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DISTRUBUTION OF THE TIDAL POTENTIAL ENERGY ALONG THE WEST AFRICAN COAST

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ABSTRACT

The intensification of extreme events coming from the sea due to climate change contributes significantly of the degradation of the West African coastal zone through the phenomena of marine submersions and coastal erosion. The solutions proposed to increase the resilience of this zone are still inadequate. The sea surface density, the tidal prediction model Tide Model Driver and tidal gauge data were used to quantify and analyze the spatio-temporal evolution of ocean tidal potential energy along the coastline. The results showed that the temporal variability of sea surface density is characterized by a slight decrease of this density over the 2000 – 2023 period. An uni-modal structure characterizes the monthly seasonal cycle of density regime; while the monthly seasonal cycle of tidal potential energy has a bimodal structure. Two seasons characterized ocean tidal potential energy seasonal variability along the West African coastline. The minor season centered on March occurs between February to April, while the energetic season that extends from August to October is centered on September. A strong interannual seasonal variability was observed in each West African coastal sections. This potential energy of the tide decreases spatially eastward, suggesting that the stretch of coastline from the Cap of Palmas to Sassandra is the most suitable for the implementation of a device to convert this energy into electrical energy. This adaptation solution is highly beneficial because it reduces the risks of coastal erosion, marine submersions and minimize greenhouse gas emissions.

Keywords : *tidal energy, renewable energy, ocean density, coastline, West Africa.*

RÉSUMÉ

Distribution de l'énergie potentielle de la marée le long de la côte de l'Afrique de l'Ouest

L'intensification des évènements extrêmes provenant de la mer en raison du changement climatique contribue à la dégradation des zones de l'Afrique de l'Ouest à travers les phénomènes de submersions marines et d'érosion côtière. Les solutions proposées pour accroitre la résilience de la côte restent jusqu'à présent insuffisantes ou inadaptées. Les données de densité de l'océan, de marégraphes et celles provenant du model prédiction Tidal Model Driver sont utilisées pour quantifier et analyser l'évolution spatio-temporelle de l'énergie potentielle de la marée le long du littoral. Les résultats ont montré que la variabilité temporelle de la densité de l'océan est caractérisée par une faible décroissance sur la période 2000 – 2023. Cette densité varie peu le long de la côte. Le cycle saisonnier mensuel a une structure uni-modale, tandis qu'une structure bimodale caractérise le cycle saisonnier mensuel de l'énergie potentielle de la marée. La variabilité saisonnière de l'énergie potentielle de la marée est marquée par une petite saison énergétique entre Février et Avril avec un pic localisé en mars et, une grande saison énergétique s'étendant d'Août à Octobre et centré sur Septembre. Une forte variabilité interannuelle de cette énergie est observée dans chaque section de côte. Cette énergie décroit spatialement vers l'Est montrant ainsi que la section de côte allant du Cap des Palmes à Sassandra est la propice à un système de conversion de l'énergie de la marée en énergie électrique. Cette solution est très bénéfique car elle permet de réduire l'érosion côtière, les submersions et les émissions de gaz à effet de serre.

Mots-clés : *énergie de la Marée, énergie renouvelable, densité océanique, littoral, Afrique de l'Ouest.*

