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WEST AFRICAN SEA LEVEL VARIABILITY UNDER A CHANGING CLIMATE –WHAT CAN WE LEARN FROM THE OBSERVATIONAL PERIOD?

Prosper I.K. Evadzi *+, Eduardo Zorita+ and Birgit Hünicke+

(+) Helmholtz-Zentrum Geesthacht, Institute of Coastal Research, Germany

(*) Brockmann Consult GmbH, Chrysanderstr. 1, D-21029 Hamburg, Germany

(Corresponding author) prosper.evadzi@brockmann-consult.de

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ABSTRACT

This study focuses on mean sea-level variability at the West African coast in the observational period (1993-2013) and its offshore waters, investigating its decadal variability, long-term trends and the large-scale climate patterns that are connected to its variability.

To achieve this objective, statistically analyses is performed on several available data sets: sea-level data from tide gauges (Takoradi, Tema and Forcados), satellite altimetry (combined TOPEX/Poseidon, Jason-1 and Jason-2/OSTM), gridded sea-level reconstruction (Church et. al. 2004), meteorological reanalysis (NCEP), a high-resolution ocean model simulation driven by this meteorological reanalysis, and, observational data sets (The Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1), and the Atlantic Multi-decadal Oscillation (AMO) index).

Ghana is the only country along the West African coast with two relatively long sea-level records available (Takoradi and Tema), but with data quality concerns (Woodworth et. al. 2007). Attempts are made to combine these two records, which cover different but overlapping periods, to construct a regional sea-level curve for Ghana (1929-1981) that may be regionally representative.

A physical connection is identified between the AMO, sea-surface temperature and sea level in the Gulf of Guinea and mean sea-level trends and variability of the West African coast. It has been found that a stronger AMO is connected with higher mean sea level in the Tropical Atlantic and in particular also at the Gulf of Guinea sea level. This connection may explain the multidecadal variability of sea level there, and in particular the negative trends between 1955 and 1975 and the positive trends thereafter. In addition, warmer sea surface temperatures in the Gulf of Guinea are also connected with higher sea level, although a simple estimation based on reasonable assumptions of the thermal expansion of the water column is not sufficient to explain the connection between sea-surface-temperature and sea-level. More detailed modelling studies will be needed to explain this link.

Although this study provides useful information for adaption strategies in Ghana, the research is unable to provide sea-level information between the years 1981 and 1993 because of lack of data.

KEYWORDS: Regional Sea-level Rise, Sea-level Variability, Climate Change, Climate Change Adaptation, Coastal Impacts

INTRODUCTION

Variations in the external climate forcing, like the increase in atmospheric greenhouse gases, affect the radiation balance of the planet and is reflected in global and regional sea-level changes (Stammer et al. 2013; Church et al. 2013; Anthoff et al. 2006). In addition to external forcing, internal climate variability usually organized in large-scale spatial patterns, such as the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Variability (AMO), may also affect the decadal and multi-decadal variability of sea-level at regional scales. In the Northern Hemisphere, sea-level trends and variability have been a subject of multiple studies, as most of the long-tide-gauges are located there. In contrast, the Southern Hemisphere provides very few long, multidecadal, -records. Recently the weight of the Southern Hemisphere for the estimation of global sea-level rise and its acceleration over the 20th century has been recently recognized. Here, we focus on a sea-level variability and trends in a region that has been so far barely studied, the Gulf of Guinea, using the very few tide-gauge records from Ghana, satellite altimetry and a global high-resolution ocean-only simulation covering approximately the past 50 years driven by meteorological reanalysis. The focus of this paper lies on the Gulf of Guinea (GoG) and in particular on the coast of Ghana. Our aims are twofold: to investigate the connections between sea-level in this region and large-scale climate variability, and (2) to improve the historical sea-level data from tide-gauges in this region to provide a more accurate, although still uncertain, estimation of the sea-level trend in this region.

The estimated global mean sea-level (GMSL) rise since the mid-19th century has been estimated to be in the range of about 1.3 to 1.7 mm/year in the last report by the Intergovernmental Panel on Climate Change (IPCC 2013). This rise is likely to have increased since 1993 to a rate of about was 3.2 [2.8 to 3.6] mm/year (IPCC 2013), although it has to be borne in mind that both estimations rely on data of different nature, tide gauges versus satellite altimetry. The estimation of global sea-level rise in the pre-satellite era is prone to large uncertainties. More recent estimates, post IPCC Fourth Assessment report, display a wider range, between 1.1 and 2. mm/year, based on long-tide-gauges records and estimation of the Glacial Isostatic Adjustment (Church and White, 2011; Jevrejeva et al. 2014; Hay et al. 2015; Dangendorf et al., 2017). Very recent estimates resolved at the level of individual ocean basins (Frederikse et al, 2018), confirm the global figure of 1.5 mm/year (+- 0.2 mm/year) and indicate a rather strong contribution of the South Atlantic, with 2.56 mm/year (+- 0.47 mm/year) and a very strong acceleration of the South Atlantic sea-level rise over the last 50 years at 0.08 $mm/year^2$. Since these results corresponding to the South Atlantic are based on extrapolation of about 10 records with variable record length, it becomes important to try to analyze the scarce available information of sea-level rise in the South Atlantic and investigate the links between sea-level variability in this region and the large-scale climate variability patterns.

The physical mechanism that is behind the sea-level rise are different at the global scale, on the one hand, and at regional and local scales, on the other hand. (Stammer et al. 2013; Cazenave and Llovel 2010). Whereas the global mean sea-level is mainly affected by the thermal expansion of the water column and the melting of land-ice - with more recent contributions from hydrologic reservoirs and groundwater usage, sea-level rise (SLR) variations across regional and local scales are also affected by the regionally heterogenous steric effects (changes in the density structure of the water column associated with temperature and salinity variations), by the spatially heterogeneous imprint of eustatic effects due to land-ice melt, and by the effects of regional changes in ocean currents, wind-induced redistributions of upper-ocean (Figure 1), all of which determine particular spatial characteristics of regional SLR (Figure 2; Timmermann et al. 2010), and sea-surface topography (Zhang et. al. 2016).

Figure 1: Schematic representation of processes that influence sea-level on global to local scales, (derived from www.nap.edu/read/13389/chapter/3#14)

Figure 2: Map of global sea-level trends derived from satellite altimetry (Topex Poseidon, Jason-I and Jason-II missions). The focus area of the analysis of this study is indicated by the magenta box (source: https://image.slidesharecdn.com/observingsealevel29112012-121203090902-phpapp02/95/observing-sea-level-16-638.jpg?cb=1354526006)

Ghana is the only country in the West African region with tide gauge data dating back to 1929, but there is concern about the data reliability (Woodworth et. al., 2007). Lack of reliable historical sea-level records and research on the influence of large-scale climate impacts on sea-level variability and trends for the GoG limits estimation of sea-level trends and forecast for the region and thus makes coastal communities within the region to be at risk of SLR. It is thus important to improve the accuracy of historical sea-level data for Ghana that can enhance the understanding of climate influence on sea-level trend along the West Africa Coast. Tano et al. (2016) based on 23-year satellite altimeter data reported that relative sea-level has increased around 3.05 mm/y in the GoG.

Natural climate variability is identified to be important for these sea-level variations across regional ocean basins. The influence of natural climate variability on sea-level patterns and trends has attracted considerable attention during the last decades (Wang and Zhang, 2013; Dangendorf et al. 2014; Tsimplis and Josey, 2001; Woolf et. al., 2003; Wakelin et al., 2003). ENSO, for example, has been identified to influence the regional sea-level variability of the Tropical Pacific (Feng et al., 2015) and has been identified to control multi-decadal variability in US extreme sea-level records (Wahl and Chambers, 2016). In the Atlantic Ocean, the Atlantic Multidecadal Oscillation (AMO) has been identified as an important factor of global and multi-decadal climate variability with the possible influence of natural climate variability in the subtropics (Chylek et al., 2014). We will explore in our analysis the link between the AMO and sea-level in the GoG.

Although there is debate over its region of influence, one widely referenced definition is the revised AMO index by Trenberth and Shea (2006) (Karl et. al. 2009; Coumou et. al. 2013; Trenberth and Fasullo, 2012; Sung et al., 2015). Trenberth and Shea (2006) defined the AMO index as the annual mean Sea Surface Temperature (SST) averaged over the region from the equator (EQ)-60°N, 0°-80°W after subtracting the global mean of SST 60°S-60°N to obtain a measure of the Atlantic variability that is presumably not related to the external climate forcing, which would be rather reflected in the global mean SST.

This observed multi-decadal (of the order of magnitude of several decades) variability has a quasi-periodicity of about 60 to 80 years (Trenberth and Shea 2006), although this difficult to ascertain due to the limited length of the observational period. The physical origin of the AMO and its main periodicities are still a matter of debate (see e.g. Booth et al., 2012; Clement et al.,2015; Wang et al, 2017).

The physical mechanisms that give rise to the AMO are not yet well established. Some studies have stressed the role of external climate forcing, and of anthropogenic tropospheric aerosols in the North Atlantic region (Booth et al. 2012). According to this point of view, the AMO would not as such exist prior to the industrial period, at least not with the presently observed amplitude. Other studies, on the other hand, have identified purely natural mechanisms that are capable of inducing oscillation in the North Atlantic SST field (Gastineau and Frankignoul 2015).

From the analysis of simulations with climate models, one theory states that changes in the salt content influence the ocean circulation in the North Atlantic Ocean (NAO) which in the turn changes the NAO thermohaline circulation (THC) resulting in the observed oscillation (Clement et al. 2015). The periodicity of peaks can thus be influenced by the additional freshwater inflow into the NAO (e.g., as a result of gulf-stream and ice-melt). Another theory (Clement et al. 2015) underlines the role of atmospheric variability in the AMO. These authors found that an atmospheric model coupled to a slab ocean model with no ocean dynamics could produce AMO-like variability with AMO being just a thermodynamic response of the ocean mixed layer to stochastic atmospheric forcing. This claim was put into question by Zhang et. al. 2016 who argued that the mechanism causing the AMO in coupled general circulation models is different from that depicted in the slab ocean model used by Clement et al (2015).

