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Effects of Natural Processes on Sea Level Change along the West African Coastline

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Abstract

Coastal hazards induced by meteo-marine forcing are exacerbated by sea level change along the West African coastline. Changes in sea level are induced by ocean processes such as ocean heat content and river discharge. However, although these processes control largely change in sea level, they remain poorly understood. This study analyzes changes in ocean heat content, river discharge, and sea level and establishes an interconnection between these parameters using several statistical methods over the 1993-2021 period. Results showed a significant correlation between sea level and ocean heat content at 2000 m depth. The yearly minimum value appears in July from Cote d'Ivoire to Benin, whilst this value appears in June in Nigeria. The temporal variability of ocean heat content, river discharge and sea level along the West African coastline exhibits three or four periods interrupted by some breakpoints with unequal duration. The results indicate that the 1993-2000 period was dominated by an increasing ocean heat content along the coastline, while the period after the 2000s exhibits mostly a decreasing trend. Positive and negative trends characterized river discharge and sea level along this coastline. The result of multiple linear regression between sea level, river discharge and ocean heat content is a good approximation of sea level trend along the West African coastline. The results of this study could be used to predict future sea level trends along the coast.

Keywords

Coastal Sea Level, River Discharge, Heat Content, West African Coast

1. Introduction

The West African coastal countries are experiencing a growing population and increasing socio-economic activities [1] [2]. The capitals of these countries contain the main infrastructures and are located along the coastal areas. These areas which also contain valuable ecosystems and growing populations are changing due to human activities such as dam building, removal of beach sand, and rapid as well as uncontrolled urbanization [3]. The changes are also due to the increasing of extreme events coming from the ocean. The extreme events are mainly due to ocean swell from the Southern Ocean Atlantic and exceptional tides are exacerbated by sea level rise [4] [5]. Coastal erosion and flooding resulting from these processes induce great damages (e.g., destruction of coastal habitats, human life and socio-economic activity losses) along the coast [2] every year. The reduction of the impacts of these risks on coastal areas requires efficient knowledge of processes such as sea level change and the factors that induce them. This knowledge facilitates understanding and predicting future changes in sea level and their impact on marine ecosystems, sustainable development of coastal areas and developing early warning for coastal hazards.

Several studies have been undertaken to understand sea level variability and trends along the coastal areas, which clearly show that sea levels have been increasing for several decades [6]-[9]. At a global scale, the analysis of tidal gauge records indicates that the total global mean sea level average did not exceed 1.9 mm/yr from 1901 to 2010 [10] [11], but recent trend based on satellite altimeter data showed that global mean sea level ranged between 2.8 $\text{mm}\cdot\text{yr}^{-1}$ and 3.6 $\text{mm}\cdot\text{yr}^{-1}$ over the 1993-2020 period [12] [13].

According to [3], sea level increases along the West African coast at about 3.05 $\text{mm}\cdot\text{yr}^{-1}$. A similar trend was previously obtained from historical tidal gauge data of Takoradi (Ghana) by [14] and along the coastline of Jamestown in Accra [15]. This trend is weaker than that recorded globally, showing that the increase of sea level is not uniform along the coastal sections. This observation shows that natural processes and anthropogenic forcings affect sea levels differently in each region. Hence, identifying and quantifying the natural processes that control sea levels allows an understanding of their implication in the dynamics of rising sea levels. Moreover, such information could also help in the prediction of sea level and fill in the missing data that characterize the West African coasts.

The rise in sea level is mainly caused by thermal expansion, melting of glaciers, land subsidence and river discharge [16]. Several studies were carried out on these natural processes and their impacts on sea level. [17] and [18] quantified the effects of river discharge on sea level along the United States Atlantic and Gulf coast, and in the tropical Atlantic, respectively. The authors showed the strong influences of this parameter on sea level dynamics at different time scales. [19] established that 10-20% of sea level and tidal variance at seasonal scale around the major river are due to the river discharge effect.

According to [20], the interannual variability and trend in sea levels are mainly due to changes in ocean heat content in the western North Pacific. Similar results have been found by [21] in the world ocean, but some uncertainties remain regarding the regional distribution of sea-level rise. The uncertainties could be linked to the changes in ocean circulation, local river discharge and ice-sheet contributions that are not taken into account in model equations. Hence, quantifying the effects of river discharge, ocean heat content and melting glaciers on sea level could be useful for a better assessment of sea level trends and variability along the coast.

This manuscript analyses the influence of the river discharge and ocean heat content in sea level change along the West African coastline. The interrelation between these parameters was also assessed. This information will fill a lack of the impact of large and small-scale climate patterns actions on the West African coastal sea-level variability and trends.

This paper is arranged as follows: the methodology including data and methods used is presented in section 1. Section 2 is devoted to results and discussion and the summary and perspectives are presented in Section 3.

2. Material and Methods

2.1. Data

The local change in mean sea-level variation and water supply to the ocean by rivers were obtained by using daily sea-level anomalies and river discharges provided by the Copernicus Marine Environment Monitoring Service. The spatial horizontal grid of sea level anomaly and river discharge dataset are of $0.25^\circ \times 0.25^\circ$ and $0.1^\circ \times 0.1^\circ$ grids, respectively, and the coverage period is from 1993 to 2021 at daily timescale. These gridded mean sea level data are derived from satellite altimeters [22]. The daily river discharge dataset is produced by forcing a hydrological modelling chain with ERA5 meteorological reanalysis data, interpolated to the Global Flood Awareness System (GloFAS) resolution [23].

