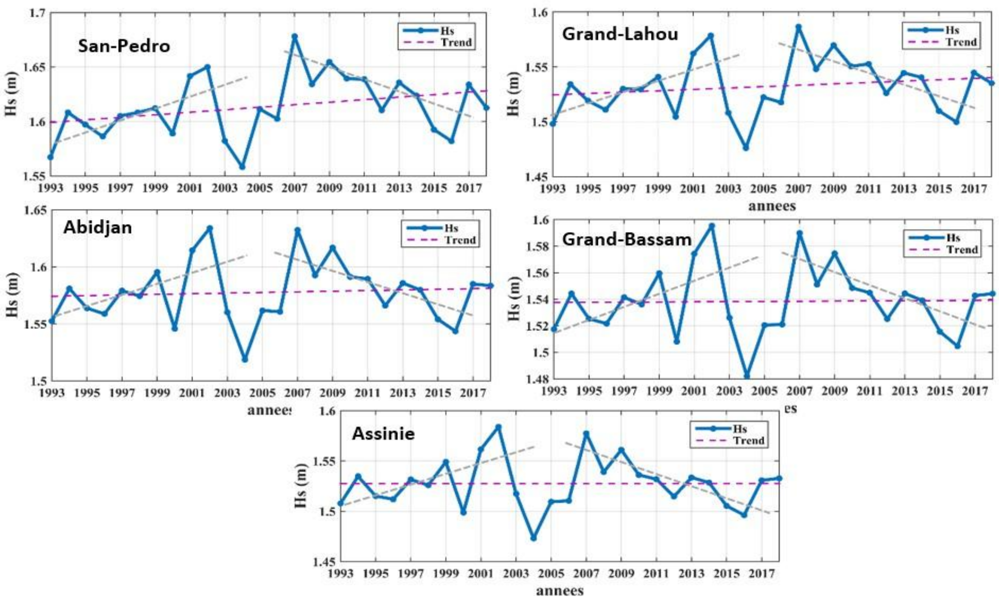

Figure 8 : *Interannual variability of wave height at each hotspot*

III-3-2. Longshore transport

Figure 9 shows that during the study period the longshore transport (LST) decreased from west to east until Abidjan where it started to grow from 1999. This growth is observed on the rest of the east coast. We also observe a downward trend over the period of 2011 - 2018 in Abidjan and the rest of the east coast. The LST ranges from 531,289 m^3/year to 632,119 m^3/year at San Pedro with an average of 572,870 m^3/year; in Grand-Lahou it ranges from 149,383 m^3/year and 208,017 m^3/year with an average of 173,267 m^3/year; in Abidjan it ranges from 105,579 m^3/year and 218,256 m^3/year with an average of 146,460 m^3/year; in Grand-Bassam it ranges from 187,690 m^3 / year to 264,009 m^3/year with 226,080 m^3/year as an average and in Assinie it ranges from 182,499 m^3/year to 257,514 m^3/year with an average of 219,818 m^3/year.

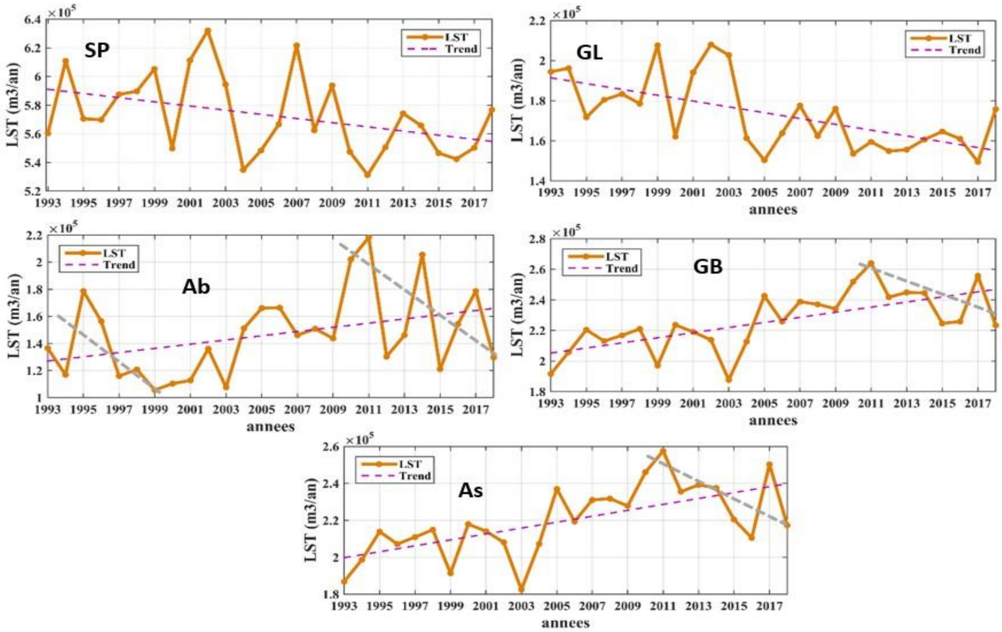

Figure 9 : *Interannual variability of the net annual longshore sediment transport on each hotspot*

