Regional sea-level at the retreating coast of Ghana under a changing climate

Dissertation

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"If we are unsure of the complex processes and interactions of coastal change and policy implementation today, how can we address impacts, deal with uncertainties, and where necessary, plan adaptation for the future?"

Brown et al. 2014

Abstract

This doctoral thesis is framed around 3 research questions with the main goal to understand regional sea-level at the retreating coast of Ghana under a changing climate. In chapter 2, the thesis presents findings to the first research question that attempts to identify the impact of large-scale climate patterns on sea-level variability and trends in the Gulf of Guinea (GoG). By performing Empirical Orthogonal Function (EOF) and other statistical analysis on different datasets ranging from sea-level data, gridded reconstruction, ocean model simulations (STORM), to meteorological and reanalysis products, the research identifies sea-surface temperature (SST) in the GoG and its associated Atlantic Multidecadal Oscillation (AMO) as the main large-scale climate factors linked to mean sea-level variability of the West African coast.

Findings relating to the second research question that seeks to quantify the contribution of sea-level rise (SLR) to shoreline change in Ghana are presented in chapter 3. By analyzing historical shoreline positions in Ghana from 1974 to 2015 from satellite images and Orthophotos using Geographic Information System (GIS) tools and by performing statistical analysis on shoreline information, estimates from satellite observations and results from Digital Elevation Model (DEM) analysis, the study estimates the historical contribution of SLR to shoreline change in Ghana to be ~31 % of the observed annual coastal erosion rate (about 2 m/y) in Ghana. The study further makes predictions of shoreline in Ghana based on modified Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Representative Concentration Pathways (RCPs) scenarios for Ghana.

The chapter 4 addresses the third research question that seeks to determine the level of awareness of respondents to SLR on the coast of Ghana and, also to explore the availability and level of integration of scientific knowledge of SLR into coastal adaptation strategies in Ghana using semi-structured interviews at national, municipal/district and coastal community scales. Through GIS analysis, the study also projected urban land loss along the Western coast of Ghana between Half Assini and Old Elubo by 2050 to be ~ 5,000 m^2, 7,000 m^2 and 12,000 m^2 for the 2.6, 4.5 and 8.5 RCPs respectively. The study reveals that, albeit the threat of SLR to property and life on the coast of Ghana, coastal dwellers interviewed cherish their proximity to the sea and are determined to maintain their occupancy close to the sea. This thesis thus provides useful information for coastal adaptation strategies.

Zusammenfassung

Diese Doktorarbeit umfasst drei Forschungsfragen mit dem Ziel den regionalen Meeresspiegelanstieg an der Küste Ghanas, hervorgerufen durch den Klimawandel, zu verstehen.

Im zweiten Kapitel werden die Ergebnisse zur ersten Forschungsfrage dargestellt. Hierbei geht es darum, den Einfluss großskaliger Klimamuster auf die Variabilität und den Trend des Meeresspiegels im Golf von Guinea zu identifizieren. Anhand einer empirischen Orthogonalfunktionsanalyse und anderen statistischen Methoden wurden verschiedene Meeresspiegel-Datensätze untersucht: gegitterte Rekonstruktionen, Ozeanmodellsimulationen (STORM) und meteorologische Reanalysedatensätze. Die Meeresoberflächentemperatur und die damit verbundene atlantische multi-dekadische Oszillation wurde als großskaliger Klimafaktor identifiziert, der die Meeresspiegelvariabilität an der Westküste Afrikas beeinflusst.

Die Ergebnisse zur zweiten Forschungsfrage sind im dritten Kapitel beschrieben. Hier wurde der Einfluss des Meeresspiegelanstieges auf Änderungen der Küste von Ghana untersucht. Durch die Analyse historischer Küstenlinienverläufe von 1974 bis 2015 auf Basis von Satellitenbildern und Orthophotos, wurde mit Hilfe von geografischen Informationssystemen (GIS) und statistischen Methoden, angewandt auf Küstenlinieninformationen (aus Satellitenbeobachtungen und digitaler Höhenmodelle), der Einfluss des Meeresspiegelanstieges auf die Küstenlinien Ghanas auf ~31% der jährlichen Küstenerosionsrate (ca. 2 m/Jahr) geschätzt. Des Weiteren wurden in der Studie Vorhersagen zur Küstenlinie Ghanas, basierend auf dem modifizierten IPCC AR5 RCPs Szenarios für Ghana, durchgeführt.

Im vierten Kapitel wird die dritte Forschungsfrage behandelt. Diese beschäftigt sich mit dem Bewusstsein für den Meeresspiegelanstieg der Bewohner der Küste Ghanas. Außerdem wurde die

Möglichkeit und das Maß der Integration wissenschaftlicher Kenntnisse des Meeresspiegelanstieges in Küstenanpassungsstrategien für Ghana untersucht, indem semi-strukturierte Interviews auf nationaler, kommunaler und küsten- gemeindlicher Ebene geführt wurden. Anhand einer GIS Analyse wurde zudem der zu erwartende Landverlust an der Westküste Ghanas zwischen Half Assini und Old Elubo für 2050 mit 5,000 m^2, 7,000 m^2 und 12,000 m^2 für die 2.6, 4.5 und 8.5 RCPs beziffert. Die Studie zeigt auf, dass die interviewten Bewohner trotz der Bedrohung durch den Meeresspiegelanstieg, ihren Wohnort an der Küste schätzen und entschlossen sind dort weiterhin zu leben. Diese Doktorarbeit liefert also wertvolle Informationen zu Adaptationsstrategien an der Küste Ghanas.

Contents

CHAPTER 1

Introduction

1.1 Statement of Purpose and Thesis Objectives

It is observed from scientific findings that global temperatures have experienced varied trends throughout history with significant increase since the 1850s and the last century, an increase largely attributed to global climate change induced by anthropogenic greenhouse gas emissions (GHG) and land-use changes (IPCC) 2013; Cazenave and Cozannet 2014). Sea-level change is one of the physical impacts that is observed to occur in response to changes in the Earth's heat budget and hydrological cycle including the addition of freshwater from land-ice melt as a result of this global temperature increase. However, regional and local scale variations of SLR occur due to steric effects (changes in the density structure of the oceans associated with temperature and salinity variations), eustatic effects due to land-ice melt, ground water use and reservoir management, and of the effects of regional changes in ocean currents. Thus, future SLR is not projected to be spatially uniform (Kopp et al. 2015).

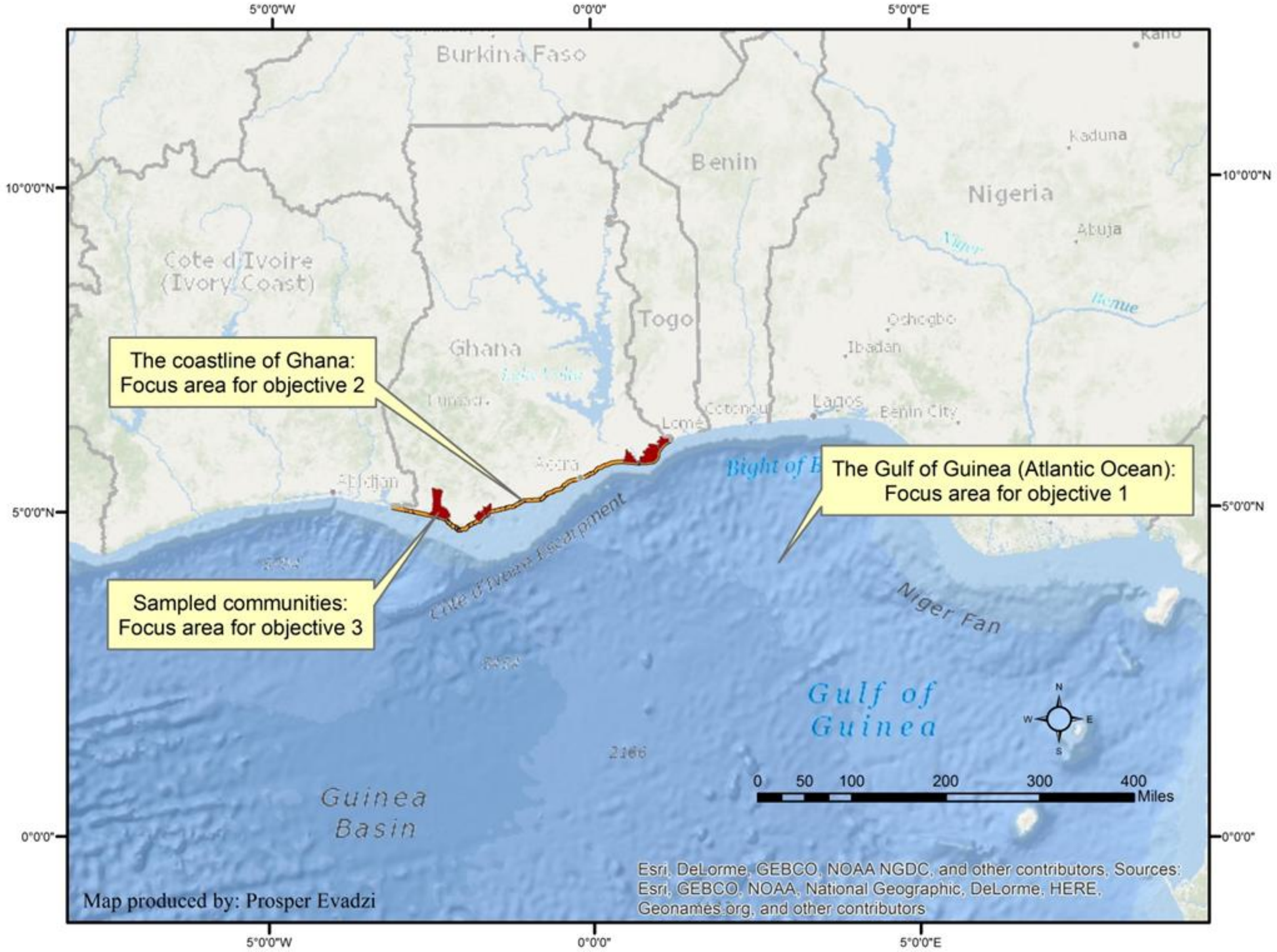
Although there exist many scientific reports on regional sea-level variability (Stammer et al. 2013; Cazenave and Llovel 2010), little of such information is available for the GoG, which to an extent is as a result of lack of accurate observations (Woodworth et al. 2007).

The coastline of Ghana, located on the GoG, is identified to be currently eroding at different rates along the coast (Appeaning Addo 2015; Appeaning Addo et al. 2011; Jayson-Quashigah et al. 2013; Wiafe 2010) and this may be partly caused by SLR. Although Appeaning Addo et al. (2008) attempted to predict the physical impact of SLR on the coastline of Accra in Ghana, based on projected global sea-level trends, this projection may differ from local sea-level change scenarios for Ghana.

If climate change adaptation strategies are to be improved for the coast of Ghana, there is need for information on sea-level variability in the GoG, with documentation on the impact of natural climate variability on the observed patterns. In addition, a study of historical shoreline changes for the entire Ghana coast detailing the contribution of SLR to the shoreline change in Ghana, as well as information on the awareness of sea-level response under climate change on the coast of Ghana will be essential. The purpose of this thesis is to attempt providing this essential information for the GoG and the coast of Ghana.

The objectives of this thesis are formulated as an attempt to provide information on regional sea-level under a changing climate at the retreating coast of Ghana that may be essential for coastal adaptation strategies that are lacking for Ghana. The research questions/objectives (represented in Figure 1.1) are as follows;
Objective 1: What is the impact of large-scale climate patterns on sea-level variability and trends in the GoG with focus on the West African coast?
Objective 2: What is the contribution of SLR to shoreline change In Ghana?

Objective 3: What is the impact of coastal erosion estimates on land cover in Ghana, and what is the level of awareness of sea-level response under climate change on the coast of Ghana?



The coastline of Ghana: Focus area for objective 2

The Gulf of Guinea (Atlantic Ocean): Focus area for objective 1

Sampled communities: Focus area for objective 3

Map produced by: Prosper Evadzi

Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 1.1: Study areas represents the spatial units investigated for the three research questions for this thesis

1.2 The West African coast, Gulf of Guinea and the Ghana Coast

The West African coast was formed about 135 million years ago, during the Cretaceous period where the South American plate broke and drifted away from the African plate to form the Atlantic Ocean/GoG. This Atlantic Ocean together with other factors including the geological composition, the geophysical characteristics of its river basins, the prevailing meteorological conditions and the slow tectonic processes continues to impact the West African coast (Allersma and Tilmans 1993). Although there is lack of information on regional sea-level variability as well as the role of natural climate variability in the GoG, coastal erosion is identified to be a serious environmental problem facing the West African coast including Ghana (Hinrichsen 1990).

Coastal erosion and the risk of climate sensitive hazards like SLR to human life, livelihoods, property and natural ecosystems represents clear threats to the coastal zone of Ghana. This zone represents only about 7% of the total Ghana land area yet inhabited by about 25% of the country's population as well as occupied by about 75% of major businesses and industries in the country (Ghana Statistical Service 2013; Armah and Amlalo 1998). Despite the socio-economic importance of the coastal zone for the country, there is no detailed information on the role of SLR to coastal erosion in Ghana. Thus, this thesis identifies three study areas (Figure 1.1) for different analyses aimed at providing essential information on regional sea-level under a changing climate at the retreating coast of Ghana.

1.3 Thesis Outline

This thesis is structured in 5 chapters, an introductory chapter (chapter 1), 3 main chapters (chapter 2, 3 and 4) addressing the three research questions and a summary and conclusion chapter (chapter 5).

Each of the 3 main chapters (chapter 2,3 and 4) form the core of corresponding articles that were prepared for peer-reviewed journals and may be read independently from the others albeit they share the same overarching goal. Each of these main chapters has an introduction, detailed description of data sets and methods, results, discussion and conclusions. Because of the independency of each chapter some repetitions were unavoidable. The last chapter of the thesis gives an overall summary of the thesis results.

Chapter 2 attempts to provide an answer to the research question (objective 1): What is the impact of large-scale climate patterns on sea-level variability and trends in the GoG with focus on the West African coast?

This chapter characterizes the large-scale climate forcing that drives mean sea-level (MSL) variability on the West African coast and its offshore waters and studies its decadal variability and long-term trends in the observational period (1993-2013).

To achieve this objective, statistically analyses is performed on available 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), ocean model simulations (STORM), and meteorological and reanalysis products (HadISST1, AMO index and surface wind stress).

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. Some physical connection is identified to exist between sea-surface temperature (SST) and its associated AMO in the Gulf of Guinea and mean sea-level trends and variability of the West African coast.

Chapter 3 estimates the contribution of regional SLR to shoreline retreat in Ghana over the last decades and the future.

This objective is achieved by first statistically computing shoreline change rates from 4 historical shoreline time series (1974, 1990, 2005 and 2015) generated from satellite images and orthophotos.

Second, statistical methods were used to quantify the SLR contribution to historical shoreline change using sea-level trend estimates from satellite observations, results from digital elevation model analysis, and shoreline change rates.

Finally, predictions of shoreline in Ghana on the basis of modified Intergovernmental Panel on Climate Change Fifth Assessment Report RCPs scenarios for Ghana were made. On average, sea-level has risen by about 5.3cm over the last 21 years and, in my estimation accounts for only ~31% of the observed annual coastal erosion rate (about 2m/y) in Ghana. On the basis of the projected model ensemble-mean rise in sea-level (2.6, 4.5, and 8.5 RCPs) scenarios and assuming that SLR will also contribute to ~31% of shoreline retreat in the future, by the year 2025, about 7, 5, and 6 m of coastland in Ghana with lowest slope range (0–0.4%) is projected to be inundated respectively. These projected changes increase to 19.8, 20.7, and 24.3 m by 2050 and further to ~37, 52, and 84 m by 2100 for the 2.6, 4.5, and 8.5 RCPs respectively. The analysis that separates sea-level contribution to coastal change from other contributing factors could provide useful information about climate impact for coastal adaptation strategies. Further research into the anthropogenic and other factors that contribute about 69% of the annual erosion rate in Ghana is recommended to help improve adaptation efforts.

Chapter 4 attempts to provide an answer to the research question (objective 3): What is the impact of coastal erosion estimates on land cover in Ghana, and what is the level of awareness of sea-level response under climate change on the coast of Ghana?

In response to climate change, coastal communities are expected to experience increasing coastal impacts of SLR. Strategies formulated and implemented to curb these impacts can thus be more effective if scientific findings on the response to climate change and SLR impacts on coastal communities are taken into consideration and not based merely on the need for coastal protection due to physical coastal erosion.

The impact of coastal erosion estimates (refer to chapter 2) on different land cover types and specific built up areas on the coast of Ghana is assessed.

An assessment of the level of awareness of respondents to SLR on the coast of Ghana and an exploration of the availability and level of integration of scientific knowledge of SLR into coastal adaptation strategies in Ghana is also made. Semi-structured interviews at national, municipal/district and coastal community scales was used to assess the level of the awareness of SLR responses to the changing climate in Ghana.

Coastal urban areas of Half Assini and Old Elubo communities with slope range (0 - 0.4 %) along the western coast of Ghana are projected to have urban land loss of ~5,000 m^2, ~7,000 m^2 and ~12,000 m^2 by 2050 for the 2.6, 4.5 and 8.5 RCPs respectively. Some coastal defence structures and settlements may be inundated by 2100 based on the 8.5 RCP scenario, but coastal dwellers interviewed cherish their proximity to the sea and are determined to maintain their occupancy close to the sea as spatial location influences their source of livelihood (fishing).
Respondents lack knowledge/understanding of SLR, as the majority of household interviewees attributed rise or fall in sea level to God. Respondents from Ngiresia alleged the ongoing coastal sea defence as a project in their community has led to increased malaria cases.