The Ocean heat content dataset used in the study was provided by the Institute of Atmospheric Physics Ocean Gridded Product. This dataset is a combination of XBT measurements together with all available in situ observations from the World Ocean Database. It covers the global ocean at $1^\circ \times 1^\circ$ horizontal resolution on 41 vertical levels from 0 - 2000 m, and monthly resolution from 1940 to the present [24].

All these data were spatially averaged at the limit of each coastal section of the West African coastline defined previously in [25] to obtain a chronological series for each coastal section.

2.2. Methods

Coastal sea level anomaly, river discharge and ocean heat content at different depth time series for each coastal section were analyzed by several statistical methods including multiple change point detection, multiple linear regression and the Mann-Kendall non-parametric test for randomness against trend.

2.2.1. Change Points Detection and Trend Analysis

Detection of abrupt changes in the characteristics of some oceanographic processes such as sea level, river discharge and ocean heat content, highlights regime changes in these processes and trend analysis. In this study, the detection of the number of change points and their positions in ocean parameters time series are computed using the Pruned Exact Linear Time (PELT) method of [26]. This method can be orders of magnitude faster than Optimal Partitioning, particularly for long data sets. The PELT leads to a substantially more accurate segmentation of data. It combines optimal partitioning and pruning to achieve an exact and efficient computational cost which is linear in n (length of the time series). The optimal segmentation F_n is defined as follows:

$$F_n = \min_{\tau}\left[\sum_{i=1}^{m+1}\left[C\left(y_{\tau_{i-1}+1}+\cdots+y_{\tau_i}\right)+\beta\right]\right] \tag{1}$$

where:

C is a cost function for the i^{th} segment, β is a penalty to guard against over fitting; m is the number of changepoints; $y_1, y_2, \cdots, y_n$ is a set of data and τ_m is a location of the m^{th}.

This method consists of by calculating F_1 and then recursively calculate $F_1, F_2, \cdots, F_n$. At each step we store the optimal segmentation up to τ_{m+1}. When F_n is reached, the optimal segmentation for the entire data is identified and the number and location of changepoints were recorded.

At each step the minimisation over τ_m covers all previous values. The computational efficiency of the PELT method is achieved by removing candidate values of τ_m from the minimisation at each step [27].

The increasing or decreasing of the ocean parameters trends was carried out by fitting Mann-Kendall test and Sen's slope estimator [28] was carried out by fitting time series. This method is useful to detect and estimate the slope of possible trends in time series as decribed in [25] was used for this study.

2.2.2. Multiple Linear Regression

The multiple linear regression is used to predict the response of predictor variables [29]. This method that was previously used by [30] to reconstruct sea level in some location sites in the south west Pacific region is adopted in this study to highlight ocean heat content and river discharge impact on sea level in West African basin. The prediction could be modeled in the case of two predictors and their combination is as follows:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_1 X_2 \tag{2}$$

where:

α_0, α_1, α_2 and α_3 are model coefficients.

Y is the response of predictors influences.

X_1 and X_1 are the predictors variables.

$X_1 X_2$ is a predictor variable resulting of the combination of the impact of X_1

and X_2 at the same time.

This method was used to carry out the possible inter-relationship between ocean parameters analyzed in this study.

3. Results

Coastal processes that induce coastal vulnerabality to temporal or permanent erosion and/or flooding are exacerbated by mean sea level rise. Mean sea level rise change could be attributed to salinity change, ocean circulation and air sea interactions at short timescale and, at long-term timescale to thermal expansion, river discharge and melting of glaciers. Here, the spatial and temporal ocean heat content and river discharge have been analyzed to show how these parameters could influence the mean sea level and increase the vulnerability of coastal communities, infrastructures and ecosystems.

3.1. Trend in Ocean Heat Content

The analysis of correlation between sea level and ocean heat content anomalies has shown a strong link ($r > 84\%$) between these two parameters at 2000 m depth. So, the ocean heat content data at this depth was be used to analyze its impact on sea level rise.

Figure 1 shows the temporal variability of ocean heat content at 2000 m depth along each coastal section of the study area.

The average ocean heat content in each coastal section of West African coastline shows that the minimum and maximum value are $5.1099\times10^{10}\ \text{J}\cdot\text{m}^{-2}$ (Togo) and $5.6851\times10^{10}\ \text{J}\cdot\text{m}^{-2}$ (Section 3 of Ghana coastline), respectively. The mean values are 5.4386×10^{10} (Cote d'Ivoire), $5.4344\times10^{10}\ \text{J}\cdot\text{m}^{-2}$ (Ghana), $5.4177\times10^{10}\ \text{J}\cdot\text{m}^{-2}$ (Nigeria), $5.3495\times10^{10}\ \text{J}\cdot\text{m}^{-2}$ (Togo) and $5.3494\times10^{10}\ \text{J}\cdot\text{m}^{-2}$ (Benin). This result shows that ocean warming decreases from Cote d'Ivoire to Benin and, increases from Benin to Nigeria.

