Long Term Sea Level Change in the Gulf of Guinea from Multi-Mission Altimetry Data

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The sea level variations from 2000 to 2015 within the Gulf of Guinea and the Atlantic Ocean with satellite altimetry information acquired from TOPEX, ERS-2, ENVISAT, CRYOSAT-2, JASON-1, JASON-2 and SARAL missions have been examined. These sea level information was recaptured and processed using the radar altimeter database system (RADS). During processing with the RADS, the 2016 upgraded geophysical and environmental corrections were put in. For the altimetry data comparison, three tidal stations were chosen in order to ascertain the correlation that exists between the ocean tide models selected for the study. Similarity in the trends of sea level fluctuations betokens impressive acquiescent between altimetry data independently obtained with GOT4.10 and FES2004 ocean tide models (OTMs). From the 16 years' altimetry data, results from both OTMs show positive sea level trend within the region. The sea level time series information from altimeter revealed that since 2000, the mean sea level in the Gulf of Guinea has been elevating—depending on the geography—at a rate of 2.4 mm/year and 3.6 mm/year with the GOT4.10 and FES2004 OTMs respectively. Also, both ocean tide models vary in the estimated sea level trends by 1.2 mm/year and have a root-mean-square difference of 1.3 cm. This kind of information is important for better understanding of the marine ecosystem, studying environmental talking points cognate to flooding probes and universal warming, overdue for an area that until now is yet to be adequately explored by the altimeter science community.

Keywords: Ocean Tides; Radar Altimeter Database System (RADS); Satellite Altimeter; Sea Level Anomaly

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LONGTERM SEA LEVEL CHANGE IN NIGERIAN COASTAL WATERS FROM MULTI-MISSION ALTIMETRY DATA

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ABSTRACT. The sea level variations from 2000 to 2015 within the Nigerian coasts of the Gulf of Guinea and the Atlantic Ocean with satellite altimetry data of the TOPEX, ERS-2, ENVISAT, CRYOSAT-2, JASON-1, JASON-2 and SARAL missions have been examined. Sea level data recapturing and processing were carried out using the radar altimeter database system (RADS). In RADS data processing, the 2016 upgraded geophysical and environmental corrections were put in. For the altimetry data comparison, three tidal stations were chosen in order to ascertain the correlation that exists between the ocean tide models selected for the study. Similarity in the trends of sea level variations betokens good acquiescent between altimetry data independently obtained with GOT4.10 and FES2004 ocean tide models. From the 16 years' altimetry data, results from both ocean tide model show positive sea level trend within the region. The altimeter sea level time series revealed that since 2000, the mean sea level in Nigerian coastal waters has been elevating at a geographically-dependent rate of 2.4mm/year and 3.6mm/year with the GOT4.10 and FES2004 OTMs respectively. Also, both ocean tide models vary in the estimated sea level trends by 1.2mm/year and have a root-mean-square difference of 1.3cm. This kind of information is important for better understanding of the marine ecosystem; studying environmental issues cognate to flood investigations and universal warming especially for an area that until now is yet to be adequately explored by the altimeter science community.

Keywords. Sea Level Anomaly, Satellite Altimeter, Ocean Tides; Radar Altimeter Database System (RADS)

1. INTRODUCTION

Unlike tide gauges with scant network located at coastal and mid-ocean islands, sea level quantifications from space facilitated by satellite radar altimetry yield near universal and common origin coverage of the world’s oceans, thereby making it possible for more accurate determination of regional sea level variation. Satellite altimeters are designed to quantify ocean level relative to the centre of the earth. Unlike tide gauges having locally measured sea level trends which are affected by vertical land movements (tectonic motions, subsidence), satellite altimetry is alien to such effects. Though tasking, the provision of geophysical/environmental corrections, altimeter range estimations and satellite orbit information of the highest accuracy, helps to achieve the desired highest possible accuracy. It is likewise reliant on nonstop satellite operations in large portions a considerable length of time and watchful control of inclinations [1].

The significance that accompanies long-term sea level change cannot be over-stated as it cuts across varying social, economic and environmental issues, particularly for the vast bit of the earth’s populace residing within coastal zones. Measurements from tide gauges have served as the primary source of data on sea level variation over the past century. However, where available, tide gauges poorly depict the global oceans, in addition to being influenced by vertical land movements which are unconnected to climate-influenced ocean level variations. Instead, in recent decades, satellite estimations have revolutionized our comprehension of sea level variation [2]. Various phenomena which include distortion of the ocean basin or land uplift/sinking, including other factors such as the melting of ice caps and thermal expansion/contraction of the oceans might be responsible for the lengthy periodic variations in ocean level.

Ocean level monitoring, an important apparatus for deciding and foreseeing changes and patterns in the ocean level, is ideally built upon accurate, dependable tide gauge measurements made over many years [3]. Unfortunately, many years of consistent tide gauge data for ocean level checking has been lacking in Nigeria and Western African region. Despite the fact that only a few of these tide gauge stations are operational, problems of inconsistent spatial location, defective equipment, breaks in data continuity and short coverage time periods diminishes the acceptability of climatic variation estimates from such data. If data from this method of measurement is used alone, without carefully considering its drawbacks, the resultant models would be seriously constrained in their use for trustworthy future projection.

According to a 2006 report by Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organization, worldwide mean ocean level has been observed since 1992, by high accuracy satellite altimetry, to be increasing at a rate of approximately 3mm per year (i.e., 3.2 ± 0.4 mm/year). In a similar vein, a report by the Intergovernmental Panel on Climate Change[4] (IPCC) revealed the global average ocean level had risen “at an average rate of 1.8 [1.3 to 2.3] mm per year over 1961 to 2003 and at an average rate of about 3.1 [2.4 to 3.8] mm per year from 1993 to 2003”. Both reports affirm the suspicion that there is an increase in the rate of rise in global mean sea level, since the early 1990s. There are many possible negative impacts on the coastal environment like beach erosion, immersion of land, increased flooding and storm damage, coastal aquifers having increased salinity and the loss of the coastal ecosystem that comes with the rise in ocean level. In view of these, it is evident that low lying areas such as beach ridges, coastal plains, deltas, estuaries, lagoons and bays would be the most devastated as a result of the enhanced sea level rise. Hence, for effective coastal management, the need for proper articulation of previous and future changes in sea level is very essential.

The earth undergoes some form of distortion caused by the weight of the ocean tides. The water in the ocean tides keeps moving and these mass redistributions cause periodic stacking of the ocean base. Due to the earth being semi-rigid, it distorts under this load. This phenomenon is described as Ocean Tide Loading. It could be viewed as variations in vertical and horizontal displacement, in gravity, tilt and in strain at a selected station. The ocean tides are products of gravitational drag of the Moon and Sun, also since their orbits have more than one periodicities because of the eccentricity, evection and the lot, it is possible to portray the ocean tides as the aggregate of several ocean tides with each having their own time portion.

In Naeije et al.[5], almost 17 years' ocean level variation was examined, combining every accessible altimeter (leaving out GEOSAT and POSEIDON). Findings from the study estimated the worldwide mean sea level rise at the rate of 2.53 mm/year. Besides, by using satellite altimetry data of the TOPEX, ERS-1, ERS-2, ENVISAT and JASON-1 missions from 1993-2008, Din et al.[6] investigated ocean level variations in the Malaysian seas with results showing a consistent rising of mean sea level since 1993 at a rate between 1.4 to 4.1 mm/year depending on the geographic location.

In most countries, tide gauges near the shoreline have given the fundamental technique to measure variation in ocean level. Yet, the absence of adequate tide gauges and lengthy period of tidal data in Nigeria and neighbouring countries mean that sea level changes currently cannot be realistically quantified with data whose accuracies are considerably less than what can be obtained using satellite altimetry technique. Also, aside the problem of uneven geographical distribution of tide gauge stations (when available), many years of tidal information which cover the vast ocean are almost non-existent. Satellite altimetry method, which measures the ocean level using space technology provides an alternative to addressing these problems. Altimetry gives beneficial possibility as an enhancement instrument to the accepted sparsely located tide gauge instruments in studying ocean level change in Nigerian seas (parts of Atlantic Ocean and the Gulf of Guinea). Sea level studies using altimetry have become very imperative, especially with the flooding experiences in recent years the country is still trying to fully grasp. Hence, this research is the maiden deliberate study on the sea level rise phenomena in Nigerian seas, dependent on satellite altimetry data record (16 years).

2. The Concept of Altimetric Measurements and Data Processes for Sea Level Rise Analysis

2.1 Multi-Missions Satellite Altimetry and Data Processing

Estimations from satellite-borne altimeter are now ceaselessly accessible since 1991, via the ERS-1, TOPEX/Poseidon (T/P), ERS-2, Geosat Follow-on, JASONs 1, 2 & 3, ENVISAT, CRYOSAT-2 & SARAL missions. Our understanding of the ocean has been extraordinarily enhanced by estimations from these instruments, through sea level investigations, climate fluctuations and ocean circulation. Launched in 1992, the T/P satellite mission lasted until October 2005. Since 2002, JASON-1 has succeeded in taking over the original ground track of its predecessor the T/P. That of Jason-1 was overtaken by Jason-2. There is a general consensus among scientist that the T/P and Jason series satellite missions when compared to others, give the most precise altimetry data because of its very precisely determined orbit. There is a repetition in the ground path pattern of these satellites every 10 days, this gives near-global (within ± 66° latitude) maps of ocean level variation with this time varying sampling [2]. By providing ocean level estimations with highly improved spatial coverage, this method seems quite assuring for the ocean level variation issue, even if satellite altimetry records cannot boast of century long data like tide gauges [7].