Although confidence in the observational analysis of the AMO is limited by its relatively short instrumental climate record, evidence of long-term internal climate variability over 1400 year control simulation of the Hadley Centre coupled model (HadCM3; Knight et al. 2006), and Coupled Model Intercomparison Project Phase 3 (CMIP3) simulations for the 20th, 21st, and pre-industrial eras (Ting et al. 2011) confirms the effect of AMO on prominent regional climate variability within the northern hemisphere such as Eastern Brazilian and African Sahel rainfall, Atlantic hurricanes and North American and European summer climate (Knight et al. 2006; Ting et al. 2011).

Timmermann et al. (2010), also found wind-induced negative sea-level changes projected for the next 100 years to be quite considerable for many low-lying Pacific Islands which were relatively small (10 - 30%) compared to recent global mean SLR estimates.

The trends along the West African coast can also be compared to each other and to the extracted dominant EOFs for the GoG region to determine how the trends are being impacted by the identified climate variables.

Although SLR will likely impact negatively on developing countries including West African countries (Dasgupta et al. 2007), there exists a lack of information on the impact of large-scale climate patterns that influence sea-level variability and trends in the (GoG), especially along the West African coast. The importance of sea-level variability, as well as climate impact information, was highlighted in a proposed coastal adaptation framework that shows the steps involved in planned adaptation to climate variability and change by Klein et al., 2006. There is available literature on coastal impacts and awareness of climate change in Ghana (Evadzi et al., 2017(a); Evadzi et al., 2017(b); Jayson-Quashigah et al., 2013; Appeaning Addo 2008, 2011 and 2013; Amlalo, 2006).

In summary, an assessment of the large-scale climate forcing that drives sea-level variability in the GoG with more focus on the West African coast was performed. Attempts to reconstruct observed instrumental sea-level data for Ghana to improve its accuracy and explains the decadal variability were also made. In the following, we specify the methodology and present the results.

METHODS

The methods section comprises two parts: the first part describes the study area while the second presents the data and processing methods used for the data analysis.

Study Area

Our study area is the Gulf of Guinea, defined here as the region in the geographical box displayed in Figure 3. This region is selected to take into account the relatively coarse resolution of simulations with climate models and satellite altimetry data. Within this region, there are only few relatively long-tide-gauge records from the Permanent Service for Mean

Sea-level (PSMSL), (Takoradi and Tema (Ghana) and Forcados (Nigeria) located on the coast of West Africa. The Forcados tide-gauge station although with fewer records, is assumed to be reasonably accurate based on data assessment by the PSMSL. The large-scale region in which the connections to GoG sea-level will be sought is defined here as the broad Tropical Atlantic region within the geographical box 80W° to 40E° and latitudes 40S° to 40N°. In this region, monthly-mean sea-surface heights (SSH) data from satellite observations and ocean models, wind stress data from meteorological reanalysis and sea-surface temperature were extracted as described below and summarised in Table 1.

Figure 3: Study area showing the Gulf of Guinea and selected tide gauge stations [Takoradi and Tema (Ghana) and Forcados (Nigeria)] along the West Africa coast

Data and methods

Our objective is to identify the large-scale drivers of sea-level variability at monthly time scales, and their trends, in the GoG. The observational basis is limited to the tide-gauge records of Takoradi and Tema. The Takoradi station reports data from 1929 onwards. However, these data have been labelled as unreliable after 1966. The Tema record covers the period 1963-1982. This record is, in contrast, deemed as accurate by the Permanent Service for Mean Sea-level. We first try to construct a synthetic Takoradi record using the data from these two tide-gauges, based on their mutual correlation during the overlapping period (1963-1965). The uncertainties in the Takoradi record are related to its long-term trends after and therefore, we first compute a high-pass filtered version of both records to correlate their monthly variations (Equation 1):

(i) $[\text{Tema}-\text{Tema}^{1963\text{-}1965}]\ \alpha\ [\text{Takoradi}-\text{Takoradi}^{1963\text{-}1965}]$

(ii) $\text{Takoradi } t = \alpha.\ [\text{Tema } t - \text{Tema } t^{\ 1963\text{-}1965}] + [\text{Takoradi } t^{\ 1963\text{-}1965}]$ (Equation 1)

In this equation

(i) represents the correlation for the overlap period

(ii) represents the estimation rule, and

α= correlating the overlap period of Takoradi t and Tema t, t= 1963-1965

Equation (1) provides a synthetic record at Takoradi using the information included in the Tema record. Therefore, this record can be considered as a regional sea-level curve for Ghana, covering five decades (1929-1981; Figure 4). The increased length of this synthetic record will increase the robustness of the following statistical analysis that aims to identify the large-scale climate patterns that are closely linked to sea-level in the GoG. We also statistically explore the connections between sea-level variability in the GoG with sea-level recorded in the neighbouring Nigeria records.

Figure 4: Reconstructed Ghana Annual Mean Sea-level (AMSL) curve together with Ghana tide gauge record Takoradi (from PSMSL, not reliable after 1966)

Statistical analysis of the sea-level pattern in the GoG by means of Empirical Orthogonal Function (EOF) and assessment of the impact of AMO on observed sea-level record for the region was performed. The EOF analysis, also referred to as Principal Component Analysis (PCA), is a multivariate statistical method that serves as a means of extracting the dominant patterns from data sets and has been widely utilized in sea-level variability analysis (Church et al. 2004; Cheng et al. 2015; Hay et al. 2015).

EOF analysis was applied to the satellite sea-level data to first identify the main patterns of large-scale sea-level variability. In this analysis, SSH data from the combined satellite missions TOPEX/Poseidon, Jason-1, and Jason-2/OSTM were included. These data have been previously widely used for sea-level analysis (Han et al. 2014; Lyu et al. 2014). There are different versions of these data sets depending on the different corrections included. These corrections may refer to the inverse barometer effect (the effect of air pressure on SSH) also the annual and semi-annual cycles. For the present analysis, we did not choose the data version corrected for the Glacial Isostatic Adjustment (GIA). The GIA is caused by the remnant viscous readjustment of the Earth crust to the ice load and its sequent demise, of the large continental ice sheets of the Northern hemisphere during the last glacial age that terminated about 10 000 years ago. This correction is very small in the GoG. An additional reason is that the tide-gauge data, with which we would also compare the satellite products, are not corrected for the GIA.

The results of the EOF analysis on the satellite altimetry data was compared with a similar analysis on two other data sets. One is the output of an ocean simulation with the model MPIO-OM of the Max-Planck-Institute of Meteorology in Hamburg. This simulation, hereafter referred to as the STORM simulation (Storch et al., 2012), has a horizontal resolution of about 10 km, and therefore the global ocean is very highly resolved. The atmospheric data used to drive the ocean model were from the meteorological reanalysis of the National Center for Environmental Prediction and the National Center for Atmospheric Research. These data are referred to as the NCEP/NCAR reanalysis (Kistler et al. 2001). They cover the period 1948 until today, although the ocean simulation here stops in the year 2010.

The atmospheric data reproduce the observed weather sequence over the last decades, and thus the output of the ocean simulation can be compared with observational data sets, with one limitation. This limitation is the contribution to sea-level rise by the melting of continental land-ice. This contribution is not included in the STORM simulation and therefore, the simulated long-term trends, which include only other factors like the thermal expansion of the water column or the impact of wind-stress on the ocean surface, will generally be smaller than the observed long term sea-level trends.

Other than this, the NCEP/NCAR reanalysis results from the combination (data assimilation) of a huge set of observations, from multiple sources such as station data, satellite data, ships observations, etc, with a numerical weather prediction model. The weather trajectories simulated by this model are readjusted within a data assimilation scheme to resemble as close as possible the set of observations available. The resulting model output covers a three-dimensional global grid of 2.5 x 2.5 (Lon. x Lat.) horizontal resolution. The wind stress data also stem from the NCAR/NCEP reanalysis

We also use the observationally-based gridded reconstruction of SSH in the period 1950-2001 by Church et al. (2004). The reconstructions are based on a statistical analysis of a set of tide-gauge monthly records, combined with the main patterns of variability derived from an EOFS analysis of the satellite altimetry fields TOPEX/Poseidon + Jason-1.

The reconstruction process is based on the identification of the spatially resolved leading patterns of sea-level variability at global scales in the satellite era by means of an EOF analysis. The time-varying amplitude of these EOF patterns (their associated principal components) in the pre-satellite era is estimated from the available tide-gauge data, by fitting the tide-gauge sea-level anomalies to the EOF patterns. This yields a spatially resolved sea-level reconstruction. The level of spatial detail and resolution of this reconstruction is limited by the spatial structures of the retained EOF patterns (Church et al., 2004).

The gridded observations of SST used here stem from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST, version 1). The data are a result of an optimal interpolation of available ships observations. This data set has found many other applications in climate studies (Feng et al. 2015; Harlass et. al. 2015).

The link between sea-level in the GoG and the large-scale climate information is conducted by statistical analysis of the long-term de-trended annual means for all dataset. This procedure avoids the identification of artefact correlations simply due to the presence of long-term trends in the data sets. It also filters out long-term trends in sea-level caused by the long-term warming of the oceans and melting of land-ice that is not reflected in trends of the other climate parameters, like wind stress. (Wu et al. 2007).

Table 1: Data used in this study with a summary description of their spatial resolution

RESULTS

The results section covers two main topics: sea-level variability and impact of large-scale climate patterns on sea-level variations.

