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ASSESMENT OF MARINE GEOID VARIATION DUE TO SEA LEVEL CHANGE AND ITS IMPACT ON OCEAN MAPPING.

A case study of Tanzanian Indian Ocean

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ASSESMENT OF MARINE GEOID VARIATION DUE TO SEA LEVEL CHANGE AND ITS IMPACT ON OCEAN MAPPING

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A Dissertation Submitted to the Department of Geospatial Sciences and Technology in Partially Fulfilment of the Requirements for the Award of Science in Geomatics (Bsc.GM) of Ardhi University

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Ardhi University dissertation titled **"Assessment of Marine Geoid Variation Due to Sea Level Change and Its Impact on Ocean Mapping, a case study of Tanzanian Indian Ocean"** in partial fulfilment of the requirements for the award of degree of Bachelor of Science in Geomatics at Ardhi University.

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(Main Supervisor)	(Second Supervisor)
Date……………………….	Date…………………….

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I, MNGOZI, RAHMA S hereby declare that, the contents of this dissertation are the results of my own findings through my study and investigation, and to the best of my knowledge they have not been presented anywhere else as a dissertation for diploma, degree or any similar academic award in any institution of higher learning.

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DEDICATION

I dedicate my dissertation work to my family and friends. A special feeling of gratitude to my loving parents, Seleman and Mariam Mngozi whose words of encouragement and push for tenacity had supported me throughout. My sisters and brothers; Tunu, Farida, Ally and Hassan have never left my side and are very special. They have contributed to the person I am today; this will always be remembered. May the Lord bless you all for your endless love, moral support, advice and encouragement throughout the whole period of my studies.

ABSTRACT

This research aims to investigate the impact of sea level changes on the marine geoid and its subsequent effects on ocean mapping. The research was undertaken on the marine region of the United Republic of Tanzania along the Indian Ocean from latitudes: 0°S to 12°S and longitudes: 38°E to 43°E, to achieve this goal the research employed the satellite altimetry models namely the mean sea surface height (MSSH) and mean dynamic topography (MDT) data. The altimetric data used are based on the TOPEX/POSEIDON reference ellipsoid. Five recent MSSH and MDT models were computed by taking the marine geoids from the difference between the MSSH and MDT. The MSSH used were MSS_CNES_CLS10, DTU15MSS, DTU13MSS, DTU18MSS and DTU21MSS. The MDT used were DTU10MDT, DTU13MDT, DTU15MDT, MDT_CNES_CLS2018 and the MDT_CNES_CLS2020 obtained from AVISO and DTU-Space research centers. Golden Surfer 20 and Microsoft Excel 2013 software were used for all data processing. Initially, satellite altimetry data is utilized to determine the sea level changes over specified time period. From the assessment of the marine geoid models with the TZG19 geoid model, it is shown that the marine geoid models obtained are closer to TZG19.

Considering years 2010-2013, 2010-2015 and 2010-2020, it has shown that the marine geoid has dropped to a rate of -0.00395m/yr, -0.00379m/yr and -0.06731m/yr respectively from the graph, implying that the marine geoid has dropped or submerged over that particular time. The decrease of marine geoid rate can be due to sea level rise as it suggests that sea levels are rising at a faster rate than previously observed. So, it is important to take cautions on the accelerating sea level rise since it highlights the urgency for coastal measures.

Also, for the years 2010-2018, 2013-2018, 2013-2020 and 2015-2018 results showed have similar trends in change of marine geoid as they have raised much to about 0.00843m/yr, 0.12381m/yr, 0.09058m/yr and 0.18398m/yr. This may be influenced by various factors such as the oceanographic processes including ocean currents, upwelling and downwelling, like changes in ocean circulation patterns, regional climate phenomena (e.g., El Niño/ La Niña) and natural climate oscillations can contribute to short-term and long-term variations in marine geoid.

Keywords: Marine geoid, Sea level change, Satellite altimetry, Sea Mean Surface Height, Mean Dynamic Topography, Ocean Mapping.