The European Space Agency (ESA) owned ERS satellites (1 and 2 launched in 1991 and 1995 respectively) were the maiden to acquire microwave radar data that were later made commercially available, which offered new vistas for varieties of remotely sensed applications. Both were not as suitable for ocean tide investigations as expected coupled with slightly less accurate orbit due to their being launched into a sun-synchronous orbit makes them more susceptible to atmospheric drag. A successor mission called the Environmental Satellite (ENVISAT) was launched by ESA in March 2002, being a further polar-revolving earth observation satellite that gives estimations of the ocean, land, atmosphere and ice [8].

In terms of Ka-band altimetric mission specifically reserved for oceanography, the India-France SARAL/AltiKa mission is the first. This joint mission called the Satellite for ARgos and ALtika (SARAL) program, conducted by the Indian Space Agency (ISRO) and the French Space Agency (CNES) is dedicated mainly to ocean measurements. Launched on 25 February 2013 at 12:31 UTC, it reached final orbit on 13 March 2013. After its switch on in February, the AltiKa altimeter began its maiden cycle on 14 March at 05:39 UTC [9]. The study of the oceanic mesoscales viability, including coastal oceanography, worldwide and regional ocean level monitoring, data gathering, and operational oceanography are the primary objectives of the mission. The secondary objectives focus on ice sheet and inland water monitoring [9].

Generally, radar altimetry appears to be a very straightforward remote sensing method. Two essential geometric estimations are involved in this technique. Firstly, the determined round-trip travel time of microwave pulses emitted downward by the satellite's radar, reflected back from the ocean, and received again on board gives the separation between the satellite and the sea surface. Secondly, autonomous tracking systems are used to determine the satellite's three-dimensional position relative to a fixed earth coordinate system. Then, joining these two estimations yields profiles of ocean surface topography, or sea level, relative to the reference ellipsoid (a smooth geometric surface which approximates the shape of the Earth) [1]. Figure 1 shows the satellite altimetry measurement principle.

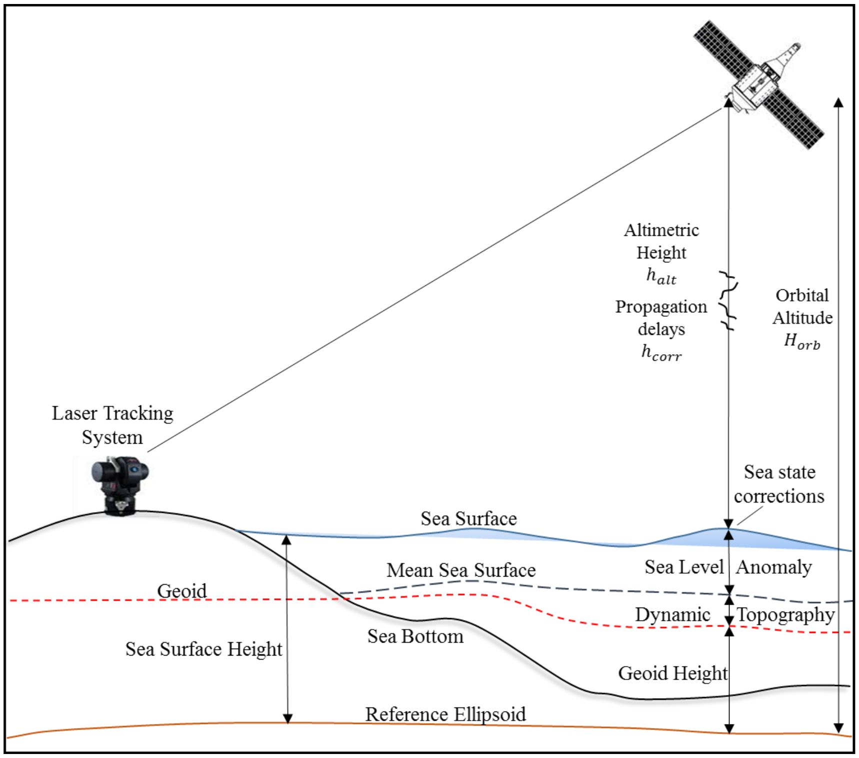

Figure 1. The Principle of Altimetry

2.2 Altimeter Sea Level with Separate Ocean Tide Models (OTMs)

The oceanic tide is a time-based occurrence of uplift and descent of the ocean level, experienced daily. It results in the transport of water masses controlled by the gravitational drag of the solar system bodies particularly the moon and the sun [7]. In the past few decades, satellite altimeters have systematically measured the sea surface level with an accuracy of a few centimetres, which in turn has hugely enhanced the accuracy of modelled ocean tide [14].

Currently, the most acceptable models of global ocean tide, in one way or the other, make measurements of sea surface height (SSH) with the use of satellite radar altimeter. They are either purely experimental templates or hydrodynamic templates tailored by altimetric observations[13]. The Goddard Ocean Tide (GOT) empirical model discussed by Ray[14] and the Finite Element Solution (FES) hydrodynamic model by Lyard et al[15] are two examples. A significant number of these modern templates leverage on over two decades of non-stop ocean surface height estimations starting with the T/P and Jasons-1&2 satellite missions [17].

The Modélisation des Ecoulements Océaniques à Moyenne et grande échelle, led by C. Le Provost, used a modelling technique dependent on hydrodynamic and similar models, produced the hydrodynamic model Code aux Eléments Finis pour la Marée Océanique (CEFMO) and the related similar model Code d’Assimilation de Données Orienté Représenteur (CADOR). From those models, tidal chart books produced were generally named finite element solutions (FES) [16]. As explained in Lyard et al[16], between 1992 and 2004, there was a nearly continuous bi-annual production which resulted in major releases, including the FES95, FES99 and FES2004 tidal atlases. The most recent release being the FES2004 atlas.

The GOT empirical model, maintained by Richard Ray at NASA-Goddard Space Flight Centre, is widely used to remove barotropic ocean tides from satellite altimetry data. GOT is distributed as a set of tidal harmonic constants on a 1/2° grid. The smooth tidal fields in GOT are appropriately represented by the 1/2° grid; however, the grid does not extend to the shoreline everywhere, making it problematic to utilize GOT for tidal corrections in the coastal zone [14]. The GOT4.10 model developed, which is the most recent update from GOT4.8, follows series of similar attempts. As in a few of the other models, it is the result of an empirical harmonic analysis of satellite altimetry relative to an embraced earlier model [18].

Recent correlations between these altimetry-dependent universal models and foot-pressure sea estimations of the ocean tides resulted in root-mean-square differences within 5 mm or better for even the biggest individual tidal element [14]. In this study, two global models GOT4.10 and FES2004 were separately used to evaluate the effects ocean tide.

2.3 Sea Level Anomaly Determination

Satellite altimetry, unlike tide gauges, estimates “absolute” ocean level variations in a geocentric reference framework. The idea here is basically the calculation of the transmitted microwave radiation from the on-board radar altimeter toward the ocean surface, which will partly rebound to the satellite [19]. The calculated back and forth travel time of the electromagnetic pulse yields the satellite range above the immediate ocean surface. The SSH over a fixed reference surface, which commonly is a conventional reference ellipsoid, is simply determined from the subtraction of the range measurement from the satellite altitude above the reference surface [19]. Chelton et al[19] explained in detail, the need to correct the SSH estimation for different variables resulting from atmospheric delays (ionosphere and troposphere), instrumental imperfections and movements, including effects of the electromagnetic diffusing of the radar pulse at the point where the air-sea interact. Plus, data cleaning being performed due to atmospheric loading, solid earth, pole and ocean tides [20]. The precision of a single SSH estimation has attained the 2–3cm level. Extra averaging over the maritime space amid an orbital cycle yields a precision of ~0.4mm for a solitary worldwide estimation of mean ocean level [20]. Normally, for SSH variation study, it is frequently more appropriate to refer the SSH to the mean sea surface height instead of to the geoid, this helps to create what is called the sea level anomaly η_{sla}, given as:

$$\eta_{sla} = H - R_{obs} - \acute{\eta}_{dry} - \acute{\eta}_{wet} - \acute{\eta}_{iono} - \acute{\eta}_{ssb} - \eta_{MSS} - \eta_{tides} - \eta_{atm}$$

Where,

H: Satellite height above the reference surface

$R_{obs} = C\left(\frac{t}{2}\right)$ is the computed range from the travel time ***t***, as recorded by the on-board ultra-stable oscillator (USO), and ***C*** is the speed of the radar pulse neglecting refraction.

$\acute{\eta}_{dry}$: Correction for dry tropospheric effect

$\acute{\eta}_{wet}$: Correction for wet tropospheric effect

$\acute{\eta}_{iono}$: Correction for ionospheric effect

$\acute{\eta}_{ssb}$: Correction for sea-state bias effect

η_{tides}: Tide correction

η_{atm}: Dynamic atmosphere correction

Din, et al[21] explained that, according to Andersen and Scharroo[22], the deduction of the mean ocean surface (η_{MSS}) suitably takes out the time-related mean of the changing sea surface height and determines sea level anomaly that, in principle, have zero mean. This is achieved, because mean sea surfaces (η_{MSS}) are ordinarily computed by averaging altimeter estimations spanning lengthy periods and preferably joining data from many similar repeat missions. Figure 2 summarizes the detailed procedure of how to derive sea level anomaly in RADS.

