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QUANTIFICATION OF SEA LEVEL RISE USING MULTI-MISSION SATELLITE ALTIMETRY DATA OVER NIGERIAN TERRITORIAL WATERS

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ABSTRACT

Many low-lying and vulnerable coastal areas especially the Nigerian coastlines are threatened by global sea level rise. Human lives and economic assets such as sea ports and tourism centres are threatened. This study assesses these threats by quantifying sea level variations and trends off the Nigerian coastline using measurements from multiple altimeter missions over 1993–2016. Sea level anomalies (SLAs) data were extracted from 9 satellite altimeter missions namely: TOPEX/ Poseidon, Jason-1, Jason-2, Jason 3, ERS-1, ERS-2, EnviSat, CryoSat-2 and SARAL. Sea level trends were determined by using moving average and time series linear regression analysis of both monthly and yearly averaged SLA solutions. The result showed that rate sea level rise trends over Nigerian territorial waters just off the coastline ranges from 2.23 ± 0.39 mm/yr to 4.90 ± 0.41 mm/yr. Over 1993–2016, the mean rising rate within the study area is 3.25 ± 0.65 mm/yr. Tidal SLA measurements of Sao Tome tide gauge station at Sao Tome and Province was used to validate SLAs from altimetry. The assessment result shows similar patterns of SLAs with high correlation coefficient of 90% and small root mean square differences (RMSE) of 3.62 cm between SLAs from altimetry and tide gauge over the same period. Predictions were made based on the assumption that sea level rise is constant every year, the obtained predictions as shows that sea level rise off the Nigerian coastline will be 0.18 – 0.21 m by the year 2041, 0.42 – 0.49 m by the year 2066, 0.66 – 0.77 m by 2091 and 0.90 – 1.05 m by the year 2116. For the few areas where the comparison in elevation of some coastal areas and the sea was done, the results showed that the difference ranges between 0.4 – 1.0

m. This study predicted the impact of such rising sea levels on the Nigerian coastal areas and proffers remedial measures to mitigate such impacts.

KEYWORDS: Sea level rise, satellite altimetry, sea level anomaly, Nigerian territorial waters.

INTRODUCTION

Many factors have contributed to global sea level rise. Climate change triggered mostly by anthropogenic activities has resulted in thermal expansion of ocean waters due to global warming. It has been the major factor of global sea level rise for 75 to 100 years after the start of the Industrial Revolution. The trend of sea level rise is proportional with the trend of rising global temperatures. Trenberth *et al., (*2007) showed that land ice glaciers, ice caps and ice sheets which store nearly two-third (2/3) of the world's freshwater are melting in response to high temperatures. (Cazenave & Llovel, 2010; Lombard *et al.*, 2005) revealed that shrinking of land ice has greatly increased in no small measure over the years.

There is evidence that these melting ice are adding water to the oceans, increasing their volume and causing sea level to rise (Cogley, 2009, Meier *et al.*, 2007; Kaser *et al.*, 2006). Church *et al.,* (2011) postulated that melting land ice contributed about one inch to global sea level from 1993 to 2008 accounting for more than half of the increase in sea level during that period. Other dominant factors such as local sinking of land, changing regional ocean currents, sediment deposits, and tectonic effects, subsidence of the land, astronomical tides, water density, ocean circulation, variations in atmospheric pressure, currents and storms etc. also can play a role in sea level rise.

The impacts of sea level rise cannot be overemphasized. It often results to inundation of wetlands and lowlands, exacerbation of coastal flooding threatening human lives and coastal structures, high rate of coastal erosion and leaching, increase in ocean salinity, threatens coastal tourism, increase in water tables and salinity of rivers, bays, and aquifers (Barth and Titus, 1984).

Nigerian coastline has a very low elevation (0 – 3 metres); rise in sea level leads to recurrent flooding and environmental degradation. The impacts of the flood includes; mortality, physical injuries, widespread infection and vector-borne diseases, homelessness, social disorders, food insecurity, economic losses (mainly through destruction of farmlands, social and urban infrastructures) and economic disruption (mostly in oil exploration in the Niger Delta), increase in water tables and salinity of rivers, tsunami, bays, and aquifers.

Furthermore, the use of coastal tide gauges has been the main and traditional technique to measure sea level change. However, there is gap in monitoring sea level changes using tide gauge data for the Nigerian coastline. This gap can be attributed to the absence of standard tide gauge stations along Nigerian coastline and estuaries (Ojinnaka, 2013). An alternative method to overcome this problem is to measure the absolute sea level from space i.e., satellite altimeter technique; this can serve as a complementary tool to the tide gauge.

Generally, radar altimetry is among the simplest of remote sensing techniques. Two basic geometric measurements are involved in this technique. Firstly, the distance between the satellite and the sea surface is determined from the round-trip travel time of microwave pulses emitted downward by the satellite's radar, reflected back from the ocean, and received again on board. Secondly, independent tracking systems are used to compute the satellite's three-dimensional position relative to a fixed earth coordinate system. Then, combining these two measurements yields profiles of sea surface topography, or sea level, with respect to the reference ellipsoid (a smooth geometric surface which approximates the shape of the Earth) (Fu & Cazenave, 2000).

