Vol. 17(7), pp. 157-166, July 2023
DOI: 10.5897/AJEST2022.3173
Article Number: 89512A871035
ISSN: 1996-0786

http://www.academicjournals.org/AJEST

African Journal of Environmental Science and Technology

Full Length Research Paper

Impact of climate variability modes on trend and interannual variability of sea level near the West African coast

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Received 21 December, 2022; Accepted 13 July, 2023

The main objectives of this study are to assess the regional distribution of sea level in terms of trend and interannual varibility and to analyze the impacts of climate variability modes such as El Niño-Southern Oscillation (ENSO) events, Tropical Atlantic Climate Modes of Variability (TACMV), North Atlantic Oscillation (NAO) on interannual variability and trend of sea level near the West Africans coasts. Indices associated with these phenomena are from the National Oceanic and Atmosphere Administration (NOAA), the Global Mean Sea Level (GMSL) time series provided by AVISO (Archiving Validation and Interpretation Satellite Oceanographic Center) and the Regional Mean Sea Level (RMSL) gridded data by CMEMS (Copernicus Marine Environment Monitoring Service). The results show that the mean regional trend of sea level is similar to the global one but the time evolution at interannual and decadal scales does not follow the pattern of global sea level. Our analysis suggests an influence of ENSO events in the Atlantic coast of West Africa. In particular, we observed negative RMSL anomalies during the two strongest El Niño events (1997-1998 and 2015) and a strong positive RMSL anomaly during the La Niña event of 2011 (the strongest over the last two decades). The analysis also reveals an influence of TACMV and NAO on the interannual sea level variability, essentially through regional Sea Surface Temperature (SST) changes. The study shows that a time series of at least 10 years is required to estimate the trend in sea level rise in West Africa. Sub-decadal trends, primarily reflect natural climate modes, rather than variations in climate change. This study also shows that the distribution of sea level rise in the West African region is heterogeneous with higher values near the coast of West Africa and near the equator.

Key words: West Africa, Sea level rising, Regional sea level variability, Climate Variability Modes, sea level interannual variability.

INTRODUCTION

Sea level rise due to anthropogenic global warming is now considered undeniable as all studies (Ablain et al., 2017; Dieng et al., 2017; Cazenave et al., 2018; Dieng et al., 2021) based on direct measurement techniques such as satellite observation and tide gauge recording reveal that the Global Mean Sea Level (GMSL) is rising. Since 1993, satellite altimetry missions have delivered accurate sea level measurements, allowing the monitoring of sea level variations on different spatial and temporal scales (Pujol et al., 2016; Ablain et al., 2017; Legeais et al., 2018).

They estimate anaverage rate of 3.1 ± 0.3 mm/yr and an acceleration of 0.1 mm/yr² of the GMSL rise from 1993 to present (Cazenave et al., 2018). They also show a significant regional variability, with some regions experiencing greater rates (Quartly et al., 2017).

Sea level rise is a highly sensitive index of climate change (Legeais et al., 2018) because it integrates changes in several components of the climate system in response to anthropogenic forcing in addition to natural factors related to natural sources and internal climate variability (Ablain et al., 2017). The GMSL rise primarily reflects ocean warming (through thermal expansion of sea water) and land ice melting, two processes that result from anthropogenic global warming (Church et al., 2013). However, at regional scale, sea level rise is also affected by regional processes leading to large variations in temperature, currents, winds, precipitation and air pressure (Fu et al., 2019). Regional studies are therefore important to better understand the sea level variations and their relation to climate change.

West Africa, our study area, is not immune to the negative effects of sea level rise. Its impacts are increasingly noticeable and felt. Many African coastal countries are vulnerable to sea level rise, particularly where large growing cities with a high population density are situated in the coastal zone (Nicholls et al., 2008; Hinkel et al., 2012; Dada et al., 2021). Coastal risks are primarily related to hazards such as flooding and coastal erosion, associated with mean sea level rise but also with storm surges and large waves, and are particularly acute when there is significant human development along the coast (Thior et al., 2019). However, there are large gaps in the knowledge of flooding and erosion processes and on the available in-situ data in West Africa. There are only six tide gauge time series available (Dakar, Nouakchott, Palmeira, Lagos, Sonora and Takoradi) and they are difficult to use for various reasons: (1) there are gaps in the time series; (2) the gauges are not connected to a Global Positioning System (GPS) that can correct errors related to vertical movements of the earth, and (3) the measurement periods do not coincide. Therefore, satellite data are currently the only way to study the regional distribution of sea level, which are used in this paper.