The ocean heat content regime has an uni-modal structure in seasonal cycle which is centred in June for Nigeria basin and July along the other coastline sections of West Africa. This result shows that the yearly cooling appears one month earlier in Nigeria basin than those of other basins. These minima appear during the major coastal upwelling period corresponding to the annual minimum value of sea level [3]. The minor upwelling is not well represented at this depth by heat content. The temporal variability exhibits five periods interupted by four breaks with unequal durations (**Figure 1**). The trends observed between 2000 and 2010 from Côte d'Ivoire to Ghana (Section 1) are not significant. The same situation is observed after 2016 from Cote d'Ivoire to Ghana (sections 1 and 2) and along the coastal sections 3 and 4 of Nigeria. Positive trends are observed in each coastal section over the 1993 – 2000 period. This increasing trend continued until 2010 along the Nigerian coastline. The slopes of these trends ranged between 0.12 $\text{J}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ (Ghana) and $22.86\times10^{6}\ \text{J}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ (Ghana). A decreasing of

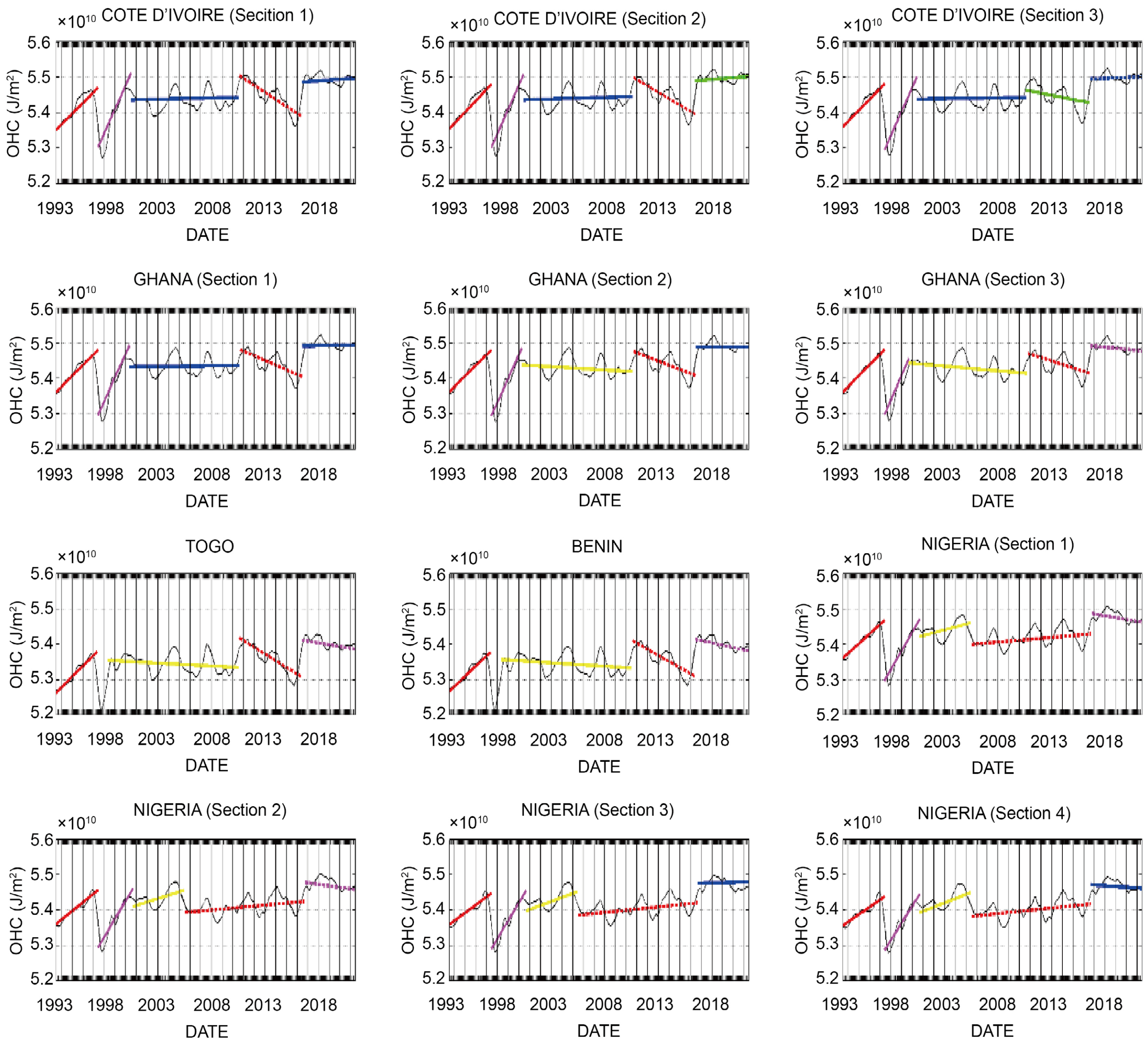
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Figure 1. Ocean heat content trends along the West African coastal sections. Solid and dashed lines in red and magenta represent significant trends at 5% level and blue and green trends are not significant.

thermal expansion is noted during 2000 to 2021 along the coastal section 1 of Côte d'Ivoire and from coastal section 2 of Ghana to Benin. This trend is observed over the 2016-2021 period through Nigeria basin. The associated coastal slopes do not exceed $-0.007\times10^{6}\ \text{J}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$. Long-term trends indicate that there is a spatial and temporal increasing of heat content from Cote d'Ivoire to Nigeria. These upward trends have slopes between $0.97\times10^{6}\ \text{J}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ (Nigeria) and $1.14\times10^{6}\ \text{J}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ (Cote d'Ivoire). The spatial and temporal variability of thermal expansion along this coastline could be linked to the El-Niño, ocean current and over climate index such as Atlantic Multidecadal oscillation that influence Gulf of Guinea ocean basin [31].

3.2. Trend in River Discharge

The coastal river discharge is another parameter which could play an important role in the mean sea level change at spatial and temporal scales.

Figure 2 shows the monthly cumulative river discharge climatology calculated for each country coastline in the study area between 1993 and 2021.