III-3-3. Characteristics of tide

Figure 10 shows the tidal signal by altimetry, at the points closest to the coast for the tracks 161, 148 and 237, reconstructed on its measurement period (1993 - 2015). The tidal range observed on the coast is low with an average of 0.7 m for track 161, 0.77 m for track 148 and 0.8 m for track 237. The tidal influence is therefore microtidal. The tide is semi-diurnal with diurnal inequality at the points closest to the coast for the tracks 161 and 237, with a value of the ratio of the diurnal amplitudes to the semi-diurnal amplitudes equal to 0.25 and 0.26 respectively on the tracks 161 and 237. At point on the track 148, we have a ratio equal to 0.24 and therefore a semi-diurnal tide. This is justified by a dominance of the semi-diurnal constituents over the diurnal constituents in these zones as presented in ***Table 2***.

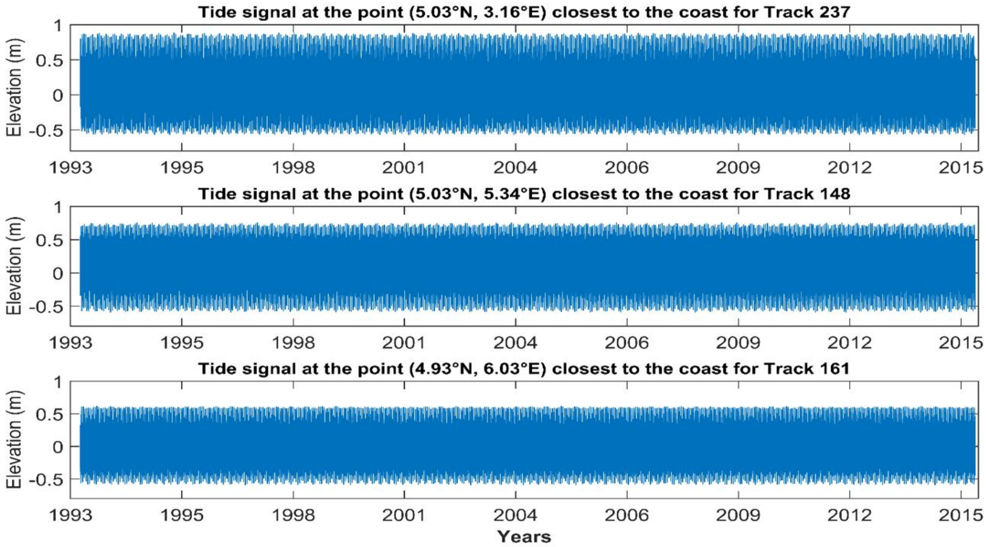

Figure 10 : *Tide signal at the points closest to coast for tracks 161, 148 and 237*

Table 2 : *Main harmonic constituents from the altimeter at points closest to the coast for the three tracks 161, 148 and 237*

Waves	Frequencies (hour-1)	Amplitude (m)			Phase (º)		
		Track 161	Track 148	Track 237	Track 161	Track148	Track237
M2	0.0805	0.3705	0.3616	0.3971	130.71	127.61	119.82
S2	0.0833	0.1225	0.1393	0.1445	155.54	150.35	144.98
K1	0.0417	0.1109	0.1004	0.1176	347.56	349.54	350.36
N2	0.0789	0.0860	0.0882	0.0885	115.19	122.94	116.90
K2	0.0835	0.0488	0.0402	0.0427	157.87	146.26	146.67
P1	0.0415	0.0311	0.0307	0.0403	8.58	334.02	352.40
O1	0.0387	0.0220	0.0205	0.0230	329.06	320.93	307.50
Q1	0.0372	0.0008	0.0058	0.0060	314.05	152.77	84.17

III-3-4. Sea level trend

Figure 11 shows the trend of SLA over the period of 2002 - 2018 in the Gulf of Guinea. We observe that the sea level on the Ivorian coast is one of the highest in the Gulf of Guinea. ***Figure 12*** presents the SLA time series, over the period of 2002 – 2018, for the points closest to the coast on the three altimetry tracks (tracks 148, 161 and 237) of Ivorian coastline. It shows an increasing trend since 2002. The growth is more significant for the points belonging to tracks 237 and 161. The point closest to the coast for track 148 shows very weak growth. We deduce from these SLA trends an average rate of rise of about 3.1 mm/year over the period of 2002 - 2018.