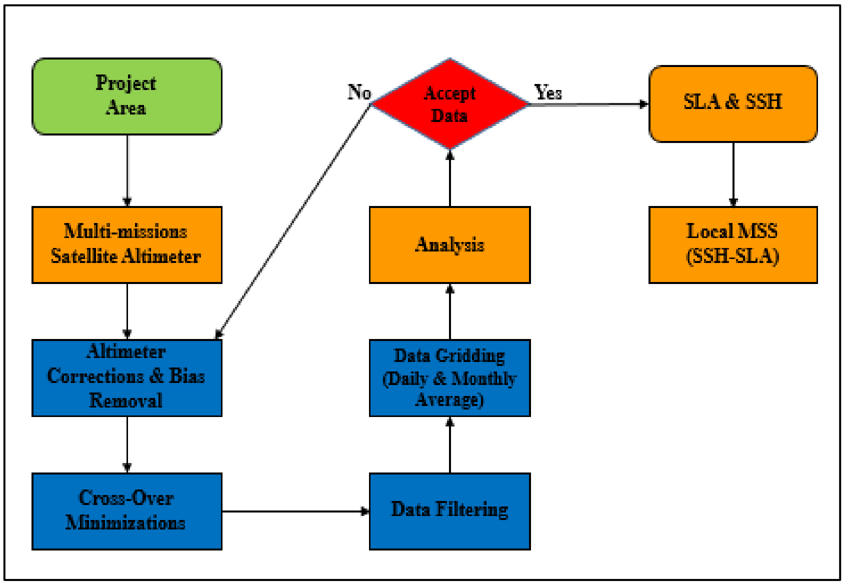

Figure 2. Altimeter Data Processing Flows in RADS

3.0 Materials and Methods.

In this study, sea level data extraction and processing were carried out utilising TUDelft's RADS, which archives and processes altimetry data [5]. This system was setup at Universiti Teknologi Malaysia (UTM) in 2005 within the context of an EU funded project (AUNP). This SEAMERGES project aim for knowledge, technique and data exchange related to satellite altimetry, Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR). The 2016 updated environmental, including geophysical corrections were applied in RADS data processing. Including corrections for orbital altitude, dry and wet tropospheric delay, ionospheric delay; altimeter instrument, sea state distortion, solid earth and ocean tides, ocean tide loading, pole tide, electromagnetic distortion and a dynamic atmosphere [6]. These various corrections have been effected for each satellite altimetry mission by applying specific models in RADS. Table 1 summarizes these corrections.

Table 1. Corrections and Models Used in RADS for Sea Level Data Extraction

Correction	Editing		Description
	Min (m)	Max (m)	
Orbit Gravity field			TOPEX: GGM02C
			JASON-1 & ENVISAT: EIGEN CG03C, ERS: DGM-E04
Wet troposphere	-0.60	0.00	All satellites: Measurement with radiometer
Dry troposphere	-2.40	-2.10	All satellites: ECMWF
Ionosphere	-0.40	0.04	All satellites: Smoothed dual-frequency
			ERS: NIC08
Dynamic atmosphere	-1.00	1.00	All satellites: MOG2D
Pole tide	-0.10	0.10	Applied (Tide produced by Polar Wobble)
Ocean tide	-5.00	5.00	All satellites: FES 2004 / GOT 4.10

Load tide	-0.50	0.50	All satellites: FES 2004 / GOT 4.10
Solid earth tide	-1.00	1.00	Applied (Flexible response to tidal potential)
Sea state bias	-1.00	1.00	All satellites: CLS non parametric
			ERS: BM3/BM4 parametric
Engineering flag			Applied

Furthermore, because of factors including orbit error and inconsistency in the satellite orbit frame, there is need for the SSHs from diverse satellite missions to be balanced with reference to a “standard” surface. The term used in describing this technique is crossover adjustment for multi-satellite missions [11]. Due to their highly accurate orbit, the SSH from the T/P & Jason series missions served as a standard surface in the stage of processing integrated data in this study. Figure 3 below shows the study area, with the three tidal stations namely Tema (located in Ghana), Lagos and Forcados (both located in Nigeria) all marked in red.

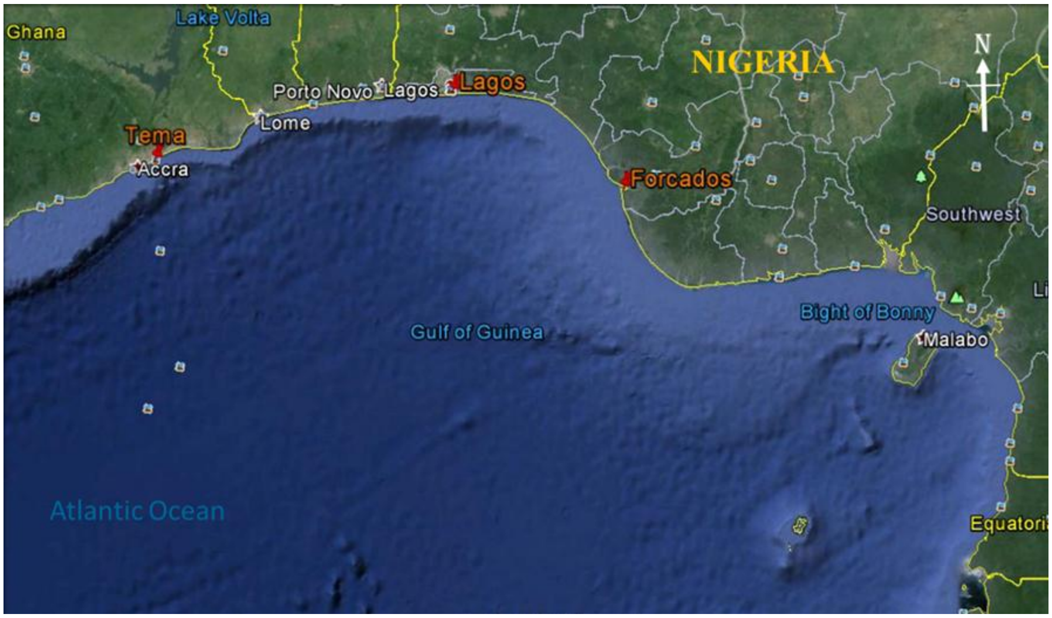

Figure 3. Study Area Showing Tidal Stations with Red Markers (Modified from Google Earth)

Since the TOPEX and JASON satellites have far more accurate orbit compared to the others, to perform the dual-crossover minimization analysis in RADS, these satellite missions were divided into two ground track cases in which the orbit of the TOPEX and JASON satellites served as reference and the ERS-2, ENVISAT, CRYOSAT-2 and SARAL satellites were adjusted simultaneously in order to carry out sea level change analysis on collinear track basis [12]. The crossovers were performed between ERS-ENVISAT-CRYOSAT-SARAL and TOPEX-JASON satellites. The region used for the crossover minimization is considerably larger than the area under investigation. This was required because of the need to have sufficient crossover data to quantify the smoothness (1 cycle per orbital revolution) inside every grid. The timeframe covered by singular crossovers is restricted to 18 days to avoid the risk of eliminating real oceanic signal and, with that, the sea level pattern [13]. Altimetry data was extracted for the study area which ranges between $1°N \leq \phi \leq 8°N$ and $0°E \leq \lambda \leq 12°E$, spanning the Nigerian seas (Gulf of Guinea and the Atlantic Ocean). The combination of TOPEX and JASONs-1&2 (10-day repeat orbit) served as the first ground track case. The alternate ground track situation is the grouping of ERS-2, ENVISAT, CRYOSAT-2 and SARAL (35-day repeat orbit, 17-day mini-cycle). To obtain the daily grids of the gridded sea level anomaly, the entire satellite altimeter missions used were merged. A sea level trend was developed using the altimetry data to perform regression analysis. Three tidal stations were chosen to investigate the ocean level variations using different ocean tide models.

3.1 Sea Level Trend Using Multi-Mission Satellite Altimetry

As mentioned previously, it is clear that satellite altimeter is able to come up with sea level estimations with improved spatial resolution compared to tide gauges. This study was conducted using 7 satellite altimeter missions. Table 2 shows the summary of satellite data used in RADS.

Table 2: Satellite Altimetry Data Used in RADS

Satellite	Source	Period	Cycles
TOPEX	NASA/CNES	Sep 2000 - Oct 2005	001 - 481
JASON-1	NASA/CNES	Jan 2002 - June 2013	001 - 425
JASON-2	NASA/CNES	July 2008 - Dec 2015	000 - 285
ERS-2	ESA	Jan 2000 - July 2011	049 - 169
ENVISAT-1	ESA	May 2002 - Apr 2012	006 - 113
CRYOSAT-2	ESA	July 2010 - Dec 2015	004 - 074
SARAL	ISRO/CNES	Mar 2013 - Dec 2015	001 - 030

To achieve the aim of comparative study of both ocean tide models used for the study, satellite altimetry data from 2000 – 2015 (16 years) was processed using two (2) different ocean tide options (GOT4.10 and FES2004) in RADS. Three tidal stations at Forcados, Lagos and Tema were chosen. This is shown in Figure 2 above. With the joint observation of the seven satellites, the approximated rate of the sea level time series of the Nigerian seas were derived separately using each ocean tide model from the averages of monthly altimetry data.

4. RESULTS AND DISCUSSION

The sea level time series of the Nigerian seas for each ocean tide model obtained through multi-mission satellite altimetry are shown in Figures 4 and 5 respectively. The rise of mean sea level is clearly conspicous in the altimetry data for both models. There were estimated sea level trends of 2.4mm/year and 3.6mm/year with the GOT4.10 and FES2004 OTMs respectively. This is an indication that the overall sea level for the Nigerian seas is rising. Also, it could be seen that both OTMs vary in the estimated sea level trends by 1.2mm/year and have a root-mean-square difference of 1.3cm.