Altimetry data have greatly improved near the coasts in recent years. Improvements resulted from recent altimetry missions such as Geosat follow-on (GFO), CRYOSAT-2 and HY-2A, which have been combined with older missions (Topex/Poseidon and Jason-1/2/3). In West Africa, several studies have been conducted for the validation of these coastal altimetry products (Cipollini et al., 2017; Dieng et al., 2019; Marti et al., 2021). In the present study, the CMEMS (Copernicus Marine Environment Monitoring Service) gridded data, DUACS DT version (DT2018) were used, which shows a great improvement in coastal areas compared to DT2014 (Taburet et al., 2019), thanks to the efforts of the DUACS (Data Unification and Altimeter Combination System) teams and to the recent altimetry missions mentioned above. Thus, our main objective is to take advantage of this progress to improve our understanding of sea level variations in West Africa in relation to the GMSL. The effect of climate variability modes on the interannual variability and trend estimation of sea level in the region will also be studied. First, we compared the sea level variations in West Africa with those of the GMSL in terms of interannual variability and trend. Then, we analyzed the effect of climate modes: El Niño-Southern Oscillation (ENSO), Tropical Atlantic Climate Modes of Variability (TACMV), North Atlantic Oscillation (NAO) and of the Sea Surface Temperature (SST) on interannual sea level variations in West Africa. The study identified the modes of climate variability that have the most significant impact on sea level variations over the altimeter period 1993-2019. Finally, we analyzed the spatial variability of sea level rise and the influence of interannual sea level variability on its estimation.

STUDY AREA, DATA AND METHODS

Our study area is the eastern part of the tropical Atlantic, near the West African coasts from Congo to Western Sahara (5°S - 25°N and 35°W – 20°E; Figure 1). In this study, we used several sources of data, that is, altimetric data and climate indices. For the satellite altimetry data, we used two different products available over the period 1993-2018:

(1) The GMSL (Global Mean Sea Level) time series provided by AVISO (Archiving Validation and Interpretation Satellite Oceanographic Center) is based on the combination of the reference missions (Topex/ Poseidon, Jason-1, -2 and -3) and the auxiliary missions (ERS-1,-2, Envisat and Saral/Altika) and is obtained by geographically averaging the sea level data between 66°S and 66°N.

(2) The CMEMS (Copernicus Marine Environment Monitoring Service) gridded data, version DT2018, are based on a larger set of altimetry missions by adding to the data of the reference and complementary missions mentioned above a complementary mission (Sentinel-3A) and opportunity missions (GFO, CRYOSAT-2 and HY-2A). These data are dedicated to the study of regional sea level variations and are provided daily on a 1/4° x 1/4° grid and on a latitudinal range from 82°S to 82°N. We applied monthly averaging on the data to remove residual high temporal frequencies, particularly related to ocean tide and atmospheric variability (Dieng et al., 2021). When time series are used to estimate interannual variability and trend, annual and semi-annual signals are removed

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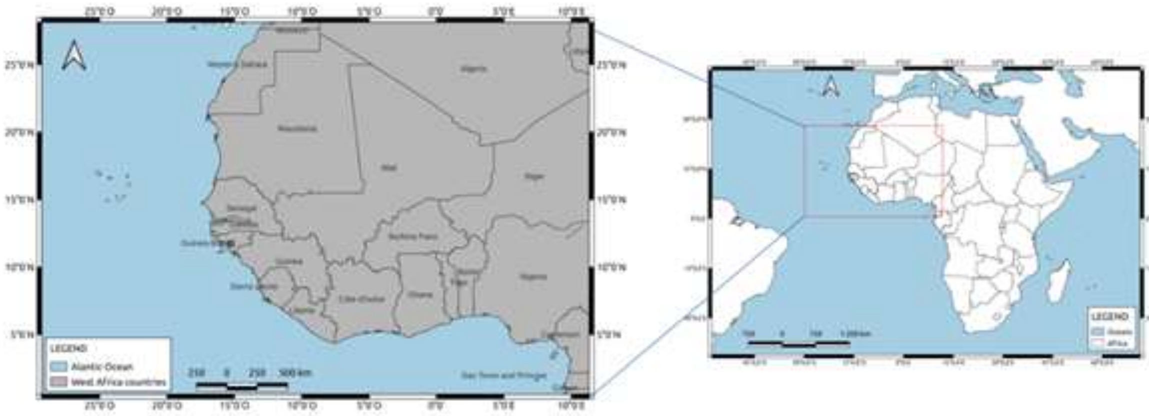

Figure 1. Map of localization of the study area.
Source: Authors

by filtering 12- and 6-month sinusoids. Regarding the modes of climate variability, we used a variety of climate indices that can have impacts on sea level variations:

(i) ENSO is a natural phenomenon that occurs in the tropical Pacific when the surface water temperature rises above 0.5 °C from normal over a period of five consecutive months due to a weakening of the trades winds that cause warm water to move east. The choice to look at the impact of ENSO on the RMSL is motivated by several studies showing a global impact on the water cycle, in particular on the interannual variability of the GMSL with strong positive anomalies during its warm phase (El Nino) and negative anomalies during its cold phase (La Nina) (Nerem et al., 2010; Llovel et al., 2010, 2011; Boening et al., 2012; Fasullo et al., 2013; Cazenave et al., 2014; Dieng et al., 2014, 2017). To characterize this phenomenon, we used 2 indices, namely the Southern Oscillation Index (SOI) and the Multivariate ENSO Index (MEI) that most characterize these events (Dieng et al., 2014). The SOI is a normalized index based on sea level pressure differences observed between Tahiti and Darwin (in Australia). The MEI is an empirical orthogonal function (EOF) time series that combines six main climate variables in the tropical Pacific: sea level pressure, zonal and meridional surface wind components, sea surface temperature, surface air temperature and total cloud fraction. The positive/negative phases of the MEI/SOI correspond to an El Niño event and negative/positive phases of the MEI/SOI correspond to La Niña.