We address here two aspects: sea variability in the GoG and the influence of the large-scale climate patterns on sea-level in the GoG.

Sea-level Variability

The identification of the leading patterns of sea-level variability in the GoG was achieved by an EOF analysis. This analysis was conducted on normalized sea-level records (each grid-cell record normalized to unit variance) for the satellite, MPI-OM, and Church et al (2004) reconstruction SSH datasets (Figure 5). This normalization is required since the different data sets may display different levels of variability. The scale bar for Figure 5 only depicts the normalized range with dimensionless values. The leading normalized EOF patterns of SSH-derived from Satellite-SSH (Figure 5a) and MPI-OM-SSH (Figure 5b) show similar patterns in the tropics, but opposite patterns in the extra-tropics. Both explain about 20% of the variability and their spatial patterns are reasonably similar. In contrast, the leading EOF pattern derived from Church-SSH (Figure 5c) displays a uniform sign for the whole region and explains 48% of the variance. The reason for this discrepancy might lie in the reconstruction method. Since the reconstruction method applied by Church et al., already incorporates a prefiltering of the small-scale patterns of variability, it is logical that the leading

EOF patterns of this data sets can already explain a larger part of the total variability of the Church et al. (2004) data sets. The results suggest that the Church et al. (2004) SSH reconstruction is not able to capture smaller-scale regional to local patterns in our region of interest (refer to Table 2 for the percentage of variance for the 4 leading EOFs of the datasets).

a) *Satellite-SSH normalized EOF1 (1993-2013) 20.22% explained variance*

b) *MPI-OM normalized EOF1 (1990-2010) 19.54% explained variance*

c) *Church rec. normalized EOF1 (1950-2001) 48.63 % explained variance*

Figure 5: Normalized patterns of leading Empirical Orthogonal Functions of the annual mean sea-surface height (de-trended) for different datasets**: a)** satellite data, **b)** ocean-only simulation from MPI-OM and **c)** reconstructed SSH from Church et al. 2004

Table 2: The percentage of the variance of the 4 leading EOFs of the annual mean SSH and SST from the different sources used in this study data sets

Impact of large-scale climate patterns

The large-scale sea-level patterns of variability were identified by means of EOF analysis. For this analysis, the SSH and the SST data were not normalized (not reduced to unit standard deviation) in each grid-cell of the corresponding data set to obtain an estimation of the real amplitude of this variability (Fig 7a and Fig 7b)

The leading EOF patterns of SST (Figure 7a) show higher values in the tropics and opposite anomalies in the extra-tropics. The study finds a positive correlation (r = 0.32) between the time-series (principal components) of the leading EOFs of satellite-SSH and the SST (Figure 6). From these two spatial patterns, we can roughly estimate if the link between these two patterns are physically plausible We can and estimate the thermosteric expansion effect of ~ 0.8 Kelvin, which is the average value of the SST EOF1 for Ghana, Figure 7a) To estimate the magnitude of the thermal expansion, we assume that the temperature anomalies at the surface are representative of the upper 50 meters of coastal seawater column and have an average salinity of about 30 psu. We also neglect in this calculation any spill-over effect of the thermal expansion of the water column in the open ocean towards more shallow coastal areas. Based on a thermal expansion coefficient of 250 x 10^{-6} /K, a one K warming of the upper 50 meters should result in an expansion of the water column of 12.5 mm.

Figure 6: Time series of AMO index (blue), principal component 1 Satellite-SSH (red) and principal component 1 of SST (green) for the period 1993-2013

We now turn our attention to investigate the links between sea-level variability in the GoG and the Atlantic Multidecadal Oscillation (AMO). The AMO has been described as the multidecadal variability of the sea-surface temperatures in the North Atlantic (Chylek et al. 2014). It has been identified as an important climate driver in this region. We explore the link between the AMO and sea-level in the GoG by calculating the correlation between the AMO index and the SST and SSH in the GoG. (Figure 8).

(a) **(b)**

Figure 7: Pattern of leading Empirical Orthogonal Functions of the annual mean sea-surface-temperature from HadISST and satellite-SSH. ***a)*** *HadlSST1 EOF1 (1993-2013) 27.34% explained variance;* ***b)*** *Satellite-SSH EOF1 (1993-2013) 20.22% explained variance*

The AMO index has also been correlated with the reconstructed SSH record at Takoradi and at the tide-gauge of Forkados in Nigeria (Figure 9). The purpose of this analysis is to establish to what extent the connection between the AMO and West Africa sea-level can be reproduced in the satellite data and in the tide-gauge data.

Figure 8: Correlation pattern between the AMO index and the annual mean SSH from satellite altimetry

Figure 9: Time series of the AMO index together with tide gauge record of Forcado/ Nigeria and the Ghana annual mean sea-level reconstruction

This analysis (Figure 8) shows relatively strong correlations between AMO and sea-level in the whole Tropical Atlantic, but the impact of AMO on sea-level seems to be larger along the West African coast. However, the pattern along the West African coast varies. For example, the correlation between AMO and SSH on the Ghana coast is stronger than at the Nigeria coast. The evidence of this AMO impact on sea-level variability at the West Africa coast is reflected in the decadal variations of AMO and the decadal variations of time series of the reconstructed Ghana AMSL and that of Nigeria (Figure 9) although the available data for Nigeria is inadequate for long term analysis. The agreement between the AMO index and the reconstructed Ghana sea-level record is poorer in the early parts of the record, before 1940, but it is much better thereafter. It shows a maximum of the AMO and of sea-level at around 1955, with declining values thereafter until around 1975. In the subsequent years, both indices of the AMO and of the reconstructed Ghana sea-level recover towards more positive values. Since the AMO and satellite-SSH were found to be positively correlated, the agreement in the long-term AMO and SSH indices support the robustness of the Ghana SSH reconstructions despite the cautions that should be placed on the Ghana tide-gauge records.

Regarding the effect of winds on sea-level variability in the GoG, although the wind has been hinted at as an important driver of sea-level variability (Thompson et al. 2014; Timmermann et. al. 2010), our statistical analysis did not find a clear connection between wind-stress and sea-level variations in the GoG.

DISCUSSION

Large-scale climate patterns are identified to impact regional sea-level variability at various locations globally which in turn could affect coastlands at different rates. Although Chylek et al. 2014 identified AMO to have a possible influence of natural climate variability in the subtropics there are different theories that attempt to explain the mechanism AMO.

With regards to sea-level change on West Africa, Tano et al. 2016 based on 23-year satellite altimeter data reported that relative sea-level has increased around 3.05 mm/y in the GoG. Evadzi et. al. 2017(a), estimated that computed sea-level trend from satellite-SSH data (1993-2013) at the coast of Ghana (2.52 ± 0.22 mm/y), contributed to ~ 31 % of observed historical shoreline change (~2 m/y) for the coast of Ghana from 1974 to 2015.

The SST variations are found to be associated with sea-level variability in the GoG since normalized leading EOF(s) patterns from satellite-SSH (1993-2013) and SST show similar spatial structure in the tropics and opposite patterns in the extra-tropics. The positive correlation found between the principal components of the leading EOFs of SSH and SST allows for an estimation of the thermosteric effect on sea-level variability, under some reasonable physical conditions (SST sharing the warming/cooling with the upper 50 meters of the water column and constant salinity at 30 psu), yielding an amplitude of SSH variability in the GoG of 1 mm per 0.8 K of SST variability.

The AMO is found to be more strongly correlated with SSH at the coast of Ghana than in Nigeria (Fig. 8). In addition, the long-term trend of the AMO also influences the long term trend of Ghana and Nigeria SSH. (Figure 9). The agreement between the AMO indices and the reconstructed Ghana SSH gives more credibility to the Ghana tide-gauge records, at least in their multidecadal variations. In particular, the declining sea-level at the Ghana coast in the period between 1955 and 1975 approximately is as reflected in similar variations of the AMO index. The connection between AMO and SSH in the Tropical Atlantic is also supported by the found correlations with satellite altimetry in the satellite era, Therefore, the common evolution of the AMO and Ghana SSH at decadal time scales in the pre-satellite era seems to be physically supported.

CONCLUSIONS

Although there exists literature on sea-level impact on the coast of Ghana there is lack of information on sea-level variability and trends for Ghana and the entire Gulf of Guinea region. This study attempts to provide this information that may be useful for adaptation strategies.

There are several factors that are identified in this statistical analysis as drivers of SSH variability in the GoG. One is sea-surface-temperature. In addition, the Atlantic Multidecadal Oscillation displays a clear link to SSH variability in this region, in both satellite altimetry data and in tide-gauge data from Ghana and Nigeria. In contrast, no statistical influence by the wind -stress on SSH variability in the GoG could be identified in this study.

Although this study reconstructed regional mean sea-level curve for Ghana, there exist no data for the period from 1981 to 1993 between the reconstructed regional sea-level curve for Ghana and existing satellite altimetry data on sea-level change for the Gulf of Guinea for detail analysis on sea-level trend for Ghana. Such research will be useful for forecast and improve coastal adaptation strategies.