This study presented sea level variations and quantified sea level trends off the Nigerian coastline using measurements from multiple altimeter missions over the period of twenty-four (24) years from 1993 – 2016. Data were extracted from nine altimeter missions, i.e. TOPEX, Jason-1, Jason-2, Jason 3, ERS-1, ERS-2, EnviSat, CryoSat-2 and SARAL to derive and quantify the absolute sea level trend off the Nigerian coastline over the period of twenty-four years (1993 - 2016). Then, use sea tidal data of Sao Tome tide gauge station to validate the satellite derived sea level trend. From the linear trends obtained; future predictions on sea level rise at 25 years interval were made for the Nigerian coastline.

1. MATERIAL AND METHODS

1.1 Description of the study area

The area of study is off the Nigerian coastline into the Gulf of Guinea of the Atlantic Ocean and the Sao Tome Principe, bounded by Latitude 0˚N to 6˚N and longitude 2˚E to 10˚E. The Nigerian coastline has a low lying topography located in the south western part of Nigeria, bounded by Latitude 4˚ 10' N to 6˚ 20' N and longitude 2˚ 45' E to 8˚ 35' E. It runs approximately 853 km through Lagos, Ondo, Delta, Bayelsa, Rivers, Akwa-Ibom and Cross-Rivers bordering the Atlantic Ocean.

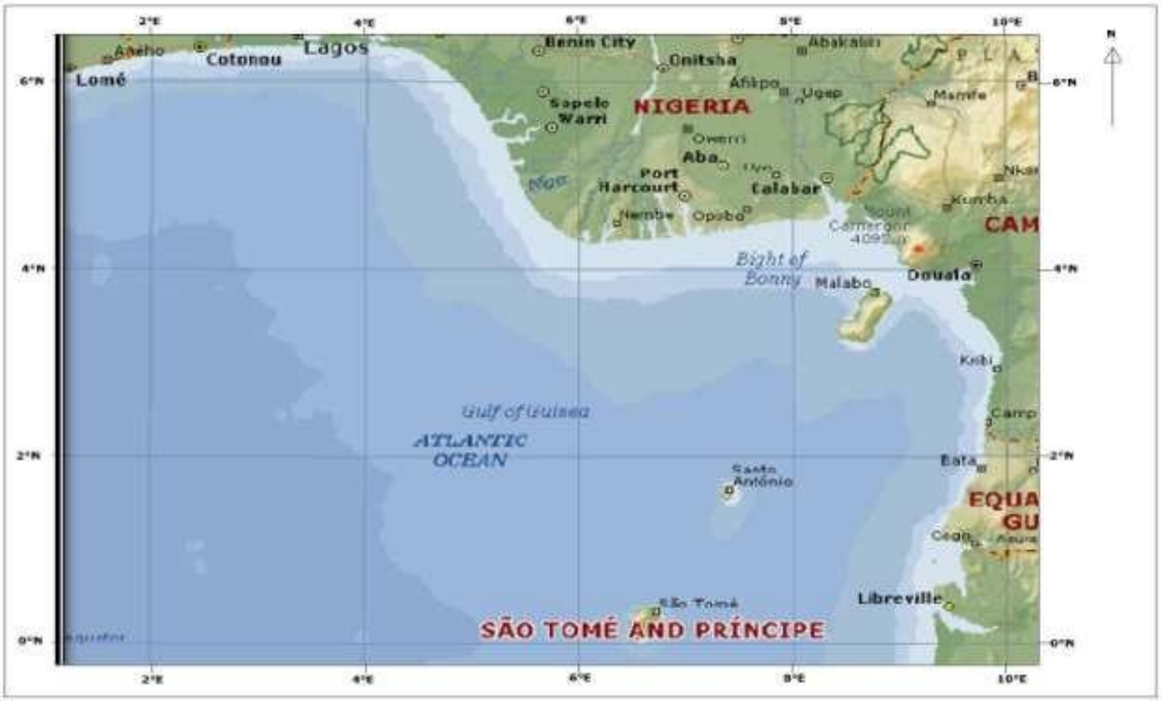

Figure 1: Map of the study area showing the Nigerian coastline, other coastal countries, Gulf of Guinea and Sao Tome and Principe (Source: Bello *et. al*., (2013).

1.2 Dataset used in the study

Three datasets were used in this study namely:

1. The Sea Level Anomaly (SLA) dataset.
2. The Sea Surface Height (SSH) dataset.
3. Tidal records of Sao Tome tide gauge station in Sao Tome and Principe.

Table 1: Summary of the Satellite Altimetry Datasets Description.