(ii) For TACMV, we used several indices that characterize the climatic variability of the tropical Atlantic, that is, in order of importance, the Atlantic Meridian Mode (AMM), the Equatorial Atlantic (EA), the Atlantic Multidecadal Oscillation (AMO) and the Tropical Northern Atlantic (TNA). Indeed, the Eastern Tropical Atlantic, which includes our study area (West Africa), is a region of strong climatic modes of variability on interannual to decadal time scales. On the interannual scale, two modes are dominant: the Atlantic equatorial mode or Atlantic Niño and the inter-hemispherical mode or the meridian mode. The Atlantic Meridional mode is the statistically dominant mode of tropical Atlantic (Nobre and Shukla, 1996; Chang et al., 1997; Chiang and Vimont, 2004). This mode manifests itself as variations in SST in the northern and southern parts of the tropical Atlantic basin, across the Inter-tropical convergence zone (ITCZ) and it is described by the AMM index. Atlantic Niño appears every two and four years on average and presents hot and cold episodes (Atlantic Niño / Atlantic Niña), similar to that of the Pacific (El Niño - hot episode / La Niña - cold episode). However, due to the narrowness of the Atlantic basin, the oscillations are not as strong as those in the Pacific. Atlantic Niño is also characterized by a change of wind regime in the west of the basin, by a change of SST in the Gulf of Guinea and by variations of sea level slope in the equatorial band (AWO et al., 2018) and is described by the EA index. The other modes of variability in the North Atlantic basin are the North Atlantic Oscillation described by the NAO index and the Atlantic Multidecadal Oscillation described by the AMO index.

The AMM indice is calculated over the area (21°S-32°N and 74°W-15°E) by applying Maximum Covariance Analysis (MCA) to the Sea surface Temperature (SST) and the zonal and meridional components of the 10-m wind field over the time period 1950-2005, using the NCEP/NCAR Reanalysis. The EA indice is calculated over (6°N-6°S and 30°W-10°E) and produced at https://psl.noaa.gov/forecasts/sstlim/ using SST ERSST V3. The AMO indice represent the average SST anomaly over O°-80°N, calculated using the Kalplan SST V2. The TNA represents the anomaly of the mean monthly SST over the area (5.5°N - 23.5°N and 15°W-57.5°W), calculated using HadISST and NOAA OI 1x1 datasets. The NAO indice characterizes the difference of sea level pressure between the Subtropical High (Azores) and the Subtropical Low (Iceland). It is manifested by opposite profiles of temperature and precipitation anomalies and is obtained by projecting the NAO loading pattern to the daily anomaly 500 millibar height field over 0°-90°N (https://www.ncei.noaa.gov/access/monitoring/nao/). The Atlantic Multidecadal Oscillation occurs over periods of 60 to 80 years and is manifested by SST anomalies in the North Atlantic between 0°N-80°N.

The TNA, ENSO and TACMV indices are from: https://psl.noaa.gov/data/climateindices/lit/ and the NAO indice is available from the following link: https://www.cpc.ncep.noaa.gov/products/precip/Cwlink/pna/nao.shtml.

RESULTS AND DISCUSSION

The main objective of this study is to investigate the regional distribution of sea level in terms of interannual variability and trend. Thus, we identified the modes of climate variability in the Atlantic basin, but also in the Pacific (ENSO), which could have a significant impact on sea level variations and trend estimation over the altimeter

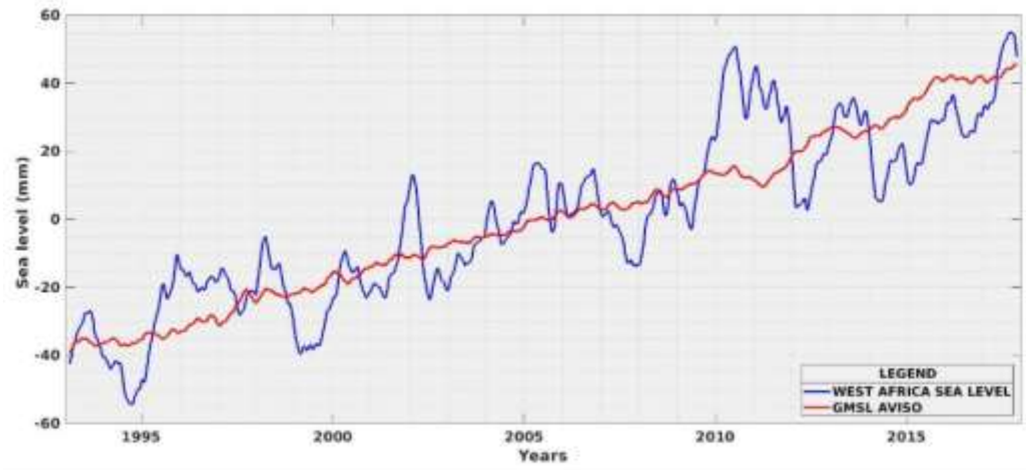

Figure 2. Regional Mean Sea Level (RMSL, in blue) from CMEMS grided data, version DT2018, and Global Mean Sea Level (GMSL) from AVISO (red). Annual and semi-annual cycles are removed and the series are smoothed over three months.
Source: Authors