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LIST OF FIGURES

LIST OF TABLES

Figure 1

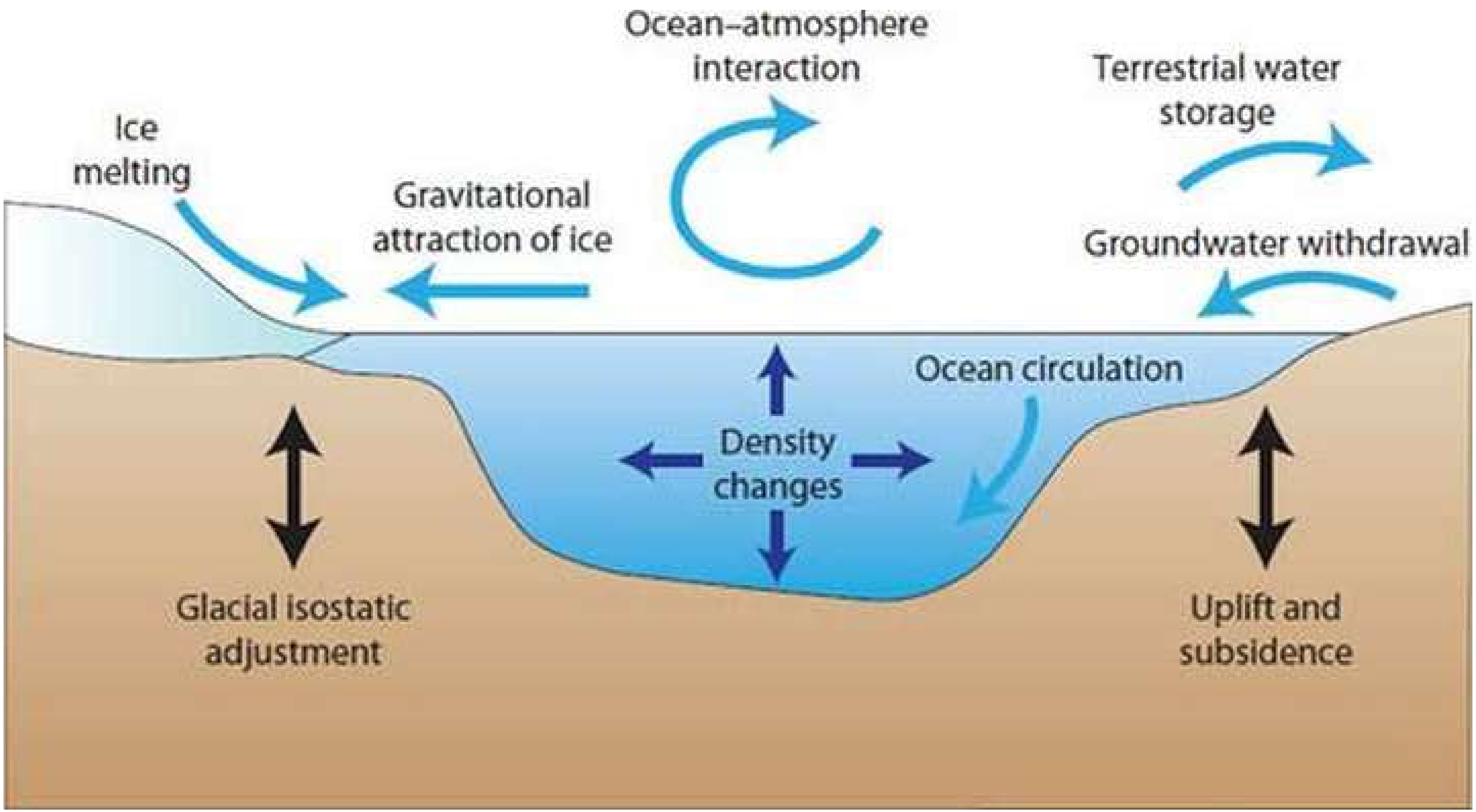

Ocean–atmosphere interaction
Terrestrial water storage
Ice melting
Gravitational attraction of ice
Groundwater withdrawal
Ocean circulation
Density changes
Glacial isostatic adjustment
Uplift and subsidence

Figure 2

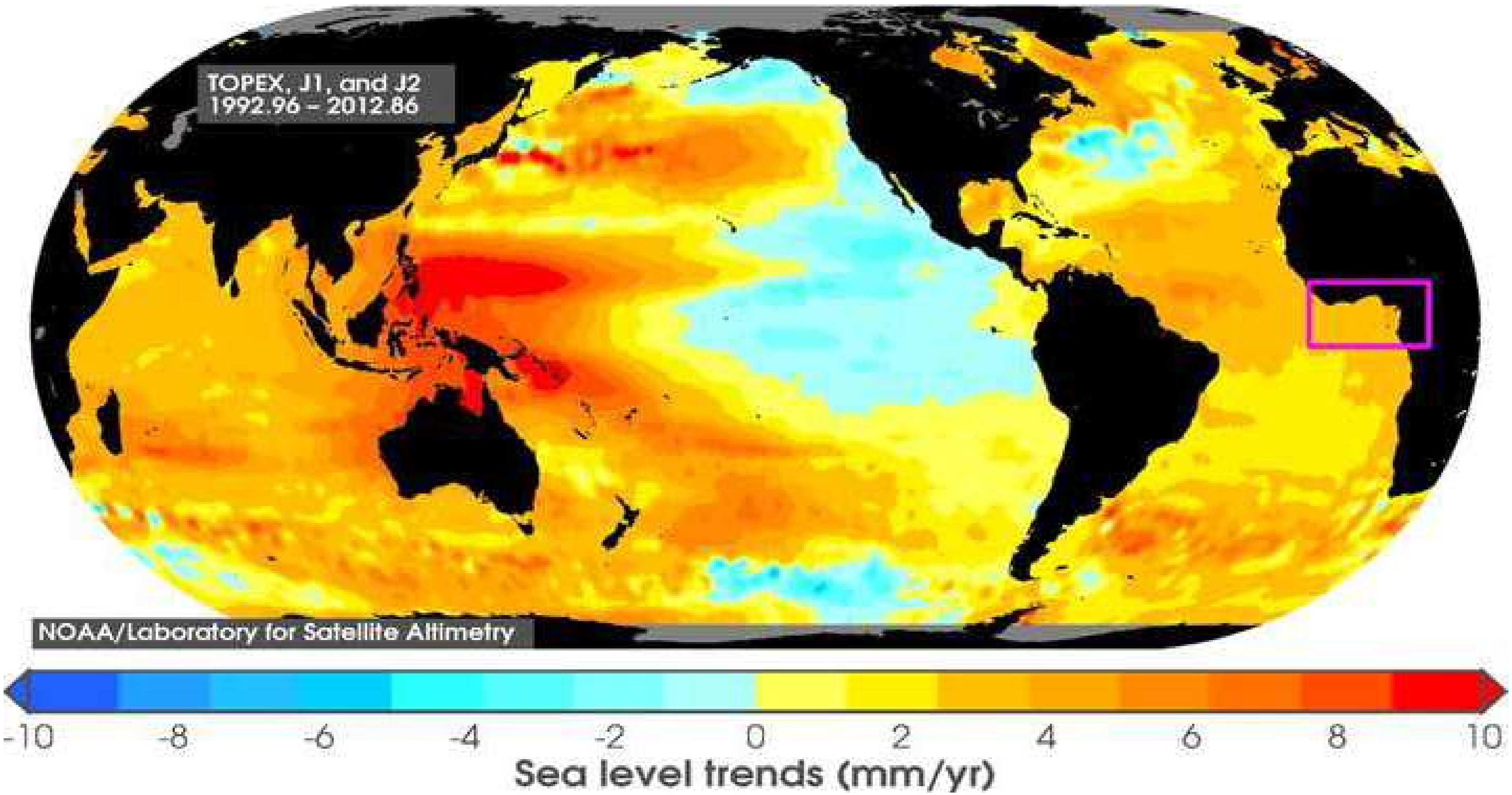

TOPEX, J1, and J2
1992.96 – 2012.86
NOAA/Laboratory for Satellite Altimetry
-10
-8
-6
-4
-2
0
2
4
6
8
10
Sea level trends (mm/yr)