CHAPTER 2

Impact of Large-Scale Climate Patterns on Sea-Level Variability and Trends in the Gulf of Guinea with Focus on the West African Coast

2.1 Introduction

Climate change affects global and regional sea-level changes (Stammer et al. 2013; Church et al. 2013; Anthoff et al. 2006). The global mean sea-level (GMSL) rise has been larger since the mid-19th century compared to GMSL during the last two millennia, that was of the order of a few tenths of mm/year (IPCC 2013). From 1901 to 1990, the rate was 1.5 [1.3 to 1.7] mm/year (IPCC 2013) which was likely to have increased since the early 1900s, and the rate from 1993 to 2010 was 3.2 [2.8 to 3.6] mm/year (IPCC 2013), although both estimations rely on data of different nature, tide gauges versus satellite altimetry.

However, regional and local sea-level changes can deviate substantially from those of the global mean (Stammer et al. 2013; Cazenave and Llovel 2010). SLR variations across regional and local scales are due to steric effects (changes in the density structure of the oceans associated with temperature and salinity variations), to eustatic effects due to land-ice melt, groundwater use, and reservoir management, and to the effects of regional changes in ocean currents, wind-induced redistributions of upper-ocean (Figure 2.1) which establish spatial characteristics of regional SLR (Timmermann et al. 2010), and topography (Zhang et. al. 2016).

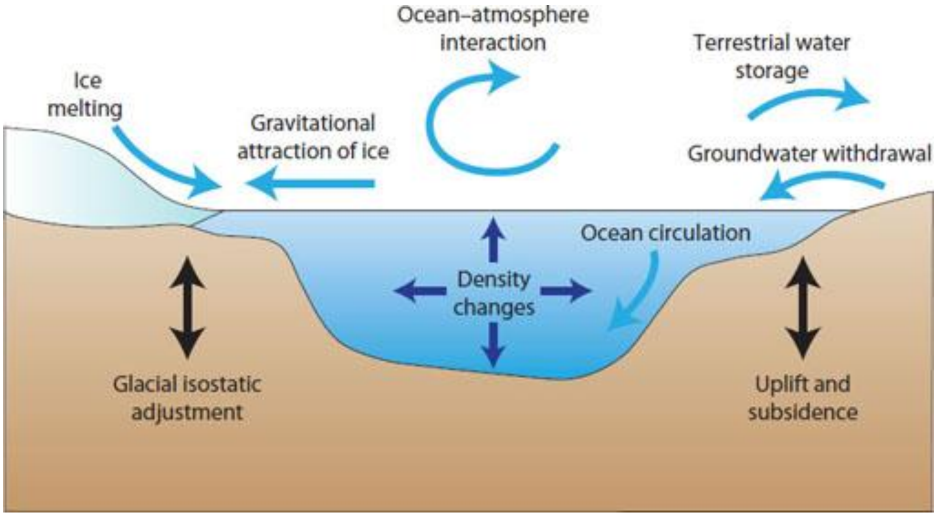


Figure 2.1: Processes that influence sea-level on global to local scales (source: www.nap.edu/read/13389/chapter/3#14)

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. Although SLR is identified to 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. 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.

Natural climate variability is identified to be important in these sea-level variations across regional ocean basins. El Niño–Southern Oscillation (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). The influence of natural climate variability on sea-level patterns and trends has experienced 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). AMO is identified as an important factor of global and multi-decadal climate variability with possible influence of natural climate variability in the subtropics (Chylek et al. 2014).

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 region from the equator (EQ)-60°N, 0°-80°W and subtract the global rise of SST 60°S-60°N to obtain a measure of the internal variability, arguing that, the effect of external forcing on the North Atlantic should be similar to the effect on the other oceans

This observed multi-decadal (of the order of magnitude of several decades) oscillation (changes in SST phases) has a quasi-periodicity between 2 peaks over a time evolution period of ~60 - 80 years (Trenberth and Shea 2006).

The physical mechanisms that give rise to the AMO is not yet well established. Some studies stress the role of external climate forcing, and in particular of 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 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. The periodicity of peaks can thus be influenced by additional fresh water inflow into the NAO (e.g., as a result of gulf-stream and ice-melt). Another theory (to a lesser degree) states that the observed AMO in the NAO is as a result of changes in the atmosphere. Commenting on the AMO for example, mechanistic report on AMO by Clement et al. 2015 from simple analysis of SST patterns and power spectra of slab-ocean models (SOMs), i.e. models with no ocean dynamics, in the NAO claim that AMO is a thermodynamic response of the ocean mixed layer to stochastic atmospheric forcing and that ocean circulation changes have no role in causing the AMO. This claim was refuted by Zhang et. al. 2016 and argue that the mechanism causing the AMO in coupled general circulation models is different from that depicted in the SOMs. The main reasons according to Zhang et. al. 2016 is that the AMO index used for regression analyses by Clement et al. 2015 should be the low-pass filtered de-trended NAO basin-averaged SST anomalies to reflect the multi-decadal variability of the AMO.

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 focus of this paper lies on the GoG and in particular on the coast of Ghana, with the aim to investigate climate influence on sea-level variability and trend and improve the historical sea-level data in this region.

The identification of the impact of large-scale climate patterns on sea-level variability and trends in the GoG can provide a basis to establish spatial characteristics of regional SLR along the West African Coast.

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 an advanced 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).

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.

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. The remaining section of the introduction gives a description of the study area.

Monthly-mean tide-gauge records for available stations [Takoradi and Tema (Ghana) and Forcados (Nigeria)] located on the coast of West Africa is used. The Forcados tide-gauge station although with fewer records, is assumed to be accurate based on data assessment by the Permanent Service for Mean Sea-level (PSMSL). Monthly-mean sea-surface heights (SSH) data from satellite observations and ocean models, wind stress data and SST were extracted over a spatial extent of longitudes - 80° to 40° and latitudes - 40° to 40° representing the GoG (Figure 2.2) and analyzed. Analysis of the impact of AMO index on the sea-level data for the GoG region (Table 2.1) was also performed.

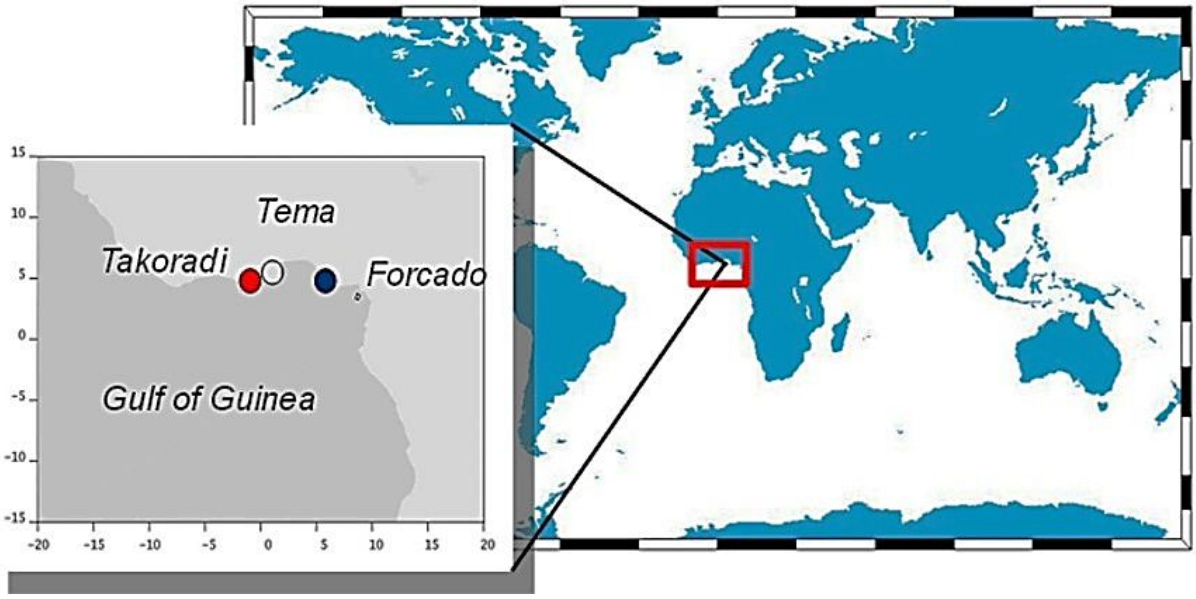


Figure 2.2: Study area showing the Gulf of Guinea and selected tide gauge stations [Takoradi and Tema (Ghana) and Forcados (Nigeria)] along the West Africa coast

2.2 Methods

The methods section describes the data, processing methods and scope of chapter 1.

As the focus is to determine the impact of large-scale climate patterns on monthly mean sea-level variability and trends in the GoG, the study attempts to improve the accuracy of the Takoradi tide gauge (reporting since 1929, but flagged by PSMSL as unreliable after 1966) for longer time scale analysis by high-pass filtering the Takoradi record together with the shorter Tema record (1963-1982) which PSMSL regarded as accurate and use the correlation in the overlapping period between the two Ghana stations (1963-1965) for reconstruction of the period 1963-1981 for the Takoradi station (Equation 2.1).

(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 2.1)

Where:

(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

This gives us a regional sea-level curve for Ghana spanning five decades (1929-1981; Figure 2.3) and thus allowing for more robust statistical analysis together with climate information as well as for better comparative analysis with the tide gauge record from Nigeria.

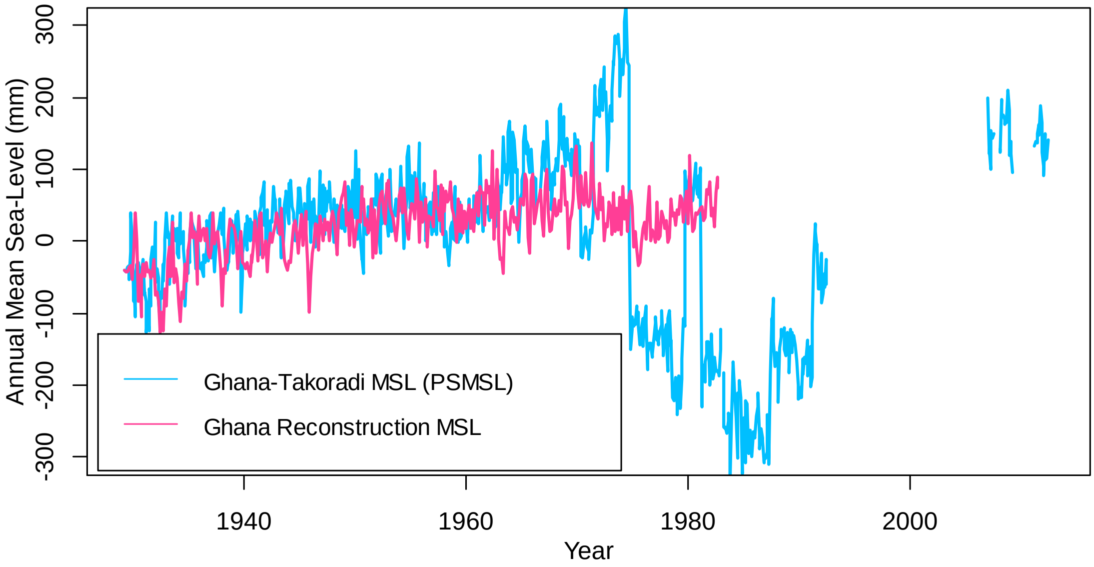


Figure 2.3: Reconstructed Ghana Annual Mean Sea-level (AMSL) curve together with Ghana tide gauge record Takoradi (from PSMSL, not reliable after 1966)

To determine the sea-level variability within the GOG, EOF analysis is performed on satellite altimetry SSH from the combined TOPEX/Poseidon, Jason-1, and Jason-2/OSTM sea-level fields. The choice is based on its wide usage for sea-level analysis (Han et al. 2014; Lyu et al. 2014). The version used includes post-processing: corrections for the inverse barometer effect, and removal of the seasonal (annual + semi-annual). The Glacial isostatic adjustment (GIA) correction is not included in this version because the GIA effect is negligible for the region. Moreover, the SSH data is also compared to tide-gauge data that has no GIA correction.

Similar analysis is made with two other SSH datasets to validate the results of the satellite SSH EOF analysis. The first is the high-resolution (spatially varying with about 10 km on average) Max Planck Institute ocean model (MPI-OM) also referred to as STORM (Storch et al. 2012). This simulation has produced a full high-resolution picture of the ocean dynamics including SSH of the ocean over the last decades and the results can be compared to the historical physical observations. The MPI-OM was driven by the Meterological reanalysis from the National Centre for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) (Kistler et al. 2001), covering the period 1948 until 2010.

The satellite SSH EOF pattern was also compared with the spatially resolved SSH reconstructions (1950-2001) that combine monthly mean tide gauge data with EOFs estimated in a 12-year TOPEX/Poseidon + Jason-1 satellite altimeter data set by Church and co-workers (Church et al. 2004).

The SST data used are from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST, version 1). It is a reconstructed SST that used a two-stage reduced-space optimal interpolation procedure, followed by superposition of quality-improved gridded observations onto the reconstructions to restore local detail (Rayner 2003), and has been widely used (Feng et al. 2015; Harlass et. al. 2015).

The wind stress data garnered was a joint product from the NCEP and the NCAR. This NCAR/NCEP reanalysis uses a state-of-the-art analysis/forecast system with data assimilation to produce a complete 3-dimensional hindcast of the state of the troposphere from 1948 to the present with a 6-hours' time resolution and 2.5 latitude x 2.5 longitude degrees spatial resolution.

De-trended annual means for all dataset were used for the joint analysis of sea level and climate information, a procedure necessary for climate data analysis with the focus on meaningful spectral results (Wu et al. 2007).

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 2.1: Data used in this Research

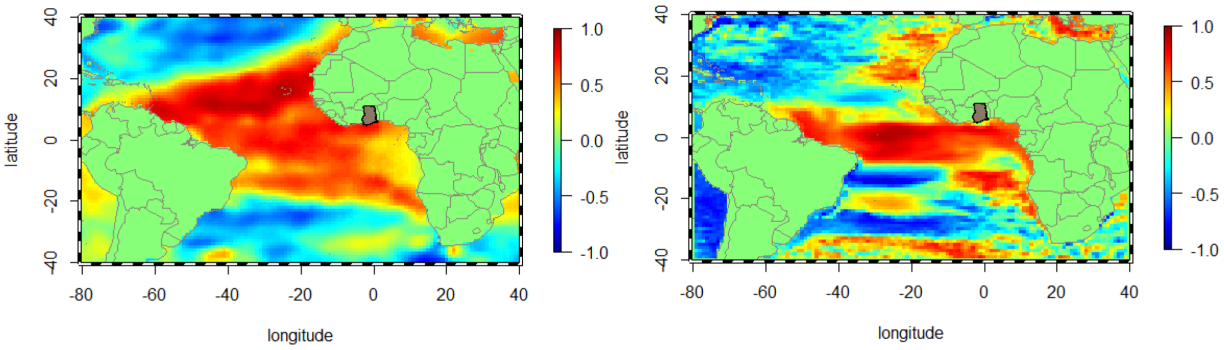
2.3 Results

The results section covers two main topics namely, sea-level variability and impact of large-scale climate patterns.

2.3.1 Sea-level Variability

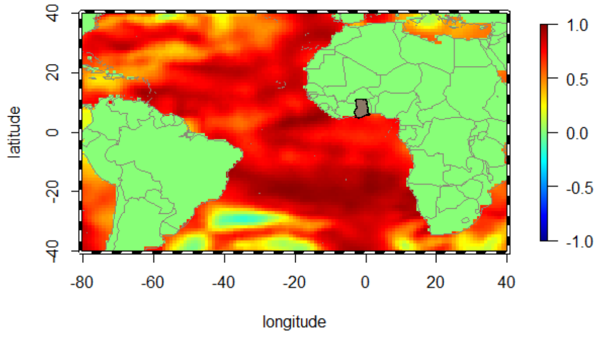
For ease of comparison of sea-level characterization in the GoG, the leading EOF patterns are normalized for the satellite, MPI-OM, and Church reconstruction SSH datasets. Thus, the scale bar for Figure 2.4 only depicts the normalized range with dimensionless values. The leading normalized EOF patterns of SSH-derived from Satellite-SSH (Figure 2.4a) and MPI-OM-SSH

(Figure 2.4b) show similar patterns in the tropics and opposite patterns in the extra-tropics. In contrast, the leading EOF pattern derived from Church-SSH (Figure 2.4c) displays a uniform sign for the whole region with an explained variance of 48 % (compared to ~20% for Satellite-SSH and MPI-OM-SSH). The reason for this discrepancy might lie in the reconstruction method or period of the Church-SSH data. The results suggest that the Church-SSH is not able to display smaller scale regional to local patterns in our region of interest (refer to Table 2.2 for the percentage of variance for the first 4 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 2.4: Normalized patterns of leading Principal Components of the annual mean sea-surface height (de-trended) for different datasets**: a)** satellite data, **b)** ocean-only simulation from MPI-OM and **c)** SSH by Church et al.

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

Table 2.2: The percentage of variance of the first 4 EOFs of the various SSH and SST

2.3.2 Impact of large-scale climate patterns

To understand the physical mechanism and the relationship between SST and SSH in the GoG, the study analyses the EOF pattern (not normalized) of the Satellite-SSH (Figure 2.6b) and SST (Figure 2.6a) as well as computes the correlation between the two variables. The leading EOF patterns of SST (Figure 2.6a) show higher values in the tropics and opposite anomalies in the extra-tropics. The study finds a positive correlation (r = 0.49) between the time-series (PC1) of the leading EOFs of satellite-SSH and the SST (; Figure 2.5), and estimates the thermosteric expansion effect of ~ 0.8 Kelvin (average SST EOF1 for Ghana, Figure 2.6a) for an assumed expansion of 50 m coastal seawater column and pressure salinity of about 30 psu to be 1mm.