S/N	Features	Sea Level Anomaly (SLA) Dataset	Sea Surface Height (SSH) dataset	Tide Dataset
1	**Spatial Resolution**	0.17˚(Latitude) x 0.17˚ (Longitude).	1˚ (Latitude) x 1˚ (Longitude).	-
2	**Temporal Resolution**	Five (5) days.	Monthly	Daily
3	**Data Format**	Network Common Data Form (NETCDF) or .nc file extension	NETCDF (.nc)	ASCII (.asc)
4	**Data Coverage**	Latitude (0˚N - 6˚N) and Longitude (2˚E - 10˚E)	Latitude (0˚N - 6˚N) and Longitude (2˚E -	Sao Tome Tide Gauge station Latitude 0.3485˚,

			10˚E)	Longitude 6.7376˚
5	**Time range**	1993 – 2016 (24 years)	January 2016 – December 2016	29th August 2004 – 9th July, 2010
6	**Sources**	Open-Source Project for a Network Data Access Protocol (OPeNDAP): *https://podaac-opendap.jpl.nasa.gov/opendap/allData/merged_alt/L4/cdr_grid/*	AVISO website *ftp://podaac-ftp.jpl.nasa.gov/allData/aviso/*	The data can be accessed freely through *https://www.psmsl.org/data/* or https://www.sonel.org/msl/

1.3 Sea level anomaly (SLA) dataset

The dataset name is JPL MEaSUREs Gridded Sea Surface Height Anomalies (SSHA): Interim Version 1609. It is a global gridded dataset derived from sea surface height anomalies (SSHA) of multiple satellite altimeters namely TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 plus ERS-1, ERS-2, Envisat, SARAL-AltiKa, and Cryosat-2. It provides gridded sea surface height anomalies (SSHA) above mean sea surface on a 0.17˚ × 0.17˚grid spacing every 5 days using kriging method of gridding. The altimetric measurements were corrected for atmospheric effects (ionospheric delay and dry/ wet tropospheric effects) and geophysical processes (solid, ocean, and pole tides, loading effect of the ocean tides, sea state bias, and the inverted barometer response of the ocean). Detailed information of the corrections can be found at the AVISO website through www.aviso.com/. The dataset was made available by NASA distributed by Physical Oceanography Distributed Active Archive Centre (PODAAC).

1.4 Sea surface height (SSH) data

This is a global gridded dataset that contains sea surface heights (SSH) above geoid distributed by Archiving Validation and Interpretation of Satellite Oceanographic (AVISO) data. The data has grid spacing of 1˚× 1˚ for both latitude and longitude and monthly temporal resolution at year 2016 epoch.

1.5 Tide data

Monthly Tidal data for Sao Tome tide gauge station was used in this study. The Sao Tome tidal data used was over the time range from August, 2004 to July, 2010. The location of the tide gauge station with its coordinates as shown in figure 2 is Sao Tome and Principe. The data was made available by the Permanent Service of Mean Sea Level (PSMSL).

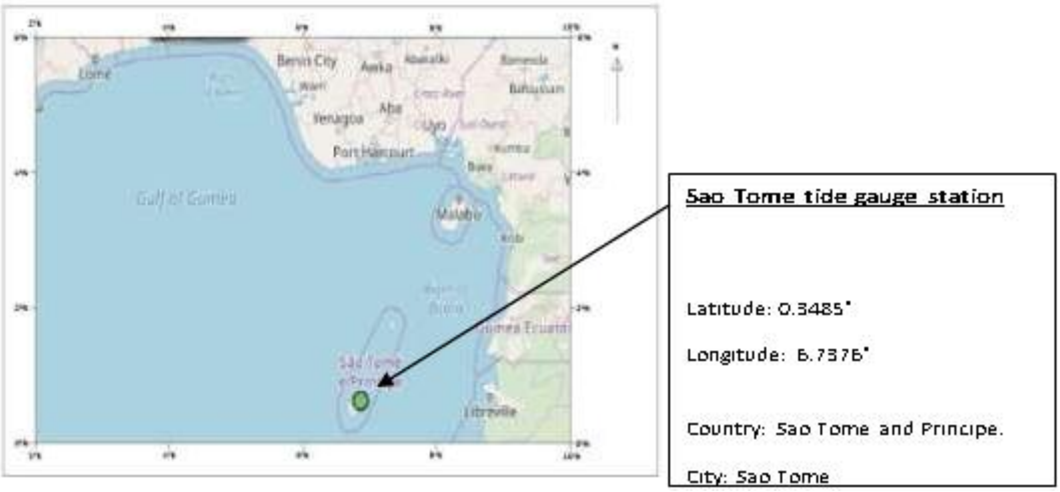

Figure 2: Map of the study area with the position of the Sao Tome tide gauge station *(Source: https://www.sonel.org/msl/)*.

Table 2: Points within the sub-areas used for sea level rise investigation.

S/N	Sub-area	Latitude	Longitude
1	Bight of Benin	5.9167°N	2.0833°E
2	Bight of Bonny	4.4167°N	8.4167°E
3	Gulf of Guinea	3.7500°N	3.7500°E
4	Atlantic Ocean	0.0833°N	2.0833°E
5	Sao Tome	0.4167°N	6.7500°E