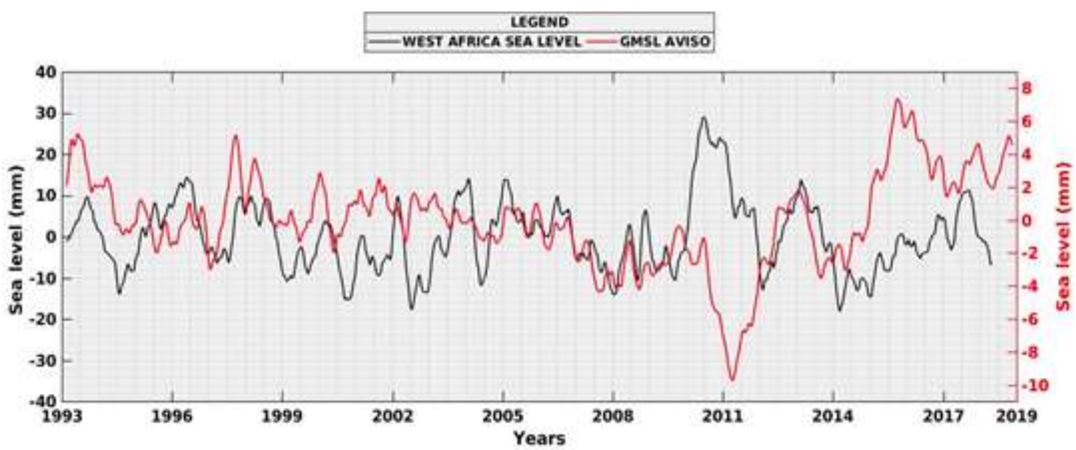

Figure 3. Interannual variations of sea level near the West African coasts and that of GMSL over the periods 1993-2018 and 1993-2019, respectively. The linear trend as well as the annual and semi-annual cycles are removed and the series are smoothed over three months. Note the different scales for the two curves.
Source: Authors

period 1993-2018.

Comparison between global and West African sea level variations

Figure 2 shows the time series of altimetry-based mean sea level variations over the period 1993-2018, at the global (GMSL) and regional (RMSL) scales. We observed a very similar trend between GMSL and RMSL, which is about 3.1 mm/year over the period 1993-2018. However, in terms of interannual variability, we noted a very large difference between GMSL and RMSL. The latter presents significant fluctuations around the trend that can reach 30 mm, that is, three times those observed on the GMSL. Interannual fluctuations are shown again in Figure 3 with linear trends removed from the time series. The differences in fluctuation can be explained by a more pronounced regional variation in the tropical Atlantic compared to the global ocean where regional variations tend to cancel out between ocean basins. We also noted that the largest interannual fluctuations are observed over the last decade compared with the earlier altimetry period. This can be related to the intensification of natural climate variability modes that has occurred for more than a decade, as suggested by Cazenave et al. (2014).

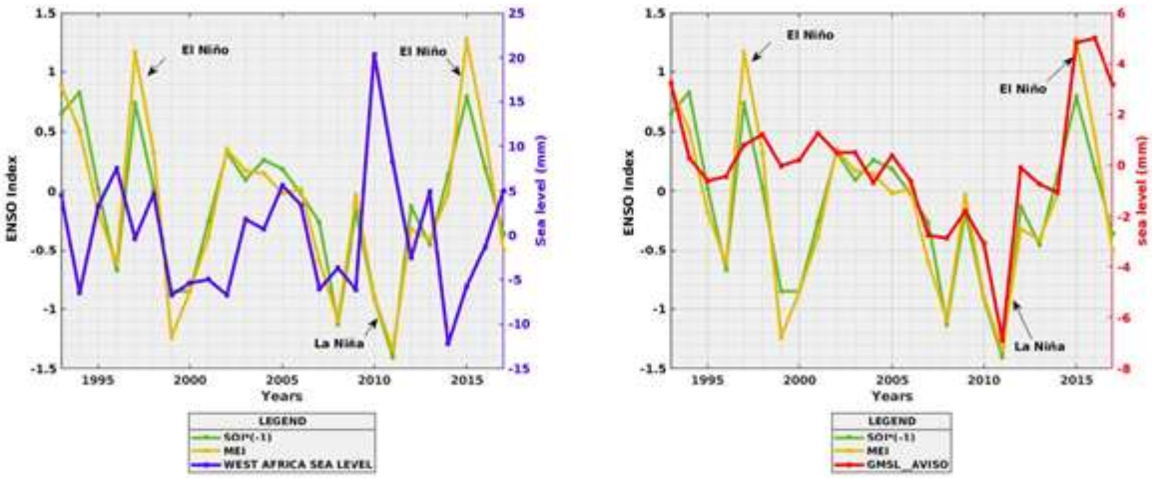

Figure 4. The ENSO indices (SOI and MEI) overlaid on the interannual variability of West Africa (to the left) mean sea level (WAMSL) and (on the right) of global mean sea level (GMSL) over the period 1993-2017.
Source: Authors