Figure 3

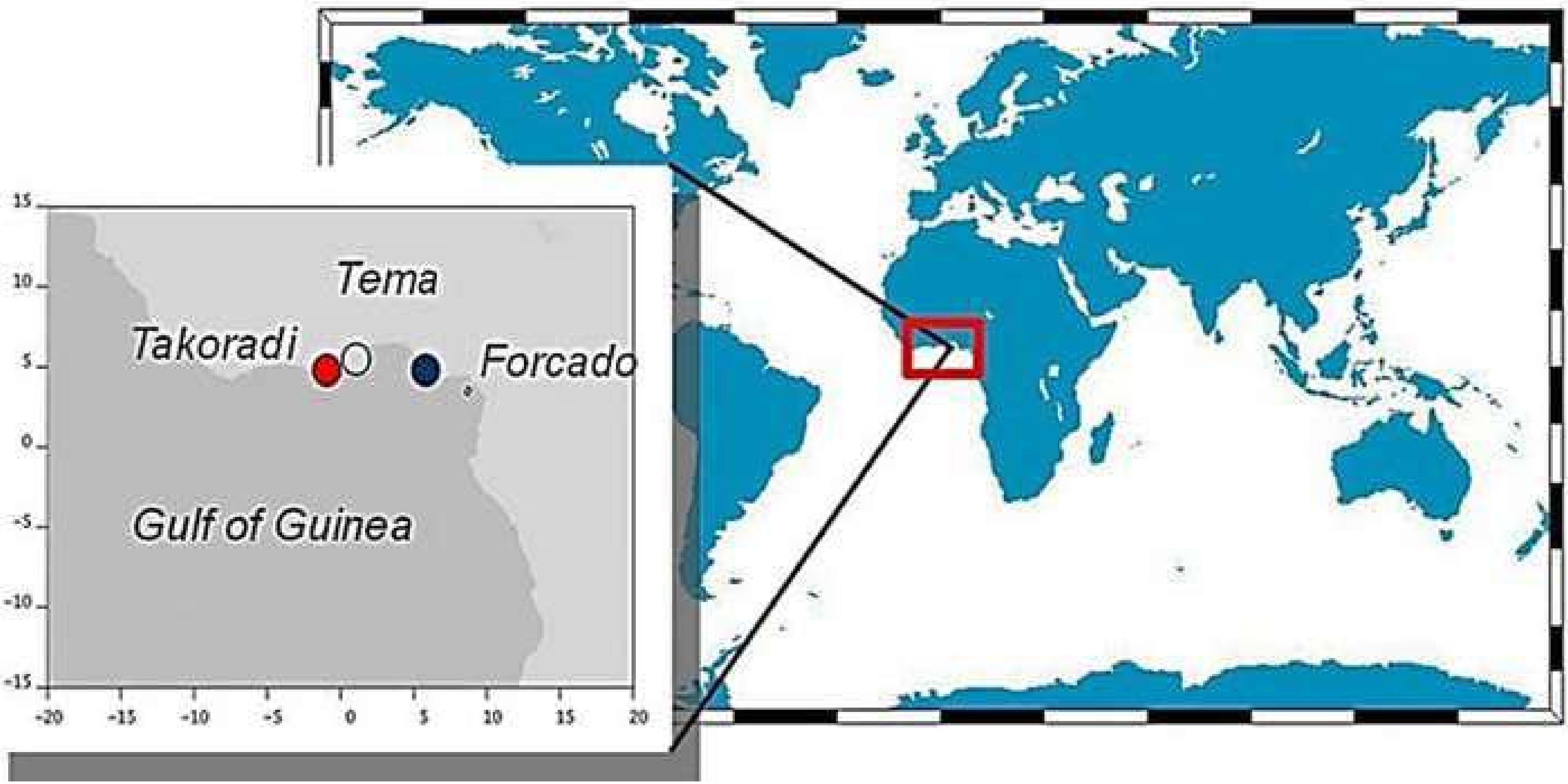
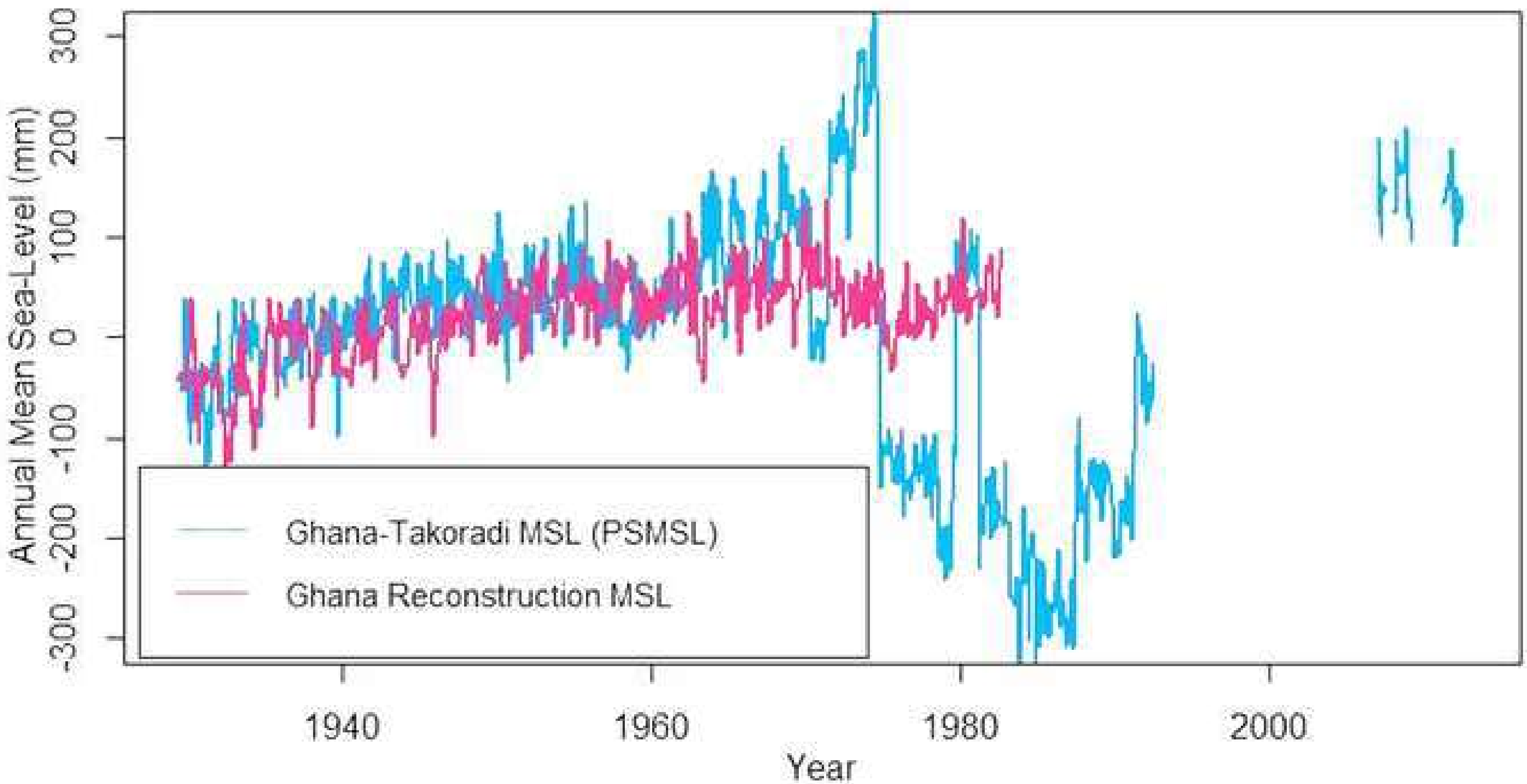
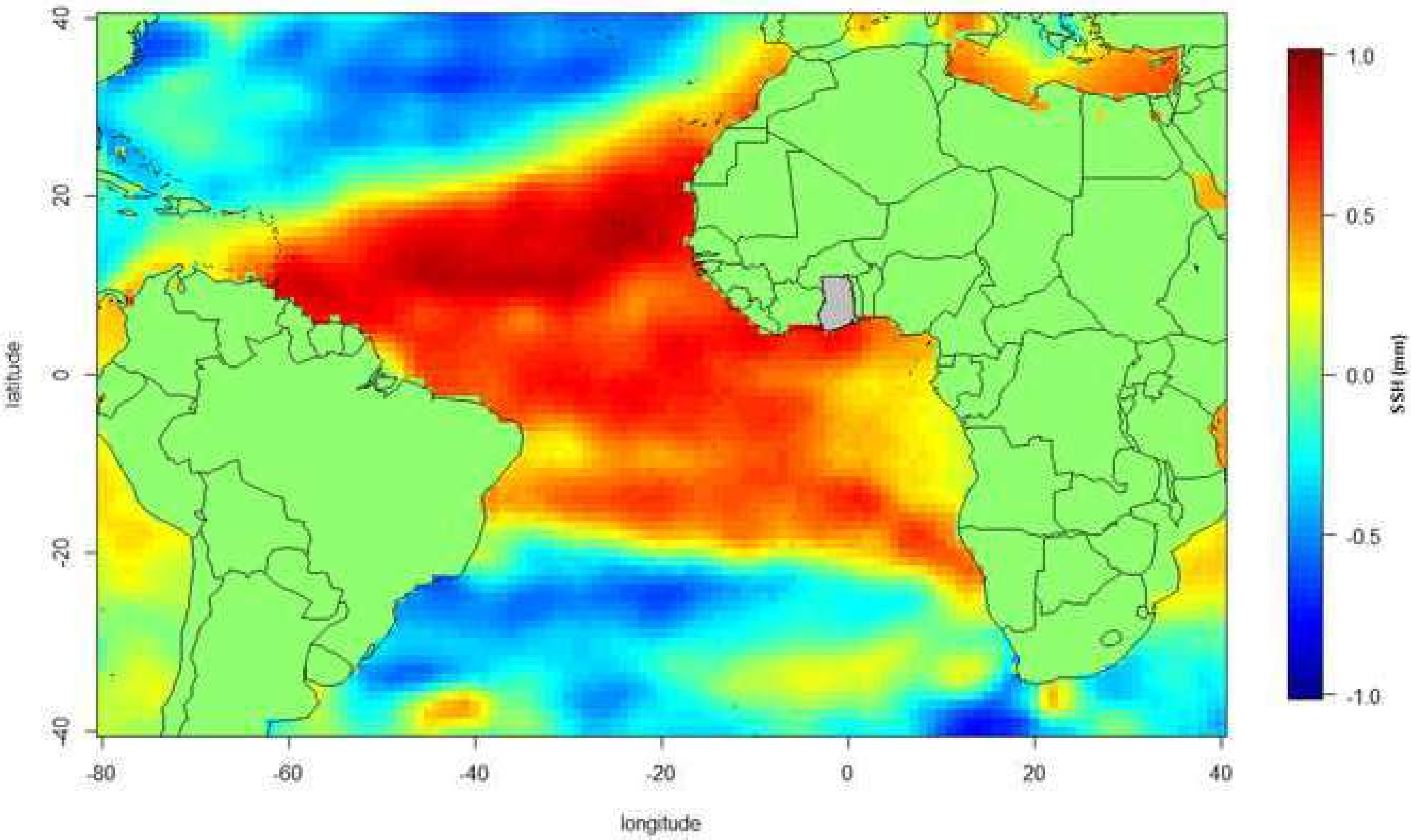

Tema
Takoradi
Forcado
Gulf of Guinea
15
10
5
0
-5
-10
-15
-20
-15
-10
-5
0
5
10
15
20