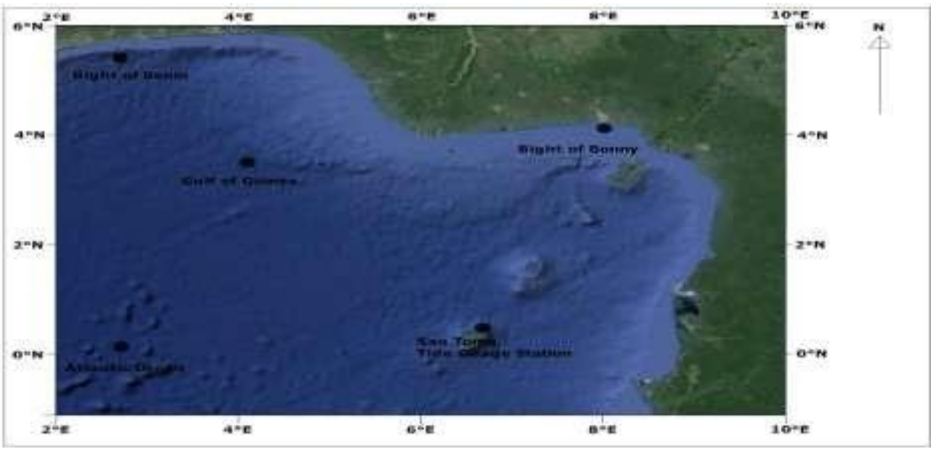

Figure 3: Points of observation off the Nigerian coastline *(Source: Google Earth)*.

2. Data Analysis

2.1 Satellite altimetry data verification

The satellite altimetry data was validated before performing trend analysis. The sea level anomaly data from satellite altimeter was compared with ground truth data (tidal data).The daily altimetry solutions were averaged into monthly solution. Sao Tome tide gauge station (latitude 0.3485˚N and longitude 6.7376˚ E) was used for data verification (see figure 2). Sao

Tome tide guage station was chosen because its location is within the study area and tidal records available at PSMSL. The results of the sea level verification were focused on the pattern and the correlation analysis between altimetry and tidal sea level anomaly (SLA) data. The comparison of sea level from altimetry and tidal data has been carried out by extracting the monthly sea level anomaly average at the tide gauge locations and the altimeter track nearby the tide gauge station. The closest point to the tide gauge station has the coordinates latitude 0.4167˚ and longitude 6.7500˚. The patterns of altimeter and tide gauge measurements were evaluated over the same period from August, 2004 to July, 2010 in order to produce comparable results and the correlation co-efficient. However, root mean square error (RMSE) measures the standard deviation of the residuals (Hyndman & Koehler, 2006) while r-squared (R^2) showed only the consistency in the pattern of the dataset (Glantz *et al.*, 1990). Though R^2 can be easily interpreted, but RMSE helped to explicitly know how much our predictions deviate, on average, from the actual in the dataset.

2.2 Time series linear regression analysis of sea level trend

The time series of the sea level trend in this study was calculated using time series linear regression. Time series linear regression is a statistical method for predicting a future response based on the response history of a dynamic parameter like sea level. Linear regression equation is written as follows:

$$y = ax + c \qquad \dots (1)$$

Where: y is the dependent variable (the trend of sea level rise); x is independent variable (time), in this case is the total months; a is the slope while c is the intercept. It helps us to understand and predict the behavior of dynamic systems (sea level) from experimental or observational data. The data used in this study was monthly and annually averaged. Monthly and yearly averaged solutions were used to study monthly sea level pattern and determine the rates of sea level rise in (mm/yr) at all points respectively.

The time series scatter plots showing the monthly sea level trend was plotted for the points and linear trend line fitted using method of least squares with the r-squared value. The r-squared (R^2) value is a statistical measure of how close the data are to the fitted regression line i.e. the goodness of fit. The value ranges between 0 and 1, with 1 representing perfect fit between the data and the fitted trend line, and 0 representing no statistical correlation between the observational data and the fitted trend line.

The annually averaged solution was used to derive the annual sea level trend at all points within the study area and trend line fitted. Based on the linear regression equation, the rates of sea level rise in (mm per year) at all points were determined by the slope of the fitted trend line in (mm/yr). The increasing trend per year was calculated using a modified formula in Cahyadi *et al.*, (2016) as follow:

$$Rate\ of\ Sea\ level\ rise\ \left(\frac{mm}{yr}\right) = \frac{Y_n - Y_0}{T} \qquad \ldots (2)$$

Where: Y_n is the value of sea level rise in month n, Y_0 is sea level rise in initial calculation, n total of months, and T is the total of years. The equation demonstrates whether the trend has increased or decreased over time, and if it has, how quickly or slowly the increase or decrease has occurred.

Furthermore, a color map was produced to show the absolute sea level trend over the study area using the coordinates of the data points and the rates of sea level rise. The sea level rise rates served as the Z-component. The color map produced using Surfer 10. With the assumption that sea level rise rate is static year to year, an estimation of the sea level rise for the years 2041, 2066, 2091 and 2116 was obtained by making future projection using the linear equation.

3. RESULTS AND DISCUSSION

3.1 Satellite altimetry data validation

Before the trend analysis was carried out, the altimetry data was compared with tidal data at Sao Tome tide gauge station. Figures 4 and 5 illustrate the sea level validation results over the study area by evaluating the sea level pattern at Sao Tome tide gauge station and a nearby point to it with coordinates latitude 0.4167˚ and longitude 6.7500˚over the same period from August, 2004 to July, 2010. The sea level anomaly values for this area ranges between -0.12 m to 0.15 m (120 mm<SLA> 150 mm) with sea level maximum in September, 2007 and minimum in July, 2008.