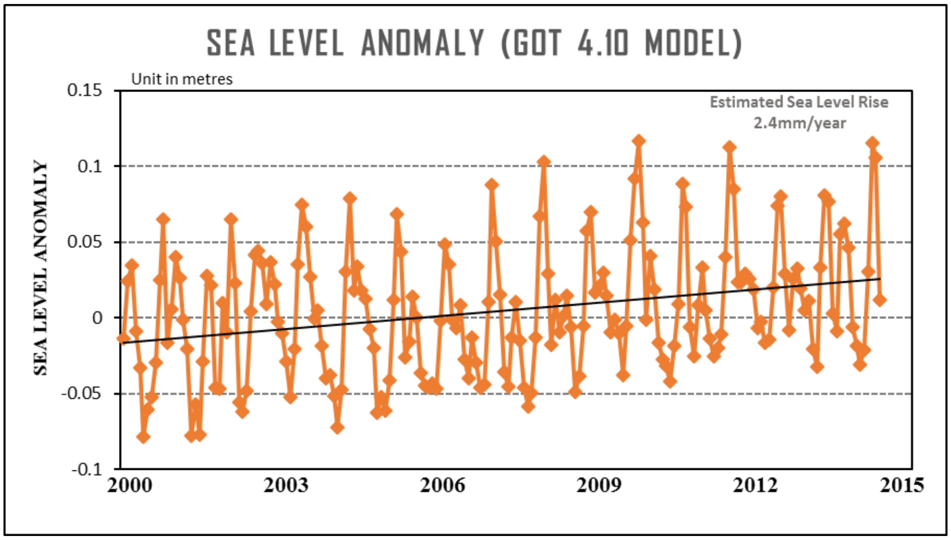

Figure 4: Sea Level Anomaly with GOT4.10 OTM

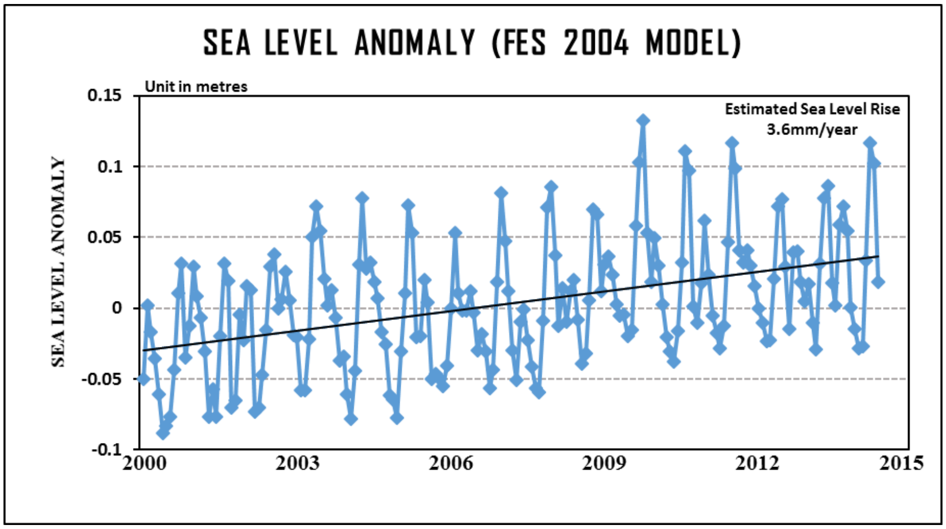

Figure 5: Sea Level Anomaly with FES2004 OTM

Results obtained show an increase in the sea level trend at all tidal stations for each OTM. However, the amount of sea level rise determined from each model varies at the tidal stations. Estimated sea level anomaly using both OTMs show strong correlation at the tidal stations. As shown in Table 3, Forcados has the largest variation with a difference of 3.123mm between GOT4.10 and FES2004. At Tema, results show that the difference between both models is slightly smaller compared to that at Forcados with a value of 2.901mm. At Lagos, a similar result to Forcados and Tema was also obtained, but with the difference between both OTMs being 2.899mm. This happens to be the smallest compared to the other tidal stations. This is basically valid because of the tidal constituents' distortion at lower frequencies (under-sampling) that are not averaged out when for instance calculating monthly means, in contrast to tide gauge data that does not have this constraint (over-sampling)[7].

Table 3: Sea Level Anomaly for each OTM at Tidal Stations

Tidal	Sea Level Anomaly (m)	Difference

Stations	GOT4.10	FES2004	(mm)
Forcados	0.006687	0.009810	3.123
Lagos	0.016146	0.019045	2.899
Tema	0.016417	0.013516	2.901

Similarly, Table 4 shows the variation in the estimated Mean Sea Surface (MSS) by the models at each tidal station. The results show a much larger difference (in centimetres) between the models.

Table 4: Mean Sea Surface for each OTM at Tidal Stations

Tidal Stations	Mean Sea Surface (m)		Difference (cm)
	GOT4.10	FES2004	
Forcados	19.638560	19.600240	3.832
Lagos	16.106945	15.990723	11.622
Tema	18.146111	18.336169	19.006

However, plotted yearly means across the Nigerian seas show an increase in the estimated MSS. These variations are not unconnected to the fact that the GOT4.10 is an empirical model whose coarse 1/2° grid does not extend to the shoreline everywhere, making it problematic to utilize GOT for tidal corrections in the coastal zone [15]. Unlike the GOT, the FES is a hydrodynamic model dependent on the resolution of the tidal barotropic equations on a less coarse new worldwide finite element 1/8° grid (~1 million nodes), which yields solutions free of in situ and remote-sensing data [15]. Figure 6 and 7 show more details graphically for both OTMs.

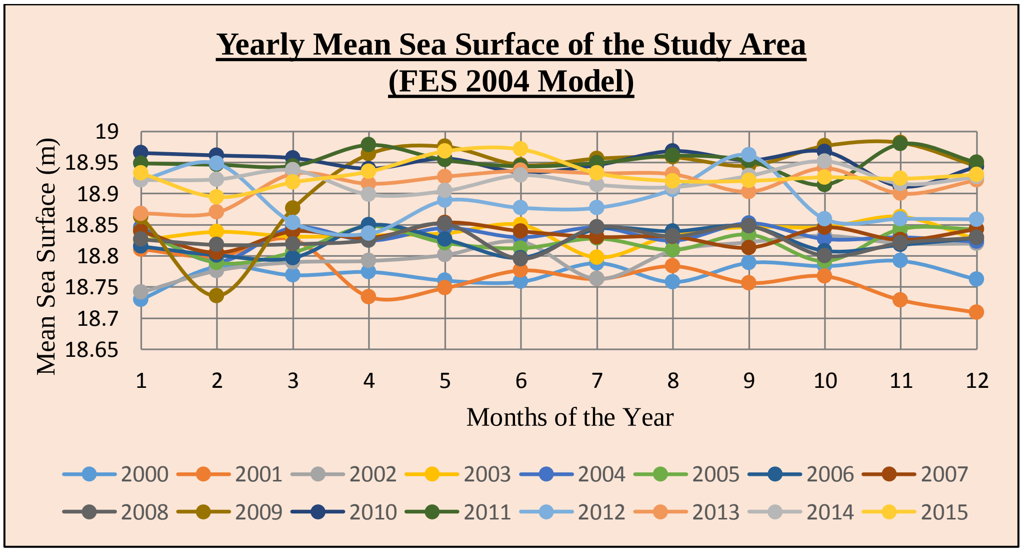

Figure 6. Yearly MSS Variation from 2000–2015 using FES2004 OTM

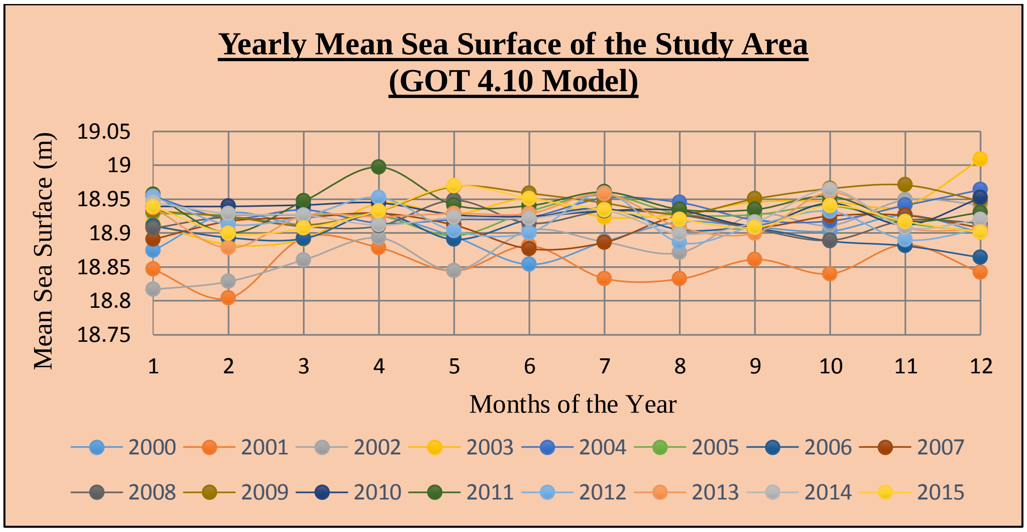

Figure 7. Yearly MSS Variation from 2000–2015 using GOT4.10 OTM

Figures 8 and 9 give the modelled spatial altimetry-based sea level anomaly trend patterns for 2000–2015 using FES2004 and GOT4.10 OTMs. The gridded sea level time series is dependent on T/P, Jason-1 and Jason-2 altimetry data supported by ERS-2, Cryosat-2, Envisat and Saral data. According to Cazenave and Le Cozannet[20], spatial patterns noticed in the sea level patterns mainly result from variations in the density structure of the oceans connected with temperature and salinity variations (steric factors), with the ocean temperature disparity being the largest contributor [23]. Also, the effect of salinity is clear due to its effect on thermal expansion [24] [25] [26].