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ACRONYMS AND ABBREVIATIONS

AOI	Area of Interest
MSL	Mean Sea Level
MLLW	Mean Lower Low Water
LAT	Lowest Astronomical Tide
TMA	Tanzania Meteorological Authority
GRACE	Gravity Recovery and Climate Experiment
MDT	Mean Dynamic Topography
MSSH	Mean Sea Surface Height
SSH	Instantaneous Sea Surface Heights
SLA	Sea Level Anomaly
IPCC	Intergovernmental Panel on Climate Change
NGA	National Geospatial-Intelligence Agency
NASA	National Aeronautics and Space Administration
ESA	European Space Agency
EGM2008	Earth Gravitational Model 2008
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
N	Geoid
CNES	Centre National d'Etudes Spatiales
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic Data
WGS84	World Geodetic System 1984
STD	Standard Deviation

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Sea level fluctuations represent a common parameter studied in both geodetic sciences and oceanography. Traditionally, the marine geoid at shorter wavelengths has been determined through altimetry techniques. However, advances in satellite altimetry have revealed that the ocean's general circulation, which once assumed to be a steady and laminar flow field, is in fact a dynamically evolving system (Stammer, 2006). The availability of highly accurate satellite data has revolutionized our understanding of the ocean, highlighting its rapid and time-varying nature.

Accurate mapping of the Earth's oceans is crucial for understanding and managing various oceanographic processes, including ocean currents, tides, and coastal erosion. To achieve precise ocean mapping, it is essential to consider the impact of sea level changes on the marine geoid, a fundamental reference surface for determining ocean depths and topographic features. However, the relationship between sea level variations and the marine geoid remains to be complex and relatively unexplored research area (Hoffmann-Wellenhof & Moritz, 2006).

The marine geoid represents the Earth's gravity field and incorporates the irregularities caused by variations in gravity due to the distribution of mass across the planet. Sea level, on the other hand, represents the average height of the ocean's surface relative to a reference point. The marine geoid and sea level are inherently linked, as changes in sea level induce variations in the marine geoid (Torge, 2001).

Thus, the rate of change in sea level directly affects variations in the geoid and the elevation datum used as the reference for topographic mapping. The sea level can change depending on various factors and thus they are categorized in two types. One is called the global sea level rise; this is caused by the rising temperatures. Sea level can rise approximately to 4.8 – 8.8 inches according to the Intergovernmental Panel on Climate Change (IPCC). The other type of the sea level rise is the relative sea level rise, which is very important for studying in the coastal areas. It refers to the change in sea levels relative to the elevation of the land and relative sea level rise includes the effect of both global sea level rise and the vertical movement of the earth (Williams et al., 2009)

The outcomes of this research will have wide-ranging implications for numerous fields, including coastal management, climate studies, marine resource exploration and environmental monitoring. Ultimately, a comprehensive understanding of the relationship between sea level heights and the marine geoid will facilitate informed decision-making and support sustainable management of the oceans.

There have been numerous studies conducted relating the marine geoid, sea level change and bathymetry from satellite altimetry such as (Meela, 2018) assessed for the best Tanzania marine geoid model from all possible global MSSHs and MDTs satellite altimetry models using TZG13 gravimetric geoid model as the reference along the Indian ocean and came up with the results that, MSS_CNES2011 and DTU10MDT of resolution 2 arc-minutes respectively is the best Tanzania marine geoid model. This is due to its smallest root mean square of ± 0.095m. Therefore, we can postulate that the pair of MSS_CNES2011 and DTU10MDT that leads to the best marine geoid model performs equally throughout the global oceans and therefore this marine geoid model can be used for all global purposes that require reliable marine geoid model.

Also, (Sideris, 2012) determined sea level changes by combining altimetric, tide gauge, satellite gravity and atmospheric observations and concluded that the combination strategy outlined is a means of deriving the signal estimation errors.(Sideris, 1997) determined a high-accuracy and high-resolution marine geoid model in the Atlantic coastal region using satellite altimetry and shipborne gravity data as the results showed that the combination of these two data improves the accuracy of gravimetric geoid model by about 2 cm.

Moreover, (Seigismund et al, 2020) suggested that, the effects of temporal changes in the marine geoid on estimates of the ocean dynamic topography are being investigated. Influences from mass redistribution due to changes of land hydrology, ice sheets, glacial isostatic adjustment (GIA), and ocean and atmospheric dynamics are considered, and the associated crustal deformation is included. Changes in ocean surface currents are routinely obtained from satellite altimetry data. A correction for changes in the geoid, the equipotential surface of gravity closest to sea level, is considered small and thus usually neglected. It is investigated that the temporal geoid height changes and potential implications on ocean circulation studies using space-borne gravity data and results from ocean and atmosphere models to discover the individual processes of mass redistribution in the climate system causing thereby changes in the geoid height. It is found that, for the period 1993–2016 and on spatial scale larger than 1,000 km or so the magnitude of the negative marine geoid height trend south of Greenland is similar to the strength of the negative trend in geocentric sea level from altimetry. So, since many researches did not conduct most studies about the relationship of marine geoid variation due to sea level change and its impact on ocean mapping henceforth, this study entailed on assessing the marine geoid variation due to sea level change and its impact on ocean mapping.