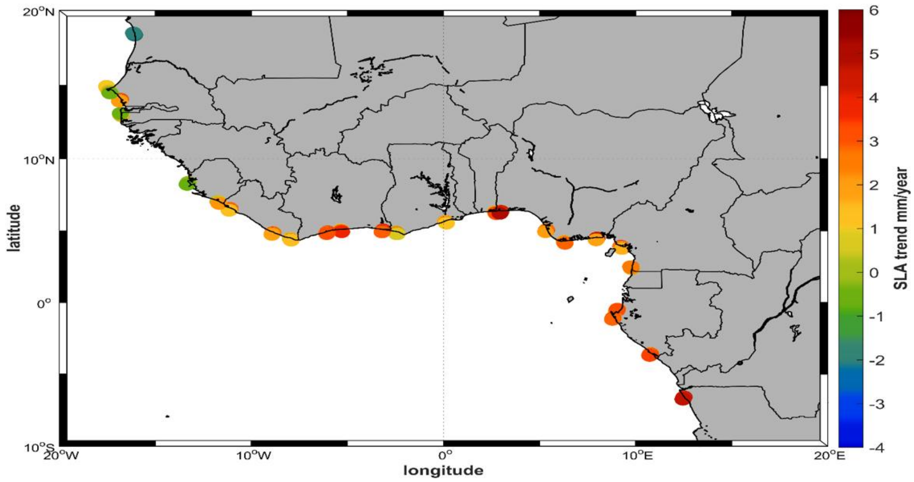

Figure 11 : *Sea level anomaly trend in the Gulf of Guinea over the period 2002 - 2018*

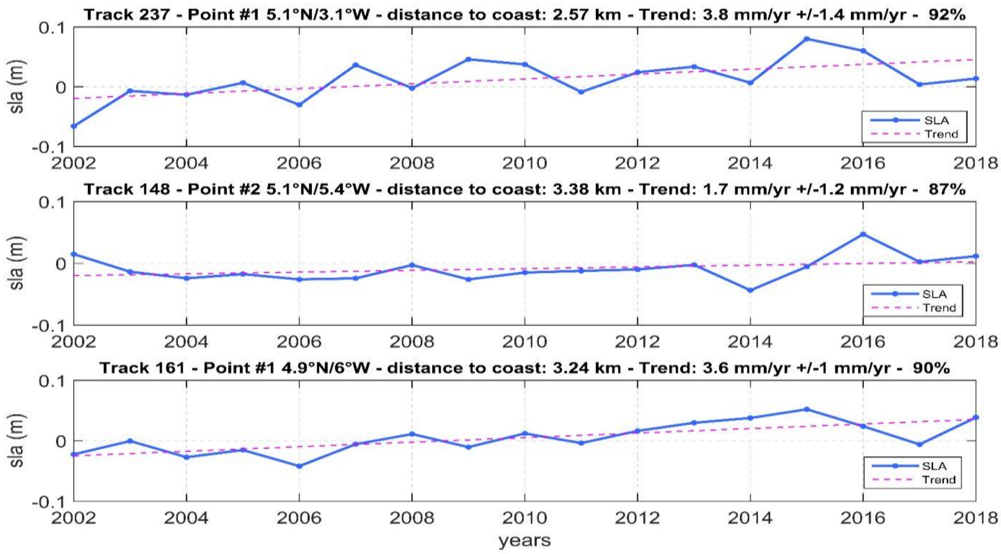

Figure 12 : *Sea level anomaly time series since June 2002 for the points closest to the coast on the three altimetry tracks of Ivorian coastline*