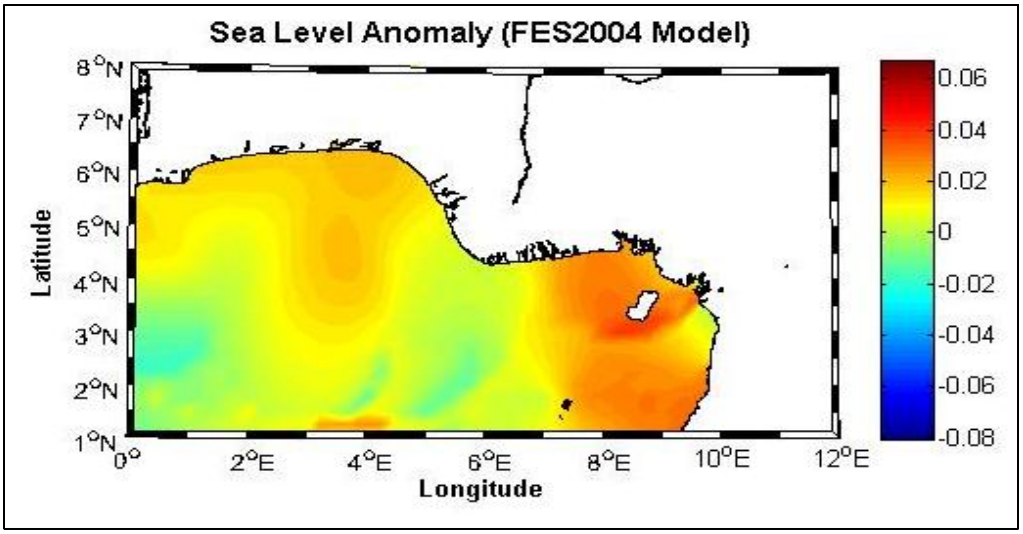

Figure 8. Model of Sea Level Anomaly using FES2004 OTM (Colour Bar unit in metres).

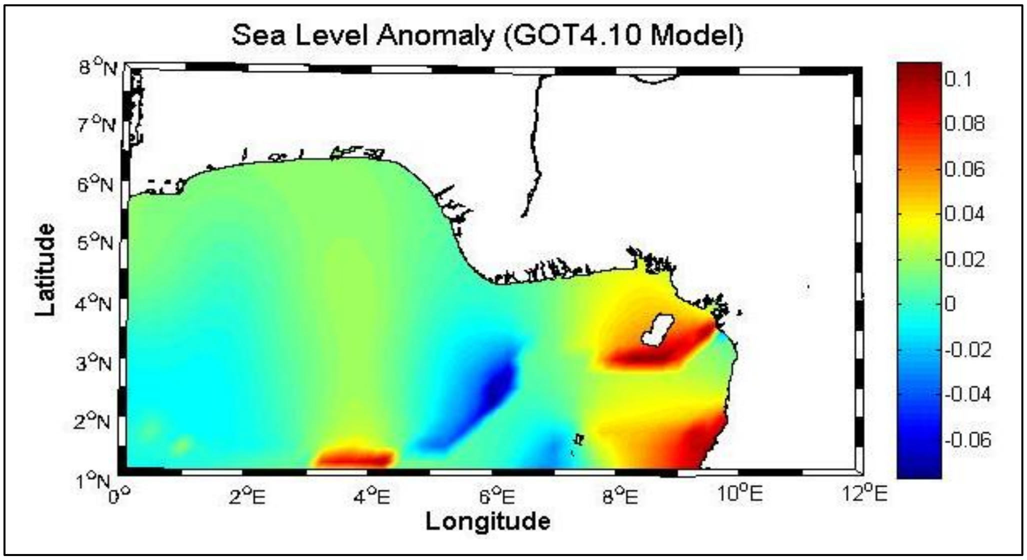

Figure 9. Model of Sea Level Anomaly using GOT4.10 OTM (Colour Bar unit in metres).

Similarly, Figures 10 and 11 further show a modelled variation in the MSS within the region for 2000–2015 using FES2004 and GOT4.10 OTMs. The gridded sea level time series is dependent on the same set of satellites as discussed above. Cazenave and Le Cozannet[19] also affirmed that, apart from the steric factors, vertical land motions such as tectonic, silt loading, groundwater pumping, and oil and gas extraction could yield sea level variations relative to the seafloor [27] [28] [29]. It is possible such local phenomena may possibly result in increase or reduction in the climate-related and static components. This is particularly true as this region is the beehive of virtually all activities related to oil and gas exploration and other marine related activities. This could be responsible for the differences in sea level variations (see Tables 3 and 4) at the three locations investigated as well as the slight difference between the gridded MSS (Figures 10 and 11) as captured by the two OTMs.

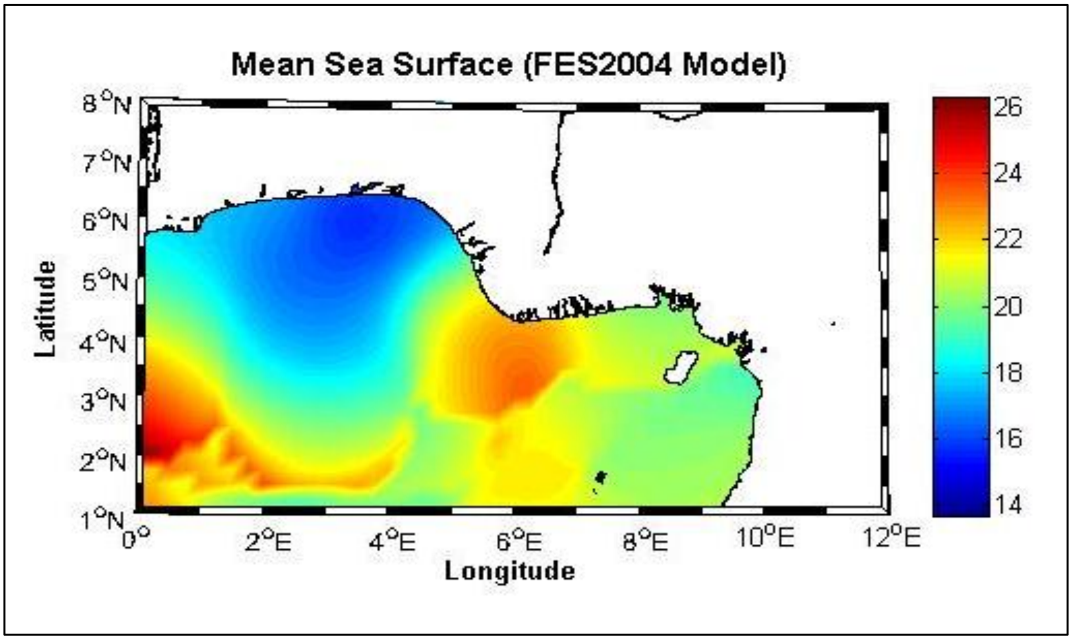

Figure 10. Mean Sea Surface using FES2004 OTM (Colour Bar unit in metres).

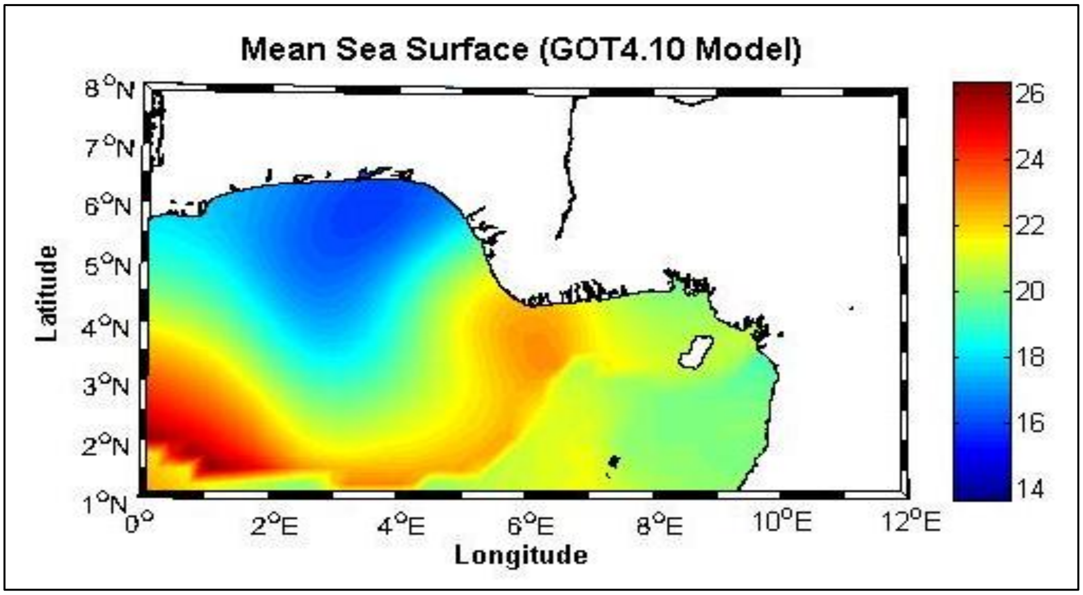

Figure 11. Mean Sea Surface using GOT4.10 OTM (Colour Bar unit in metres).