Figure 4



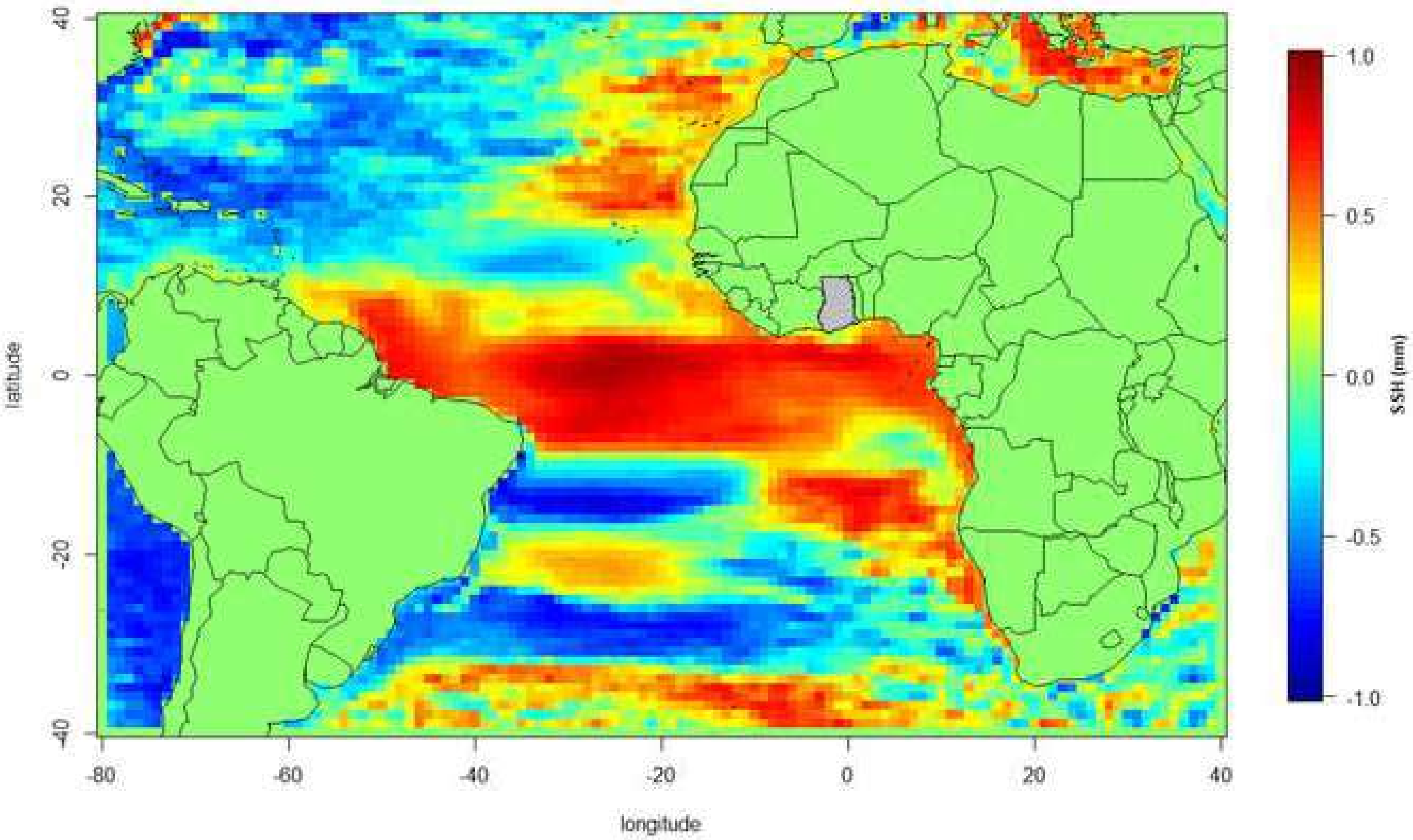
Annual Mean Sea-Level (mm)
300
200
100
0
-100
-200
-300
Ghana-Takoradi MSL (PSMSL)
Ghana Reconstruction MSL
1940
1960
1980
2000
Year

Figure 5a



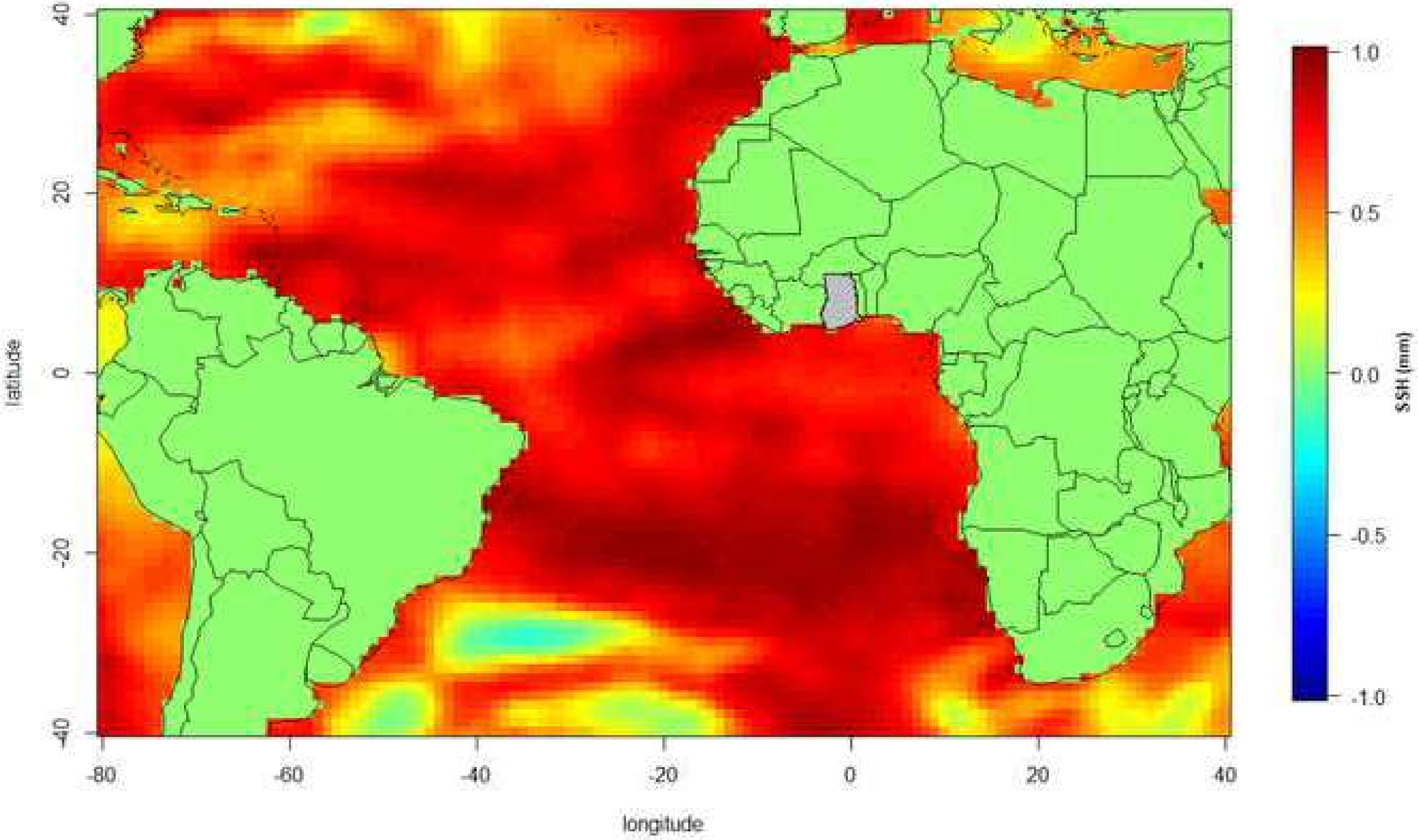
latitude
40
20
0
-20
-40
-80
-60
-40
-20
0
20
40
longitude
1.0
0.5
0.0
-0.5
-1.0
SSH (mm)

Figure 5b



latitude
40
20
0
-20
-40
-80
-60
-40
-20
0
20
40
longitude
1.0
0.5
0.0
-0.5
-1.0
SSH (mm)

Figure 5c



40
20
0
-20
-40
latitude
-80
-60
-40
-20
0
20
40
longitude
1.0
0.5
0.0
-0.5
-1.0
SSH (mm)