I - INTRODUCTION

The West African coastal communities are vulnerable to coastal risks including coastal erosion and marine submersions [1]. These oceanic forces pose a threat for coastal ecosystems, infrastructure and economic activities. which contribute significantly to the national gross domestic product of the developing countries such as those of West Africa countries [2 - 6]. To reduce the vulnerability of these coastal zones, a number of solutions have been undertaken, including hard solutions such as construction of groynes and dykes, reforestation of the seafront with mangroves, beach nourishment and relocation of populations directly affected by extreme events [4, 7] were adopted. However, many of these solutions exacerbate the problem through the modification of sediment transit by groynes and disruption of livelihood activities of the coastal community. It is therefore essential to consider other solutions that can address the concerns of this community and of coastal zone management. The conversion of ocean tide energy into electrical energy appears to be a credible alternative for reducing the impact of ocean tides on coastal resources. This energy, primarily driven by the lunar cycle, is reliable and predictable over years or even decades. The use of this renewable energy will also reduce emissions of greenhouse gases [8 - 10] such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) which are in increasing over the years in the West African region [11]. To implement this solution, it is important to assess ocean tidal energy along the coast at national and regional scales [12] because this energy depends on the density of the ocean, which is not uniformly distributed, and on the tidal range, which can vary from one section of coast to another. In addition, the knowledge of the spatial distribution of this energy will enable to identify areas that could home a conversion system, in order to avoid unprofitable investments [13]. The aim of this study is to assess the potential energy of the ocean tide along the different coastal sections of the West African coastline at different spatial and time scales. This study will quantify the potential energy of the tide in each coastal section and identify the most energetic section. The manuscript is organized as follows: description of the study area, data and methods used constitute the first part. The second part is devoted to results and discussion. The final section focuses on conclusions and perspectives.

II - MATERIAL AND METHODS

II-1. Study area

The study area extends from Cape of Palmas to the Cameroon border between longitudes 7°30' W and 9° E and latitudes 4° and 6° N ***(Figure 1)***, corresponding to the coastal zone. This zone is subdivided into twelve zones including three zone for the Ivorian and Ghanaian coasts, one zone for Togo and Benin coast and four zones for the Nigerian coast. The first zone of the Ivorian coastline extends from Cape Palmas to Sassandra. Rocky coast dominates the coastal geomorphic features. Medium cliff characterize the second zone that lies from Sassandra to Abidjan and, the third zone that lies from Abidjan to Cape of Three Pointes is constituted by sandy beaches interrupted by lagoons [3]. The Western coastal section of Ghana extends from the border with Cote d'Ivoire to Ankobra River. it covers 90 km of coastline and consists of flat and wide beaches backed by coastal lagoons. Rocky headlands and sand bars or spits enclosing coastal lagoons that represents 340 km of coastline and extending from Ankogra River to the West of Prampram represents the central section of Ghana's coastline. The Eastern section that lies from the West of Prapram to Togo border covers 140 km of the coastline. It is a high-energy coast. Sandy beach interrupted by some lagoon characterized the coastal geomorphology of Togolese coast, stretching over 50 km, and Benin's coast extending over 125 km of the shoreline. The first section of the Nigeria coastline is situated between the border with Benin and Benin River. It consists of barrier lagoon. The mahin mud coast (second section) lies between Benin River and Niger delta. The third section is comprised between the end of the Niger Delta and Imo River border and the fourth section extends from Imo River to the Cameroon border. [5]. According to previous studies, the tide is semi-diurnal with diurnal inequality. The average tidal range reaches up 1.3 m during exceptional tides and 0.3 m during low tides period [14]. The swells that wash the coast can sometimes reach 2.8 m in height. These swells are more energetic along the Western section than to the East [4].