The leading EOF of the satellite-SSH has an average value 1 mm for Ghana, suggesting that an increase of 0.8 K in SST in the GoG will possibly result in 1mm SLR in Ghana.

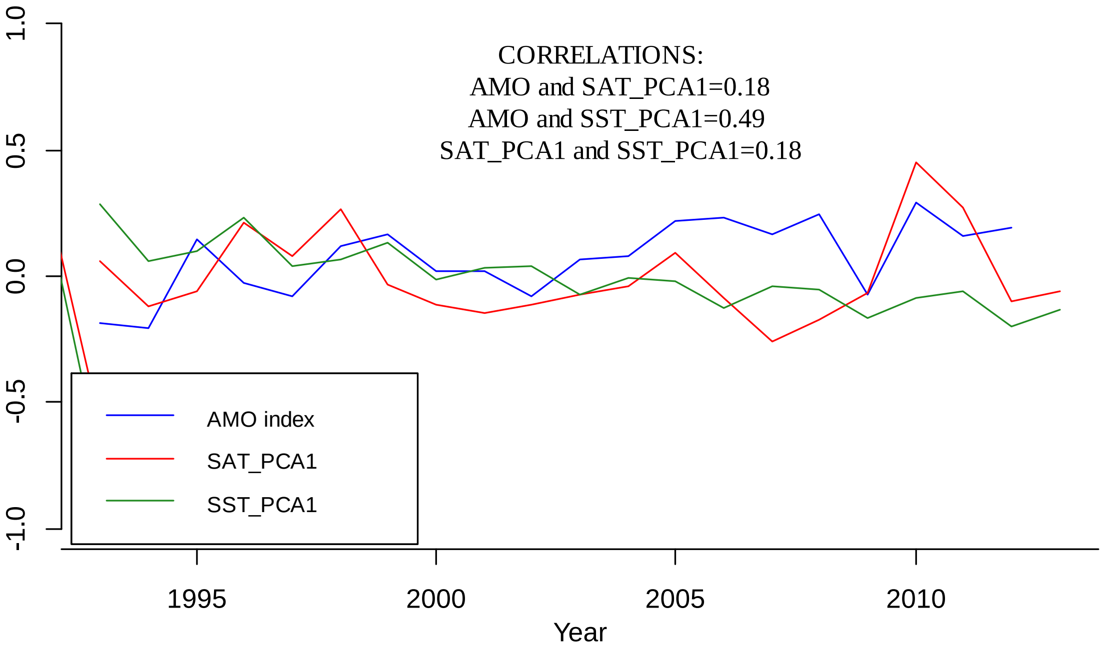


Figure 2.5: Time series of AMO index (blue), PC1 Satellite-SSH (red) and PC1 of SST (green) for the period 1993-2013

Since Chylek et al. 2014 and other reports identified AMO as an important factor of global and multi-decadal climate variability, coupled with the EOF results that showed a positive correlation and connection between SST and SSH in the GoG, an examination of possible multi-decadal variations in sea-level change in the GoG as a result of AMO by correlating the AMO index with both satellite-SSH (Figure 2.7) is made.

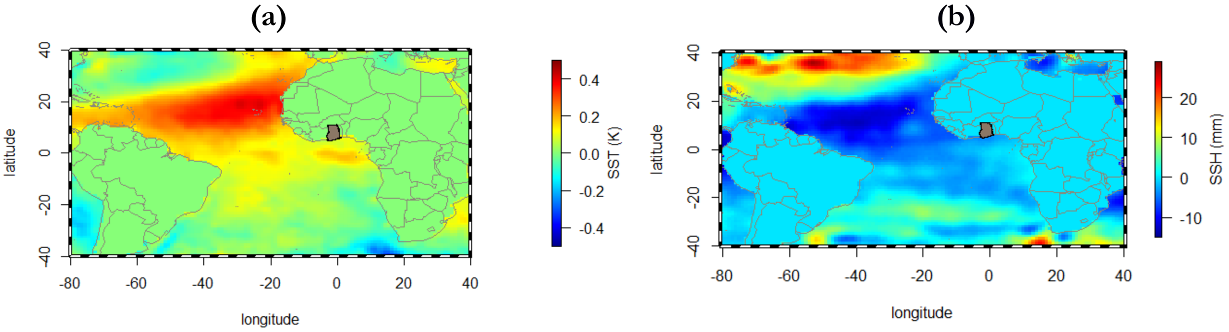


Figure 2.6: Pattern of leading EOFs of the annual mean sea-surface-temperature from HadISST and satellite-SSH. ***a)*** *HadISST1 EOF1 (1993-2013) 27.34% explained variance;* ***b)*** *Satellite-SSH EOF1 (1993-2013) 20.22% explained variance*

A similar correlation analysis is performed between the AMO index and the reconstructed tide gauge data for Takoradi in Ghana as well as with the Forcados tide gauge in Nigeria (Figure 2.8). The idea is to find out if observed correlation pattern between the satellite-SSH and AMO are similar to that between AMO and the tide gauge data on the West Africa coast.

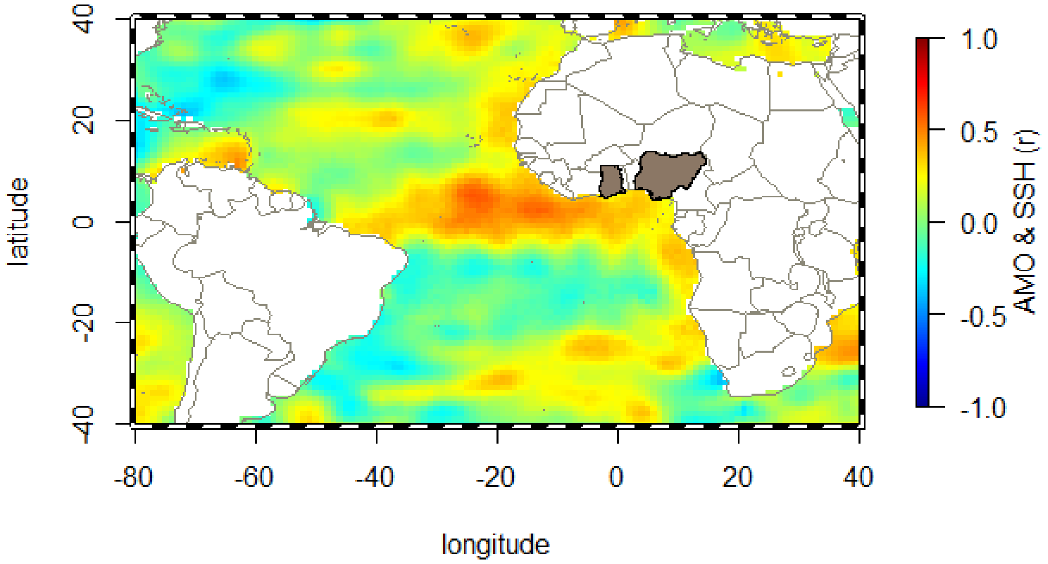


Figure 2.7: Correlation pattern between the AMO index and the annual mean SSH from satellite altimetry

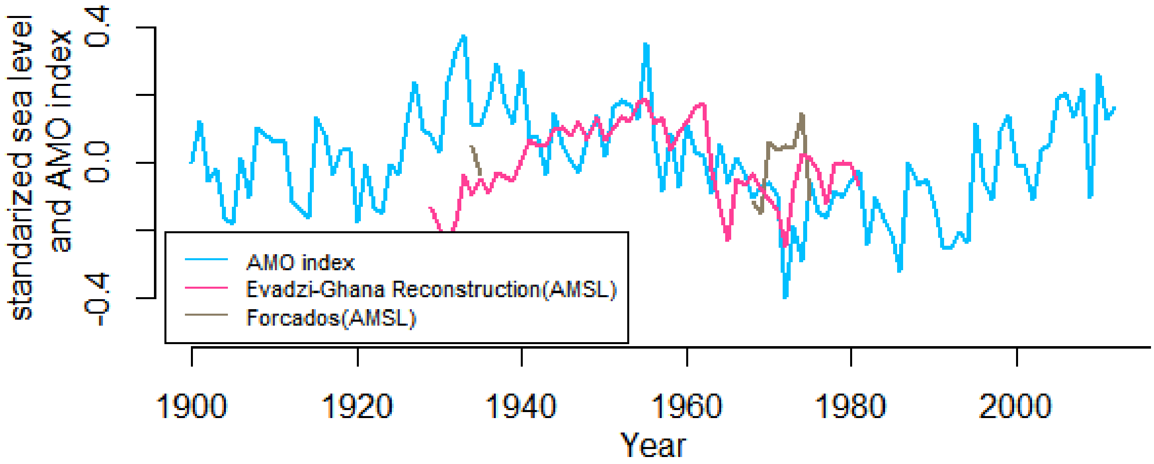


Figure 2.8: Time series of the AMO index together with tide gauge record of Forcado/ Nigeria and the Ghana annual mean sea level reconstruction

This analysis (Figure 2.7) shows the impact of AMO on sea level 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 trend pattern of AMO and the time series of the reconstructed Ghana AMSL and that of Nigeria (Figure 2.8) although the available data for Nigeria is inadequate for long term analysis.

Although there are reports on a significant effect of the wind on regional sea-level change (Thompson et al. 2014; Timmermann et. al. 2010), the results found wind stress variability to be less significant for sea-level variations within the GoG region.

2.4 Discussion

Large-scale climate patterns are identified to impact regional sea-level variability at different locations globally which in turn could affect coastlands at different rates, however, little is known about the influence of large-scale climate patterns on sea-level variability in the GoG with a focus on the coast of 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, whereas Evadzi et. al. 2017, 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.

SST is identified 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 patterns in the tropics and opposite patterns in the extra-tropics. The study finds a positive correlation between the time-series (PC1) of the leading EOFs of satellite-SSH and the SST (r=0.49; Figure 2.5), and estimates the thermosteric expansion effect of ~ 0.8 K (average SST EOF1 for Ghana, Figure 2.6a) for assumed 50 m coastal seawater column and salinity of about 30 psu to be 1 mm. Thus, from this analysis, 1 mm SLR is expected for 0.8 K increase in SST over the coastal ocean of Ghana.

The result shows stronger correlation between AMO and SSH at the coast of Ghana than at the Nigerian coast (Figure 2.7). This AMO impact on sea-level variability at the West Africa coast is also reflected in the trend pattern of AMO and the time series of the reconstructed Ghana AMSL and that of Nigeria (Figure 2.8).

2.5 Conclusions

According to the various data garnered and analyzed, SST is identified as an important large climate variable that influence sea-level variability in the GoG. The AMO index explains the multi-decadal variability in sea-level variability in both satellite data for the GoG and the Ghana reconstructed AMSL and tide gauge data for Nigeria over the West Africa coast. No significant connection, however, exists between wind stress and sea-level variability in the GoG.

CHAPTER 3

Quantifying and Predicting the Contribution of Sea-Level Rise to Shoreline Change in Ghana: Information for Coastal Adaptation Strategies

3.1 Introduction

SLR caused by the combination of changes in the density structure of the oceans associated with temperature and salinity variations, land-ice melt, ground water use, and reservoir management, and of the effects of regional changes in ocean currents is affecting coastlines worldwide and will continue to affect coastlines in the future (IPCC 2013).

The coastline of Ghana is identified to be affected by SLR, geology, changes in the supply of sand to the coast, and anthropogenic factors (Armah and Amlalo 1998; Appeaning Addo 2011; Woodruff et al. 2013). SLR affects economic activities on the coast of Ghana in several ways. It destroys fishing boat landing sites through coastal erosion and contributes to flooding of salt pans used for salt production on the coast of Ghana. These are currently the main livelihood for most coastal dwellers in Ghana (Akyeampong 2001; Kufogbe 1997). SLR may also erode some archaeological sites as well as other infrastructural investments on the coast (Appeaning Addo 2009). According to Olympio and Amos-Abanyie (2014), locations of some recreational services and tourist attractions in Accra could be affected by SLR in the future. Twenty-five hot spots (locations) in Ghana where coastal erosion has been strong resulting in various patterns of morphological changes were identified along the coast, of which Keta is the most affected community (Armah and Amlalo, 1998; Nail et al. 1993).

Coastal erosion is, however, not solely the result of SLR. Human activities may also have an important impact on coastal morphology. Ly (1980) revealed that as a result of the construction of the Akosombo Dam, there has been a significant increase in coastal recession along the central to eastern coasts of Ghana, which hitherto were replenished by sand from the Volta River. According to Ly (1980), at Labadi, the retreat has proceeded with an average rate of 3 m/y after the dam construction, whereas at Ada, the rates are almost the same before (average 2.2 m/y) as after (2.4 m/y) the construction of the dam. In the Keta area, the rate of shoreline retreat before the construction was an average of 4 m/y. Also, Angnuureng et al. (2013) reported increased coastal recession in Keta from 3.2 m/y during the preconstruction period to 17 m/y during postconstruction of the Keta Sea Defence and this constructed sea defence adversely affected neighboring coastal communities through trapping of sediments in the littoral drift. Also, analysis of shoreline changes in Keta on the basis of medium-resolution satellite images by Jayson-Quashigah et al. (2013) revealed that the Keta shoreline is receding at an average rate of 2 ± 0.44 m/y. According to this report, some transects near the estuary and to the east of the Keta Sea Defence site receded at rates as high as 16 m/y, which reveals the influence of the Keta Sea Defence Project on erosion along the eastern coast of Ghana.

In an assessment of the physical impact of SLR on the eastern deltaic shoreline of Ghana, Boateng (2012) utilized an approach adopted and used by Alo and Pontius (2008), Castellana et al.

(2007), and Tol et al. (2008), and revealed that the entire east coast of Ghana is under serious threat of coastal recession.

In an analysis of shoreline recession in Accra, Appeaning Addo et al. (2008) noted that the coast of Accra has receded in the past (using four different shoreline positions from 1904 to 2002) by 1.3 ± 0.17 m/y with varying rates for different subsections due to prevailing geomorphic, geologic, and hydrodynamic conditions, and with the extent of human influence modifying the erosion pattern and trend. Appeaning Addo et al. (2008) used a process-based numerical model, SCAPE, geometric approaches including historical trend analysis, the modified Bruun model, and Sunamura's shore platform model to predict the outlook for Accra's coast 250 years into the future on the basis of assumed SLR from 2 to 6 mm/y. According to that report, some low-lying elevations and wetlands will be inundated, thus affecting the habitat of about 35,000 migratory birds. The study noted that some tourist sites including the Kwame Nkrumah Mausoleum, the Christiansburg Castle, and the National Independence Square would be affected by future coast recession under rates of SLR from 2 to 6 mm/y. Although Appeaning Addo et al. (2008) predicted future shoreline change for Accra, this prediction was based on projected global sea-level trends, which may differ from local sea-level change scenarios for Ghana as future SLR is not projected to be spatially uniform because of the spatially heterogeneous storage of heat in the oceans and the heterogeneous SLR fingerprint of polar ice melting (Hünicke and Zorita 2016; Kopp et al. 2015).

Researchers have utilized in the past photogrammetry data and spatial analysis techniques for determining beach erosion/shoreline changes in Ghana (Appeaning Addo et al. 2008; Jayson-Quashigah et al. 2013). Few studies have utilized other data sets to determine beach erosion/shoreline changes such as Storm-induced BEAch Change model (Wise et al. 1996), Bruun Rule (Bruun 1962), Hallermeier equation (Hallermeier 1981), shoreline evolution model (Patterson 2009), and shoreline response model (Huxley 2009). Apart from the reliability of the method itself, the suitability of the method also depends on the availability, spatial extent, and timescale of data. Except photogrammetry, which records historical coastal changes, the other methods are based on a combination of models and data, which are more useful when trying to estimate hazard extent where there is limited historical information. Methods for shoreline analysis vary in approach and accuracy. Delineating and using shoreline positions from photos to compute shoreline change analysis also require identification and quantification of biases and uncertainties associated with the shoreline position, such as photo resolution, georeferencing error, shoreline position error (tidal changes), and shoreline digitization error because these errors or uncertainties in turn influence the estimation of the shoreline change rate (Genz et al. 2007).

These studies on coastal recession in Ghana have also lacked information on the contributions of regional SLR to coastal recession in Ghana, which to a large extent is a result of deficient historical tide gauge data for Ghana. Despite the questionable quality of historical tide gauge data, the National Oceanic and Atmospheric Administration (NOAA 2013), attempted to compute sea-level trends for the Takoradi tide gauge station in Ghana, yielding a rate of 2.16 ± 0.39 mm/y of relative SLR, taking into consideration only monthly tide gauge data covering the years 1929 to 1965, and some selected monthly records for 1992, 2007, 2008, and 2009 that were considered to provide accurate data. There is the need for more information on SLR, how SLR contributed to historical shoreline change in Ghana, and if possible the need for predictions of future shoreline in Ghana. The research purpose is to provide this useful information for coastal adaptation strategies by analyzing historical shoreline change for the entire Ghana coast, and quantify and predict the contribution of SLR to the shoreline change in Ghana.

To achieve these research objectives, the research first performs coastline change analysis in Ghana from 1974 to 2015 using different photogrammetry data types (high-resolution orthophotos and Landsat images) and second, quantifies the contribution of sea-level change to shoreline changes in Ghana using the coastline/shoreline change rates, estimates from slope analysis, and sea-level data analysis. Finally, the research makes future projections of shoreline recession on the basis of modified projections of regional SLR for Ghana from climate simulations included in the CMIP version 5 (CMIP5) driven by the IPCC AR5 RCPs and augmented by estimations of land-ice melting is made. Such analysis will provide essential information for the formulation of coastal adaptation strategies for Ghana. The remaining section of the introduction gives a description of the study area.