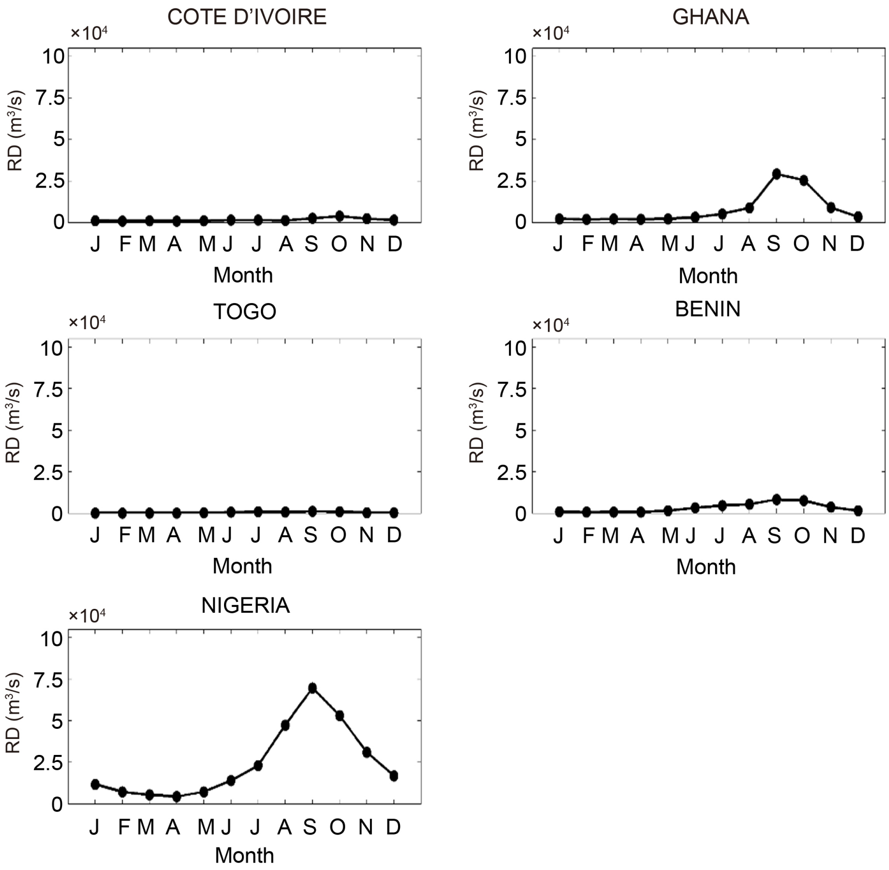

Figure 2. Monthly seasonal cycle of river discharge (1993 to 2021).

From Cote d'Ivoire to Togo, a bi-modal structure is observed in the seasonal cycle of the river discharge regime. The peaks are centered in June and October. **Figure 2** illustrates the weak impact of the major rainy season on river discharge. The high values of river discharge observed in October could be linked to both minor and major rainy seasons along the coastal area and/or in the sahel region.

The river discharge regime has an uni-modal structure in the seasonal cycle along the Benin and Nigeria coastlines. The peak of this seasonal cycle is centered in September and coincides with the major rainy season. One can conclude that the river discharge regime alone is governed mostly by the coastal precipitation regime of Nigeria. The different modes observed in the seasonal cycle of river discharge along the different coastal sections are governed by the latitudinal displacement of the Inter-Tropical Convergence Zone (ITCZ) [25] [32] [33].