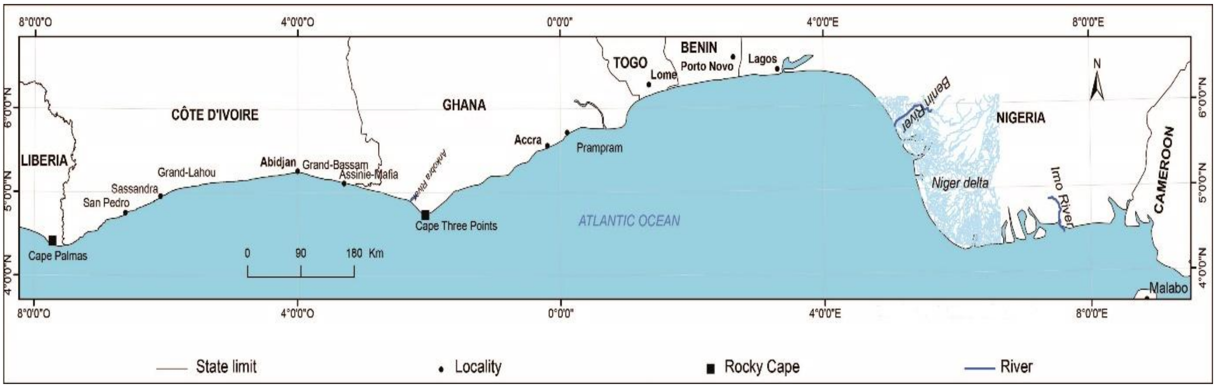

Figure 1 : *Map of study area*

In this coastal area, economic activities are dominated by agriculture, fisheries, mineral, oil and Gas extraction, and trades. The transportation activities are supported by 14 harbors located along the West African coastline. The rapidly growing population increases urbanization, economic activities and the energy demand. The increase in socio-economic activities affects the state of the coastal environment due to the increasing of greenhouse gases emissions and confirms environmental information to help protect property and save lives through the implementation of adequate adaptation strategies.

II-2. Data

The data used in this study come from a variety of sources, including in situ and satellite measurements. The Sea Surface Density (SSD) that provided by Copernicus marine data service is a combination of in situ data andsatellite multimission altimetry satellites measurement. These data cover the entire ocean with a spatial resolution of 0.125°x0.125° longitude/latitude and have a daily resolution on the 1993 - 2023 period [15, 16]. They were spatially averaged within the limits of each coastal section of West African coastline to produce a time series. The ocean tide characteristics were extracted from the EOT20_ocean.nc model developed by [17, 18]. The data for this model were obtained by analyzing tidal residuals provided by multi-mission altimetry satellites over a period from 1992 to 2019. The complex amplitude h included in this model have a spatial resolution of 1/8° and cover all the world's oceans. It also includes 17 tidal constituents, the main waves being M2, S2, K1 and O1. According to [19, 20], the height of ocean tide is a sum of mean sea level and tidal residual called harmonic constituents. The mean sea level of each coastal section of the West African coastline used in this study were obtained in tidal station of the Global Sea Level Observing System (GLOSS) archive database [21]. The hourly tidal gauge data of this database that have undergone quality control covers the period from 1982 to 1988 for Vridi (Cote d'Ivoire), from 2004 to 2005 for Takoradi (Ghana) and from 1992 to 1996 for Lagos (Nigeria). The hourly time series from 1991 to 1994 recorded in the harbor of San-Pedro (Cote d'Ivoire) were also used in this study for assessing mean sea level value along this coastal section. These data were used to predict the ocean tide along the coast of The West African coastline lies between the Cape of Palmas and the Nigerian border with Cameroon country.

II-3. Methods

The temporal evolution of ocean surface density along the coastal zone was analyzed by using the Mann-Kendall non-parametric test for randomness against trend [22, 23]. The Mann-Kendall test was used to characterize the temporal evolution (presence or absence of trend) of this density over the study period. To predict the ocean tide along the coastal zone, the Tidal Model Driver (TDM) was used in this study. This model predicts the ocean tide along ocean coasts at a given time from existing tidal models [24] and derives the tidal range, which is an important input for calculating the tidal energy along a given coastline point. The tidal height ***Equation*** can be expressed as follow:

$$z(t) = z_0 + \sum_{i=1}^{n} h_i exp(\omega_i t) + \overline{h_i} exp(\omega_i t) \quad (1)$$

where, $z(t)$ is a tidal height at a given point and time; z_0 is a mean sea level around which the ocean tide oscillates. It has been estimated in this study by T-TIDE model [20]; h_i is the complex amplitude of wave i and $\overline{h_i}$ is its complex conjugate.; ω_i is the pulsation of wave i; n is the number of constituents used for predicting ocean tide. In this study, the TMD use $n = 17$ constituents to predict tidal height at given location.