The coastline of Ghana (~550 km; Figure 3.1) is generally low lying, with a narrow continental shelf outward of between 20 and 35 km, except off Takoradi where it reaches up to 90 km. The coast is serrated by beaches and lagoons with rocky headlands and sandbars located between Cape Three Points and Tema (Ly 1980) and bordered by the Atlantic Ocean/Gulf of Guinea. The gulf is characterized by an eastward-flowing current, by varying annual patterns of coastal upwelling (Armah and Amlalo 1998), and by a tidal range of 1 m for the coast of Ghana (Appeaning Addo 2013). The general climate of the coastal zone of Ghana is tropical, with about two-thirds lying within the dry coastal savanna region and an annual rainfall average of 900 mm that peaks in June and is at its minimum in January (Armah and Amlalo 1998).

The coastal zone of Ghana has witnessed increased urbanization with a stronger infrastructure development than the middle and northern parts of the country. The coastal administrative regions alone account for 43.4% of Ghana's population of about 24 million at present (Ghana Statistical Service 2013). As the number of coastal dwellers is expected to increase because of the concentration of national infrastructure and private business investments in these regions, so also is its concomitant human-induced stresses on the coastal environment through exploitation of coastal resources such as sand mining, gravel/stone quarrying for building, and reclaiming lagoons for settlement leading to coastal vegetation depletion, draining of wetlands, pollution, and developments close to the shore (Alvarado 2003; Appeaning Addo 2011).

Some areas on the coast of Ghana have been identified to be currently eroding at different rates. Attempts are made to quantify shoreline change for the entire Ghana coastline as well as the contributions of SLR to coastal recession in Ghana.

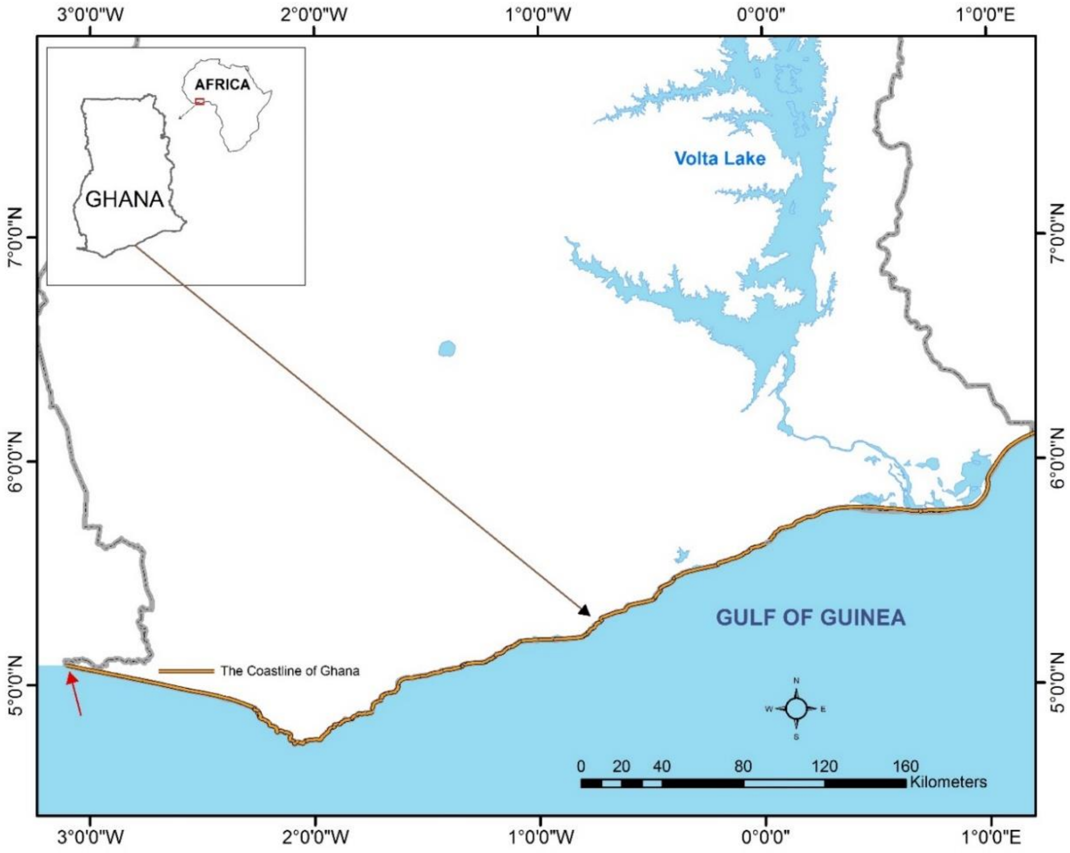


Figure 3.1: Location of the Study Area: The coastline of Ghana; ~ 550 km (red box) on the West Africa Coast and the Gulf of Guinea. Coastal change due to SLR is computed for the research Area. The red arrow represents the starting point used to measure the distance along the coast in Figure 3.3

3.2 Methods

The methods section comprises three subsections. The first subsection explains the shoreline definition while the second section describes the data used. The third section describes the methodology.

The definition of a shoreline has over the years been debated and there are challenges in adopting a single definition because of the dynamic nature of coasts (Alves 2007; Bird 1985; Boak and Turner 2005). However, the shoreline definition referred to as the "wet–dry" line, also referred to as the high-water line, along the coast has been the most widely used definition for shoreline mapping because it can be identified both on images and physically in the field (Crowell et al. 1991; Dellepiane et al. 2004; Leatherman 2003).

The research uses this wet–dry line definition for shoreline analysis for Ghana because it serves as a good indicator for historical shoreline change monitoring (Appeaning Addo et al. 2008).

Different data sets (Table 3.1) is used to quantify and predict the contribution of regional SLR to shoreline change in Ghana. For the shoreline change analysis uses a delineated 1974 shoreline shapefile from orthophotos by the Ghana Environmental Agency and generates shoreline shapefiles from Landsat 5 (1990), Landsat 8 (2015), and orthophotos (2005). The Landsat images are level 1 (L1T) products that are processed using a posteriori geolocation information with the effects of terrain relief quantified (Northrop 2015). These Landsat images provide synoptic capability for monitoring coastlines at relatively coarse (30 m) spatial resolution (El-Asmar 1999). The orthophotos used for the shoreline analysis also provide this monitoring capability at a relatively higher (0.5 m) spatial resolution. The satellite images used for the shoreline analysis cover the Ghana coastline with less cloud cover.

Besides the images used for the shoreline analysis, digital elevation model (DEM) data for the coast of Ghana are also utilized for coastal terrain analysis. This DEM is a digital cartographic data set of elevations in XYZ coordinates at 200-m horizontal resolution to analyse slope dynamics on the Ghana coast.

SSH data for the coast of Ghana spanning a period of 2 decades (1993 to 2013) from combined TOPEX/Poseidon, Jason-1, and Jason-2/OSTM (satellite radar altimeters that monitor mean sea-level changes) is also utilized. The SSH data together with shoreline information and terrain slope on the coast of Ghana helped to statistically quantify regional SLR contribution to historical shoreline change in Ghana.

In addition to the quantification of SLR contribution to historical shoreline change, future projections of the IPCC AR5 SLR data extracted for Ghana is used to explore possible future shoreline changes. The raw data (extracted for the coast of Ghana) are obtained for the projections of regional SLR climate simulations included in the CMIP5 driven by the RCPs scenarios put forward by the IPCC in its AR5 and augmented by estimations of land-ice melting (Carson et al. 2016).

Name/Acronym	Location/description	Years	Data source
1974 shoreline	Ghana Shoreline shapefile based on Orthophoto	1974	Ghana, Environmental Protection Agency (EPA)
Multispectral satellite images	Landsat 5 and 8 (30m*30m spatial resolution, monthly, orbit 16days/705km	1990 and 2015	U.S. Geological Survey (USGS) 2015
Aerial photo	Orthophoto (0.5 m*0.5 m)	2005	Ghana Town and Country Planning Department
DEM	Digital Elevation Model (200m*200m)	Not stored	Ghana Town and Country Planning Department
SSH	Near-global (extracted for coast of Ghana),1°×1° grid	1993-2015	Combined TOPEX/Poseidon, Jason-1 and Jason-2/OSTM sea-level fields
SSH	IPCC SSH scenarios ,1°×1° grid	1970-2100	IPCC AR5 (2013)

Table 3.1: Data used for this Research

In Ghana, several studies of shoreline changes using the 'wet-dry' line definition have been conducted based on the application of GIS (Appeaning Addo 2015; Appeaning Addo et al. 2011; Jayson-Quashigah et al. 2013; Wiafe 2010). However, apart from Wiafe 2010, other research on shoreline change in Ghana focused on only some sections along the coast of Ghana, and thus their results are difficult to extrapolate for national adaptation planning. Wiafe 2010 used only two shoreline positions (1974 and 2005) and calculated shoreline change for Ghana based on the End Point Rate (EPR). However, the EPR approach is unable to estimate temporal variations between the two periods (1974 and 2005) due to lack of data and hence is less useful for long-term rates of change assessment for the entire coast of Ghana.

Weighted Linear Regression (WLR), an alternative to EPR, is identified to be one of the best approaches for shoreline change assessment because it includes the information provided at several points in time and their estimated uncertainties (Himmelstoss 2009; Morton et al. 2004). WLR is a variant of Ordinary Least Squares (OLS) Regression, in which a linear link between the dependent variable (in this case shoreline position) is assumed to be proportional to the independent variable (in this case time) plus a random contribution by other unknown factors. The proportionality coefficient is estimated by minimizing the sum of the residuals squared. Assuming certainty statistical properties of the residuals, like statistical independence, normal distribution with equal variance, this minimization leads to the normal equations for the proportionality coefficient. In the cases, as this one, in which the variance of the residuals cannot be considered equal because the uncertainty in the estimation of the shoreline position depends on time, OLS can be modified to WLR, leading to a similar set of normal equation, in which the influence of each measurement on the final estimation is larger when its uncertainty is small and vice versa. Inherent to the estimation of the proportionality coefficient is also the estimation uncertainty. This is also provided by WLR, and is a function of the magnitude of the uncertainties of the individual measurements and how far apart in time these measurements are distributed.

The weight [Equation (3.1)] of each measurement (W) is thus expressed as a function of the variance in the uncertainty (e) of the measurement (Genz et al. 2007).

$$W = 1/e^2 \quad \text{(Equation 3.1)}$$

where, e = shoreline uncertainty value.

The total uncertainty is a combination of several contributions. This research identifies four sources of uncertainties associated with the shorelines, namely, uncertainty relating to photo resolution (Upr), uncertainty relating to shoreline position accuracy/georeferencing error (Upa), uncertainty of shoreline position relating to tidal fluctuation, and uncertainty relating to shoreline digitization (Ud). The tidal range (1 m) for the coast of Ghana is negligible (Appeaning Addo 2013) and not included for the calculation of annualized uncertainty for each of the shorelines. The research computes the annualized/total uncertainty (Ut) as the square root of the sum of squares (Equation [2]) of the Upr, Upa and the Ud uncertainties (Fletcher et al. 2003; Hapke et al. 2010) and incorporates these uncertainties estimates (Table 3.2) for the shoreline change analysis. The uncertainty values used are from Jonah et al. (2016), metadata files of the images, and from the shoreline processing. From the 2005 high-resolution (0.5 m) aerial photo, the research generates the 2005 shoreline at the boundaries between two individual pixels that defines the wet–dry line and estimates the shoreline digitization error as the average resolution of the two pixels (0.5 m).

$$Ut = \pm\sqrt{Upr^2 + Upa^2 + Ud^2} \quad \text{(Equation 3.2)}$$

Measurement errors (m)	**1974 Shoreline**	**Landsat 5 Satellite Image (1990)**	**Aerial photo (2005)**	**Landsat 8 Satellite Image (2015)**
Positional accuracy /uncertainty	4	5	-	9.4
Digitizing uncertainty	1	-	0.5	-
Photo resolution uncertainty	-	30	0.5	15
Total shoreline position uncertainty	2.24	5.92	1	4.94
Source	Jonah et al., 2016	Landsat data Metadata (USGS)		Landsat data Metadata (USGS)

Table 3.2: Uncertainties associated with the Shoreline datasets

Shoreline positions are delineated for Ghana after the wet–dry line definition using both automatic extraction and manual digitization approaches and attempts to quantify long-term shoreline change for the entire coast of Ghana in the past (1974 to 2015) using Digital Shoreline Analysis System (DSAS) and other tools resident in ArcGIS.

The images garnered for the shoreline analysis were already georeferenced and projected into Universal Transverse Mercator Zone 30 North. The panchromatic band of the Landsat 8 images is used to sharpen the other Landsat 8 bands (30-m resolution) to derive a new image at 15-m resolution. The Landsat 5 (1990; 30-m resolution) images are resampled using nearest-neighbor and first-order polynomial transformation to derive a new image at 15 m. This resampling procedure did not add any spatial information to the original data and this is only to standardize the Landsat images for shoreline delineation.

After the Landsat data resolution standardization, the study performs histogram threshold and automatic shoreline extraction using ENVI classic software to separate the land and water on the basis of band ratios (b2/b5 for Landsat 5 data) as described in Appeaning Addo 2015 and Ghanavati et al. 2008. Similar analysis is made for the Landsat 8 data with different bands (b3/b6) to separate the land and water because of different Landsat 8 band wavelengths for land and water discrimination. Deltaic regions show some areas (small in extent) as shorelines because of the presence of a water-saturated zone at the land–water boundary, but these do not meet the wet–dry boundary definition used for this investigation. These deltaic coastline areas are manually digitized. The 2005 shoreline for the coast of Ghana is generated by manual digitization. The study proceeds to compute the shoreline change rates using DSAS.

With regard to the DSAS application setup and shoreline change analysis, the research first creates a geo-database for the identification and storage of shoreline information including uncertainties, and for generating change statistics. The study also constructs baseline (manually digitized a line at 500 m away from the closest shoreline toward the GoG) and casts perpendicular transects at 100-m intervals that intersect the multiple historical shorelines at specific positions along the entire stretch of coastline from east to west and uses WLR as the statistical method resident in DSAS for the shoreline change rates computation.

The research also statistically quantifies the effect of sea level on the Ghana coastline by first performing trend analysis of SSH data for Ghana from the combined TOPEX/Poseidon, Jason-1, and Jason-2/OSTM and proceeds to make future projections on the basis of the corrected SLR projections of IPCC AR5 for Ghana. The modification process of these projections is explained in the remaining section below.

The research computes data field means of estimated SLR under the 2.6, 4.5, and 8.5 RCP scenarios for the Ghana coast and derives linear sea-level trends for the RCPs. The linear sea-level trends derived from projections of regional SLR for the coast of Ghana for the present period (2007 to 2014) compared with the research estimate of the sea-level trend (2.52 ± 0.22

mm/y) from observed SLR derived from satellite altimetry for the same period (2007 to 2014) reveals an overestimation in each of the three RCP ensemble means (RCP 2.6 [4.68 ± 0.4 mm/y], RCP 4.5 [3.5 ± 0.62 mm/y], and RCP 8.5 [4.8 ± 0.44 mm/y]). Note that the trend in the RCP 4.5 scenario is lower than the trend in the RCP 2.6 scenario over this short period. The model values are the result of averaging over many model simulations, and therefore the discrepancy between observations and simulations is very likely not due to random internal climate variability of the simulations, as their magnitude is strongly reduced by considering the average of many simulations. It could be due to an inherent overestimation of the model projections or to an extreme random fluctuation of the real SLR at the coast of Ghana. Although this latter possibility can never be ruled out, the research assumes that the trend estimated from observations reflects the SLR caused by the anthropogenic climate change and it is therefore justified to compare it with the values derived from the simulations. The research assumes that the difference between the observed and simulated trends is mainly due to the estimation of land-ice melting, since this estimation has much larger uncertainties than the steric contribution.

The research thus examines the trends of the steric-only simulated contribution to SLR in the models mean (2.5, 4.5, 8.5 RCPs) and assumes that the difference between the observed SSH and simulated steric trends is the correct contribution of land-ice melting for the satellite observation period. The research computes ratios between this assumed land-ice melt contribution during the satellite observation period and the land-ice contribution trend estimated for the RCPs ensemble mean(s) from 2007 to 2020. These ratios have values of 0.12, 0.24, and 0.15 mm/y for the 2.6, 4.5, and 8.5 RCPs models means respectively and the research uses these ratios to proportionally rescale the contribution of land-ice melting projections over the entire 21st century.

Clearly, this assumption may not be valid for periods farther into the future, when this contribution may become either smaller because of reduced input from glaciers or larger because of accelerated melting from the polar ice sheets (Figure 3.2). However, it is a reasonable assumption for the next few decades.

3.3 Results

Findings from the research are presented in this section. The results cover four main topics namely, Long-term SLR in Ghana, Coastline Change, SLR and Coastline Change, and Impact of SLR on Future Coast Change.

3.3.1 Long-term SLR and Coastline Change in Ghana

Trend analysis of annual means of SSH (average along the Ghana coast) from the combined TOPEX/Poseidon, Jason-1, and Jason-2/OSTM sea-level fields (1993 to 2014) reveals a positive sea-level trend of 2.52 ± 0.22 mm/y.

On average, the coast of Ghana has been receding approximately at a rate of 2 m/y from 1974 to 2015. The eastern portion of the coast of Ghana is receding faster than this national average. The high recorded accretion at locations around 450 km and 130 km (Figure 3.3) represents the locations of the Ada Estuary and the Takoradi Estuary around Africa Beach Hotel respectively.