Figure 6

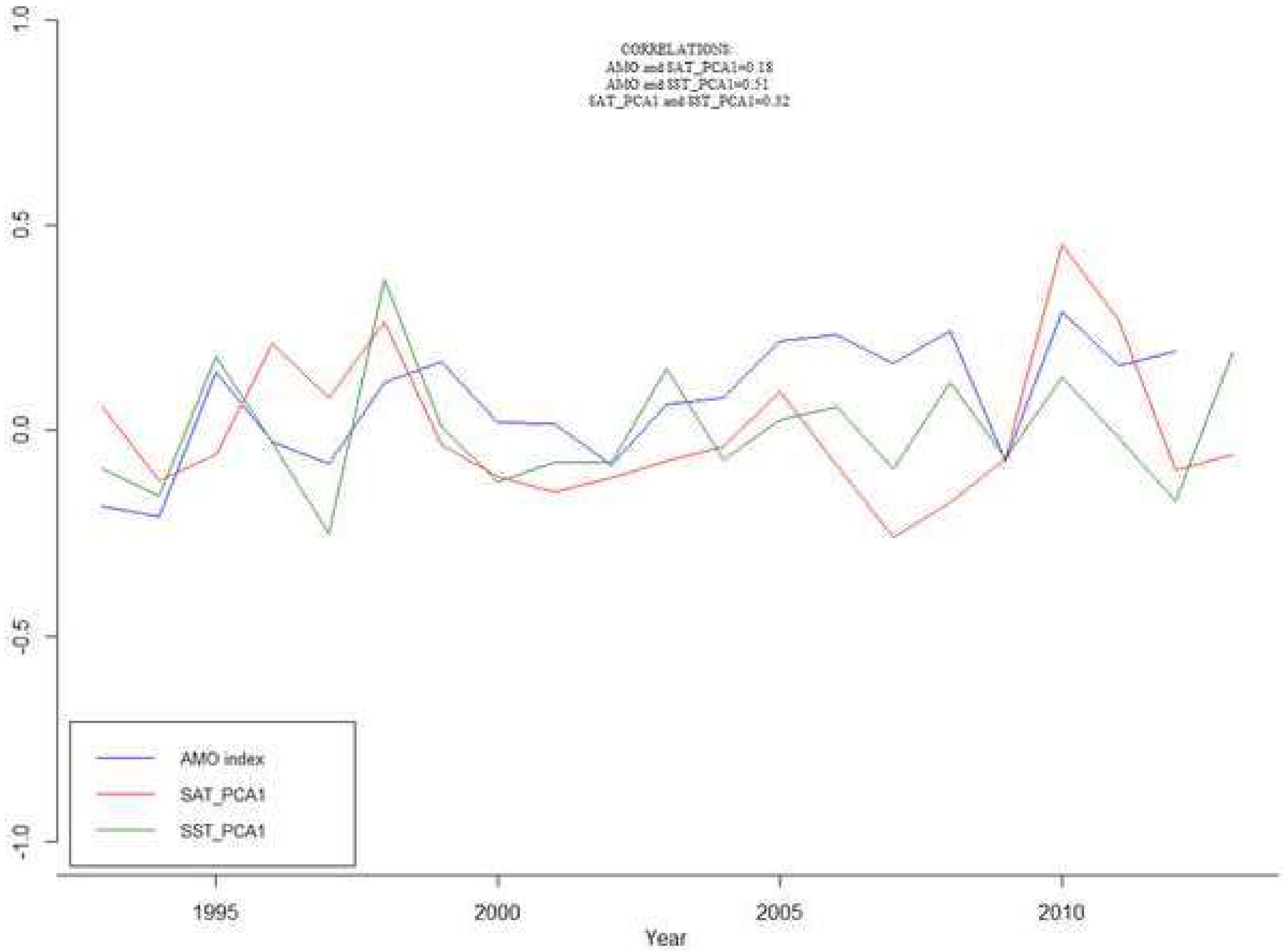
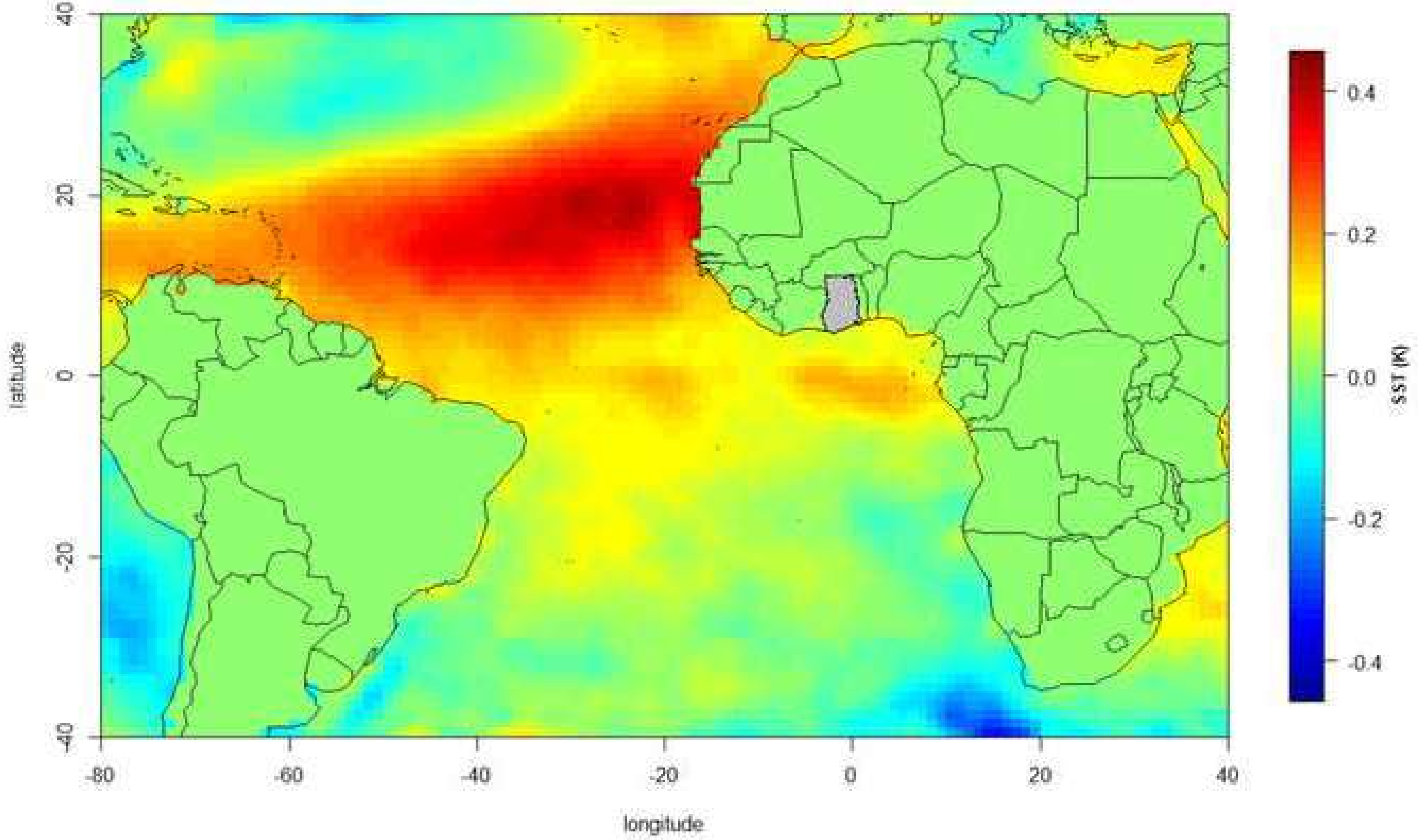

CORRELATIONS:
AMO and SAT_PCA1=0.18
AMO and SST_PCA1=0.51
SAT_PCA1 and SST_PCA1=0.32
AMO index
SAT_PCA1
SST_PCA1
1.0
0.5
0.0
-0.5
-1.0
1995
2000
2005
2010
Year

Figure 7a



latitude
40
20
0
-20
-40
-80
-60
-40
-20
0
20
40
longitude
SST (K)
0.4
0.2
0.0
-0.2
-0.4