Figure 3 illustrates the temporal evolution of the cumulative river discharge in

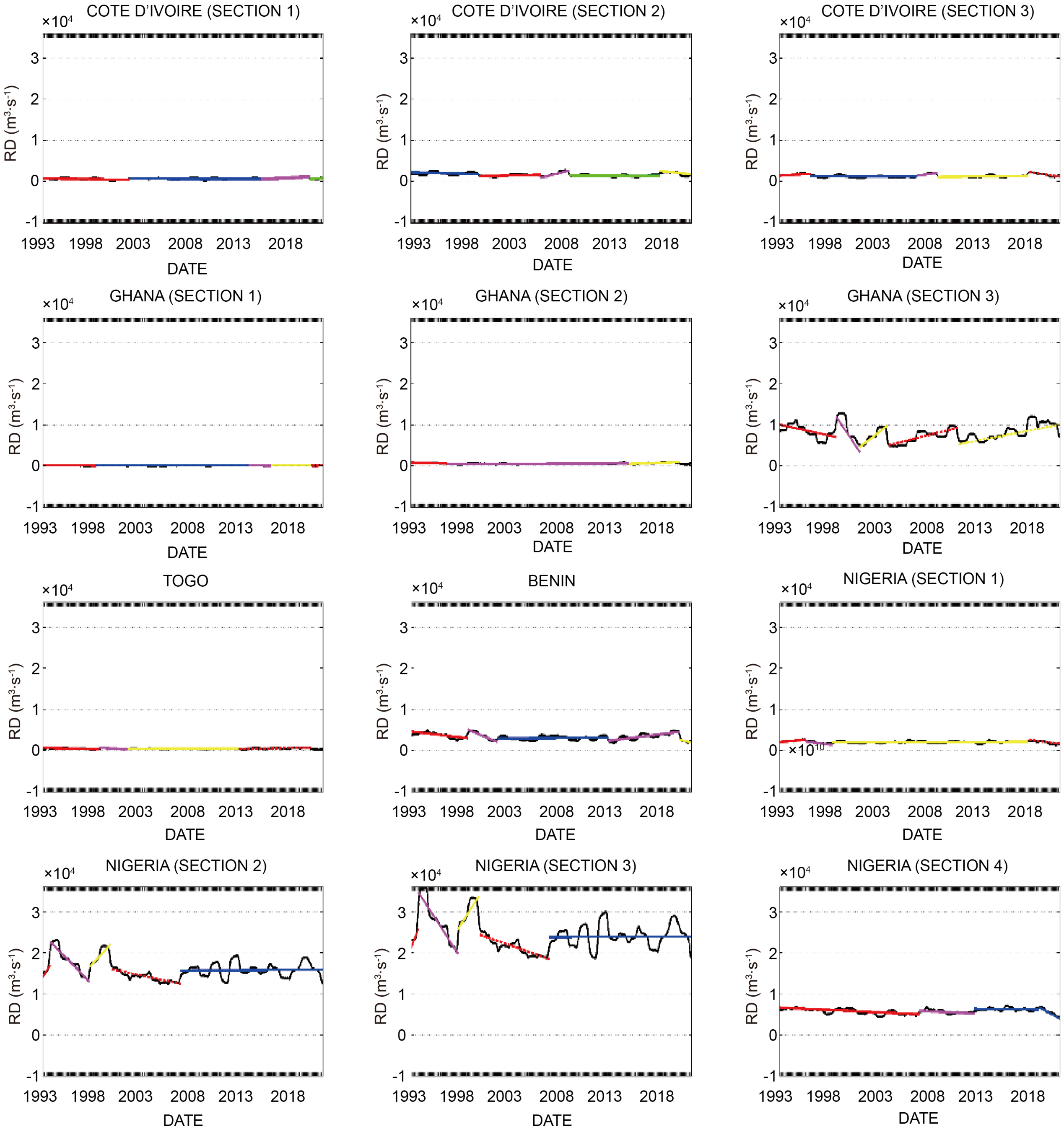

Figure 3. Trends of cumulative river discharge along the West Africa coastal sections. Solid and dashed lines in red and magenta represent significant trends at 5% level and bleue and green trends are not significant.

each coastal section of the northern coast of the Gulf of Guinea over the 1993-2021 period. The temporal average of the cumulative river discharge in each country coastal basin is characterized by the values ranging between 1.119 $m^3 \cdot s^{-1}$ (Togo) and 3463.8 $m^3 \cdot s^{-1}$ (Nigeria). The mean values are 56.365 $m^3 \cdot s^{-1}$ (Cote d'Ivoire), 96.001 $m^3 \cdot s^{-1}$ (Ghana), 16.156 $m^3 \cdot s^{-1}$ (Togo), 107.995 $m^3 \cdot s^{-1}$ (Benin), 461.776 $m^3 \cdot s^{-1}$ (Nigeria).

The analysis of change points by linear segmentation method [26] [34] in each coastal subsection time series exhibits three periods along the coastal subsections 1 and 3 of Cote d'Ivoire, 2 of Ghana and 1 of Nigeria. The other coastal subsections time series are characterized by four breakpoints. The slopes of associated trends ranged between -127.93 and $129.83\,\text{m}^3\cdot\text{s}^{-1}\cdot\text{yr}^{-1}$ (Coastal section 3 of Nigeria) over 1994-1998 and 2000-2007, respectively (**Figure 3**). The temporal variability of river discharge is characterized by an increasing or a decreasing with unequal duration of the cumulative river discharge along each coastal section on the northern coast of the Gulf of Guinea. Negative trends followed by positive trends are observed along the coastal sections 1 (*i.e.*, Cote d'Ivoire), 3 (Ghana) and Togo. This trend is reversed in the third section. Negative and positive trends alternate along the sections 2 (Côte d'Ivoire) and 1 - 3 (Nigeria). Only one trend has a weak positive slope value along the Benin coast and the coastal section 4 of Nigeria. Negative trend dominates the variability of river discharge over the 1993-2021 period. These trends are governed by precipitation dynamics [35] and human activities through dam building for agriculture and hydropower generation [36] [37].

The long-term variability of river discharge from Cote d'Ivoire (except section 2) to Ghana is characterized by a positive slope ranging from $0.023\,\text{m}^3\cdot\text{s}^{-1}\cdot\text{yr}^{-1}$ (section 1 of Ghana coast) to $0.95\,\text{m}^3\cdot\text{s}^{-1}\cdot\text{yr}^{-1}$ (Togo). This means that river discharge increases over the period 1993-2021. A negative trend with slopes between $-2.96\,\text{m}^3\cdot\text{s}^{-1}\cdot\text{yr}^{-1}$ (section 3 of Nigeria coast) to $-0.021\,\text{m}^3\cdot\text{s}^{-1}\cdot\text{yr}^{-1}$ (Togo) characterized the long-term variability of the river discharge from Togo to Nigeria, and the coastal section 2 of Cote d'Ivoire.

3.3. Trend in Sea Level

Figure 4 represents the temporal and spatial change in sea level trend along the West African coastline over the study period. These are obtained by removing seasonal cycles and residuals in the original signal of the sea level anomaly time series. Different trends separated by breaks are observed in each coastal section. Five trends were noted in each coastal section from Cote d'Ivoire, Ghana, to Nigeria, except section 1 of Nigeria coast where four trends are recorded. All these trends are statistically significant at a 5% level according to the Mann-Kendall test and Sen's slope estimation method. The minimum slope of $-0.53\ \text{mm}\cdot\text{yr}^{-1}$ was observed from 2003 to 2009 in coastal section 3 of Nigeria and the maximum slope of $2.29\ \text{mm}\cdot\text{yr}^{-1}$ obtained in the coastal section 3 of Cote d'Ivoire is consistent with regional trend [3].