Influence of ENSO on the interannual sea level variability in West Africa

In order to analyze the influence of the ENSO phenomenon on the interannual variability of sea level in West Africa, Figure 4 presents the MEI and SOI indices (SOI is multiplied by -1 because pressure variations are inversely proportional to temperature variations). We observed negative RMSL anomalies during the two strongest El Niño events (1997-1998 and 2015) and a positive RMSL anomaly during the La Niña event of 2011 (the strongest over the last two decades). Therefore, as opposed to GMSL, RMSL has positive sea level anomalies during La Niña and negative anomalies during El Niño. However, RMSL only responds to strong ENSO events that have global impacts. This result suggests an influence of strong ENSO events beyond the Pacific basin to the Atlantic coast of West Africa. This is in agreement with previous studies (Nerem et al., 2010; Llovel et al., 2011; Boening et al., 2012; Fasullo et al., 2013; Cazenave et al., 2014; Dieng et al., 2017) showing a modification of the global water cycle with an excess of water over the ocean and a deficit over the continents (for example, in the Amazon basin) during El Niño and the opposite during La Niña. However, we are unable to explain by what mechanism strong El Niño/La Niña events can lead to negative/positive anomalies of RMSL, in opposition to GMSL.

Influence of TACMV and NAO on the interannual sea level variability in West Africa

In order to analyze the effect of the TACMV and of the NAO on the interannual sea level variability in West Africa, their associated indices (AMM, EA, NAO*(-1) and AMO) were used. Figures 5 and 6 show that the sea level peak observed in 2011 coincides with a positive phase of the AMM, EA, NAO and AMO. This particular year coincides with very high SST anomalies in the Atlantic basin (at the same time in the North Atlantic, North tropical Atlantic and in the Gulf of Guinea). Also, the correlations obtained between the interannual sea level variability in West Africa and the two main dominant climatic modes in the Atlantic (AMM and NAO indices) are quite high (correlation (NAO) = 0.51; correlation (AMM) = 0.65) and significant (P-value (NAO) = 0.0086; P-value (AMM) = 4.985 10^{-4}). This suggests that the TACMV and NAO have a major influence on the interannual sea level variability in West Africa, in addition to ENSO, which shows an impact during strong events.

Influence of SST Variability on the interannual sea level variability in West Africa

In order to analyze the impact of SST variations, we compared the Tropical North Atlantic (TNA) SST anomaly index (calculated with SST in the box 55°W to 15°W and 5°N to 25°N) with the sea level interannual variability in West Africa (Figure 7).

We observed a strong correlation (correlation=0.68) that is very significant (P-value (TNA) =1.797e^{-04}) between these two variables. This may suggest that SST interannual variations control a large part of the interannual sea level variability through regional thermal expansion. This would thus be the main process through which the natural modes of climate variability affect the region.

Spatial variability of sea level rise in West Africa

Figure 8a illustrates regional variations in sea level trend

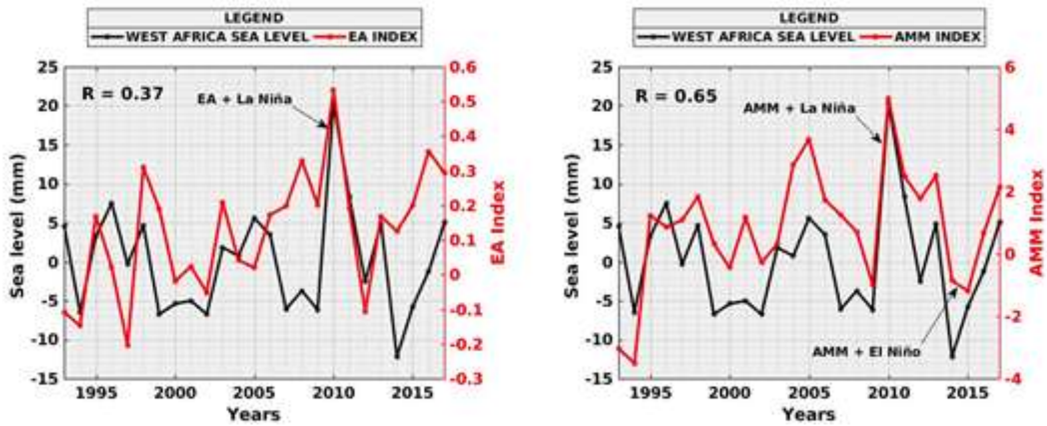

Figure 5. Interannual variability of sea level in West Africa over the period 1993-2017 and the TACMV indices (AMM and EA).
Source: Authors