1.2 Statement of the problem

Since the establishment of the marine geoid its variation due to sea level change has not been studied much and its effect on ocean mapping has not been clearly stated. So, observation of sea level changes and the determination of the differences in the sea's mean level compared with the marine geoid is therefore, potentially very important. But the observation of the sea level effect on the marine geoid with the help of tide gauges is insufficient to comprehend in a satisfactory way since the Tanzania tide gauge network includes only few operational stations so the assessment of the marine geoid variation due to sea level change was easier with the help of satellite altimetry as it provides a means of overcoming the limitations of the tide gauge measurements because the measurements are truly global in distribution and tied to the Earth's center-of-mass in a well-defined reference frame defined by the satellite tracking stations. In addition, the synoptic observation of the sea level together with its assessment on its variation on the marine geoid is becoming a reality with the current development of satellite altimetry techniques which are ongoing to make it possible to draw up charts of the topography of all oceans to an accuracy of within a few centimeters and also to study other ocean related processes such as the bathymetry.

1.3 Objectives of the research

1.3.1 Main objectives

The main objective of this research is to assess the marine geoid variation due to sea level change and its impacts on ocean mapping.

1.3.2 Specific objectives

- To determine the rate of sea level change and the marine geoids, which is the equipotential surface of the Earth's gravity field that closely represents the mean sea level.
- To show how the variations in the marine geoids due to sea level change affect ocean mapping including bathymetry mapping and other oceanic processes.

1.4 Research Questions

A few questions are posed prior to the research in order to ensure the objectives are met which include;

i. How does the sea level change impact the marine geoid and to what extent?
ii. What is the relationship between sea level change and variations in marine geoid?
iii. How can the results of the assessment of the marine geoid variation due to sea level change be applied to improve ocean models and our understanding of sea level change processes?

1.5 Scope/limitations of the research

The research study area is Tanzania mainland along the Indian Ocean across some selected areas of Dar-es-salaam, around where satellite data of sea level change are available.

1.6 Significance of the research

This study will be useful in overcoming the problem of relating oceanographic to geodetic measurements in understanding the concept of marine geoid as well as the models used to determine marine geoid for instance mean sea surface heights (MSSH) and mean dynamic topography (MDT) based on satellite altimetry technique. The marine geoid assessed here as it accounts for effects of tides, winds and ocean current, it will also be useful in satisfying the important requirement findings and application in geodesy as it enables effective monitoring of sea level change and geoid variability from tide gauges and altimetry. Also, the geoid height change for possible impact on ocean studies for the oceanographers and the hydrographers. As it will allow the TMA to monitor the sea level change, modelling climatic change and provides information to people around the coastal areas since sea level rise poses a great threat. Also, through the Ocean mapping people and organizations will establish more sustainable ocean management and assessment processes. For geodesists this research is useful in determining the marine geoid model for updating the vertical datums in marine areas.

1.7 Beneficiaries of the research

Beneficiaries of this research includes the hydrographic surveyors, oceanographers, geodesists, navigators, fisheries and the Tanzania Meteorological Authority to forecast weather since they all depend on the data of the sea level change and how it contributed to the marine geoid variation and their impacts in ocean mapping. In geodesy, geodesist can use this as the vertical datum since it may be precise compared to the current datum which is based on Tanga tide gauge observations which is local, temporary and outdated. Also, for oceanographers, the best marine geoid model will be useful in determination and modeling of ocean currents, also in weather forecasting. It is anticipated that the pair of MSSH and MDT that leads to the best marine geoid model within Tanzania Coast will perform equally all over the globe and thus the marine geoid is the best in global marine areas.