The first breakpoint appeared in 1997 along all coastal sections. The associated trends increase from 1993 to 1997 with slopes ranging between 0.23 and 0.79 $\text{mm}\cdot\text{yr}^{-1}$ corresponding to the coastal sections 4 (Nigeria) and 1 (Cote d'Ivoire).

The second breakpoint was observed between 2000 and 2005 in all coastal sections except the coastal sections 2 - 3 of Cote d'Ivoire and the coastal section 1 of Ghana where a change in sea level regime occurred in 1998. An acceleration of the increasing trend with slopes between 0.52 and 2.06 $\text{mm}\cdot\text{yr}^{-1}$ was noted.

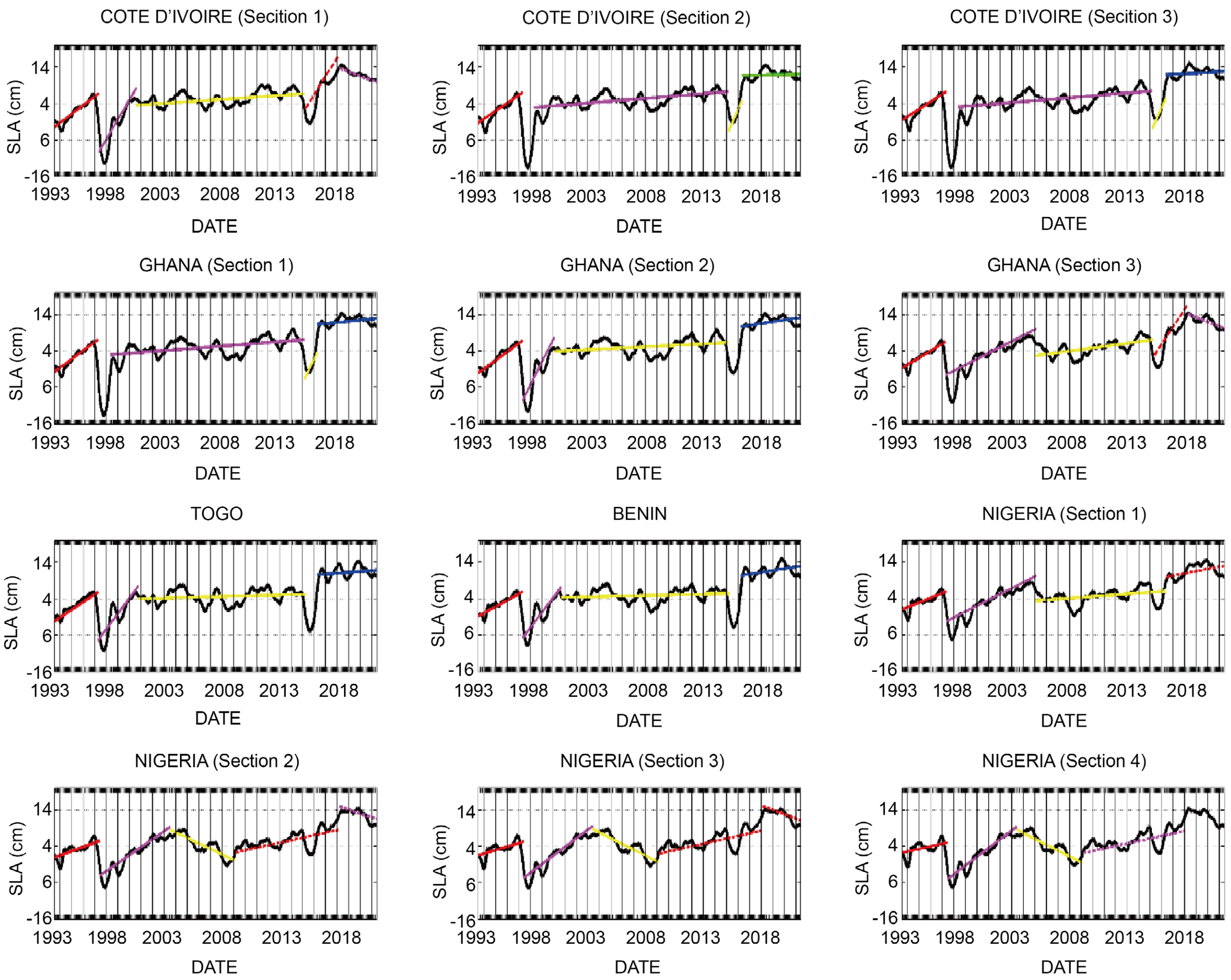
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Figure 4. Trends of sea level along the West African coastal sections. Solid and dashed lines in red and magenta represent significant trends at a 5% level and blue and green trends are not significant.

The third breakpoint occurred in 2015 from Cote d'Ivoire to Benin coastline, in 2016 and 2009 along the coastal section 1 and coastal section 2 - 4 of Nigeria, respectively. A weak positive trend with a slope not exceeding 0.14 mm·yr^{-1} characterize the temporal evolution of sea level trend in most of the coastal sections of West African coastline over the 1998-2015 period.

The temporal change is expressed by a negative trend with a slope of ~ −0.5 mm·yr^{-1} along the Nigeria coast.

The fourth breakpoint occurs mostly in 2016 along the coast, except in the coastal section 1 of Cote d'Ivoire, section 3 of Ghana and section 2 - 4 of Nigeria coast. Positive trends are noted over this fourth period and their slope can reach 2.29 mm·yr^{-1} as the case of coastal section 3 of Cote d'Ivoire.