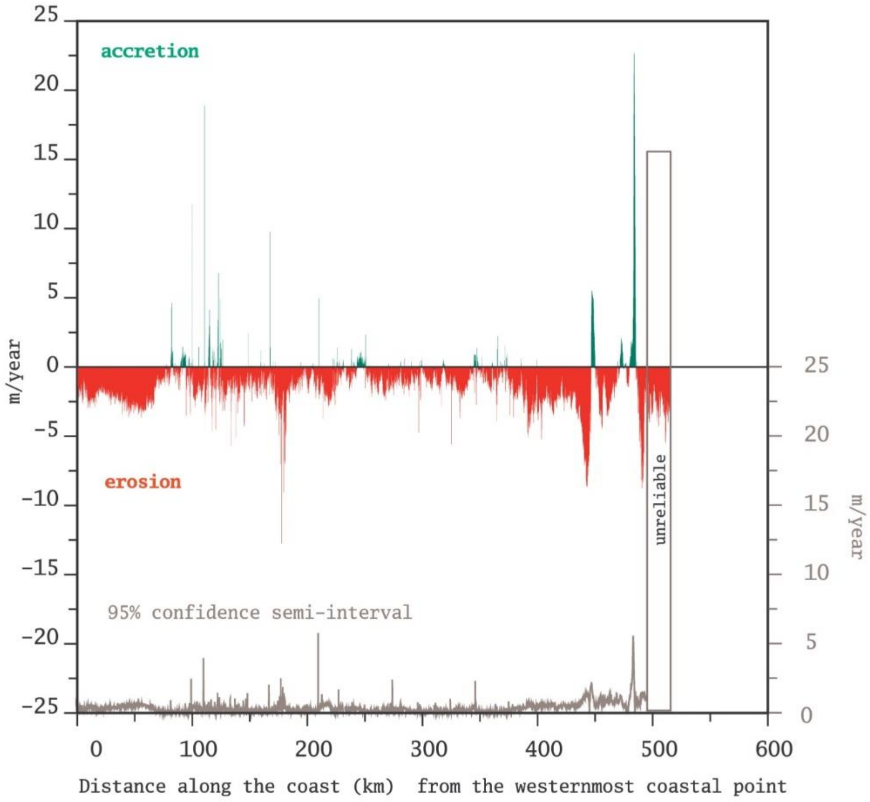


Figure 3.3: Ghana Coastline Change rate [(m/y, 1974-2015) from Ghana's West coast (represented as 0 Km, red arrow in Figure 1) to East (represented as 500 Km)]: Green line; Accretion, Red line; Erosion, Grey line; Confident Interval. Unreliable Box refers to portion on the coast of Ghana with some shoreline missing data. The entire coast is retreating at ~ 2m/y, with the Eastern portion of Ghana's coast retreating faster than other areas

3.3.2 SLR and Coastline Change

The analysis of the slope of the terrain at the coast on the basis of DEM for Ghana shows that the open coast of Ghana has mainly low slope range (up to 0.4%), thus making the coastline susceptible to retreat with increasing sea level (Figure 3.4). The landscape-level analysis shows that current SLR contributes on average ~31% of the estimated average recession rate (2 m/y) in

Ghana. This estimate is based on the assumption of an average slope of 0.4% under the computed present SLR (2.52 ± 0.22 mm/y) along the coast of Ghana. This decreases with medium to steep slopes. This analysis did not take coastal infrastructural developments including coastal fences into consideration.

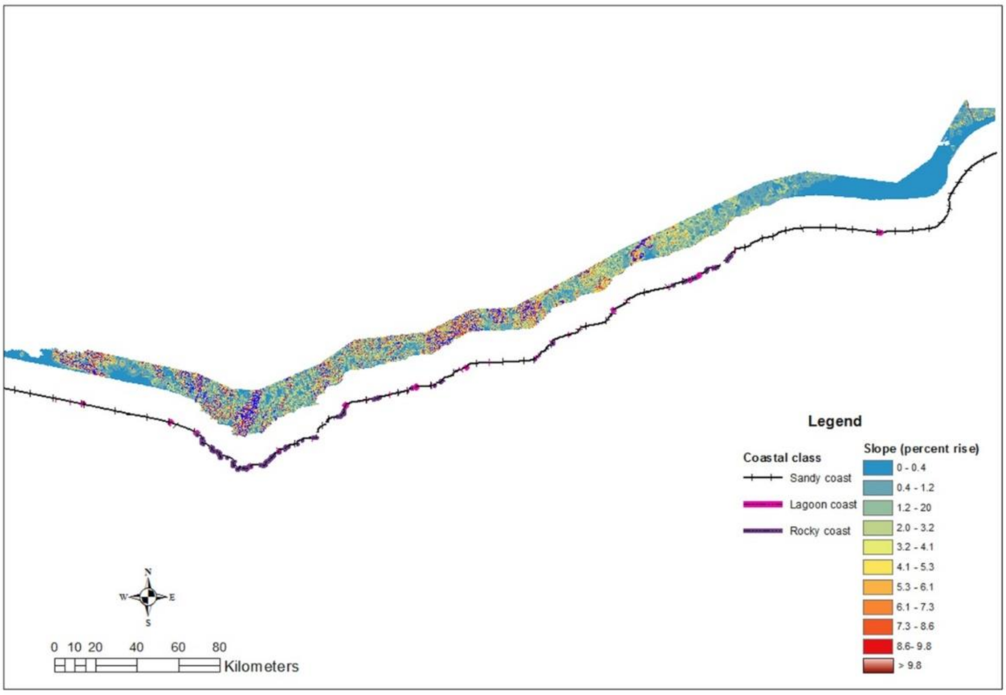


Figure 3.4: Ghana Coastal Landscape Classification and Coastal Change expressed as Slope (% Rise); Shows the Ghana Coast to be predominantly Sandy and with a Slope of (0-0.4 % Rise)

3.3.3 Impact of SLR on Future Coast Change

The SLR estimates based on the model means at the coast of Ghana by 2025 are 26.4, 18.7, and 23.1 mm for the IPCC AR5 RCPs 2.6, RCP 4.5, and RCP 8.5 scenarios, respectively. By 2050, SLR expected for the RCPs 2.6, 4.5, and 8.5 scenarios are 79.2, 82.8, and 97.2 mm, whereas by 2100 the expected SLR is 146.2, 206.4, and 335.4 mm, respectively (Figure 3.2).

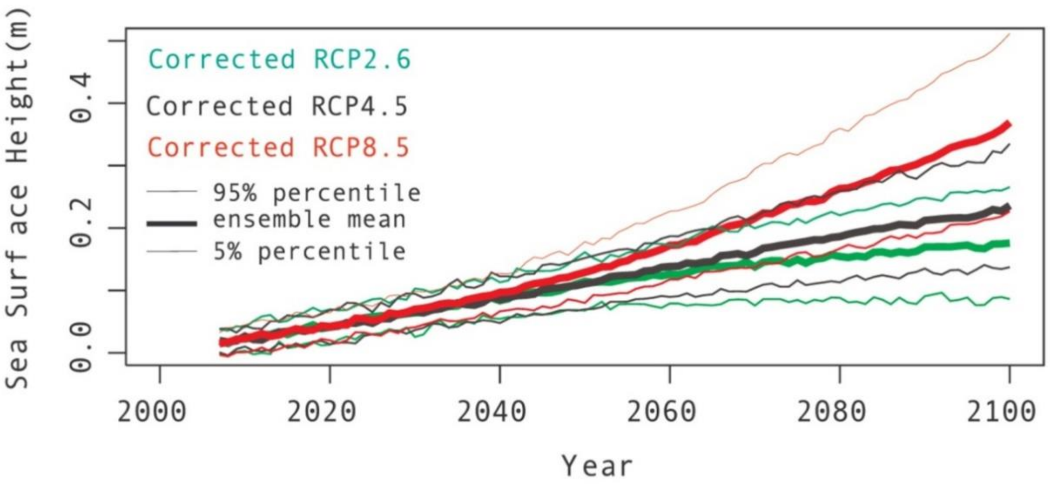


Figure 3.2: Corrected projections of projections of regional sea-level derived from the climate simulations of the CIMP5 driven by three RCP emission scenarios and augmented by estimations of land-ice melting (2007 to 2100, see text for a more detailed description of this correction); The thick color lines represent the all-models ensemble means. The thin lines below and above each thick line represent the 5% and 95% percentiles in each RCP simulation ensemble

3.4 Discussion

On the basis of the historical shoreline analysis from 1974 to 2015, on average, the coast of Ghana has receded at an approximate rate of 2 m/y. The research identifies the shoreline for the portion of the Accra Metropolis coast (~340 to 355 km from the western corner) to have receded on average of 1.8 m/y, with some areas within this region recording a recession average of 1 m/y (Figure 3.3). This portion of the coast is among the lowest receding areas on the entire coast of Ghana and confirms the shoreline rate of erosion (1.13 ± 0.17 m/y) computed by Appeaning Addo et al. 2008, in their detailed study of the Accra coastal region based on data from 1904 to 2002. Appeaning Addo et al. 2008 further explained that existing consolidated rocks at some areas in Accra are a factor that accounted for the lower computed rate.

The computed average of recession estimated farther eastward from the Accra Metropolis displays higher rates (~3 m/y), which are higher than those estimated for the Keta area in earlier investigations, including the shoreline analysis by Jayson-Quashigah et al. 2013. Manson et al. 2013 recorded ~2.32 m/y the erosion rate for the Keta coastal area, whereas Jayson-Quashigah et al. 2013 recorded the shoreline recession rate (2 ± 0.44 m/y) for the same Keta coastal zone. The portion between Tegbi and Keta (~470 to 480 km) also recorded the highest accretion rate for the entire coast of Ghana (Figure 3.3). Although this high accretion rate confirms earlier results by Anthony et al. 2016, and by Jayson-Quashigah et al. 2013, there is the need for a detailed analysis based on high-resolution images to either validate or disprove the computed rate of change for this particular region.

The difference between the computed sea-level trend at the coast of Ghana (2.52 ± 0.22 mm/y) from satellite observations and that computed by NOAA 2013 for the same region based on Takoradi tide gauge data (2.16 ± 0.39 mm/y) can be attributed to different periods used for the trend analysis, of which the satellite altimeter data are more current. This difference between the rates is, however, not very wide and is within the uncertainty range reported by NOAA (2013).

Comparing the SSH trend for Ghana from the combined TOPEX/Poseidon, Jason-1, and Jason-2/OSTM sea-level fields (1993 to 2014) to a linear sea-level trend derived from projections of regional SLR for the coast of Ghana (2007–2014) from climate simulations included in the CMIP5 driven by the IPCC AR5 RCPs scenarios and augmented by estimations of land-ice melting (Church et al. 2013) reveals an overestimation in the three model-ensemble means. Since the ensemble means use all models available from the CMIP5, it is unlikely that this overestimation is due to decadal variability in the models, although it could be due to an episode of decadal variability in the observations. However, the modelled thermal expansion of the ensemble mean in the period 2007–2014 is below the trend estimated from observations, so that the overestimation in the model estimate is likely due to the contribution of land-ice melting. This latter estimate is much more uncertain than the simulated thermal expansion, as it is strongly based on expert knowledge. A heuristic approach has been adopted in the research to correct the estimate of land-ice melting to align the model estimate with the observed sea-level trend in Ghana. However, uncertainties remain within this approach, as the observed trend may be the result of the combination of the forced climate change signal and decadal internal variability. To separate both contributions in this region is not possible without an accurate and spatially resolved estimation of the real land-ice melting from 1993 to 2014.

Although the research identifies SLR to account for about 2 m/y of the observed annual coastal erosion rate in Ghana, Jonah et al. 2016 identified levels of coastal sand and stone mining activities to be directly related to trends in coastal erosion along the coast of Cape Coast. Also, Ly 1980 revealed that the central to eastern coasts of Ghana, which hitherto were replenished by sand from the Volta River, experienced significant increase in coastal recession after the construction of Akosombo Dam.

In summary, the research provides essential information for coastal adaptation strategies by estimating SLR contribution to shoreline recession in Ghana to be ~31% for the lowest slope range (0–0.4%) and suggests that on the basis of the projected rise in the sea level, by the year 2025, about 6.6, 4.7 and 5.8 m more of coastal land for the lowest slope range (0–0.4%) of the low-lying coast of Ghana may be inundated on the basis of the 2.6, 4.5, and 8.5 RCPs scenarios, respectively. This may increase by 2050 to 19.8, 20.7, and 24.3 m and further to 36.6, 51.6, and 83.9 m by 2100 on the basis of the RCPs 2.6, 4.5, and 8.5 scenarios respectively, for the coastal land within the lowest slope range (0–0.4%).

3.5 Conclusions

The research achieves the purpose of providing information on SLR contribution to shoreline change that may be essential for coastal adaptation strategies by first analyzing historical shoreline change in Ghana from 1974 to 2015 using satellite images and orthophotos. Second, the research quantifies SLR contribution to historical shoreline using sea-level trend estimates from satellite observations, results from DEM analysis, and shoreline change rates and finally makes predictions of shoreline in Ghana on the basis of modified IPCC AR5 RCPs scenarios.

Although SLR accounts for only ~31% of the observed annual coastal erosion rate (about 2 m/y) in Ghana, this percentage (assumed same for the future) is sufficient to inundate approximately 20 m of coastal areas within the lowest slope range (0–0.4%) by the year 2050 on the basis of future emission pathways of the corrected IPCC AR5 RCPs.

This quantification of the likely impacts of SLR under changing climate to coastal change may improve sustainable adaptation planning if incorporated into adaptation strategies. It serves as a springboard for further research not only into anthropogenic activities but also other natural factors that may contribute to coastal change in Ghana.

CHAPTER 4

Awareness of Sea-Level Response under Climate Change on the Coast of Ghana

4.1 Introduction

Since the 1980s, anthropogenic climate change has raised growing concerns about SLR and its risk to many low lying coastal areas (Nicholls et al. 2007; McGranahan et al. 2007; IPCC 2013). With the increasing awareness of SLR impacts, various mitigation measures are being taken to curtail the future threat of increasing temperatures by human interventions to reduce the sources and enhance the sinks of greenhouse gases. In addition, climate change adaptation measures that modify natural or human systems to moderate harm or exploit beneficial opportunities are encouraged (Klein et al. 2005; Hamin and Gurran 2009; Laukkonen et al. 2009).

Although adaptation to climate variability in some areas acts as a catalyst for social and technological innovation, harsh physical impacts, for example, increased rates of coastal erosion due to SLR, have prompted reforms in the economics and politics of climate change at global, regional and national scales (UNFCC 2006; Carter et al. 2015). It is observed however that investments in coastline protection through building hard structures in developing countries have remained ineffective (Klein et al. 2005).

Coastal erosion is one of the serious environmental problems facing West African countries situated along the Gulf of Guinea (Hinrichsen 1990). The coastal research report by Tilman et al.1989 on the Bight of Benin (the bay of the coast of West Africa) extending eastward for about 400 miles (640 km), from Cape St. Paul (Ghana) to the Nun outlet of the Niger River (Nigeria), highlighted the need for coastal management along the region due to coastal erosion.
Ghana's coast continues to suffer from coastal erosion and flooding which in many cases has led to loss of infrastructures thus posing additional cost to its conventional development agenda (refer to chapter 3; Jayson-Quashigah et al. 2013; Appeaning Addo 2011; Amlalo 2006; MoWH 2011).

In the 1990s several coastal zone policies and management strategies were developed in Ghana, such as the National Environmental Action Plan (1994), the Draft Integrated Coastal Zone Plan (1998), and the Coastal Zone Management Indicative Plan (1990). Although these reports, including the national Climate Change Vulnerability and Adaptation of Coastal Zone of Ghana (EPA 2000), identified SLR as having significant impacts on the coast of Ghana for which some projections were made, the sea-level projections for Ghana were based on global IPCC projections and not informed by scientific knowledge on sea-level change at the local Ghanaian scale.

Although the national Climate Change Vulnerability and Adaptation of Coastal Zone of Ghana report (EPA 2000) identified SLR in Ghana to impact shoreline recession, flooding and inundation of low-lying coastlands in Ghana, there is lack of information on the response to sea-level change and its integration into adaptation planning.

On the coast of Ghana, human activities of some coastal dwellers, mainly aiming for economic gains such as sand mining for construction purposes, mining of alluvial gold, and encroachment on lagoons, have made the coast more susceptible to erosion (Anim et al. 2013; Mensah 1997).

In view of the physical evidence of coastal erosion and flooding, the government of Ghana adopted a reactive measure to reduce the erosion impacts through building sea defence structures on Ghana's coast. The Keta Sea Defence Project (KSDP) is the first of such reactive projects which started in the year 2000. Geophysical surveys, geomorphic investigations and numerical modeling were the main assessments carried out to determine the causes of the coastal erosion in the Keta region before the construction of the KSDP. Similar investigations were carried out at Ada, a coastal town located near the Volta River estuary (Bollen et al. 2011) and other sea defence projects within Western, Central and Greater Accra administrative regions of Ghana. These assessments did not include scientific knowledge nor perceptions of local communities of sea-level responses to climate change on the coast of Ghana. Both will be addressed in the following, including information on the estimated impact of future coastal erosion in Ghana.

Coastal areas in the world are identified to have a wide variety of ecosystems, providing several services that influence human welfare, directly through human exploitation or indirectly through regulation of services in other environments (Martinez et al. 2007; Alves et al. 2009). These services may be lost or negatively affected by coastal erosion which is an obvious outcome of SLR (Dwarakish et al. 2009) although human activities may also have an important impact on coastal erosion (Ly 1980).

The sensitivity or susceptibility of coastal areas to sea erosion and the lack of capacity to cope and adapt to phenomenon determines how vulnerable the coast is (Boateng et al. 2016). Thus, information on coastal vulnerability caused by SLR may contribute to coastal management efforts aimed at minimizing risks or mitigating possible consequences (Hinkel and Klein 2009).