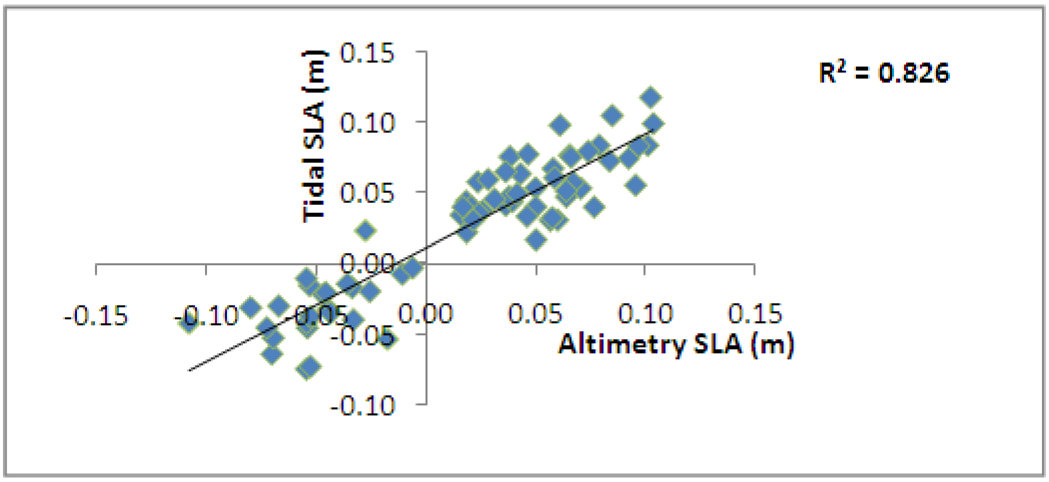

Figure 4: Evaluation Scatterplot of both Altimetry Data and Tide Data.

The similarity in the pattern of sea level from altimeter and tide gauge indicated good agreement accordingly. The correlation coefficient is 0.9126 or 91% with root mean square error (RMSE) of 3.62 cm. The high value of the correlation co-efficient between the tidal and satellite altimetry anomalies does not indicate high level accuracy rather; it shows that both sea level patterns are in phase with one another. Also, there is good consistency in the pattern of the datasets with r- squared value of 82%.The year to year variation sea level variation can be seen from the tidal and altimetry trends.

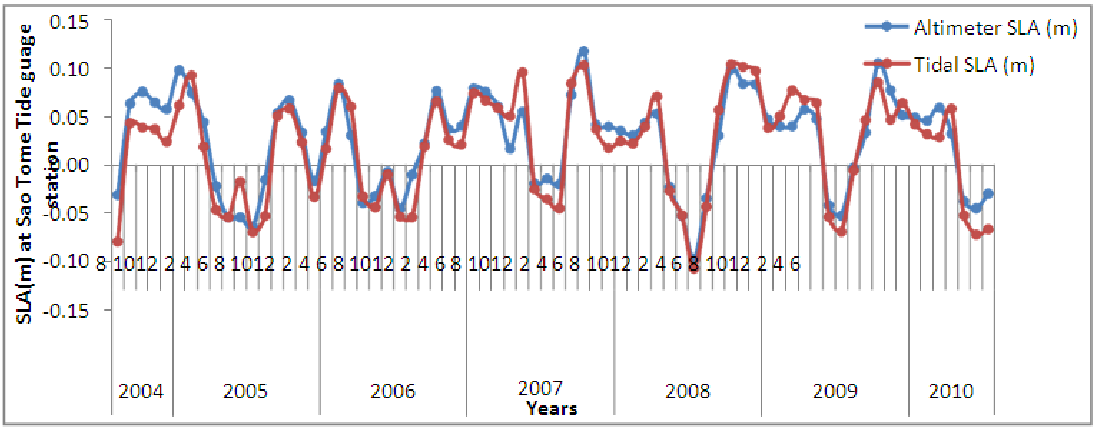

Figure 5: Evaluation plot between tidal (red) time series and altimetry (blue) time series with its correlation respectively.

3.2 Sea level trend using time series linear regression

From the time series analysis conducted at 5 test points in different sub-areas using the monthly averaged SLA solution, the monthly sea level trend obtained are shown in figures 5

(A,B,C,D and E). At the 5 points, different values were obtained for the sea level trend. There was consistency and good correlation in the pattern of the datasets based on the values of the r- squared (see Table 3). Rise in sea level was observed at all points since; the fitted trendline produced a positive slope which represents an increase in rate of sea level trend. The moving average trend verged in red removed short term fluctuations to reveal long-term trend.

Table 3: R-squared Values Obtained at points in the Sub-areas.

S/N	Sub-areas	Latitude	Longitude	R2
1	Bight of Benin	5.9167˚N	2.0833˚E	0.8843
2	Bight of Bonny	4.4167˚N	8.4167˚E	0.8357
3	Gulf of Guinea	3.7500˚N	3.7500˚E	0.8167
4	Atlantic Ocean	0.0833˚N	2.0833˚E	0.8153
5	Sao Tome	0.4167˚N	6.7500˚E	0.8605

Based on monthly SLA data and chart changes in sea level fluctuations, the maximum and minimum SLA for 24 years was obtained (see Table 4). The maximum SLA occurred mostly in November, 2010 then October (2012 and 2015). The minimum SLA occurred mostly in June and July. The complexities of the patterns are arguably due to dominant wind stress that causes ocean upwelling and down-welling, seasonal anomalies and varying sea surface temperatures (SST).