During the 2018-2021 period, negative trends are observed in costal sections 1(Cote d'Ivoire), 3 (Ghana) and 2 - 4 (Nigeria). The slopes of these trends ranged between −0.45 and −0.35 mm·yr^{-1}. One observes a weak and gradual increasing trend with slope reaching 0.08 mm·yr^{-1} along the other coastal sections.

3.4. Impact of Ocean Heat Content and River Discharge on Sea Level

Figure 5 shows the spatial and temporal evolution of normalized trends of ocean heat content (red line), river discharge (blue line) and sea level (black line) along the West Africa coastline. These were obtained by removing annual cycle and residual in original time series. Some similar changes are observed between ocean heat content and sea level in each coastal area. The temporal change between river

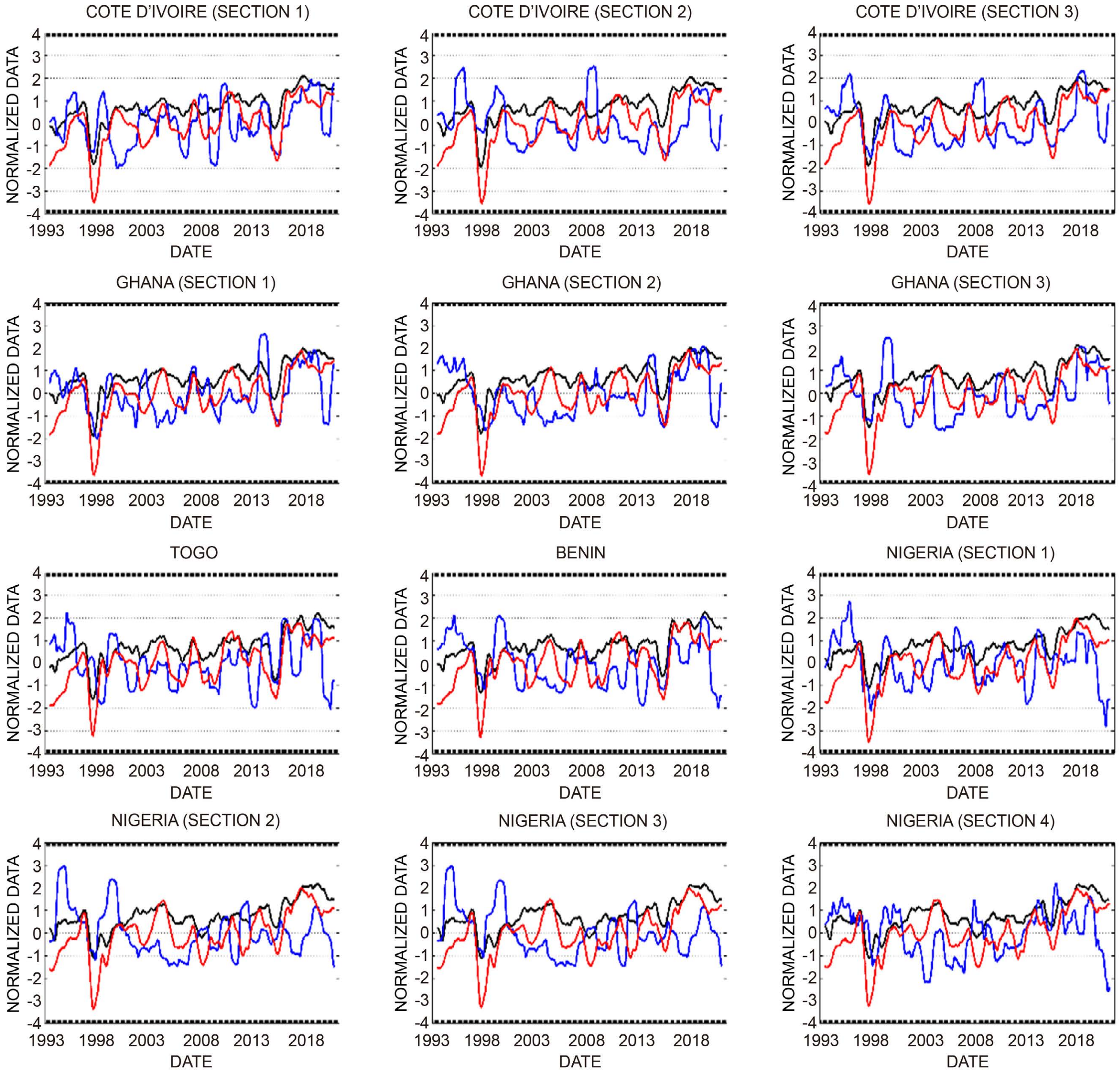

Figure 5. Temporal evolution of normalized trends of ocean heat content (red line), river discharge (blue line) and sea level (black line) along the coastal sections of West Africa.

discharge and sea level is similar during the study period. During certain period, one can see a decreasing of river discharge and an increasing of sea level. This observation shows that ocean heat content has a strong impact on sea level change along the West Africa coastline. In this case, the possible contribution of river discharge to sea level rise could be assigned to the warming through coastal rivers discharge as the case of Niger river along the West Africa coastline [38].

Previous results have shown the existing dependance between sea level change, river discharge and ocean heat content at 2000 m depth. This dependance could be expressed by the following equation :

$$T_{SL} = 0.73 + 0.02T_{RD} + 0.62T_{OHC} + 0.05T_{RD}T_{OHC}$$

where:

$T_0 = 0.73$ is a constant of the model;

T_{SL} : trend of normalized sea level anomaly data;

T_{RD} : trend normalized river discharge data;

T_{OHC} : trend of normalized ocean heat content data at 0 - 2000 m depth.