CONCLUSION

This study has been able to show using altimetry, for the first time, the rate of sea level rise within the Nigerian seas. With both OTMs showing positive trends over a period of 16 years, which indicate regional sea level variations. Furthermore, the study has shown that the sea level trends using both OTMs vary geographically at the selected tidal stations. The reason being the variability in the composition of the ocean tide models. In spite of significant progress being realised during the past couple of decades in measuring ocean level variation globally and perhaps in the region, a lot still has to be done in maximising the opportunity afforded by altimetry to extensively examine the marine/coastal surroundings in the region in terms of observations, modelling, and impact studies.

ACKNOWLEDGMENT

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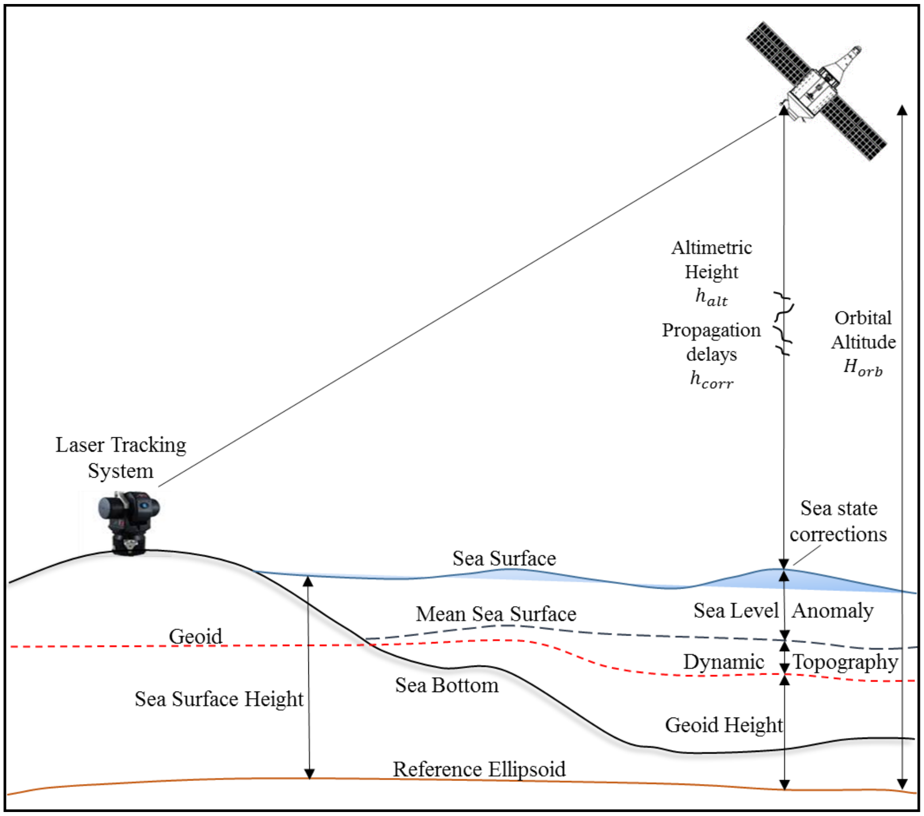
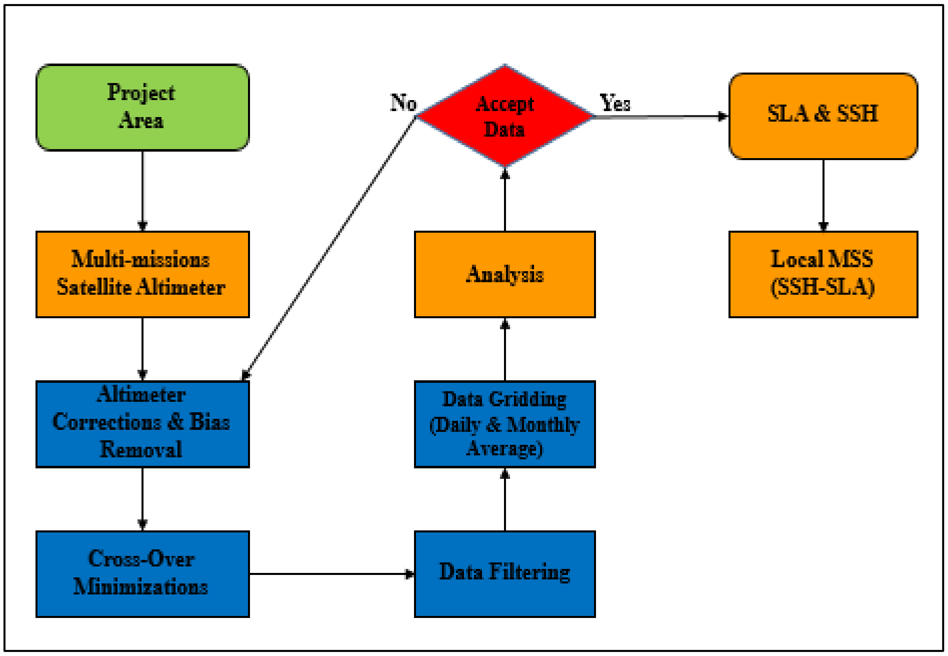
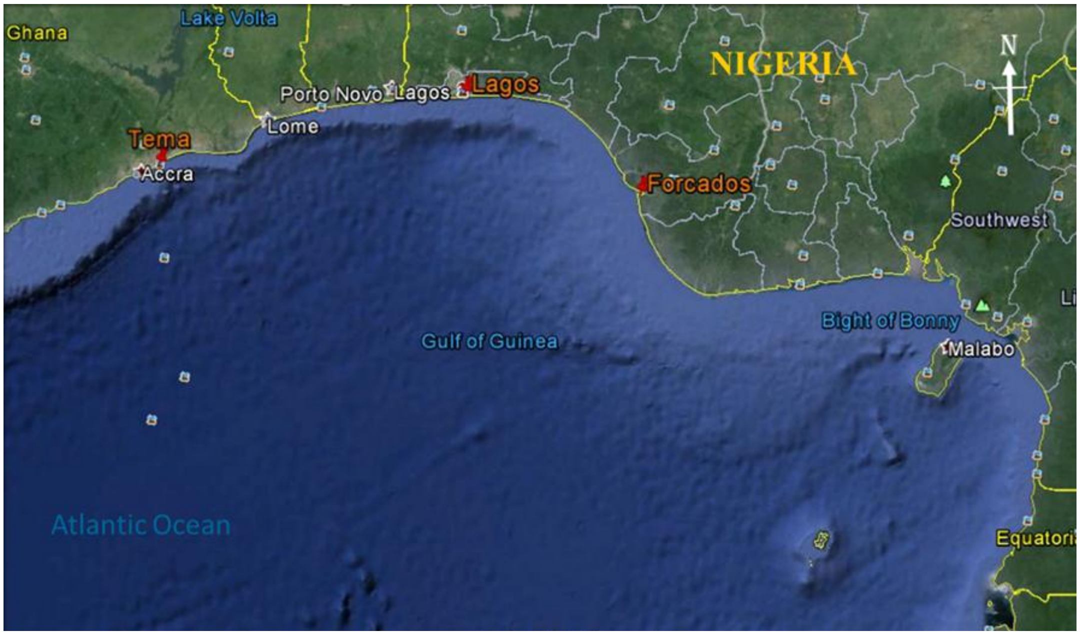
1. The Principle of Altimetry



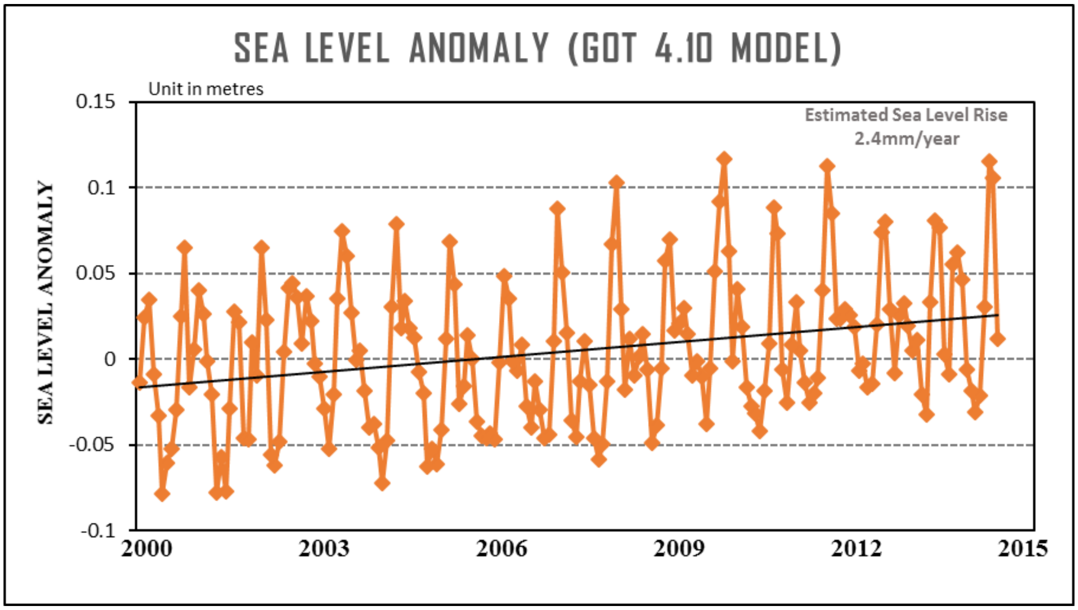
2. Altimeter Data Processing Flows in RADS