IV - DISCUSSION

IV-1. Evolution of the coastline

In this study, the evolution of the Ivorian coast from 1998 to 2018 shows that the west coast (from Tabou to Fresco) is stable as a whole with small eroding areas. On the central coast (from Grand-Lahou to the west jetty of Vridi) erosion and accretion are felt and as for the east coast, it is largely eroded. This distribution of the sensitivity of the coast to erosion is corroborated by [48] assessment on the erosion of the Ivorian coast. The stability of the west coast is linked to the almost rocky nature of this coastline. Erosion and accretion on the central and east coasts are due on the one hand to their sandy structure and on the other hand to the presence of the pier (a length of 1,7 m and a width of 1,05 m) of the port of Abidjan. This pier retains sediment that must transit to the east coast, causing sediment build-up on the west side of the jetty and erosion on the east side (the east coast). On the west coast, the port area of San-Pedro (around the east jetty) is the most affected by erosion with a retreat of -0.89 m / year over the period 1998 - 2018. The recoil of the shoreline in this area is in agreement with the work of [49], who from beach profiles observed a decline of -1.2 m / year from 1993 to 1997. The evolutionary trend of the coast of Grand-Lahou is in accordance with the study by [50] who followed the evolution of this coastline from Landsat data over the period 1998 - 2014. Their study shows a decline of -0.84 m / year at Lahou-Kpanda against -0.41 m / year in our study. This difference would be due to the different study periods. The Jacqueville-Canal de Vridi sector experienced an overall accretion (+1.18 m/year) but setbacks were observed on the western half of the coastal perimeter. According to [51] this coastal perimeter experienced an accretion rate of +1.2 m/year between 1998 and 2015, a result obtained from analysis of aerial photographs. In addition, according to [11] this coastline experienced an accretion rate of +1.35 m/year over the period of 1998 - 2008. On the coast of Port-Bouët we have shown that the shoreline experienced an erosion rate of -1.02 m / year during the observation period. This observation is generally in agreement with the work carried out by [9, 13, 51]. These studies have concluded that the shoreline has eroded between 1 and 2 m/year. Monitoring the evolution of the coast of Grand-Bassam over the study period revealed an average decline of -0.63 m/year and -0.94 m/year around Mondoukou. According to [52], who followed the dynamics of this coast using Google Earth images from 1984 to 2016, the shoreline is less eroded with a decline rate of the order of -0.23 m/year and -0.86 m/year at Mondoukou. In addition, the study by [53], based on a compilation of data from satellite images and topographic surveys, showed a retreat rate of -0.57 m/year from 2001 to 2014 for this sector. These results differ from that of this study due to the difference in study periods and methods used. As for the Assinie coastline on the border with Ghana, the observed trend is in agreement with the work of [14, 27]. These authors have shown that when heavy swells pass this coastline undergoes significant retreat, as is the case in this study for the year 2002, and that apart from exceptional swells the area undergoes an alternation between erosion and accretion. The study by [14], from aerial photographs and topographic surveys, revealed that the Assinie coastline experienced a decline of -1.85 m/year over the period 1990 - 2007 against -0.44 m/year in our study. This difference would be due to the different methods and periods of study. The decreasing trend in the rate of erosion shown in this study (Table 1) was also observed by [54] on the coasts of the Bay of Benin (Ghana, Togo and Benin) over the period 1990 - 2015.

IV-2. Impact of waves

The study revealed that the interannual variation of the significant wave height increases over the period 1993 - 2007 and then a decrease until 2018. This growth and decrease in the heights observed would be due respectively to an increase and a decrease of westerlies in the South Atlantic over the respective periods of 1993 - 2007 and 2007 - 2018. Indeed, as demonstrated by [55], the Southern Annular Mode (SAM) which characterizes the atmospheric circulation in the Southern hemisphere, presents a positive index since 1970. This positive trend of the SAM is materialized by a decrease in westerly winds, which leads to a decrease in the height of the westerly swells. However, from 1993 to 2007 the SAM index showed a decrease which led to a strengthening of the westerly winds. The variation in wave direction directly influences that of longshore transport, as it depends on the angle between the obliquity of the waves and the normal to the coast. The climatic phenomena at the origin of the directional variability of the swells are the same as those at the origin of the variability of longshore transport. The decrease in longshore transport observed over the study period would be linked to a decrease in the intensity of Westerly winds associated with their movement towards the South, as well as a strengthening of the trade winds (at the origin of the easterly swells), which reduce the potential transport of sediment to the East. This variability of winds in the South Atlantic has been observed by [36, 56]. The growth of longshore transport on the East coast is explained by the presence of easterly swells on the one hand and the change in orientation of the coast on the other. The Ivorian coastline is very sensitive to variations in swell heights, as this study illustrates with a huge retreat of the shoreline in 2002 ***(Table 1)*** due to the strong swells over this year ***(Figure 8)***. The decrease in the erosion rate observed on the coast ***(Figure 13)*** can be partly attributed to the decrease in wave heights and longitudinal sediment transport on the coast. With regard to the influence of climate change on the wave climate, general circulation models predict [36, 54] a stabilization of the SAM (whose index currently shows a positive trend which decreases the westerly winds towards the equator and orients them towards the South) and we can therefore expect a slight modification of coastal sediment transport on the Ivorian coast.