The parameters of this model are statistically significant because $\text{p} - \text{value} = 3.19 \times 10^{-161} \ll 5\%$. This model could be used for sea level monitoring trend along the West African coastline.

4. Discussion

In this study, a trend analysis was conducted on ocean heat content, river discharge and sea level along the West African coastline between 1993 and 2020. The interconnection between these processes was also established over the same period.

The analysis of ocean heat content shows spatial and temporal variability (increasing and/or decreasing thermal expansion of the ocean along the coastal areas of West Africa). A similar trend has also been pointed out at a global scale by [10] [39] [40]. The main reversal trend observed by [41], which was also noted along the coastline which lies between Côte d'Ivoire and Benin in the 2000s. The cooling trends that appeared after the 2000s and the strong Atlantic cooling observed until 2000 by [40] are close. The warming trends over the period 1993-2000 could be attributed to El-Nino—Southern Oscillation (ENSO) in Atlantic basin previously noted by [42] [43]. Negative trends observed in some periods could be linked to the transition from El-Niño to La Niña [44].

The global linear trend of ocean heat content at the 2000 m depth which is $8.43 \times 10^6\ \text{J} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ for 1955-2010 [21] is higher than those observed in each coastal section of West africa coastline where the trends do not exceed $1.14 \times 10^6\ \text{J} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ for the 1993-2021 period. The yearly minimum that appears in July is in agreement with previous work of [45] along the coastline from Côte d'Ivoire to Benin.

The river discharges analyzed in this work are characterized by spatial and temporal variability (increasing/decreasing) in each coastal section of the West

African coastline [46] [47]. These trends are consistent with those observed in West Africa precipitation trends estimated previously by [33]. This result confirms the strong impact of precipitation on river discharges as mentioned by [44] [48] [49]. Human activities such as land use/cover and due to rapid urbanization and agriculture could also influenced river discharge variability across West Africa coastal area [50].

The trends in mean sea level observed along the coastal section of West African coastline are lower than those observed at global scale by [7]. This observation could be explained by the fact that ocean basins are not influenced by the same mechanism. Along the Vietnam for example, local Sea Surface Temperature (SST), wind stress, PDO and ENSO influenced significantly the variability of coastal sea level [9]. At regional scale, ocean heat content seems to contribute more significantly to sea level rise and variability at the coast, consistent with [51]. Moreover, change in sea level could be attributed to a change in ocean density due the effect of salanity. But along the West African coast, change in sea level due salanity could be observed at seasonal scale because [4] does not observed any trend in salanity change at long-term scale.

The trends in mean sea level, river discharge and ocean heat content vary similarly over the study period. This result is in agreement with previous study conducted by [19] [52]. The strong correlation between sea level and river discharge [17] shows the important role played by river discharge in coastal flooding events [53] [54] and ocean circulation [19]. The causal relation between sea level and river discharge etablished by [17] could be extended by integrating ocean heat content as presented in this work. The integration of climate indices such as ENSO although it is weak [55] and Atlantic Multidecadal Ocillation already mentioned by [31] could improve sea level change and variability [8] along the West African coastline.

5. Conclusions

This study aims to analyse the effects of ocean processes such as river discharge and ocean heat content on West African coastal sea level and to establish their connections.

The analysis of ocean heat content shows spatial and temporal variability over the 1993-2021 period. The monthly climatology of heat content in countries' basins has a minimum value located in July during the major upwelling season from Cote d'Ivoire to Benin. This minimum continues in June along the Nigeria coastline. Five periods interrupted by four breakpoints characterize the temporal variability of heat content in each coastal section. From 1993 to 2000, the trends are positive. The negative trends characterize mostly heat content trends after the 2000s. The analysis of the long-term trend of ocean heat content shows an increase in warming over the 1993-2021 period. The slopes of the trends ranged between $0.97\times10^{6}\ \text{J}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ (Nigeria) and $1.14\times10^{6}\ \text{J}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ (Cote d'Ivoire).

The analysis of river discharge along the coast also indicates a spatial and temporal variability over the study period. A bimodal structure characterizes the seasonal cycle of river discharge from Cote d'Ivoire to Togo whilst the seasonal cycle from Benin to Nigeria has an uni-modal structure. The yearly maximum values are observed in June and October from Cote d'Ivoire to Togo while the maximum values are observed yearly in September from Benin to Nigeria. The analysis of the temporal evolution of river discharge in each coastal section is characterized by four and five periods that correspond to three and four breakpoints. The long-term variability of river discharge from Cote d'Ivoire (except section 2) to Ghana is characterized by positive trends over the 1993-2021 period. A negative trend characterized the long-term variability of the river discharge from Togo to Nigeria, and the coastal section 2 of Cote d'Ivoire.

The temporal variability of sea level along the coastal sections exhibits four periods in each coastal section of Cote d'Ivoire, Ghana and Nigeria and, five periods along the coastline from Togo to Benin. These periods are separated by three and four breakpoints. The associated trends are mainly positive.

The natural processes (ocean heat content, river discharge, sea level) have similar temporal evolution and sea level trends could be assessed by using river discharge and ocean heat content at 2000 m depth trends.

The ocean heat content used in this study is limited to 2000 m depth. So, future studies could analyse this parameter at a depth below 2000 m to evaluate its effect on sea level change. Including other parameters, such as ocean current and melting, could help the accuracy of the model prediction.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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