Boateng et al. 2016 utilized a Coastal Vulnerability Index (CVI) based approach to assess the vulnerability of the coastline of Ghana to erosion and ranked sections of coastline in terms of their potential for change. The report ranked the eastern and western portions of the Ghana coastline to be very highly vulnerable to SLR (see Figure 4.1)

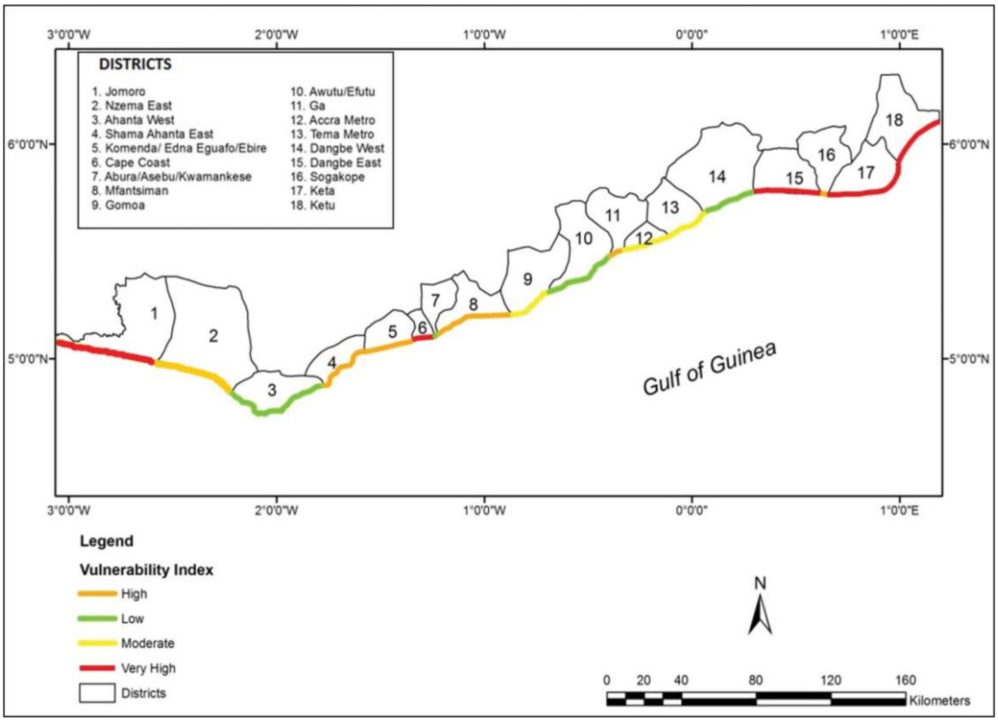


Figure 4.1: Ghana's coast showing various degree of vulnerability and related coastal districts (Boateng et al. 2016)

Olympio and Amos-Abanyie (2014) also identified locations of some recreational services and tourist attractions in Accra that could be impacted by SLR in the future, however, there is no assessment of local SLR impacts on land cover for the entire coast of Ghana.

Although concerns exist about integrating uncertainties of scientific sea-level research in adaptation planning (Brown 2016), first estimates of coastal erosion exist. A study by Appeaning Addo et al. 2008 revealed that in 250 years some low-lying elevations and wetlands will be inundated on the coast of Accra. Chapter 3 revealed that the entire coast of Ghana has experienced different rates of coastal erosion. According to the research, on average, the sea-level in Ghana has risen by about 5.3 cm over the last 21 years and SLR accounted for ~31 % of the observed annual coastal erosion rate (about 2 m/y) in Ghana. The study identified various sources of uncertainty associated with the shoreline data, computed annualized uncertainty as the square root of the sum of squares for each of the shoreline data and WLR to generate the shoreline change rates. Statistical and spatial analysis based on the IPCC AR5 projected the rise in the model-ensemble-mean of the sea-level scenarios (2.6, 4.5 and 8.5 RCPs) for Ghana. These results show that by the year 2025, about 6.6 m, 4.7 m, and 5.8 m of coastland in Ghana with lowest slope range (0 - 0.4 %) is projected to be inundated, increasing projected changes to 19.8m, 20.7 m and 24.3 m by 2050 and further to 36.6 m, 51.6 m and 83.9 m by 2100 for the 2.6, 4.5 and 8.5 RCPs respectively (refer to chapter 3).

These estimates may not be valid for periods further into the future, when the contribution to SLR in Ghana may become either smaller due to reduced input from glaciers or larger due to accelerated melting from the polar ice sheets (refer to chapter 3). Albeit these limitations, the estimates may be reasonable for next few decades.

Expanding previous work, there is the need to assess the impact of local SLR on different land cover types on the coast which may provide useful information for coastal adaptation strategies. Besides this need, there is often a relationship between the lack of understanding of the sediment redistribution process that shapes the coast and human-induced shoreline change (Anthony et al. 2016). Besides developing adaptation strategies to harness opportunities and reduce vulnerabilities to coastal erosion in Ghana, there is the need for continued assessment of coastal communities to understand the causes of coastal erosion, inform planning and improve community support to adopt the adaptation strategies. Research findings show that societal support setbacks remain considerable if adaptation practices aimed at sustainable development do not cater for community livelihood systems (Ziervogel et al. 2010; Adger et al. 2009; Adger et al. 2003).

Although the Keta Sea defence has achieved some success with regard to reducing the perennial flooding of the deltaic region (Jayson-Quashigah et al. 2013), in the view of the research the response to coastal erosion in Ghana is not integrative enough as coastal erosion has become severe in less affected neighboring communities. An example of this 'problem shifting' was reported by Bokpe (2016) on how the coastal erosion is steadily destroying 5 Keta communities.

The research thus assesses the impact of coastal erosion estimates on various land cover types and conducts semi-structured interviews at three scales (national, municipal and district level) to solicit responses on climate change awareness and adaptation strategies. This three-scaled semi-structured interview approach was used not only to increase the validity of the data but also to allow an exploration of the contradictions in responses garnered from respondents. In the following, we specify the methodology and present the results. The remaining section of the introduction gives a description of the study area.

The coast of Ghana (Figure 4.2) and the entire West African coast has been formed by and continues to be influenced by several factors, including processes of the Atlantic Ocean, the geological composition of the coast, the geophysical characteristics of the river basins, the prevailing meteorological conditions and its slow tectonic processes (Allersma and Tilmans 1993). The western portion of the coast of Ghana from the Ankobra River to Ghana’s Ivory Coast (Ghana's western neighboring country) and its eastern portion extending from Aflao (a border town to Togo) to Laloi lagoon west of Prampram, have sandy beaches with similar geomorphic characteristics. The central portion of the coast is however made up of rocky beaches (Ly 1980). Ghana's coast is generally low lying, with a narrow continental shelf reaching outward to between 20 and 35 km except off Takoradi where it reaches up to 90 km (EPA 2000). The coast is drained by many rivers including Tano, Ankobra, Butre, Pra, Kakum, Densu and Volta Rivers, and has over 90 coastal lagoons that shape the geomorphic composition of the beach (Armah and Amlalo 1998). The Volta delta, for example protrudes the coast, discharging on its western flank, which results in the formation of a very narrow sand barrier which separates the Keta Lagoon from the sea (Allersma and Tilmans 1993).

About 70 % of the total population of Ghana lives in the southern half of the country (Ghana Statistical Service, 2013). The coastal zone represents about 7 % of Ghana's land mass yet is inhabited by 25 % of its people as well as occupied by ~75 % of the nation's industries. The main occupation of inhabitants along the coast of Ghana is fishing, farming, transportation of goods and services, sand and stone mining for building and road construction, oil extraction and for tourism activities (EPA 2000).

The coastal zone of Ghana is rich in coastal habitats and biodiversity including, estuarine wetlands, lagoons, lagoonal depressions and their associated marshes, sandy shores, rocky beaches and pools, savanna (grassland) to semi-deciduous and wet evergreen secondary tropical forests with rich biodiversity (EPA 2000). Not only does the response to SLR under climate change contribute to coastal erosion in Ghana but the increased physical infrastructure development on the coast relies heavily on coastal sand and pebbles, which have accelerated coastal environmental degradation in Ghana (Mensah 1997; Jonah et al. 2016). Appeaning Addo (2015) projected some communities in Dansoman to be inundated by 2065 due to SLR.

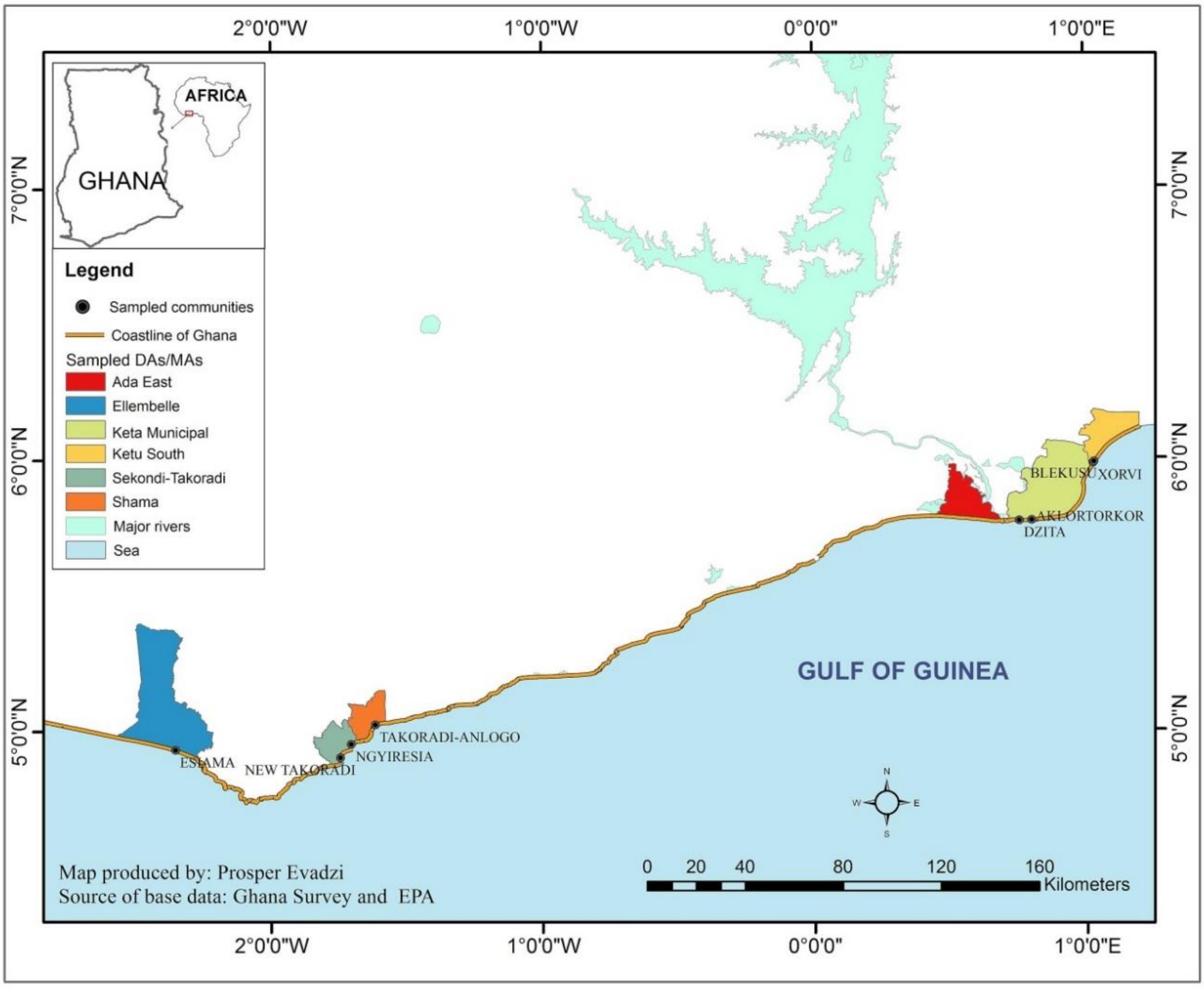


Figure 4.2: Study area showing the entire coastline of Ghana and sample sites for the primary data collection

4.2 Methods

The methods section describes the data and processing methods used for the data analysis.

The research consists of two components. First, this paper overlays the coastal erosion estimates generated by Evadzi et al. (2017; referring to chapter 3) on land cover data on the coast of Ghana and quantifies different land cover types at risk of future SLR by the years 2050 and 2100. The different land cover types (12 classes) are; grass/herb with/without scattered trees (0-5 trees/ha), grassland with/without scattered tree/shrub, lagoon, moderately closed tree (>15 trees/ha) canopy with herb and bush cover, moderately dense herb/bush with scattered trees (<15 trees/ha), mosaic of thickets and grass with/without scattered trees, planted cover, river, settlement, shrub thicket with or without trees, unclassified area due to cloud cover and wetland.

The second and main focus of this paper uses data from both primary (semi-structured interviews) and secondary sources (policy documents on coastal management in Ghana) to assess the level of SLR awareness in Ghana and find out whether scientific knowledge of the response of SLR under climate change on the coast of Ghana was available and integrated into coastal adaptation strategies in Ghana. The research solicits views from three scales/levels (national, municipal/district assemblies and coastal communities) for cognitive assessment of views related to coastal erosion and SLR responses under climate change on the coast of Ghana. At the national level (first scale), the research solicits views through semi-structured interviews from key informants at the EPA, the Ministry of Environment Science and Technology (MEST), and the Hydrological Department of the Water Resources Commission whose mandate includes management of conditions along the entire coast of Ghana. For the municipal/district level (second scale), informants were interviewed from selected Municipal and District Assemblies (MDAs), namely, Keta Municipal Assembly (KMA), Sekondi Takoradi Municipal Assembly (STMA), Ada East District Assembly and Ellembelle District Assembly. At the community level (third scale), respondents from eight communities (Ngyiresia, Esiama, New Takoradi, Anlogo and Blekusu from the western part of the coast of Ghana and Akplortorkor, Xorvi, Blekusu and Dzita from the eastern part of the coast of Ghana) were interviewed.

These communities were selected because they depend largely on the coastal resources for their sustenance and are within zones of potential threat to SLR (refer to chapter 3; Appeaning Addo

2015; Ly 1980). The research did not carry out a complete listing of community households for sampling because of cost and types of settlements but rather devised a pattern to select interviewees from these coastal communities to make room for randomness and unbiased response. The study thus selected 5 major spatial areas (~30 meters apart) in each of the 8 communities for household sampling. In each spatial area, the interviewer selects the first household and identify 4 other households within 10 m radius around this core household. The distance between and around the 5 main spatial areas in each community was chosen because of the spatial extent of these communities and the type of settlements which are predominantly nucleated settlements with compound houses. The measurement was aided by a handheld Global Positioning System (GPS) device. Each household offered a person willing to be interviewed. The outcomes of the analyses were views expressed in simple cross-tabulations and graphs with some views inserted as recorded speeches.

Informants and respondents from all categories address similar questions. This approach is adopted to identify contradictions in responses at these scales, especially from the first and second scales which are directly involved in coastal management in Ghana. The interviewer asked both open and close-ended questions for which respondents gave responses. Some of the sea-level awareness, coastal impact and adaptation questions for which responses were garnered from respondents from the communities are condensed in the box below. Informants at the national and municipal/district assembly also gave responses to questions on adaptation strategies (see box).

------------------------------------**Box start**---

Selected open-end questions for interviews

Sea-level awareness, coastal impact and adaptation questions

- Do you know about SLR (briefly explain if ‘yes’)?
- Is climate change mainly caused by human activity, on a scale of 1 to 7, where 7 means you are absolutely certain, and 1 means Not at all?

- Do you know whether for the past 5 to 10 years the volume of sea water close to this community has risen or fallen? How did you know?
- Is the coast nearby receding (briefly explain if ‘yes’)?
- Have you lost any item or property situated close to the coast due SLR and coastal flooding (briefly explain if ‘yes’)?
- When and what really transpired including items lost?
- Did the event lead to your evacuation and resettlement (when and from where if ‘yes’)?
- Do you know any household close-by that also suffered from this disaster?
- Is the issue a reoccurring phenomenon (if yes, explain the nature of event)?
- Do you know of any state/public (communal) infrastructure affected by the incident?
- Briefly explain how you respond to the disaster associated with the rising sea-level and coastal flooding?
- Did National Disaster Management Organization (NADMO) or any organization assist you or the community due to the disaster?
- Is the government putting some mitigation measures in place to offset future impacts to sea-level in your community?
- Are you satisfied with the government’s mitigation option?
- Are there some communities outside the mitigation region that are suffering from increasing coastal flooding because of the mitigation measure(s) adopted by this community?
- Is this community suffering from SLR and increasing coastal flooding because of mitigation measure(s) adopted by other communities?

Questions on adaptation strategies

- What do you think is the best mitigation option for the community?
- What is the District Assembly or government doing to adapt to and mitigate future occurrence of such disaster?
- Are you satisfied with the government’s adaptation option (briefly explain)?
- Is the adaptation option adopted (if any) based on scientific and expert knowledge on sea-level change and coastal impact assessment in the affected areas?
- Is there a national adaptation plan for SLR based on scientific and expert knowledge for coastal communities in Ghana? (Any document to support?)
- Are there some communities benefiting from the DA’s or government’s adaptation/ mitigation (please underline) plan?
- Are there some communities outside the mitigation region that are suffering from increasing coastal flooding as a result of the mitigation measure(s) adopted by this community?
- Is/are this/these community(ies) suffering from SLR and increasing coastal flooding as a result of mitigation measure(s) adopted by other communities?
- In your assessment (no reference to ranking) what are the barriers to the development of adaptation plan for sea-level change (local/national).

-------------------------------------**Box end**---

While the open-ended questions allow the respondent to express his/her view on a particular question in detail (e.g. what causes climate change?), the close-ended questions demand 'yes' or 'no' responses (e.g. Do you know about climate change?). The interviews are conducted in four languages (English, Ewe, Ga and Twi) depending on spatial location and dialect of interviewees; the responses were recorded and summarized in English, analyzed and expressed in simple cross-tabulations, graphs and verbatim text by the interviewer. The responses given by respondents were not suggested by the interviewer.

To make room for randomness and unbiased responses from interviewees in the coastal communities, respondents are selected from 20 households that spread across the community and not from only one spatial unit. The research uses simple cross-tabulations for most of the analysis because the research attempts to summarize the relationship between two categorical variables.