The potential energy of the tide can be calculated according to [25,26] through the following ***Formula*** :

$$E = \frac{1}{2}\rho g R^2 \tag{2}$$

where, ρ is the density of the ocean in $kg.m^{-3}$; g is the acceleration of gravity in $m.s^{-2}$; R is the tidal range (difference between consecutive high and low tide) in meter (m). The potential power derived from this potential energy is given by :

$$P = \frac{\rho g R^2 A}{2\Delta t} \tag{3}$$

where, Δt is the time step in seconds (s) ; A is the surface area in square meters (m^2); P is the potential power in watts (W).

III - RESULTS AND DISCUSSION

III-1. Sea surface density

Figure 2 shows daily variations of the ocean surface density along the coastline of West Africa. The minimum and maximum values of this density are 1020.3 and $1023.1\ \mathrm{kg.m^{-3}}$ respectively. These extrema have been observed along the Togolese coastline. This value is weak than the standard value of $1025\ \mathrm{kg.m^{-3}}$ commonly used for characterizing ocean density [27, 28]. The difference between these two values could be explained by the fact that the parameters such as salinity and temperature on which this density depends are not uniformly distributed across the different oceans basins [27]. The slope of the linear trend ranged between $-0.008\ \mathrm{kg.m^{-3}}$ (coast of Cote d'Ivoire) and $0\ \mathrm{kg.m^{-3}}$ (coast of Ghana) indicates that the interannual variability of sea surface density decreases slowly over the 2000-2023 period. This relatively decreasing of the sea surface density observed between 2000 and 2023 may be the result of increased precipitation over this period [30], leading to desalination of coastal waters. The minimum density values appearing in September may be linked to the long rainy season extending from May to July, due to the resulting desalination of coastal waters. That could be also a reason for the increasing of extreme events contributing to the vulnerability of West African coastal areas [31].

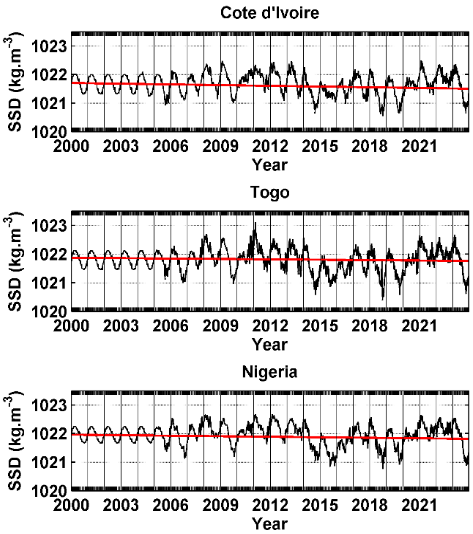

Figure 2 : *Daily variation of sea surface density (kg.m^{-3}) along the West African coastline during 2000-2023 period. Linear trend (in red) was added on each figure*

An uni-modal structure is observed in the seasonal cycle of the sea surface density ***(Figure 3)*** along the West African coastline. The SSD at the Ivorian coast decreases from February to September and increases from September to January. Minimum values appear annually during September; that is, one month after the major upwelling season [32]. Along the coastline of Ghana and Togo, the peak of the seasonal cycle is centered in February coincides with the dry season where fresh water supplies are weak and the minimum value is observed in October during the minor rainy season. In the case of the Nigeria coastline, the peaks of the maximum and minimum are centered in February and November, respectively. The observation show that the temporal change of water density is governed by the latudinal displacement of the Inter-Tropical Convergence Zone (ITCZ) [6].