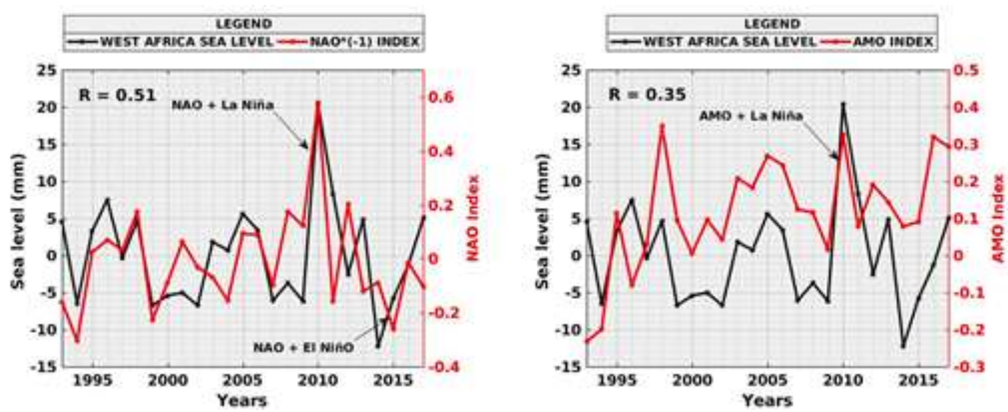

Figure 6. Interannual variability of sea level in West Africa over the period 1993-2017 and the North Atlantic modes of variability indices (NAO and AMO index).
Source: Authors

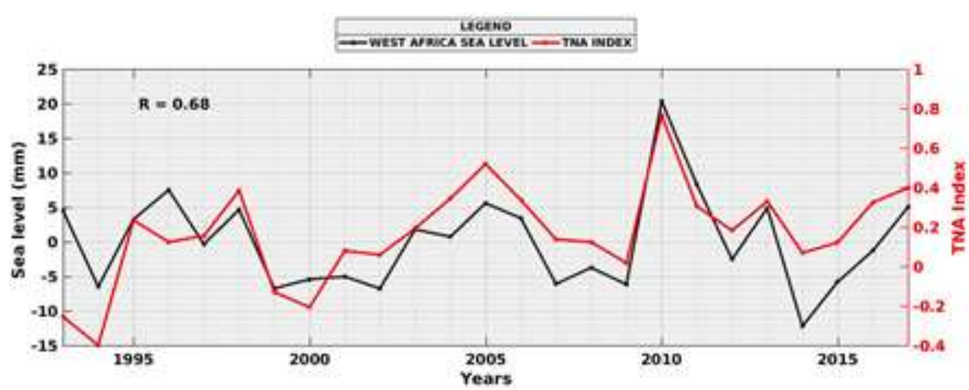

Figure 7. Interannual sea level variability in West Africa over the period 1993-2017 and the TNA index (SST index).
Source: Authors

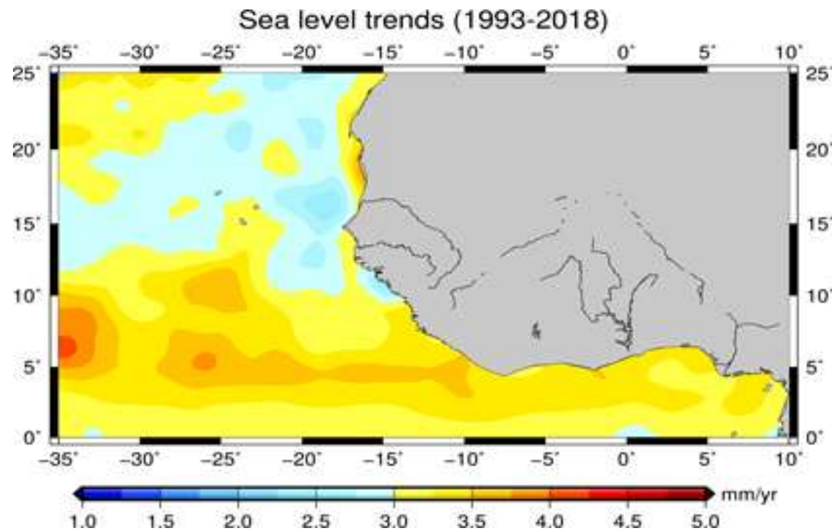

Figure 8a. Map of West African sea level rise in mm/year from the CMEMS (Copernicus Marine Environment Monitoring Service) gridded data, version DT2018, over the period 1993-2018.
Source: Authors