The respondents interviewed at the community scale are largely dependent on the coastal resources for their livelihood. Fishing is their most important livelihood source, about 34 % of the respondents depend solely on fishing, 8.5 % combined fishing with farming as their sources of livelihood and 24 % of the respondents are fishmongers (Table 4.1). Although there are other non-fishing income-earning activities in the study area, they are mostly linked to the fishing sector. An example is carpenters specialized in building fishing boats. For these fishing dependent households, their proximity to the sea is to reduce their operational cost.

		%
Agricultural-Fishing sector	Fisherman	34.0
	Fisherman and Farmer	8.5
	Fishmonger	24.0
Fishing sector -total		66.5
Non-Fishing	Farmer	6.5
	Farmer and Trader	.5
	Carpenter	7.5
	Mason	1.0
	Trader	6.5
	Food Vendor	1.5
	Tailor/Seamstress	3.5
	Driver	.5
	Public Servant	1.5
	Teacher	3.5
	Student	.5
Non-Fishing -total		33
Unemployed		.5
Total		100.0

Table 4.1: Classification of households by main livelihood activities (%), N = 200

4.3 Results

Findings from our study are presented in this section. The results cover four main topics namely, SLR and coastal inundation, climate change and SLR awareness, SLR adaptation strategies, and barriers to integrated coastal adaptation planning.

4.3.1 SLR and Coastal Inundation

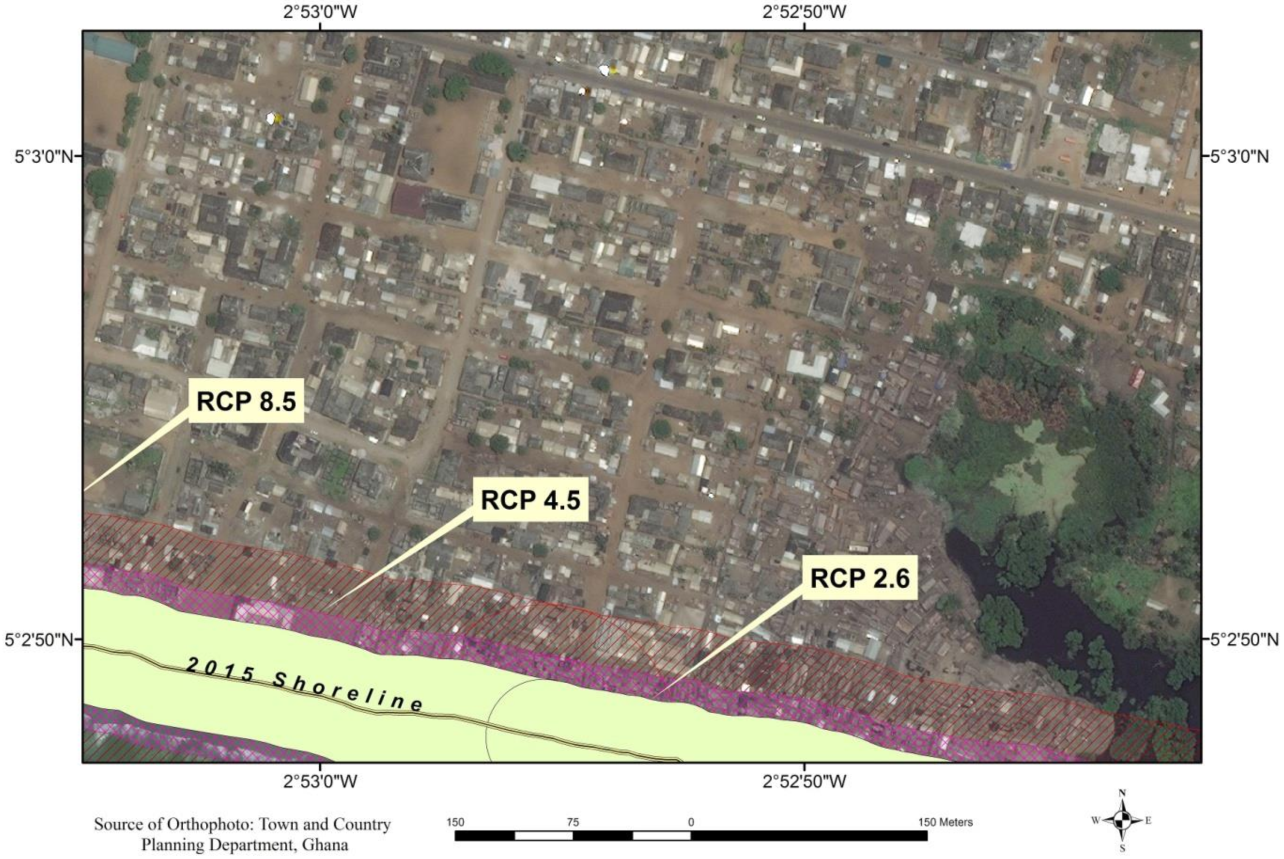
Simple overlay of future sea-level induced coastal erosion estimates (refer to chapter 3) on 2010 coastal land cover of Ghana reveals that the following approximate land areas will be at risk of inundation by the year 2050 for the 2.6, 4.5 and 8.5 RCPs respectively: 2.66 km², 2.77 km² and 3.24 km² of coastal settlements; 2.10 km², 2.20 km² and 2.58 km² of lagoons; 1.39 km², 1.46 km² and 1.71 km² of wetlands. These projected land cover losses would further increase by 2100 to approximately 4.83 km², 6.72 km² and 10.70 km² of coastal settlements; 3.87 km², 5.45 km² and 8.84 km² of lagoons; 2.74 km², 3.57 km² and 5.71 km² of wetlands (Table 4.2).

Similar analysis focused on specific urban communities located on the western, central and eastern parts that involved overlay of the future sea-level induced coastal erosion estimates on a 2015 Landsat image of the coast of Ghana reveals that coastal urban areas of Half Assini and Old Elubo communities with slope range (0 - 0.4 %) along the western coast of Ghana are projected to have urban land loss of ~5,000 m², ~7,000 m² and ~12,000 m² by 2050 for the 2.6, 4.5 and 8.5 RCPs respectively. These projected urban land losses would further increase by 2100 to 42,000 m², 70,000 m², 138,000 m² for the 2.6, 4.5 and 8.5 RCPs respectively (Figure 4.3). By 2100, ~24,000 m², ~34,000 m² and ~55,000 m² urban land loss may be expected for the Dansoman coastal area in Accra between the Densu River delta and Chorkor based on the 2.6, 4.5 and 8.5 RCP scenarios respectively.

Many communities along the coast of the Keta Municipal Assembly are projected to be inundated, including a constructed sea defence infrastructure around Adzidze, by 2100 based on the 8.5 RCP SLR scenario. Some of the communities to be potentially affected include Cape Saint Paul, Ahaworyikope, Asiata, Aeleglokope, Klamatsi and Wogona.

Landcover Types	**RCP 2.6 (km²)**		**RCP 4.5 (km²)**		**RCP 8.5 (km²)**	
	2050	2100	2050	2100	2050	2100
Grass/herb with/without scattered trees (0-5 trees/ha)	2.21	4.06	2.31	5.71	2.71	9.26
Grassland with/without scattered tree/shrub	1.24	2.28	1.30	3.20	1.52	5.18
Lagoon	2.10	3.87	2.20	5.45	2.58	8.84
Moderately closed tree (>15 trees/ha) canopy with herb and bush cover	0.40	0.73	0.42	1.03	0.49	1.65
Moderately dense herb/bush with scattered trees (<15 trees/ha)	3.94	7.22	4.12	10.12	4.82	16.29
Mosaic of thickets & grass with/without scattered trees	2.43	4.45	2.54	6.24	2.97	9.99
Planted cover	2.31	4.26	2.42	5.99	2.84	9.66
River	0.44	0.81	0.46	1.14	0.54	1.86
Settlement	2.66	4.83	2.77	6.72	3.24	10.70
Shrub thicket with/without trees	0.43	0.78	0.45	1.07	0.53	1.67
unclassified area due to cloud cover	0.09	0.18	0.10	0.26	0.12	0.46
Wetland	1.39	2.74	1.46	3.57	1.71	5.71

Table 4.2: Different land cover types at risk of coastal erosion, based on 2050 and 2100 coastal erosion estimates



Source of Orthophoto: Town and Country Planning Department, Ghana

Figure 4.3: Urban land area loss estimates for 2.6, 4.5, and 8.5 RCPs by 2100 at Half Assini in Ghana.

4.3.2 Climate Change and SLR Awareness

Figure 4.4 represents the summary of the responses on climate change awareness of household respondents on the coast of Ghana. Although about 81 % of all respondents said they were aware of climate change, about 38 % of those claimed that this a change in the weather caused by God whilst 12 % said it is a long-term change in the weather system (Figure 4.4). The research did not solicit information on interviewees religious backgrounds and reasons of attributing the change in weather to God.

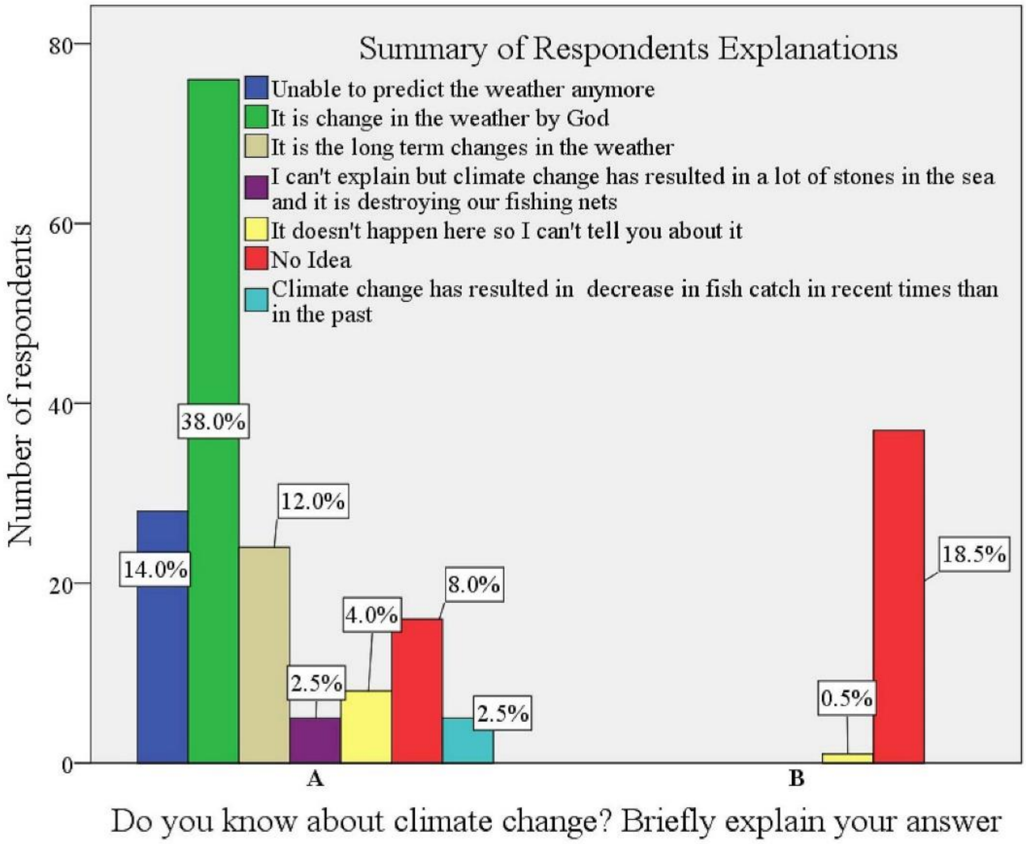


Figure 4.4: Respondents' awareness and perception of climate change. (A) Refers to respondents who initially said 'Yes' they do have an idea about climate change. (B) Refers to respondents who initially said they have 'No' idea about climate change

Only 10.5 % of the total respondents were certain that human activities are the main cause of climate change (Figure 4.5). This further buttressed earlier results on climate change awareness where 81% of the respondent attributed climate change to weather changes caused by God (Figure 4.4).

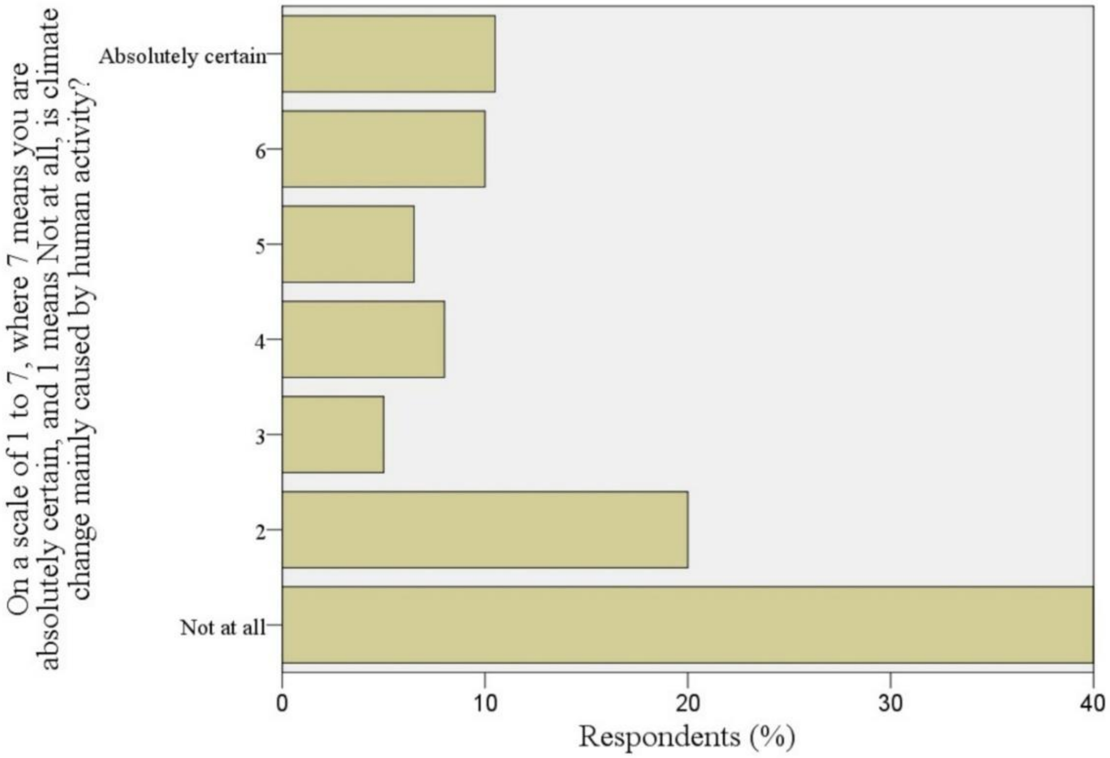


Figure 4.5: Degree of respondents' certainty about human activities as the main cause of climate change

Most of the respondents (151 out of 168) who claim to have knowledge about SLR, said they noticed a rise in the sea-level since about 5 to 10 years ago, attributing their assessment to coastal recession (Table 4.3). However, 7 respondents from Ngyiresia (2 out of the 6 who claim sea-level has 'fallen', together with 5 out of 11 respondents who claim to have 'no idea' about the change in the sea-level), said some land was reclaimed from the sea during construction activities at the Takoradi Harbour, and as a result they are unsure whether sea-level has risen or fallen.

		Sea-level 5 to 10 years ago			**Total**
		Risen	Fallen	No idea	
Do you know about SLR?	Yes	151	6	11	168
	No	22	4	6	32
Total		173	10	17	200

Table 4.3: Respondents' awareness of change in sea-level close to their community for the past 5 to 10 years

All interviewees from the national as well as from municipal and district assemblies are aware of SLR. Their sources of information were physical evidence, research reports, conference proceedings, mass media and national documents (National Climate Change Policy, and Medium-Term Development Plans).

According to 140 out of the 200 respondents interviewed on the coast of Ghana who claim to have lost items to coastal erosion, 115 also claim that the incident resulted in evacuation or resettlement (Table 4.4). The items listed to be affected are fishing nets, boats as well is buildings and household items.

		B		**Total**
		Yes	No	
A	Yes	115	25	140
	No	60	0	60
Total		175	25	200

Table 4.4: SLR and coastal impact, **(A)** Have you lost any item or property situated close to the coast due to SLR and coastal flooding? **(B)** Did the incident in 'A' lead to your evacuation and/or resettlement?

A respondent of Blekusu (Figure 4.6) who could not hold back her tears during the interview claimed she lost her building due to SLR: *"Since I was a child till now, I have seen submerged buildings* *and even one human death caused by the sea, but to think that my family house which was far from the sea today is also suffering makes me sad. But can I fight the sea? My children have left to Keta but I am old, I have nowhere to go "*.

Figure 4.6: A resident of Blekusu responding to questions about the impact of SLR

93.5% of all the respondents interviewed said the coastal erosion process has resulted in a continuous reduction of their land over the years. However, 19 out of 25 respondents from Akplortotor said the coastal retreat has stopped after the construction of the sea defence in their community. 24 out of 25 respondents from Dzita, however, expressed concern about the increasing rate of coastal erosion in their community after the sea defence project at Akplorwotorkor. A recent report by Seth J. Bokpe, published online on the 20th February 2016 by Graphic online, a Ghanaian local news agency, presented narratives how coastal erosion was steadily wiping out 5 communities within the Keta municipality including Dzita.