Table 4: SLA Minimum and Maximum Values.

S/N	Sub-areas	SLA (m)			
		Min	Period	Max	Period
1	Bight of Benin	-0.0962	June, 1994	0.1150	November, 2010
2	Bight of Bonny	-0.0934	June, 1993	0.1574	October, 2015
3	Gulf of Guinea	-0.1039	July, 1994	0.1322	November, 2010
4	Atlantic Ocean	-0.1295	June, 1994	0.1136	November, 2010
5	Sao Tome	-0.1280	July, 1996	0.1491	October, 2012

Changes in sea surface (both increases and decreases) were due to several factors. Llovel *et al.*, (2010) has stated that the most influential factor to changes in sea level is the regional and global changes in steric sea level due. A change in steric sea level is defined as the change in the density of the water column due to temperature and salinity anomalies.

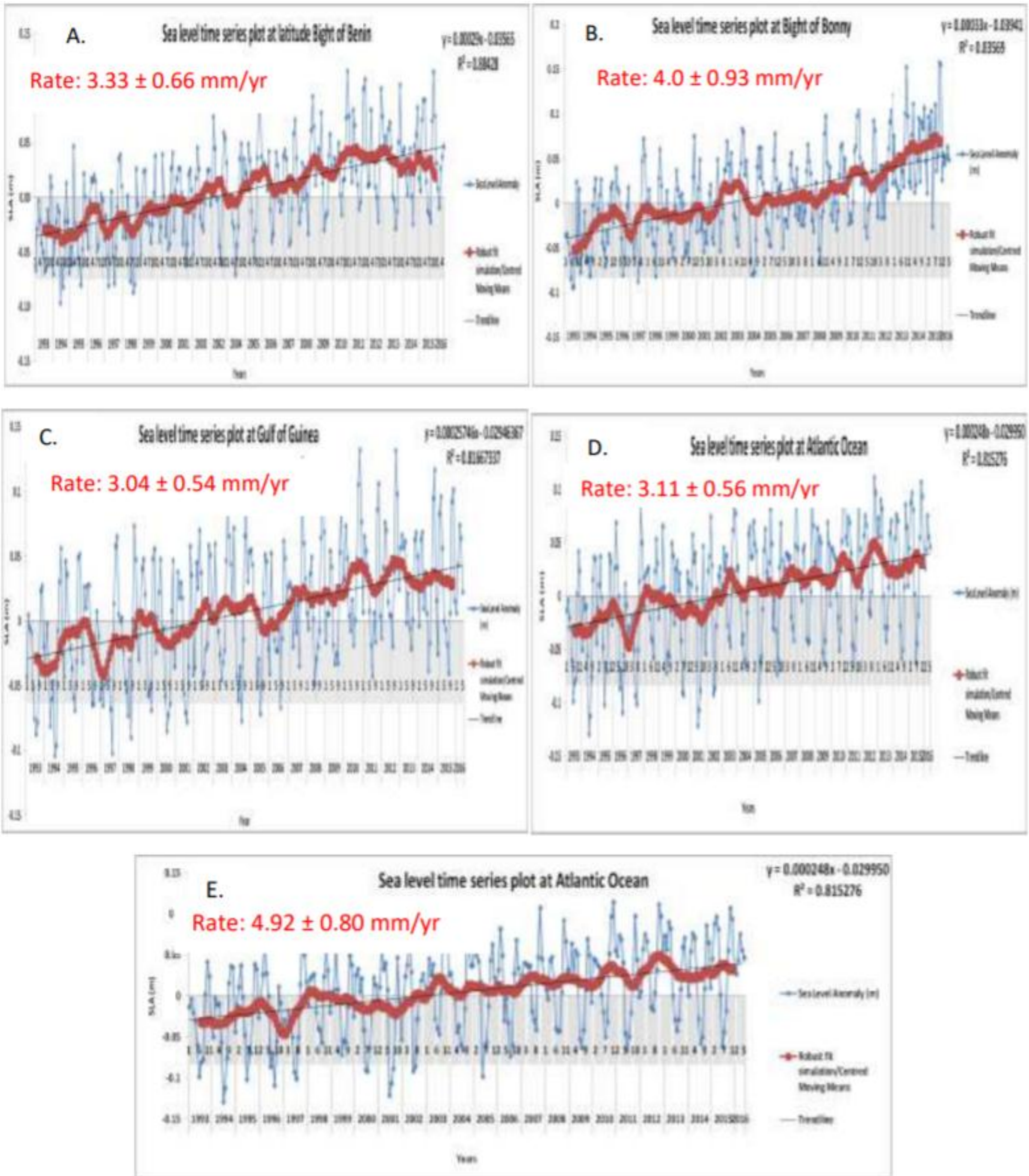

Figure 6: (A) Sea level time series plot at station 1 (Bight of Benin), (B) Sea level time series plot at station 2 (Bight of Bonny), (C) Sea level time series plot at station 3 (Gulf of Guinea), (D) Sea level time series plot at station 4 (Atlantic ocean), and (E) Sea level time series plot at station 5 (Atlantic ocean).

Table 5: Sea level Rates at the Sub-areas.