Figure 7b

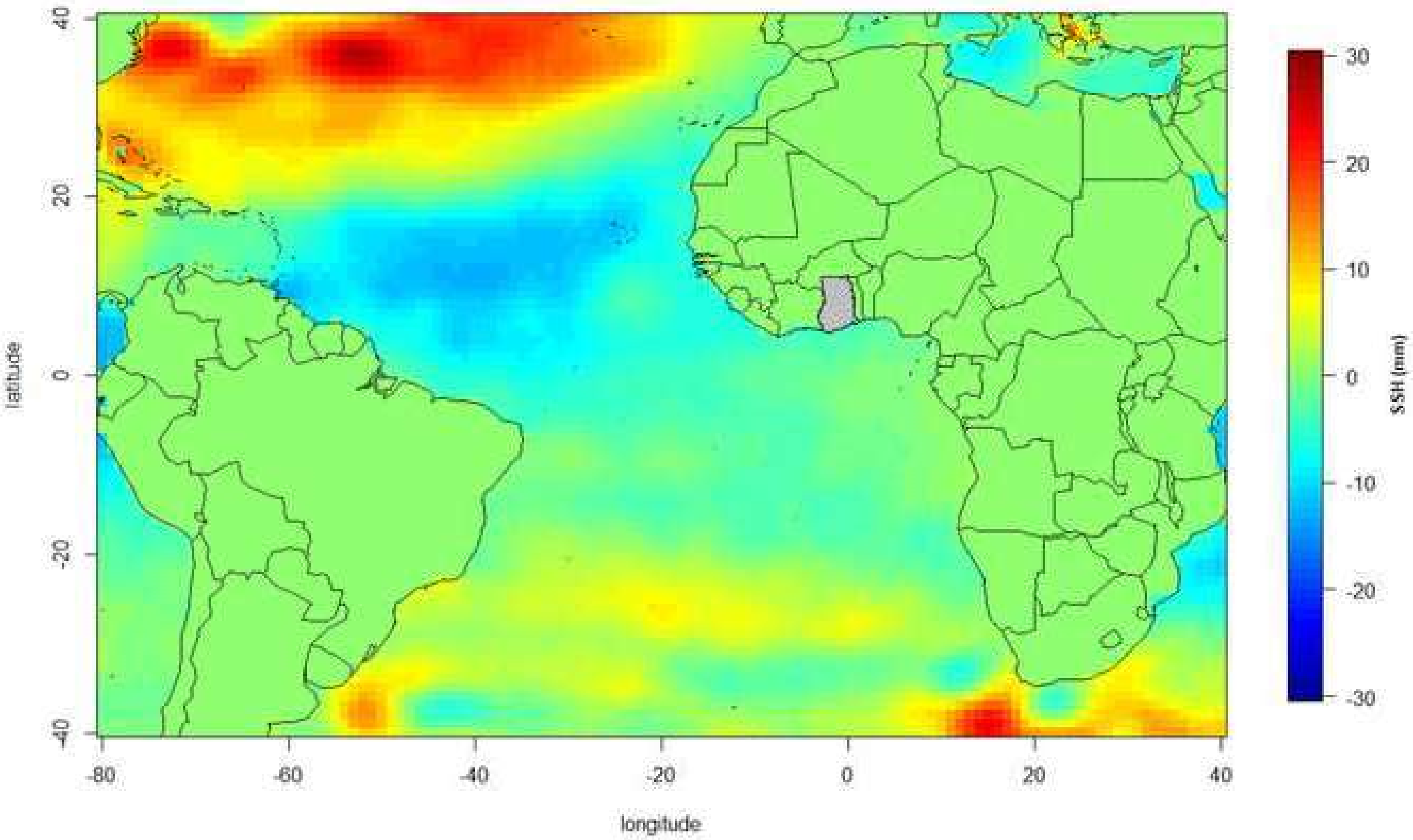
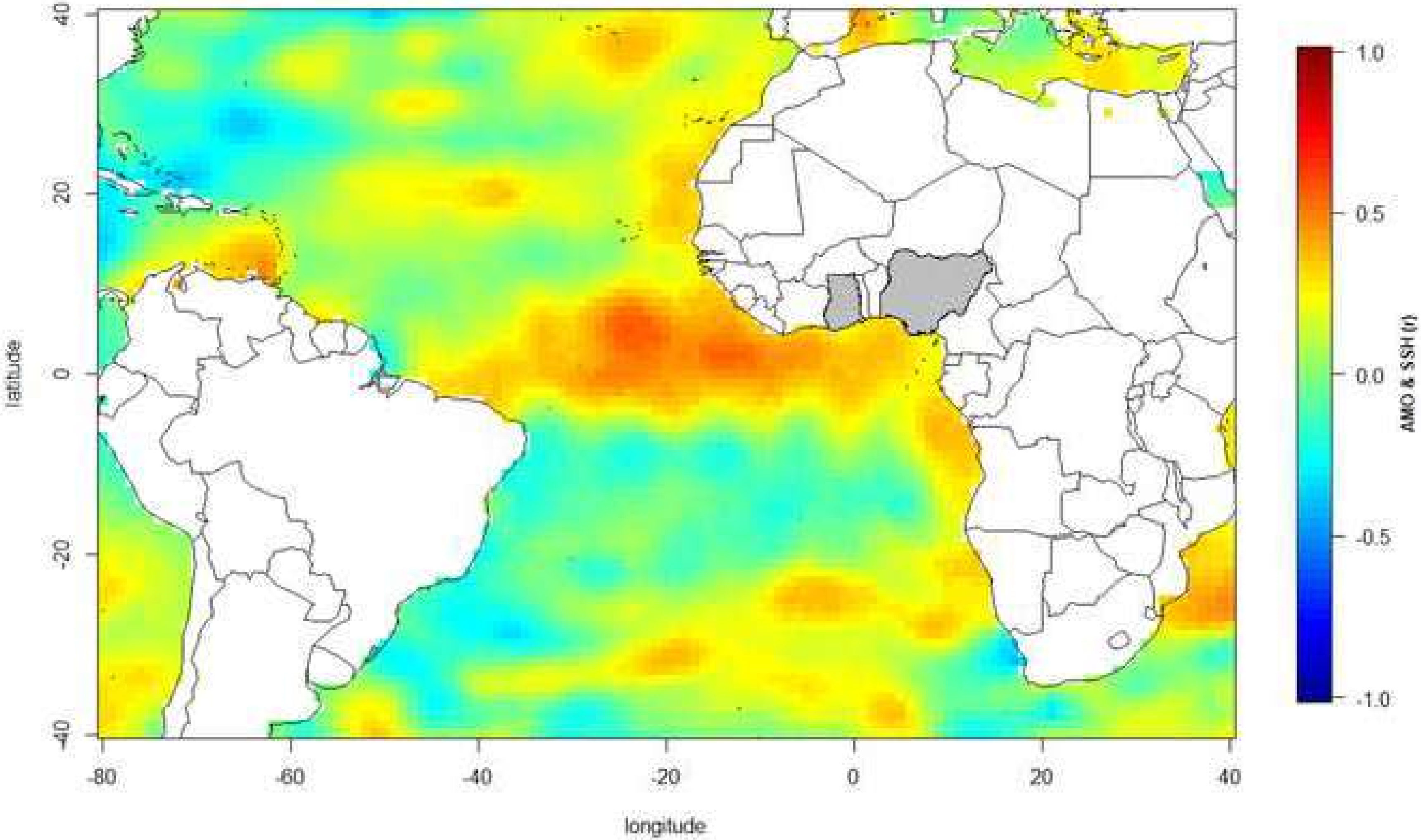
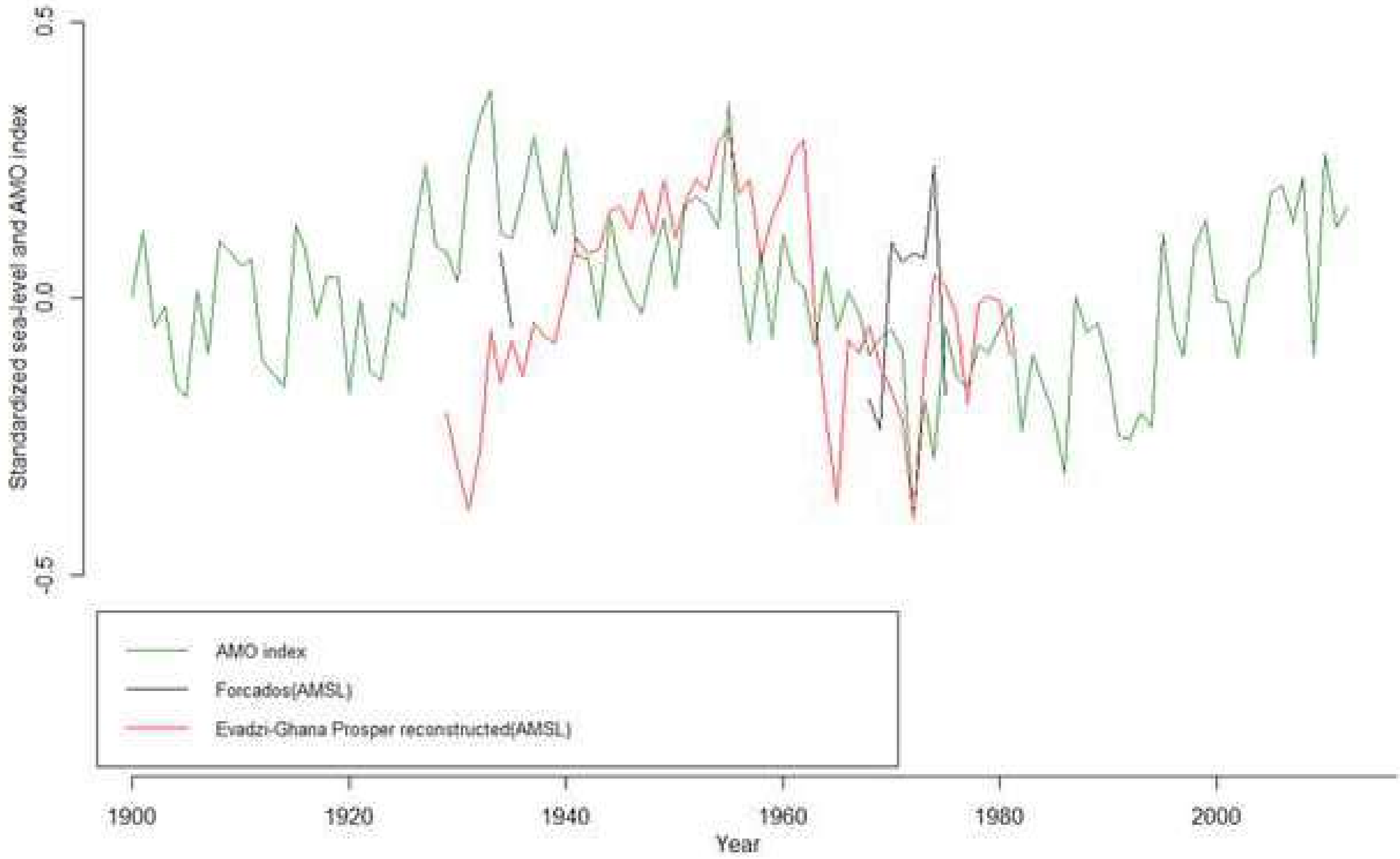

latitude
longitude
SSH (mm)
40
20
0
-20
-40
-80
-60
-40
-20
0
20
40
30
20
10
0
-10
-20
-30

Figure 8



40
20
0
-20
-40
latitude
-80
-60
-40
-20
0
20
40
longitude
1.0
0.5
0.0
-0.5
-1.0
AMO & SSH (r)

Figure 9



Standardized sea-level and AMO index
0.5
0.0
-0.5
AMO index
Forcados(AMSL)
Evadzi-Ghana Prosper reconstructed(AMSL)
1900
1920
1940
1960
1980
2000
Year

Table 1

Name/Acronym	Location/description	Years	Data source
SSH	near-global (65°S to 65°N),1°×1° grid	1993-2013	Combined TOPEX/Poseidon, Jason-1 and Jason-2/OSTM sea-level fields
Monthly tide gauge data	Gulf of Guinea/ East Atlantic		PSMSL
Reconstructed SSH	near-global (65°S-65°N), 1°×1°×1month grid	1950-2001	Church et al. 2004
MPI-OM (STORM)	global ocean only simulation/model MPI-OM on a 0.1°×0.1° grid	1950-2010	Storch et al. 2012
HadISST 1	1° gridded global data	1870-2013	Rayner et al. 2003
AMO index	Index derived from HadSST (monthly mean)	1854-2012	http://climexp.knmi.nl/amo.cgi (Accessed 2014)
Wind stress	monthly gridded mean of momentum flux, U-component)	1948-2014	NCAR/NCEP Reanalysis. http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html (Accessed 2014)

Table 2

Data(scaled)	Components	% of variance
Satellite Altimetry data(SSH)	EOF 1	20.22
	EOF 2	13.09
	EOF 3	10.86
	EOF 4	9.29
MPI-OM (SSH)	EOF 1	19.54
	EOF 2	13.28
	EOF 3	10.13
	EOF 4	7.72
Church et al. (SSH)	EOF 1	48.63
	EOF 2	15.04
	EOF 3	9.01
	EOF 4	7.50
HadISST 1 (SST)	EOF 1	21.37
	EOF 2	11.32
	EOF 3	9.91
	EOF 4	7.34