1.8 Study Area

The study is located on the marine region of the United Republic of Tanzania in the Indian Ocean from latitudes: 0°S to 12°S and longitudes: 38°E to 43°E as shown in Figure 1-1 below;

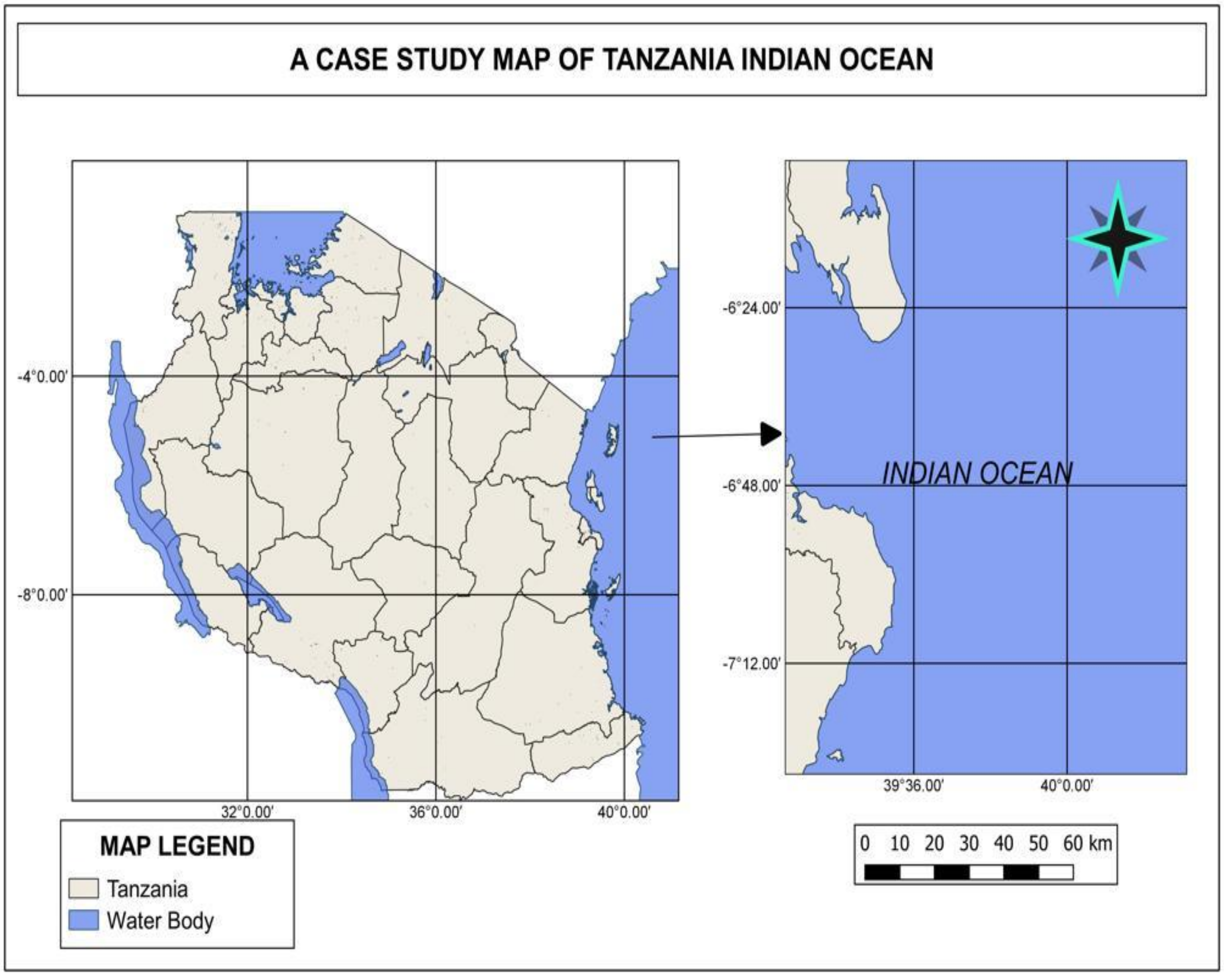

Figure 1-1: Study Area

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of marine geoids, sea level change, ocean mapping and satellite altimetry.

The marine geoids, sea level change, ocean mapping and satellite altimetry are interconnected concepts that play vital roles in understanding Earth's oceans, climate and geophysical processes. Thus, the integration of marine geoid models, sea level change data, ocean mapping techniques and satellite altimetry measurements is essential for comprehensive understanding of ocean processes and their influence on global climate patterns. These combined efforts contribute to ongoing research on climate change, sustainable coastal development, marine conservation and accurate navigation.