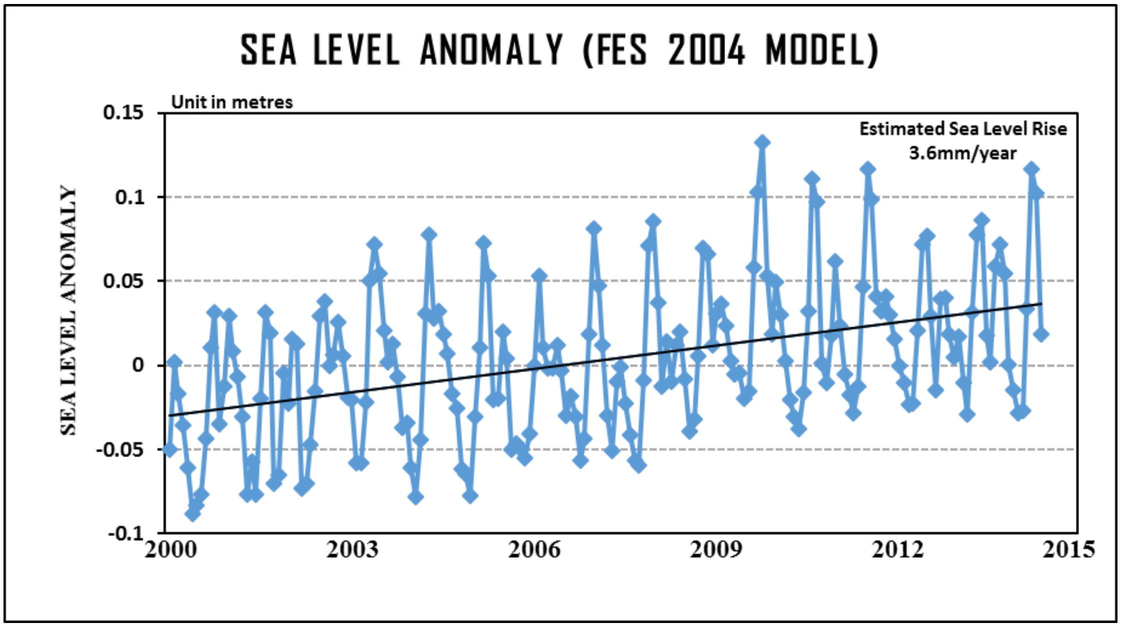
3. Study Area Showing Tidal Stations with Red Markers (Modified from Google Earth)



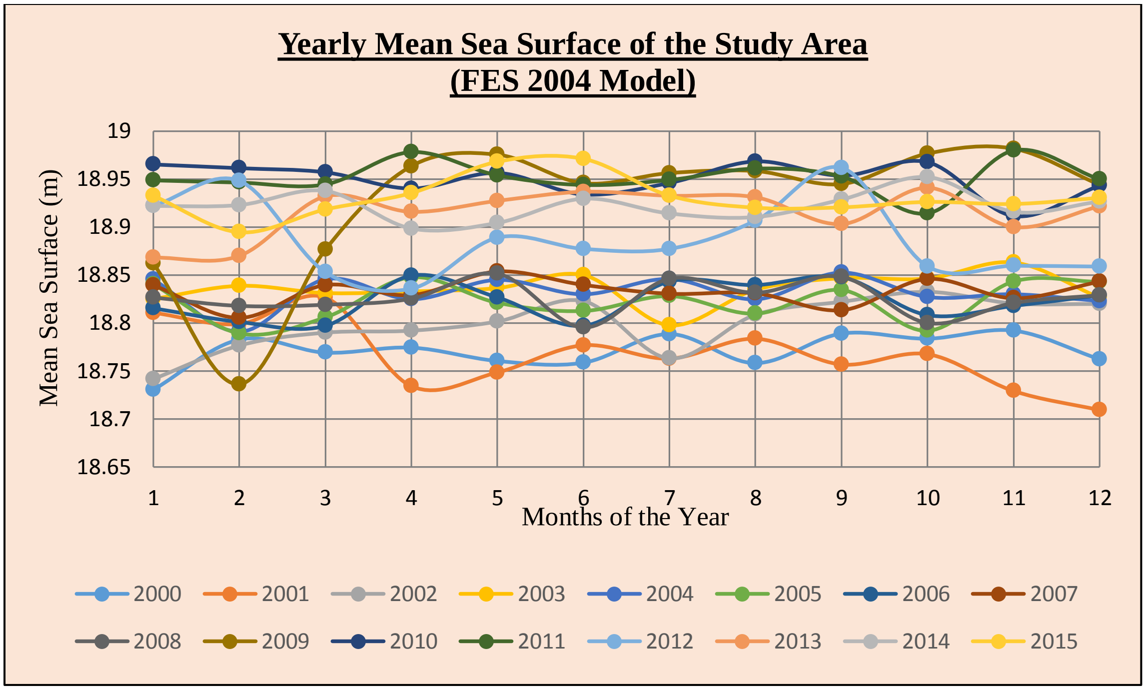
4. Sea Level Anomaly with GOT4.10 OTM



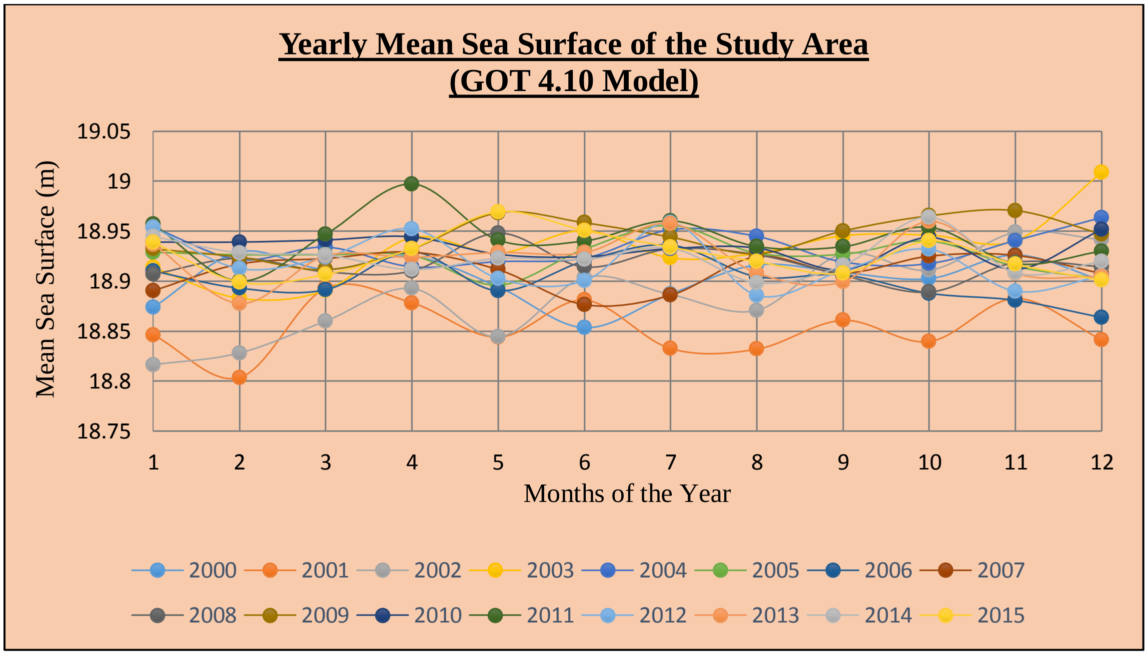
5. Sea Level Anomaly with FES2004 OTM



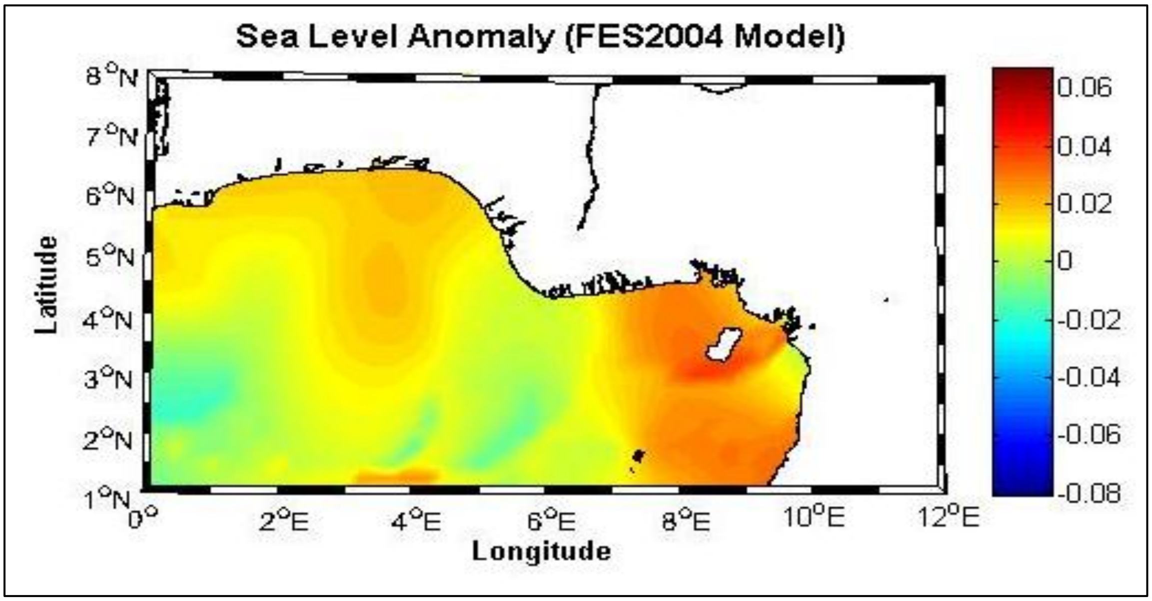
6. Yearly MSS Variation from 2000–2015 using FES2004 OTM