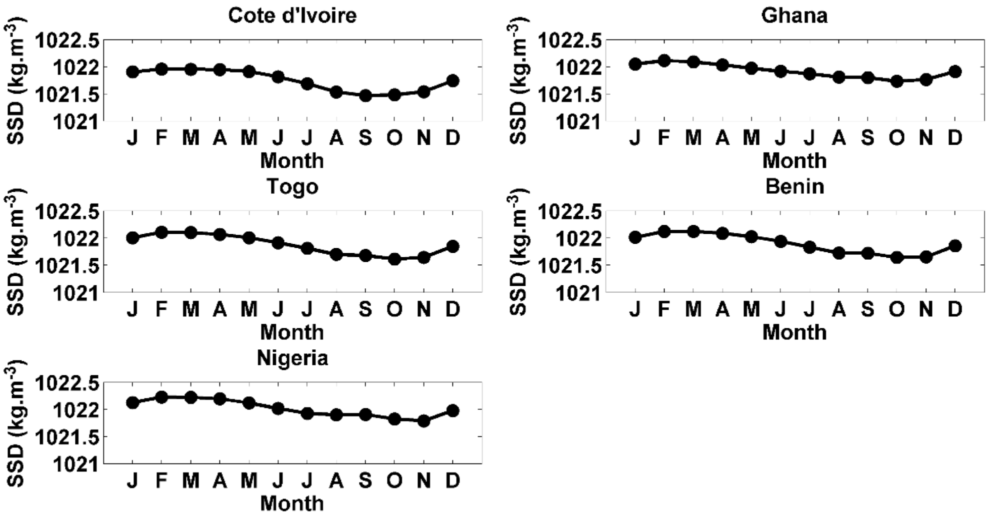

Figure 3 : *Seasonal cycle of sea surface density (kg.m^{-3}) calculated from data ranging from 2000 to 2021 for each country coastline in study area*

II-2. Spatial and temporal variation of the potential energy of the tide along the coastline

The ocean tide recorded by multimission altimetry satellites has the same characteristics as that recorded by tide gauges. This tide is semi-diurnal with diurnal inequality [33]. The maximum value of this tidal range decreases spatially towards the east from 1.551 m along the four coastal section of Nigeria to 2.254 m along the Western section of the Ivorian Coast. Maximum daily values exceeding 2 m have already been observed in tide gauge records according to [6, 34]. This tidal range appears to be higher than that observed by the tide gauge installed at the entrance to the Vridi canal [33]. The difference could be linked to the attenuation of the ocean tide signal by the water coming from the Vridi canal. The associated tidal potential energy over the 2000-2023 period varies spatially from $480.79\,\mathrm{J.m^{-2}}$ in the fourth coastal section of Nigeria to $989.70\,\mathrm{J.m^{-2}}$ in the first coastal section of Cote d'Ivoire ***(Figure 4)***.

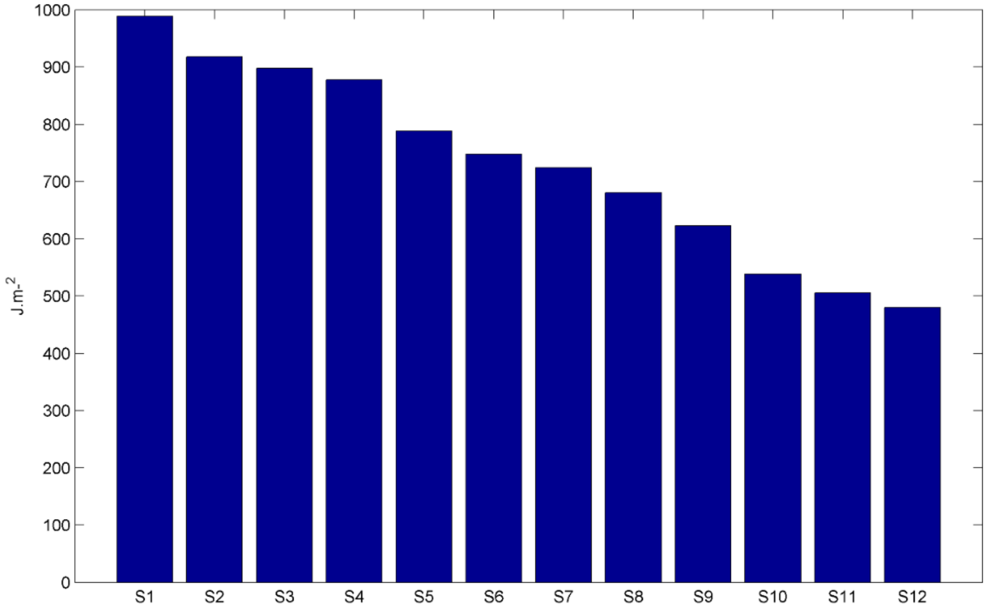

Figure 4 : *Spatial variation of tidal potential energy per area unit (J.m^{-2}) along each coastal section of the West African coastline during 2000-2023 period*