All Municipal Assemblies (MAs) and District Assemblies (DAs) respondents said they have witnessed or experienced some coastal erosion/flooding events in their communities, however, all respondents from national institutions interviewed, become aware of the incident through the mass media, mainly through radio and television. One of the respondents at the district level said: *"You can even see for yourself what is happening to this District Assembly building due to its location close to the sea. That road (pointing at the road) was reconstructed twice away from the sea because the sea consumed the previous ones. Just yesterday, Azizanya communities came here demanding for 'their sand (land)' saying their community is on extinction due to the sea defence project at Ada".*

One respondent at the national scale who was involved in the coastal project construction and monitoring in Ghana, commenting on the Azizanya coastal erosion problem said, *"I am aware they are suffering, but some communities are not supposed to be where they are".*

4.3.3 SLR and Adaptation Strategies

Construction of the coastal defence wall (Figure 4.7A) is the main adaptation strategy adopted by the Ghana government, however not all communities visited currently benefit from this facility. Coastal communities have resolved to temporary relocation when there is coastal flooding or inundation by the sea. In either situation, they salvage items that could be transported and relocate temporarily to higher grounds. The victims return to their structures if the flooding events do not result in permanent inundation (Figure 4.7B). These communities are linked by their profession (mainly fishing; Figure 4.7C), and in such events the other community members assist the victims to salvage some items.

The household interviewees expressed dissatisfaction at the NADMO in particular, for failing to provide needed relief assistance to the victims of the communities involved in this seemingly indefinite climatic phenomenon (Table 4.5).

		B				**Total**
		Support from NADMO	Support from NGOs	Support from community	Others forms of support	
A	Yes	8	25	39	16	88
	No	-	-	-	-	112
Total						200

Table 4.5: Relief assistance during coastal disaster events, **(A)** Did NADMO or any other organization assist you or the community due to the disaster? **(B)** Source of support if received some form of support ('yes')

Interviewed respondents from national institutions lacked details with regard to whether NADMO or any governmental organization offered any support to individuals and communities affected by the recent destruction related to SLR along the coast of Ghana, but said NADMO always provides relief to victims. Interviewees from MAs and DAs admitted that some assistance was received by victims from NADMO in recent cases. A key informant in the Ellembelle District Assembly however said: *"Although NADMO is expected to assist with items such as clothings, beddings, iron sheets, etc. they were unable to assist the Esiama when people lost their buildings and properties along the coast because they had no items to give"*.

Temporary relocation is the main strategy adopted by members of the communities during coastal flooding. Some used less expensive materials for the construction of their houses close to the sea to minimize loss during such events.

All respondents from Ngyiresia said the community initially opposed the construction of the sea defence project in their community because the design of the infrastructure will affect their livelihood and would result in loosing the landing sites for their boats. Although a modified design (Figure 4.7A) was implemented, 17 respondents representing 68% of the respondents from Ngyiresia said they are not satisfied with the defence project because it does not allow drains to flow easily from mainland into the sea thus creating favorable moisture conditions that mosquitoes need to hatch their eggs, which they alleged to have resulted in increased malaria cases in the community.

Figure 4.7: Selected photos of the coast of Ghana showing sea defence structure at New Takoradi **(A)**; Coastal settlers relocate close to the sea at Ngyiresia after a flooding event **(B)**; Community members pulling in a fishing net at Blekusu **(C)**.

Apart from the respondents from the Keta Municipal Assembly, other MAs and DAs expressed different levels of dissatisfaction with the reactive measure adopted by the government. One of the respondents whose unit is benefiting from the project said: "*I think there is lack of understanding of the cause of the problem because surrounding communities are suffering. Even some groins were reconstructed due to erosion. The engineers also said there has been accretion but I saw them filling the site with transported sand from other places and they also dredged the sea*".

A key respondent at the national level expressed satisfaction with the ongoing coastal defence projects in Ghana and made reference to some areas, including the Keta lagoon and the area behind the Adisadel College to be successful. However, in responding to questions on whether the ongoing coastal protection projects in Ghana are based on scientific and expert knowledge on SLR and coastal impact assessment in the affected areas, this key respondent said *"We did a lot of coastal engineering simulations including wave simulations but no thorough investigation on SLR. There are just some projections for SLR by EPA but I don't know what informed it".*

An interviewee at the EPA whilst responding to a similar question said: *"I know about SLR through education, conferences, etc, however, our reports are based on IPCC projections. I doubt that the ongoing coastal protection along the coast of Ghana included a thorough scientific assessment of sea-level change along the coast of Ghana."* Interviewees at the district level all said they have no scientific knowledge of SLR along the coast of Ghana.

4.3.4 Barriers to integrated coastal adaptation planning

Ghana has no integrative coastal adaptation plan, and respondents at the national and municipal/district levels acknowledge the need for such a policy with scientific knowledge on the response to SLR under climate change on the coast of Ghana. With no importance to ranking of barriers, respondents responded to the question, "In your assessment what are the barriers to the development of sea-level change adaptation plan for Ghana?", and listed barriers to the sea-level change adaptation plan in Ghana under the headings of governance, policy, psychosocial, resources and uncertainty. Among the identified barriers to sea-level change adaptation plan for Ghana were lack of political will and clarity of roles and responsibilities across levels of government; public disbelief in the science of climate change; lack of scientific and expert knowledge on SLR; and uncertainty about climate impacts (Table 4.6).

Governance	- Lack of political will and clarity on roles and responsibilities across levels of government. - A mismatch between the time horizons for adaptation and political and management practices.
Cultural	- Public disbelief in the science of climate change. - Cultural resistance to change.
Resources	- Lack of scientific and expert knowledge on SLR. - Capital costs of engineering solutions - Lack of staffing, skills and expertise. - Lack of access to funding.
Uncertainty	- Uncertainty about climate impacts. - Lack of data. - Lack of confidence in climate change projections. - Uncertainty about appropriate planning tools and methodologies. - Lack of research focusing on adaptation. - Lack of standards for interpreting data reliability.

Table 4.6: Barriers to integrated national adaptation plan for Ghana

4.4 Discussion

Coastal areas in the world have a wide variety of ecosystem services that may be lost as a result of SLR (Martinez et al. 2007; Alves et al. 2009; Dwarakish et al. 2009) although human activities are also identified to contribute to coastal erosion (Ly 1980).

Analysis of sea-level, DEM and historical shoreline data by Evadzi et al 2017 reveals that SLR has ~ 31 % shoreline recession in Ghana for the lowest slope range (0 - 0.4 %) and suggested that based on the projected rise in the sea-level, by the year 2050 about 19.8 m, 20.7 m and 24.3 m and further to 36.6 m, 51.6 m and 83.9 m by 2100 more of coastal land in Ghana may be inundated based on the 2.6, 4.5 and 8.5 IPCC AR5 RCPs scenarios. The research reveals that by 2100 several square kilometers may be lost for different types of land cover (coastal settlements, lagoons, wetlands).

Appeaning Addo and Adeyemi 2013 reported that accelerated SLR will destroy homes of inhabitants, inundate Densu wetland in Ghana and destroy the habitats of migratory birds and some endangered wildlife species such as marine turtle. Analysis focused on some specific communities undergoing different rates of shoreline change in Ghana that involves simple overlay of coastal erosion estimates for Ghana by Evadzi et al. 2017 (referring to chapter 3) on 2015 Landsat data reveals that by 2100, tens of thousands of m^2 urban land loss may be expected for the Dansoman coastal area between the Densu River delta and Chorkor.

Although this result on the exposure of the Dansoman coastal area to SLR confirms findings by Appeaning Addo et al. 2011, the research estimates the most likely recession by 2100 based on the AR5 8.5 RCP to be 86 m from the coast of Dansoman while in Appeaning Addo et al. 2011 the most likely recession based on IPCC Special Report on Emissions Scenarios - fossil intensive (SRES A1F1) was estimated at 202.06 m. The difference could be explained by the SLR scenarios used by both studies. As the research is based on the expected land cover loss analysis of climate simulations included in the CMIP5 driven by the IPCC RCPs and augmented by melting of land-ice estimations for the coast of Ghana, that of Appeaning Addo et al. 2011 was based on Commonwealth Scientific and Industrial Research Organization General Circulation Models (CSIRO_MK2) global SLR scenarios.

Dansoman is not among the sampled communities in the research, however the results from the research reports 87.5% of respondents claiming to have evacuated or resettled due to past coastal flooding events whereas Appeaning et al. 2011 reported 70% of respondents from Dansoman to have evacuated due to coastal flooding events. These two exclusive studies all claim coastal dwellers are aware of sea-level change and its impact on their community. However, 81 % of the community respondents from the research attributed the cause of climate change to God. This result is partly confirmed by the identification of public disbelief in the science of climate change by the national and municipal/district assembly respondents as one of the barriers to the development of the adaptation plan.

Although there is recognition and inclusion of climate change adaptation practices in some development processes detailed in the National Climate Change Policy (2014) and the draft of the Policy Action Program for Implementation (2015-2020) as well as from other national reports, the research through semi-structured interviews reveals that there is no comprehensive coastal adaptation plan for Ghana that includes information of the response of SLR under changing climate. MDAs are aware of the ongoing reactive coastal adaptation program but had no knowledge whether the adaptation strategies adopted are based on scientific knowledge of SLR. This claim by MDAs of lack of information adaptation strategies is confirmed by Adu-Boateng 2015 and Mensah et al. 2016, who claim that there is not only limited stakeholder engagement in climate adaptation issues that could increase adaptation costs but also most existing climate change adaptation policies in Ghana are a mosaic of policies, actors, and strategic action priorities, which lack coordination.

4.5 Conclusions

There is lack of information on the extent to which different land cover types including wetlands, lagoons and settlements may be lost to coastal erosion in the future as well as information on the awareness of SLR and coastal impact in Ghana. The research attempts to provide this information that may be useful for adaptation strategies.

According to the data garnered, most communities on the coast of Ghana are aware of SLR and the coastal erosion impact on their communities. The cause of SLR however has been largely attributed to God by interviewees on the coast of Ghana suggesting the need for education outreach programs on SLR at the coast of Ghana. This education programs may positively affect any coastal adaptation project.

Although respondents in some communities have expressed satisfaction with the ongoing coastal defence projects, other communities are dissatisfied based on the physical design of the project. Respondents from Ngyiresia for example alleged that the defence wall in their community does not allow drains to flow easily from mainland into the sea thus creating favorable moisture conditions that mosquitoes need to hatch their eggs, which allegedly have resulted in increased malaria cases in the community. Some respondents claim that their source of livelihood (fishing) is being threatened by the sea defence project because it made no provision for landing sites.

Municipal and District Assemblies are not sufficiently integrated into the sea defence projects and thus lack scientific knowledge on SLR in Ghana. There is the need for cooperative relationships between national, district, local authorities, coastal research scientists and engineers, and communities along the coast of Ghana through facilitated discussion learning programs.

There is a high readiness to adapt to climate change on the part of the Ghanaian government based on the physical evidence of ongoing coastal defence projects in Ghana. Despite the success chalked by the projects in some communities including Keta, the project has exacerbated the coastal erosion in neighboring and other communities which hitherto experienced low levels of coastal erosion prior to the construction of the sea defence projects. In the opinion of the research, the identified reactive measure is not comprehensive and integrative enough and lacks sound scientific knowledge on climate change impact on the coast of Ghana.

Integrated and comprehensive coastal management policies informed by thorough research findings about natural and anthropogenic causes of coastal erosion along the entire coast of Ghana as well as the identification of suitable adaptation options for different spatial units are needed to interactively and sustainably curb the devastating coastal erosion in Ghana.

Although the 2010 land cover data provides useful information on which land cover types on the coast of Ghana are expected to be impacted by accelerated SLR, there is the need for current data on land cover types on the coast of Ghana as well as estimates of their economic values.

CHAPTER 5

Summary and conclusions

5.1 Summary and conclusions

This doctoral thesis is the product of an analysis of the climate sensitivity and sea-level impact focused on the Gulf of Guinea and Ghana in particular. The project was developed as an attempt to provide useful but currently lacking information on regional sea-level under a changing climate at the retreating coast of Ghana that may be essential for coastal adaptation strategies. This thesis put forward 3 main research questions and utilized different datasets and approaches to answer them in the quest to fulfill the purpose of this thesis. The first objective which has its analysis presented in chapter 2 attempted to identify the impact of large-scale climate patterns on sea-level variability and trends in the GoG with focus on the West African coast. Different datasets ranging from sea-level data [tide gauges (Takoradi, Tema and Forcados), satellite altimetry (combined TOPEX/Poseidon, Jason-1 and Jason-2/OSTM), gridded reconstruction (Church et. al. 2004), ocean model simulations (STORM)], to meteorological and reanalysis products (HadISST1, AMO index and wind stress) were statistically analyzed to make logical conclusions. The logical conclusion deduced from this investigation is that SST in the Gulf of Guinea and its associated AMO is the main large-scale climate factors linked to mean sea-level variability of the West African coast.

This thesis's second research question seeking to quantify the contribution of SLR to shoreline change in Ghana was presented in chapter 3. The investigation involved analysis of historical shoreline change in Ghana from 1974 to 2015 using satellite images and Orthophotos and proceeded to quantify the contribution of sea-level to shoreline change in Ghana. It used the computed shoreline change rates together with estimates from satellite observations and results from DEM analysis to estimate the contribution of sea-level to shoreline change in Ghana and finally made predictions of shoreline in Ghana based on modified IPCC AR5 RCPs scenarios for Ghana. The main deduction is that, on average, sea-level has risen by about 5.3 cm over the last 21 years and accounts for only ~31 % of the observed annual coastal erosion rate (about 2 m/y) in Ghana.

On the basis of the historical shoreline analysis from 1974 to 2015, the research revealed that on average, the coast of Ghana has receded at an approximate rate of 2 m/y. The research identifies the shoreline for the portion of the Accra Metropolis coast (~340 to 355 km from the western corner) to have receded on average of 1.8 m/y while farther eastward from the Accra Metropolis displays higher rates (~3 m/y), which are higher than those estimated for the Keta area in earlier investigations.

The research provided essential information for coastal adaptation strategies by estimating SLR contribution to shoreline recession in Ghana to be ~31% for the lowest slope range (0–0.4%) and suggests that on the basis of the projected rise in the sea level, by the year 2025, about 6.6, 4.7 and 5.8 m more of coastal land for the lowest slope range (0–0.4%) of the low-lying coast of Ghana may be inundated on the basis of the 2.6, 4.5, and 8.5 RCPs scenarios, respectively. This may increase by 2050 to 19.8, 20.7, and 24.3 m and further to 36.6, 51.6, and 83.9 m by 2100 on the basis of the RCPs 2.6, 4.5, and 8.5 scenarios respectively, for the coastal land within the lowest slope range (0–0.4%).

The last main chapter (chapter 4) addressed the third research question of this thesis that seeks to determine the level of awareness of respondents to SLR on the coast of Ghana and explores the availability and level of integration of scientific knowledge of SLR into coastal adaptation strategies in Ghana using semi-structured interviews at national, municipal/district and coastal community scales. Assessment of the awareness of SLR responses to the changing climate in Ghana is made. This chapter also assessed the impact of probable coastal erosion scenarios on different land cover types and some built-up areas at the coast of Ghana based on the modified RCPs of the IPCC fifth Assessment Report.

Although the future coastline erosion estimates computed confirms the report by Appeaning Addo et al. 2011 that the Dansoman coastal area is exposed to coastal inundation induced by SLR, there exist differences in the values of the estimates which could be explained by the SLR scenarios used by both studies.

The research noted that albeit this threat of SLR to various land cover types, property and life at the coast of Ghana, coastal dwellers interviewed cherish their proximity to the sea and are determined to maintain their occupancy close to the sea as spatial location influences their source of livelihood (fishing).

The study shows that coastal dwellers are aware of sea-level change and its impact on their community. However, 81 % of the community respondents from the research attributed the cause of climate change to God. This result is partly confirmed by the identification of public disbelief in the science of climate change by the national and municipal/district assembly respondents as one of the barriers to the development of the adaptation plan.

Abbreviations

AMO	Atlantic Multidecadal Oscillation
AMSL	Annual Mean Sea-level
AR5	Fifth Assessment Report
CMIP	Coupled Model Intercomparison Project
DAs	District Assemblies
DEM	Digital Elevation Model
DSAS	Digital Shoreline Analysis System
ENSO	El Niño–Southern Oscillation
EOF	Empirical Orthogonal Function
EPA	Environmental Protection Agency
EPR	End Point Rate
GMSL	Global Mean Sea-level
GoG	Gulf of Guinea
HadISST	Hadley Centre Sea Ice and Sea Surface Temperature
IPCC	Intergovernmental Panel on Climate Change
KSDP	Keta Sea Defence Project
MAs	Municipal Assemblies
MDA	Municipal and District Assemblies
MPI-OM	Max-Planck Institute Ocean Model
NADMO	National Disaster Management Organization
NAO	North Atlantic Ocean
NCAR	National Center for Atmospheric Research

NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
OLS	Ordinary Least Squares
PCA	Principal Component Analysis
PSMSL	Permanent Service for Mean Sea-level
RCP	Representative Concentration Pathway
SLR	Sea-level Rise
SRES A1F1	Special Report on Emissions Scenarios - fossil intensive
SSH	Sea-Surface Heights
SST	Sea Surface Temperature
Ud	Uncertainty relating to shoreline digitization
Upa	Uncertainty relating to shoreline position accuracy/georeferencing error
Upr	Uncertainty relating to photo resolution
Ut	Annualized/total uncertainty
UNFCCC	United Nations Framework Convention on Climate Change
WLR	Weighted Linear Regression

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Evadzi, P.I.K., Zorita, E. and Hünicke, B. 2017: Quantifying and predicting the contribution of sea-level rise to shoreline change in Ghana: Information for Coastal Adaptation Strategies. Journal of Coastal Research, in press.

Evadzi, P.I.K., Scheffran, J., Zorita, E. and Hünicke, B. (2017) Awareness of sea-level response under climate change on the coast of Ghana. Journal of Coastal Conservation, accepted with corrections

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Eidesstattliche Versicherung

Declaration on oath

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare, on oath, that I have written the present dissertation on my own and have not used other than the acknowledged resources and aids.

Hamburg 2017