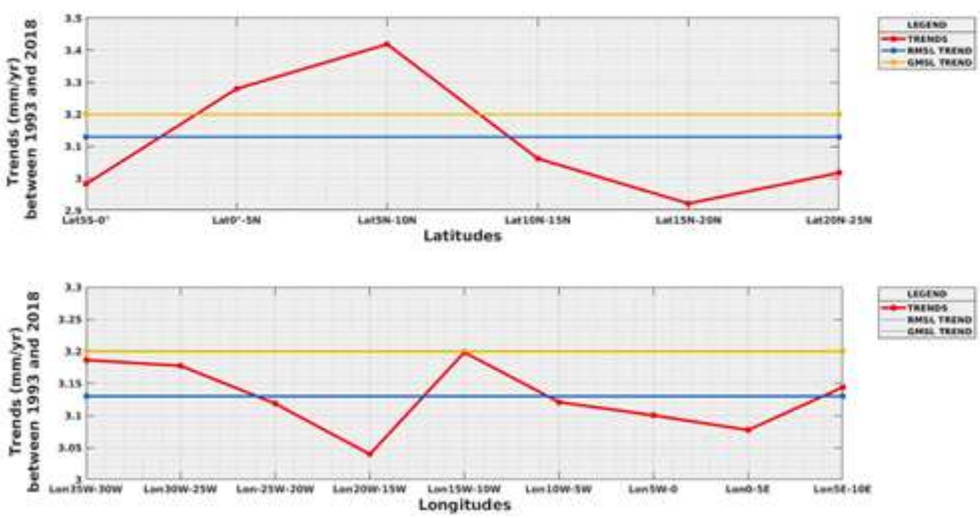

Figure 8b. (Red curves) Latitudinal (top) and longitudinal (bottom) variability of sea level rise near the West African coasts between 1993 and 2018. The mean GMSL and RMSL trends are shown for comparison.
Source: Authors

over the period 1993-2018 near the West African coast. It shows a non-uniform distribution of the regional sea level rise near the West African coast. To go further, we analyzed the spatial variability of sea level rise by bands (that is latitudinal and longitudinal variability). Figure 8b presents an SLR (Sea Level Rise) analysis on 5° latitude and 5° longitude bands, showing a strong spatial variability. Low latitudinal bands (0°N-5°N) and (5°N-10°N) are marked by a high rate, greater than that of RMSL (3.13 mm/yr) or GMSL (3.1 mm/yr). On the contrary, at higher latitude, the rate is lower than the regional and global means. Longitudinal variability in SLR increases from the coastal to the offshore zone. This is consistent with Marti et al. (2021) who show that SLR near the West African coast is significantly different from that offshore. In our data, the rate is weaker in the band

Table 1. Errors on the regional trend at different periods.

Periods	Trends (mm/year)	Errors	Errors (%)
5 years			
1993-1997	7.1571	0.2469	24
1998-2002	3.0124	0.2402	24
2003-2007	6.7458	0.1387	13
2008-2012	13.0690	0.2347	23
2013-2018	4.2029	0.1705	17
6 years			
1993-1998	5.6990	0.1634	16
1999-2004	5.5926	0.1554	15
2005-2010	-0.0944	0.1433	14
2011-2016	-2.3257	0.1696	16
2013-2018	4.2029	0.1705	17
7 years			
1993-1999	5.2441	0.1157	11
2003-2009	1.7458	0.1080	10
2012-2018	4.9518	0.1207	12
8 years			
1993-2000	2.4602	0.1142	11
2002-2009	2.1982	0.0919	9
2011-2018	1.9761	0.1146	11
9 years			
1993-2001	2.5953	0.0876	8
2010-2018	0.22	0.1057	10
10 years			
1993-2002	2.7305	0.0703	7
2009-2018	1.4225	0.0906	9
11 years			
1993-2003	2.8061	0.0627	6
2008-2018	2.2860	0.077	7
12 years			
1993-2004	2.6847	0.0522	5
2007-2018	3.0626	0.0695	6
13 years			
1993-2005	2.8995	0.0442	4
2006-2018	2.9119	0.0585	5

Source: Authors

(15°W-20°W) near the coasts of the Sahel and Sub-Saharan Africa areas. In the Gulf of Guinea, the rate is high in both the eastern zone (10E-5E, near the coasts of Cameroun and Equatorial Guinea) and western zone (15W-10W, near the coasts of Liberia). They are even higher than the regional rate while in the middle of the Gulf (10W to 5E, near the coast of Côte d'Ivoire, Ghana, Togo, Benin and Nigeria) the rate is lower.

Influence of interannual sea level variability on SLR estimation near the coast of Africa