2.1.1 Marine geoids

The marine geoid defines the hydrostatic equilibrium shape that sea level would take in the absence of tides, currents and winds. The geoid is not directly observable, but its height above a reference ellipsoid may be calculated from a model of the Earth's gravity field. Satellite altimeters measure the instantaneous sea surface height, which is the sum of the geoid plus the dynamic topography associated with the ocean's responses to tidal and atmospheric forcings (Smith, 2010). In the early days of altimetric oceanography, knowledge of the geoid was poor and so altimeters are usually placed in exact repeat orbits to facilitate observation of the temporal variations in sea surface height. Recent gravity field models have geoid height errors around 5 cm and geoid slope errors around 1.5 μrad. Errors in the models are primarily at full wavelengths shorter than 20 km, so that some dynamic topography signals may now be directly observed (Smith, 2010). While satellite gravimetry from missions such as GRACE has improved the long wavelength geoid, there is considerable geoid power at wavelengths too short to be measured by gravimetry at orbital altitude. Determination of the geoid at mesoscale and shorter wavelengths has come from altimetry. Careful filtering has allowed to separate the geoidal height and ocean dynamics signals in the altimeter data, and thereby to refine the marine geoid. Verification of this comes from comparison of marine gravity field models against ship gravimetry (Smith, 2010). Further improvements in the accuracy of the marine geoid will require a satellite altimeter mission with improved signal to-noise ratio and a spatially dense (less than 5 km) network of ground tracks. One may hope that CryoSat-2 will offer some improvement (Smith, 2010).

Thus, the determination of accurate marine (quasi) geoid models is essential for geodetic and engineering applications but also can be required in oceanographic research. The advances in satellite gravimetry like the use of GRACE mission data will allow to determine marine geoid with an accuracy of few centimeters for longer wavelengths, also the geometrical change in the mean sea level can be derived directly by satellite altimeter measurements such as Topex as they provide broad band of information about the sea level change with a high accuracy as well as high spatial and temporal resolutions (Stammer, 2006).

2.1.2 Sea level changes

Sea level refers to the height of the ocean surface at any given location which is measured either with respect to the surface of the solid earth or a geocentric reference such as the reference ellipsoid. According to the NASA's satellite data, the sea level is raising by 3.3 millimeters every year. Thus, the geometrical sea level change is regarded as a new mass distribution which changes also the Earth's gravity potential. The change of geoid due to the change of potential will be studies along the Indian Ocean. Sea level change refers to an increase in the level of the world's oceans due to various effects of mass redistribution and the hydrological processes. Between 1901 and 2008 the sea level globally rose by 15-25 cm per year on average, but the rate is recently accelerating to 3.7mm (Nicholls & Cazenave, 2010), (Williams et al., 2009) and (Cabanes et al., 2001).

2.1.2.1 Factors that lead to sea level change

- ✓ **Surface and Ground water storage**; an important contribution to the present-day sea-level change could result from changes of amount of water stored in the ground, on the surface in lakes and reservoirs, changes in surface storage also have an impact on sea level as if there is excessive runoff from precipitation, it can increase the amount of water flowing into the ocean, which can cause temporary rise in sea level. Conversely, if there is drought, there may be less runoff, which can cause sea level to drop temporarily. Also, if there is excessive withdrawal of groundwater from aquifers located near the coast, it can lead to a decline in the water table level, which can cause land subsidence. The largest positive contribution to sea level probably comes from ground water mining, which means the extraction of ground water from storage in aquifers in excess of the rate of natural recharge. Ground water is estimated to be mined at a rate that has been increasing in time, currently equivalent to 0.2 to 1.0mm/yr (Gornitz et al., 1997).

This land subsidence can then lead to an apparent rise in sea level, as the land surface sinks lower relative to the sea. This effect is known as "relative sea level rise" and can cause flooding in coastal areas (Hannah, 2004).