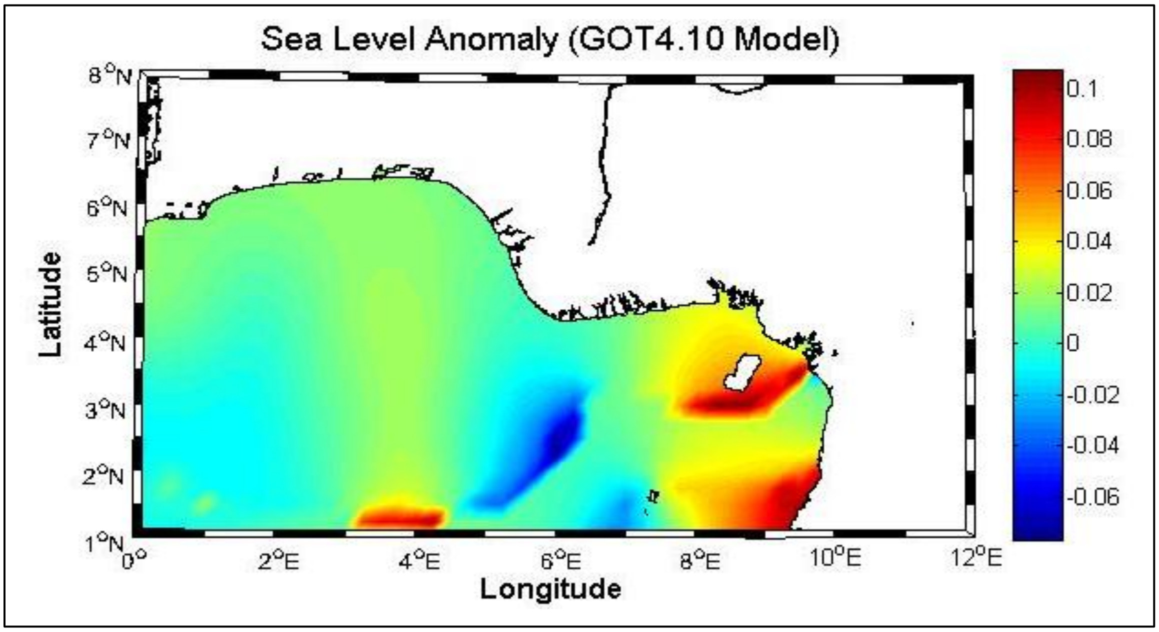
7. Yearly MSS Variation from 2000–2015 using GOT4.10 OTM



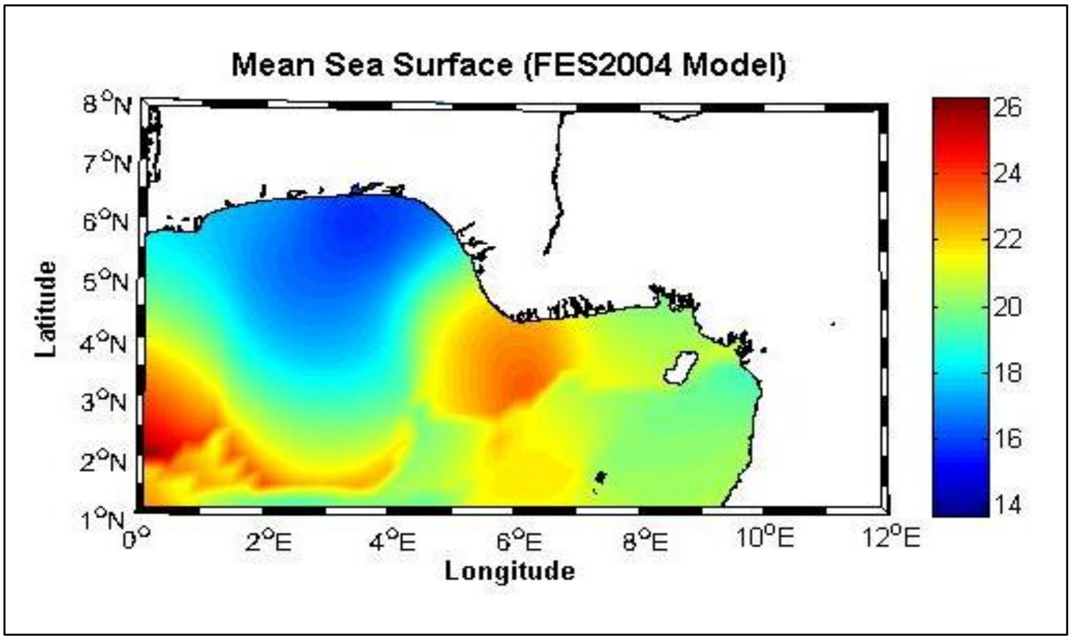
8. Model of Sea Level Anomaly using FES2004 OTM



9. Model of Sea Level Anomaly using GOT4.10 OTM



10. Mean Sea Surface using FES2004 OTM



11. Mean Sea Surface using GOT4.10 OTM

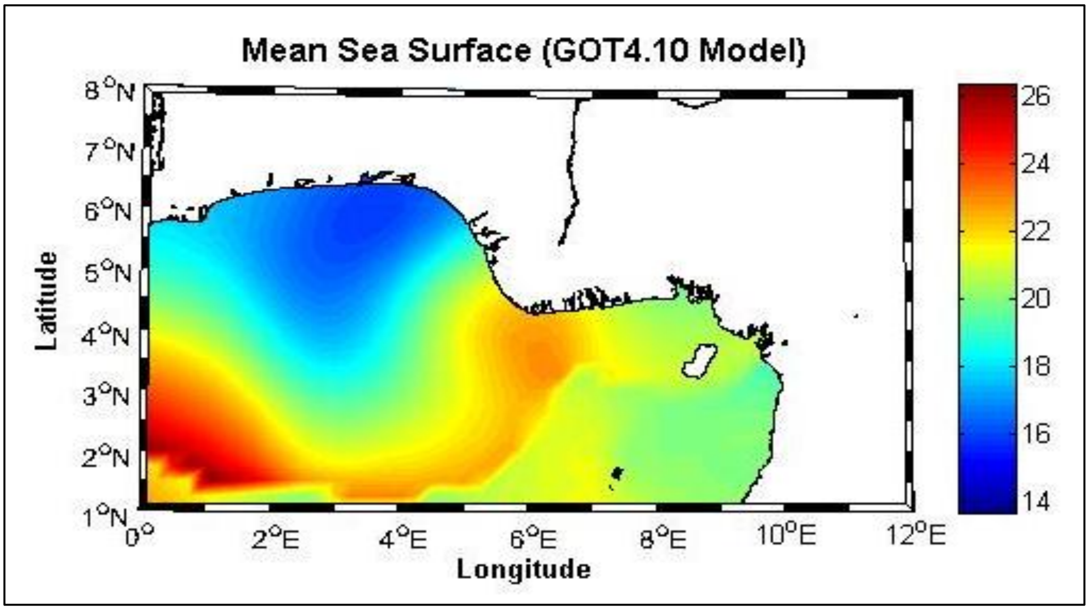


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Table 1. Corrections and Models Used in RADS for Sea Level Data Extraction

Correction	Editing		Description
	Min (m)	Max (m)	
Orbit Gravity field			TOPEX: GGM02C
			JASON-1 & ENVISAT: EIGEN CG03C, ERS: DGM-E04
Wet troposphere	-0.60	0.00	All satellites: Measurement with radiometer
Dry troposphere	-2.40	-2.10	All satellites: ECMWF
Ionosphere	-0.40	0.04	All satellites: Smoothed dual-frequency
			ERS: NIC08
Dynamic atmosphere	-1.00	1.00	All satellites: MOG2D
Pole tide	-0.10	0.10	Applied (Tide produced by Polar Wobble)
Ocean tide	-5.00	5.00	All satellites: FES 2004 / GOT 4.10
Load tide	-0.50	0.50	All satellites: FES 2004 / GOT 4.10
Solid earth tide	-1.00	1.00	Applied (Flexible response to tidal potential)
Sea state bias	-1.00	1.00	All satellites: CLS non parametric
			ERS: BM3/BM4 parametric
Engineering flag			Applied

Table 2: Satellite Altimetry Data Used in RADS

Satellite	Source	Period	Cycles

TOPEX	NASA/CNES	Sep 2000 - Oct 2005	001 - 481
JASON-1	NASA/CNES	Jan 2002 - June 2013	001 - 425
JASON-2	NASA/CNES	July 2008 - Dec 2015	000 - 285
ERS-2	ESA	Jan 2000 - July 2011	049 - 169
ENVISAT-1	ESA	May 2002 - Apr 2012	006 - 113
CRYOSAT-2	ESA	July 2010 - Dec 2015	004 - 074
SARAL	ISRO/CNES	Mar 2013 - Dec 2015	001 - 030

Table 3: Sea Level Anomaly for each OTM at Tidal Stations

Tidal Stations	Sea Level Anomaly (m)		Difference (mm)
	GOT4.10	FES2004	
Forcados	0.006687	0.009810	3.123
Lagos	0.016146	0.019045	2.899
Tema	0.016417	0.013516	2.901

Table 4: Mean Sea Surface for each OTM at Tidal Stations

Tidal Stations	Mean Sea Surface (m)		Difference (cm)
	GOT4.10	FES2004	
Forcados	19.638560	19.600240	3.832
Lagos	16.106945	15.990723	11.622
Tema	18.146111	18.336169	19.006