Given the importance of interannual sea level variability near the West African coast, it is important to estimate its impact on the calculation of the RMSL trend, in order to determine the minimum period to be used for a significant estimation in our study area. To do this, we recalculated the RMSL trend over periods of 5 to 13 years. For example, the 5-year periods correspond to 1993-1997, 1998-2002, 2003-2007, 2008-2012 and 2013-2018. The trends with associated statistical errors are shown in Table 1. As expected, the error is smaller when the length of the time series increases. If we assumed an acceptable statistical error to be less than 0.1 mm/yr (or 10% of SLR), a reliable estimation of SLR in West Africa requires at least a time series of ten years. For smaller series, year to year anomalies can strongly impact the estimation. For example, the high rate obtained over the period 2008-2012 (13.07 mm/yr) can be explained by the large positive sea level anomaly (> 30 mm) of 2010-2011. Similarly, the negative trends for 2005-2010 (-0.09 mm/yr) and 2011-2016 (-2.33 mm/yr) can be explained by the negative sea level anomalies of 2008 and 2012-2015 respectively (Figure 3 and Table 1). Based on the previous error analysis, we now look at the SLR trend changes in West Africa using 10 years' time periods and comparing them to that of GMSL. We considered two cases: (1) successive trends, described by the first, second and last decades of the altimetric measurements (that is, 1993-2002, 2001-2010 and 2009-2018); (2) running trend, described by decades starting at three-year intervals (that is, 1993-2002, 1995-2004, 1997-2006, 1999-2008). Figure 9 shows that the trends are not constant or linear in time and the West African evolution do not correlate with that of GMSL. For example, the running trend shows an acceleration of RMSL in 1995-2004, 1997-2006 and 1999-2008 as opposed to GMSL (the rates in West Africa are: 1.73 mm/yr, 3.70 mm/yr and 4.09 mm/yr; and for GMSL: 3.42 mm/yr, 3.22 mm/yr and 3.04 mm/yr). We also had periods when RMSL is slowing down in West Africa (2003-2012, 2005-2014, 2007-2016 and 2009-2018) and speeding up in GMSL (the rates in West Africa are: 5.18 mm/yr, 3.70 mm/yr 2.62 mm/yr and 1.42 mm/yr; for GMSL: 2.59 mm/yr, 3.12 mm/yr 4.00 mm/yr and 4.49 mm/yr). With respect to changes in the successive decades (Figure 9, right panel), it also appears that regional and global trend changes are

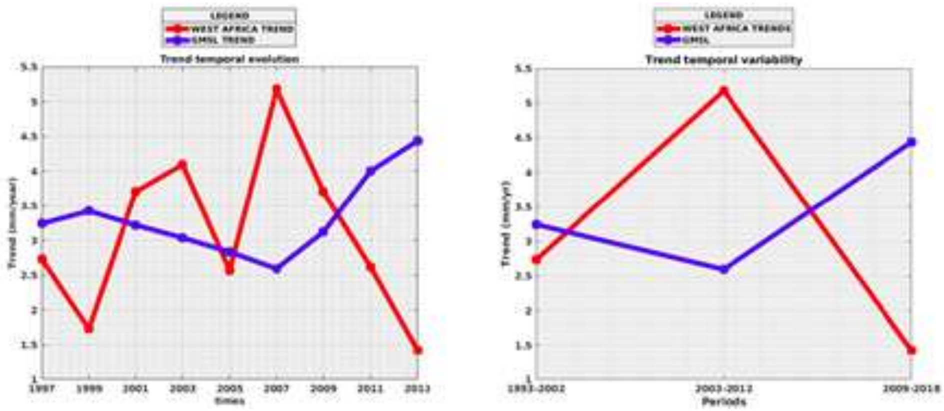

Figure 9. SLR running trend (left) and successive trend (right) over decades in West Africa (red) and GMSL (blue).
Source: Authors

anticorrelated, although the small number of decades available does not permit statistical significance. In the first decade of altimetric measurement, the RMSL in West Africa is lower than that of GMSL (+2.73 mm/yr versus +3.24 mm/yr). Then, during the second decade, it is twice larger (+5.18 mm/yr versus +3.59 mm/yr). Finally, over the last decade (2009-2018), there has been a considerable slowdown in RMSL in West Africa while there has been a global acceleration (+1.4 mm/yr versus +4.4 mm/yr). This apparent anticorrelation is reminiscent of that observed in the interannual variability (Figure 3) and shows the impact of this variability on the estimation of RMSL. This result is in agreement with Cazenave et al. (2014) who suggested removing the variability associated with natural climate modes for a better estimation of the sea level trend due to climate change.

Conclusions

This study aimed to improve the understanding of the current variations of sea level near the West African coasts. To that end, the study re-examined the spatial variability of the regional sea level trend and described its evolution over time using GMSL time series provided by AVISO and CMEMS gridded data, version DT2018 (specifically dedicated to regional sea level studies). The study shows that the distribution of sea level trend is not uniform in the region of West Africa and its evolution is not linear over time. In addition, if the mean tendency is similar in regional and global sea level, the time evolution of RMSL at interannual and decadal scales does not follow that of GMSL. This paper identified some factors related to global and regional internal (natural) climate variability that may have an influence on sea level interannual variability and trend in West Africa. The analysis is based on comparison of RMSL and GMSL with several indices associated with these climate modes. The study shows that regional climate variability, particularly that affecting regional temperature, has a strong influence on the trend and interannual variability of sea level in West Africa. Strong ENSO events are particularly efficient contributors. However, in the future it would be interesting to also analyze the influence of other environmental factors such as wind, precipitation and atmospheric pressure. The West African sea level budget could also be improved by identifying the main climatic factors contributing to regional sea level rise, which would address the lack of in situ data in the region.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENT

The authors are grateful for the financial assistance given by the European Union, DeSIRA project ‘Mangroves, mangrove rice and mangrove people: sustainably improving rice production, ecosystems and livelihoods’ (Grant Contract FOOD/2019/412-700).

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