- ✓ **Atmospheric pressure**; Atmospheric pressure can have temporary effect on sea level, but it is not a significant factor that leads to long -term sea level change. Atmospheric pressure is the force exerted by the weight of the earth's atmosphere on the surface. For instance, low atmospheric pressure can cause the sea level to rise slightly, while high atmospheric pressure can cause it to fall. However, these effects are temporary and only last as long as the atmospheric pressure anomaly persists. An increase in surface air pressure over the ocean produces a depression in the sea surface of 1 cm per Hectopascal(hPa), water is practically incompressible, this cannot lead to a global average sea level change, but a long- term trend in surface air pressure patterns could influence observed local sea level trends (Nicholls & Cazenave, 2010).
- ✓ **Tectonic land movement**; this is defined as the part of the vertical displacement of the crust that is of non-glacial -hydro-isostatic origin. It consists of rapid displacements associated with earthquake events and also slow movement in and on the Earth. Large parts of the earth are subject to active tectonics which continues to shape the planet's surface. Where the tectonics occurs in coastal areas, one of its consequences is the changing relationship between the land and sea surface as shorelines retreat or advance in response to the vertical land movements (Hannah, 2004). Where the tectonics occur in coastal areas, one of its consequences is the changing relationship between the land and the sea surfaces as shorelines retreat or advance in response to the vertical land movements.
- ✓ **Ocean process**; the pattern of sea level in ocean basins is maintained by atmospheric pressure and air-sea change of momentum, heat and fresh water. This allows properties of water masses, set by interaction with the sea ice, to be carried thousands of kilometres

into the ocean interior and thus provides a pathway for warming of surface waters to enter the ocean interior. This thermal expansion occurs at all ocean temperatures is one of the major contributors to sea level changes. Water at high temperature expands more for a given heat input, so the global average expansion is affected by the distribution of heat within the ocean. Salinity changes within the ocean also have a significant impact on the local sea level, but have a minimal effect on global average sea level change (Houghton et al., 2001).

2.1.2.2 Effects of sea level rise on marine geoids

Sea level rise can have significant effects on marine geoids, which are the equipotential surfaces of the Earth's gravity field that approximate mean sea level in least squares sense. Here are some of the main effects;

- **Changes in geoid shape**; As sea level rise is primarily caused by the influx of water from melting ice sheets and glaciers, as well as the expansion of seawater due to higher temperatures. As this additional water mass is distributed across the Earth's surface, it causes non-uniform change in the planet's gravitational field. This uneven mass distribution leads to a deformation of the marine geoid from its previous equilibrium shape. The geoid will generally rise in the response to the increased volume of water in the oceans, leading to shift in its shape (FitzGerald et al., 2008).
- **Gravity changes;** The Earth's gravity field is directly related to its mass distribution. With the accumulation of water in the oceans due to sea level rise, there is an increase in the overall mass of the Earth-ocean system. This, in turn, alters the gravitational attraction experienced by nearby objects. As the distribution of mass changes, so does the gravitational force, which is closely tied to the shape and height of the marine geoid (FitzGerald et al., 2008).
- **Local effects;** Sea level rise is not uniform globally and can vary significantly from one region to another. The factors contributing to these local variations include differences in ocean currents, wind patterns and land movements. Additionally, the melting of polar ice caps and glaciers is not spread evenly across the Earth's surface. Consequently, some

regions experience higher rates of se level rise than others, leading to localized effects on the marine geoid in those areas (Williams et al., 2009).

- **Vertical land movements;** The Earth's crust is not rigid, and it responds to various forces such as the melting of large ice sheets from past glaciations and human activities like ground water extraction and oil and gas extraction. In regions that were covered by ice sheets during the last ice age, the land is still adjusting to the loss of that massive weight, a process known as post-glacial redound. On the other hand, in areas where humans are extracting significant amount of underground water, the land may be subsiding. These vertical movements of the land can affect marine geoid since the gravitational field is also influenced by changes in the Earth's mass distribution (Baker, 1993).

2.1.3 Ocean mapping

Ocean mapping or seafloor mapping commonly referred to as bathymetry, is the study of underwater depth of ocean floors which provides us with the seabed topography since it refers to the shape of the land when it interfaces with the ocean. These shapes are obvious along the coastlines, but they also occur in significant ways underwater. The marine topographies include coastal and oceanic landforms ranging from coastal estuaries and shorelines to the continental shelves and coral reefs. Recently, the seabed topography can be obtained from the satellite altimetry as the satellite radar maps deep-sea topography by detecting the subtle variations in the sea level caused by the gravitational pull of the undersea mountains, ridges, and other masses. Bathymetry data is usually referenced to tidal vertical datums, for deep water bathymetry, this is typically MSL, but most data used for nautical charting is referenced to the MLLW in American surveys and LAT in other countries (Dixon et al., 1983).