The seasonal cycle of the potential energy of the ocean tide along the West African coastline is characterized by a bimodal structure, with two relative energetic seasons. The minor energetic season appears between February and April with a peak centered in march ***(Figure 5)***. The associated maximum value is $0.975 \pm 0.662\ \mathrm{kJ.m^{-2}}$. The most energetic period extends from August to October, with a maximum centered in September. The associated maximum value is $1.027 \pm 0.62\ \mathrm{kJ.m^{-2}}$. This period corresponds to the period of exceptional equinox tides, which contributes significantly at the vulnerability of the coastal zone to marine submersions and coastal erosion [33]. The standard deviation of the potential energy evolution represents 67.89 % in March and 60.33 % in September of the average of the potential energy time series over the 2000-2023 period. The interannual seasonal variation of this energy during the minor and major energetics seasons is characterized by a strong variability which could be linked to the variability of ocean density. The potential energy is minimal in June along the entire coastline. That implies that extreme events observed in this month are caused by energetic swell wave coming from southern Atlantic Ocean [6].

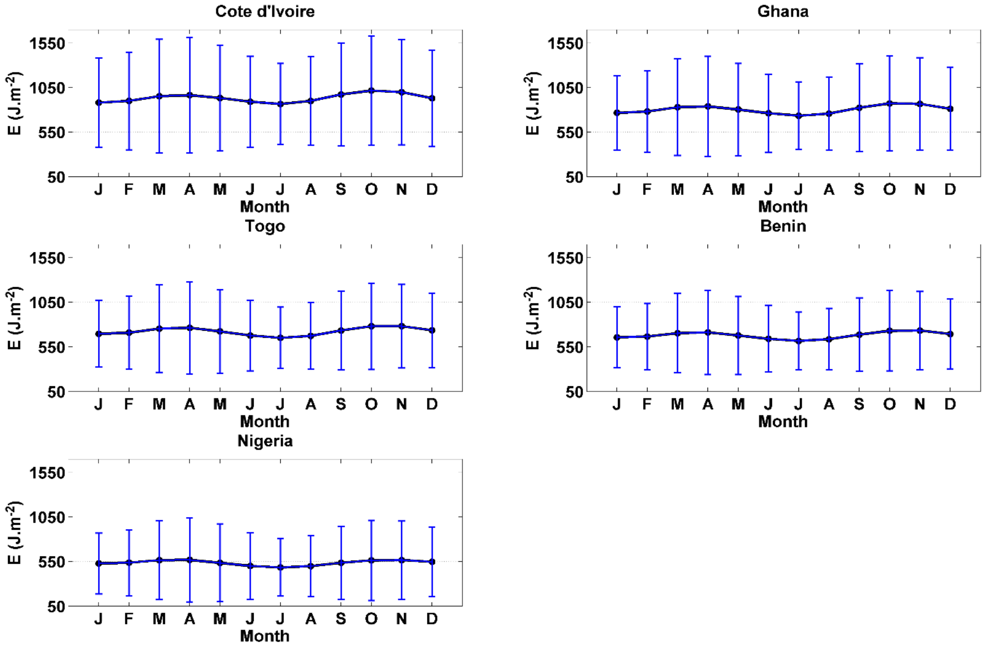

Figure 5 : *Seasonal cycle of the potential energy of the tide per area unit ($J.m^{-2}$) calculated using data ranging from 2000 to 2023 for each country coastline in study area*