S/N	Sub-areas	Latitude	Longitude	Rate of sea level rise (mm/yr)
1	Bight of Benin	5.9167˚N	2.0833˚E	3.33 ± 0.66
2	Bight of Bonny	4.4167˚N	8.4167˚E	4.00 ± 0.93

3	Gulf of Guinea	3.7500˚N	3.7500˚E	3.04 ± 0.54
4	Atlantic Ocean	0.0833˚N	2.0833˚E	3.11 ± 0.56
5	Sao Tome	0.4167˚N	6.7500˚E	4.92 ± 0.80

The absolute sea level trend over the study area derived from multi-mission satellite altimetry data (see figure 7). The result clearly shows that the absolute sea level trend is rising and varying from place to place within the study area.

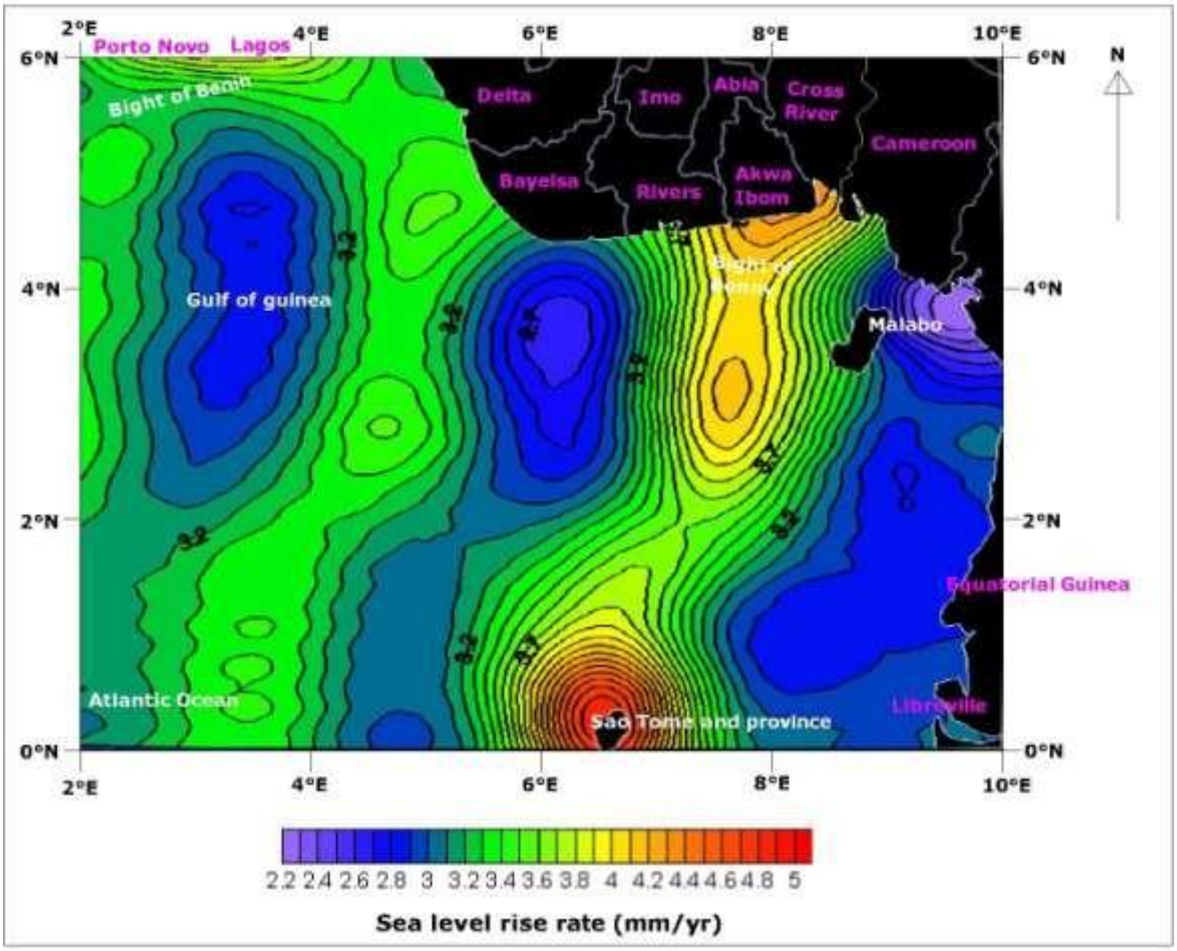

Figure 7: Map of Absolute Sea Level trend over the Study Area.

For the entire study area, the rate of sea level rise varies and ranges from 2.23 ± 0.39 mm/yr to 4.90 ± 0.41 mm/yr with mean sea rising rate of 3.25 ± 0.65 mm/yr. The result shows that rate of sea level rise within Gulf of Guinea ranges from 2.7 ± 0.47 mm/yr to 3.34 ± 0.63 mm/yr while for Bight of Bonny has a higher rate between 3.8 ± 0.87 mm/yr to 4.1 ± 0.5 mm/yr. The Sao Tome region has the highest rate of sea level rise up to 4.90 ± 0.32 mm/yr while the lowest rising rate occurred close to Malabo at 2.2 ± 0.39 mm/yr. The reason for the regional variability in rates of sea level rise can be attributed to land subsidence especially in Gulf of Guinea and Sao Tome, ocean current and regional temperatures. Sao Tome is saddled with volcanic activities due to its mountainous topography. This is suspected to have contributed to its high rising sea level rate.