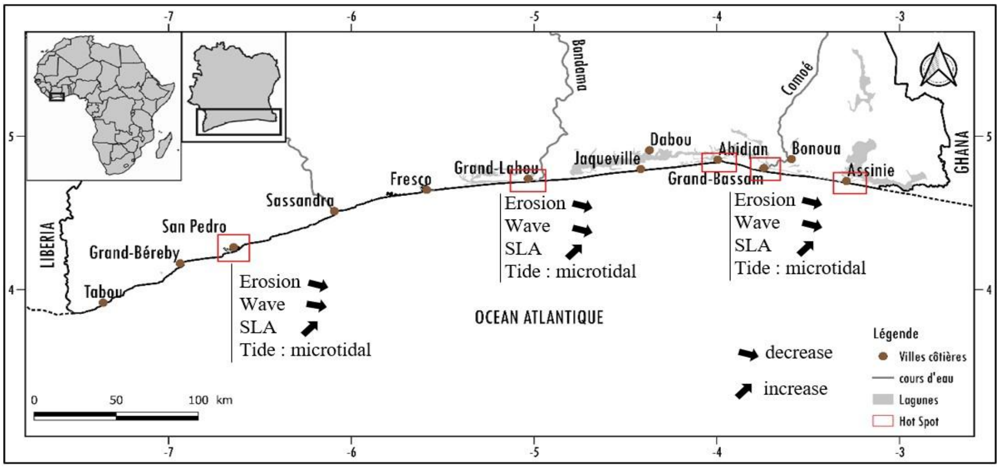

Figure 13 : *Map of summary of the evolution of the coastline and hydrodynamic forcing*

IV-3. Influence of the tide

The characteristics and type of tide revealed in this study converge with the work of [57] and [58] who respectively studied the propagation of the tidal wave at the port of San Pedro and that of Abidjan. The microtidal influence of the Ivorian coastline would make the shoreline vulnerable to the effects of storms (retreat of the shoreline). Indeed, as demonstrated by [59] at Chesapeake Bay in the United States, on microtidal coasts, the narrow width of the foreshore causes waves to break near the shore at low or high tide.

IV-4. Influence of sea level variation

As presented above, sea level rise has a speed of around 3.1 mm/year on the Ivorian coast, a value very close to the recent global trend estimated at 3.2 mm/year by [60] over the period of 1993 - 2015. As demonstrated by [61], this rise in sea level is a direct consequence of global warming and results from two main causes: the increase in the temperature of oceans and associated thermal expansion; the melting of continental ice, glaciers and polar caps. The downward trend of erosion rates of the Ivorian coast and the upward trend of sea level rise ***(Figure 14)***, observed in this study, suggests that sea level rise is not the main agent of the dynamics of the shoreline on the Ivorian coast. This converges with the studies of [62] and [63] who showed that sea level rise does not explain the variability of shoreline movements they observed. However, the continuation of this trend in the future will have a very noticeable impact on the Ivorian coast. The study by [64] thus presents a case in which a subsidence of tectonic origin generated a relative sea level rise of more than

50 cm. In this case, the coastline effectively retreated. In addition, sea level rise worsens the effect of extreme events (such as storms) by increasing their frequencies and/or intensities, which would cause the shoreline to retreat further. Modeling of future climate change indicates that sea level will continue to rise over the next decades and even centuries [65, 66], so we can expect coastal hazards to worsen.

V - CONCLUSION

The objective of this work was to study the spatio-temporal variation of coastal hydrodynamic forcing by altimetry and to relate them to the erosion observed on the Ivorian coast. It was first a question of identifying critical erosion points (hotspots) by mapping and it was discovered that only the west coast is stable (as a whole). The rest of the coast is in the process of erosion and accretion with a decrease in the rate of erosion over the study period. The evolution of the shoreline on the Ivorian coast can be considered as the overall result of different forcings (waves, tides and sea level rise), which have acted and are acting on different time scales. The erosive trend of this coastal strip is, however, mainly linked to the wave climate. The results of this study on the Ivorian coast show that satellite altimetry offers great potential in providing quality information on tides and sea level, for the purpose of managing coastal environments, when observations in the field are rare or non-existent, as we get closer to the coast. As a contribution to the struggle or adaptation strategies for coastal resilience, we recommend that the competent authorities ensure the application of Law N° 2017-378 of June 2, 2018 relating to the development, protection and integrated management of the coastline, which is an essential tool for coastal resilience; to set up a national coastal sea observatory which will be equipped with cutting-edge tools for research and monitoring of these ecosystems, and the restoration of wetlands such as mangroves which are endangered on the Ivorian coast.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors on demand, without undue reservation.

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