Figure 6 illustrates the daily variation of tidal potential energy of the coastal sections 1 (in red), 2 (in blue) and 3 (in black) of Cote d'Ivoire and Ghana coastline and of Togo and Benin coastline (in red). This fig shows also the daily variation of tidal potential energy of the coastal sections 1 (in red), 2 (in blue), 3 (in black) and 4 (in green) of Nigerian coastline. The analysis of this daily evolution of tidal potential energy in each coastal section shows a similar variation of tidal potential energy behavior along the coastline. The maximum values are comprised between $1.23\ \mathrm{kJ.m^{-2}}$ in the fourth coastal section of Nigeria and $2.60\ \mathrm{kJ.m^{-2}}$ in the first coastal section of Cote d'Ivoire. The maximum potential energy available along the coastline over the study period is lower than that observed by [27] along the Indonesian coast and by [13] along the American coast. This difference can be explained by the fact that the tide is more energetic in their studies areas than that observed along the West African coastline, which is classified as micro-tidal coast [33]. The corresponding tidal potential power for a given surface of $700\ km^2$ which represents the surface of buyo barrage in Cote d'Ivoire [34] are 9.95 MW and 21 MW. Along the coastline from Togo to Nigeria, the potential energy of the tide does not reaches $2\ \mathrm{kJ.m^{-2}}$ or 16.2 MW. This result shows that the coastal section from the Cape Palmas to Togolese border is the most favorable for renewable energy production such tidal energy.

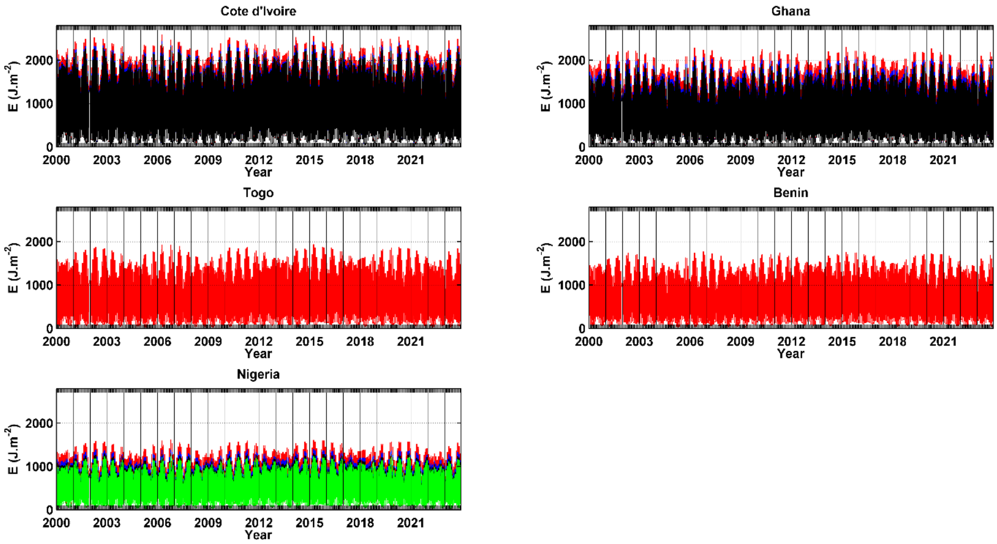

Figure 6 : *Daily variation of tidal potential energy per area unit (J.m^{-2}) along the West African coastline during 2000-2023 period*

IV - CONCLUSION

This study aims to assess the potential energy of tide along the West African coastline at spatial and temporal scales. The sea surface density decreases from 2000 to 2023 along the coastline. The annual cycle for this parameter shows a single absolute minimum that appears in September. The tidal range predicted by the ocean tide model decreases spatially towards the east. The greatest tidal ranges are observed between the Cape of Palmas and Sassandra. Two energy season characterize the annual cycle the tidal energy. The minor energetic season extends from February to April and the most energetic season lies between August to October. The potential energy of the tidedecreases eastward. For a given surface area, this energy is greater from the Cape Palmas to Sassandra than in other sections of the West African coastline. This coastal section is therefore more suitable than other sections for the development of tidal potential power to convert this energy into green electrical energy. Future studies could be focused on estimating the costs and benefits of converting ocean tide energy into electrical power along the West African coastline and its impact on the greenhouse gases emission reduction.

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