Williams (2013) revealed that sea level began rising at a global average rate of 1.7 mm/year. The published value by AVISO's sea level research team (2016) where from the year 1993 to 2015, the global sea level rise is estimated at a rate of 3.39 mm/yr by using only a combination of Topex/Poseidon, Jason-1 and Jason-2 altimetry data. This means that the rate of sea level rise within the study area is slightly less than the world's as at 2016. Using this research, predictions were made based on the assumption that sea level rise is constant every year (see table 5). The sea level rise off the Nigerian coastline will be 0.18 – 0.21 m by the year 2041, 0.42 – 0.49 m by the year 2066, 0.66 – 0.77 m by 2091 and 0.90 – 1.05 m by the year 2116.

Table 5: Sea Level Rise Predictions per 25 Years.

Years	Sea level rise minimum (m)	Sea level rise maximum (m)
2041	0.18	0.21
2066	0.42	0.49
2091	0.66	0.77
2116	0.90	1.05

Using ground truth data, the Obolo Creek at Eastern Obolo in Akwa-Ibom State with geographical coordinates 4.533˚N and 7.7˚E has range of orthometric heights between -1.371 m and 3.113 m with mean of 1.007 ± 0.7 m. Bille in Degema, Rivers State with geographical coordinates 4.577˚N and 6.883˚E has orthometric height range between 1.002 m and 2.04 m with the average orthometric height to be 1.568 ± 0.3 m.

Table 6: Comparison in elevation between Subareas within the Study Area and some Coastal Areas.

S/N	Sub-areas	Coordinates	Average SSH above the geoid (m)	Coastal Areas	Coordinates	Average Orthometric Heights (m)	Difference (m)
1	Bight of Bonny	4.4167˚N 8.4167˚E	0.501 ± 0.06	Obolo Creek, Akwa- Ibom	4.533˚N 7.700˚E	1.007 ± 0.7	0.506
				Bille,	4.577˚N	1.568 ± 0.3	1.067
				Degema, Rivers State	6.883˚E		
2	Bight of Benin	5.9167˚N 2.0833˚E	0.498 ± 0.03	Epe, Lagos State	6.583˚N 3.983˚E	0.925 ± 0.2	0.427

From all indications, the Nigerian coastal areas are under threat due to sea level rise and it is the major economic zone of the country. Continuous rise in sea level will adversely affect the economy due to loss of land, loss of infrastructures and physical capital, additional cost from extreme events and coastal floods and erosions etc. Also, greater populations living within the coastal areas are vulnerable to displacement and in worst case scenario death. Coastal tourism and recreation is also vulnerable to impact of the sea level rise due to damage to tourist infrastructures example beach resorts, roads. Nigeria has a good number of these coastal tourism centres like the Lagos Lekki Beach, Elegushi Beach etc. This also rubs off on the economy as tourism is one of Nigeria's economy drivers.

CONCLUSION

Most recent developments indicate that sea level is currently rising. By having enough confidence in the data and selecting the best methods for processing and analysis of the data altogether from year 1993 to 2016, the results show that the study area which contains Gulf of guinea, Atlantic ocean, Bight of Bonny, Bight of Benin has an upward sea level rise trend. The rate of sea level rise ranges between 2.23 ± 0.39 mm/yr to 4.90 ± 0.41 mm/yr, with a mean rising rate of 3.25 ± 0.65 mm/yr solely based on satellite altimetry. This sea level rate obtained is a bit lower than the published value by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) Sea Level Research Team (2016), where from the year 1993 to 2015; the global sea level rise is estimated at a rate of 3.39 mm/yr by using only a combination of Topex/Poseidon, Jason-1 and Jason-2 altimetry data. It was predicted to have an additional sea level of which will be 0.18 – 0.21 m by the year 2041, 0.42 – 0.49 m by the year 2066, 0.66 –0.77 m by 2091 and 0.90 – 1.05 m by the year 2116 on the assumption that sea level rise is constant every year.

RECOMMENDATIONS

The information about sea level trends in this region is indeed valuable for the coastal management, town development, and flood mitigation. It is also important to be used in projecting the sea level rise for future regional climate. Sea level rise projection information can be used for coastal adaptation. Thus, adaptation measures are necessary to reduce the possible impacts of sea level rise especially in coastal zones. In order to limit the negative impact of sea level rise at the Nigerian coastline, the adaptation measures such as coastal defenses, beach nourishment, offshore barriers, flood gate; mangrove creation etc. should be implemented.

There is need for more studies on assessing the vulnerability of coastal communities to flooding and inundation upon a rise in sea level. This will build efforts in contingency planning and adopting preventive measures in the event of flooding due to sea level rise.

Frequent dredging of Nigerian coastal waters can help widen the difference in height between coastal land and the sea. This will help to reduce the inundation of coastal lands due to sea level rise. Government can also shore up areas along the Nigerian coastline with very low lying topography.

There is need to maintain an efficient tide gauge network along the Nigerian coastline as they can be used not only to monitor and understand sea level changes but, can be used to calibrate signals derived from satellite altimetry.

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