Many other datums are used in practice, depending on the locality and tidal regime. Analysis of bathymetric measurements is one of the core areas of modern hydrography and fundamental component in ensuring ocean safety. High-resolution seafloor mapping is a critical tool for regulating underwater resource exploration, extraction and equipment allowing the ocean users to decide what and where is safe. Seafloor maps also ensure that ships are able to safely maneuver around natural and human made structures on the ocean bottom. And, these maps provide information vital to protecting and tracking marine life, allowing us to characterize marine habitats and make decisions for solid, sustainable conservation measures (Smith & Sandwell, 1997). In ocean mapping, marine geoid is used as a reference surface to define the heights of the ocean surface relative to a common datum. This is important because it provides a consistent and accurate representation of the ocean surface.

2.2 Techniques in sea surface heights measurements.

Upon determination of marine geoid there are three techniques that can be used in measurements of sea surface heights such as; Satellite altimetry, Airborne and Shipborne altimetry.

2.2.1 Airborne altimetry

The potential of airborne laser altimetry especially lies in regions where conventional methods encounter problems due to lack of sufficient texture or fast deforming terrain, where the establishment of reliable ground control points is difficult or impossible. In seven oceanography-related projects, airborne laser altimetry is mainly aimed at sea level determination in coastal areas, to bridge the gap between deep sea satellite radar altimetry data and coastal tide-gauge stations (Limpach, 2010). Airborne altimetry technique involves the measurement of distance between the aircraft laser and water surface, combined with positioning knowledge, the sea surface heights of ocean surface points are determined (Shija, 2017).

2.2.2 Shipborne altimetry

Shipborne altimetry technique combines position and attitude information acquired from the multi-antenna Global Positioning System (GPS) mounted on the boat to determine the sea surface heights. The method relies on one or more low-cost industrial ultrasonic distance sensors mounted on a boat, providing continuous information on the distance to the sea surface. In combination with the position and attitude information from a multi-antenna GPS system installed on the boat; this method allows for highly reliable sea surface height determination by direct georeferencing. It provides a low-cost alternative to airborne laser altimetry (Limpach, 2010). Apart from these techniques, Stokes formula can also be used to compute marine geoid when marine gravity anomaly is well computed from the difference between the actual gravity on the geoid and normal gravity values on the ellipsoid.

2.2.3 Satellite altimetry

This is an established technology for studying sea level, altimetry measure time taken by the radar pulse to travel from the satellite antenna to the surface and to the satellite receiver. Combined with precise satellite location, altimetry measurement yield sea-surface heights. Satellite altimetry has been providing high-resolution measurement of the ocean surface topography with global coverage and a revisit time of a few days or weeks. Measurement of the round-trip travel time provides the height of satellite above the instantaneous sea-surface (called altimeter range) (Ablain et al., 2016). The quantity of interest in oceanography is the height of instantaneous sea-surface above the fixed reference surface. Since the past two decades a number of satellite altimeters were launched. The list of satellite altimeter missions is as summarized in the Table 2-1 below;

Table 1-1: Recent ongoing satellite altimetry mission carrying radar altimeter

Satellite	Duration	Inclination (degrees)	Repeat time (days)
JASON-1	2001- 2013	66	10
JASON-2	2008- 2019	66	10
ENVISAT	2002 - 2012	81.5	35
Topex- Poseidon	1993-2005	66	10
ERS-1	1991-2000	81.5	35
ERS-2	1995-2011	81.5	35
GEOSAT	1985-1990	72	17

2.2.3.1 Principle of Radar Altimeter.

Radar altimeter permanently transmit signal to Earth and receive the echo from the surface. The satellite orbit has to be accurately tracked and its position is determined relative to an arbitrary reference surface and ellipsoid. The sea surface height (SSH) is the difference between the satellite position on orbit with respect to an arbitrary reference surface; the reference ellipsoid and the satellite to surface range (Ablain et al., 2016).

Radar altimeter on board satellite permanently transmits signals at high frequency to Earth and receive an echo from the sea surface. This is analyzed to derive a precise measurement of the round-trip time between the satellite and sea surface. The time measurement, scaled speed of light at which the electromagnetic waves travel yields a range of measurements. By averaging the estimates over a second, this produces a very accurate measurement of the satellite-to-ocean range. However, as electromagnetic waves travel through the atmosphere, they can be decelerated by water vapor. The ultimate aim is to measure sea level to a terrestrial reference frame. This requires independent measurement of the satellite orbital trajectory i.e., latitude, longitude and altitude coordinates (Ablain et al., 2016). Figure 2-1 shows satellite altimetry principle below;

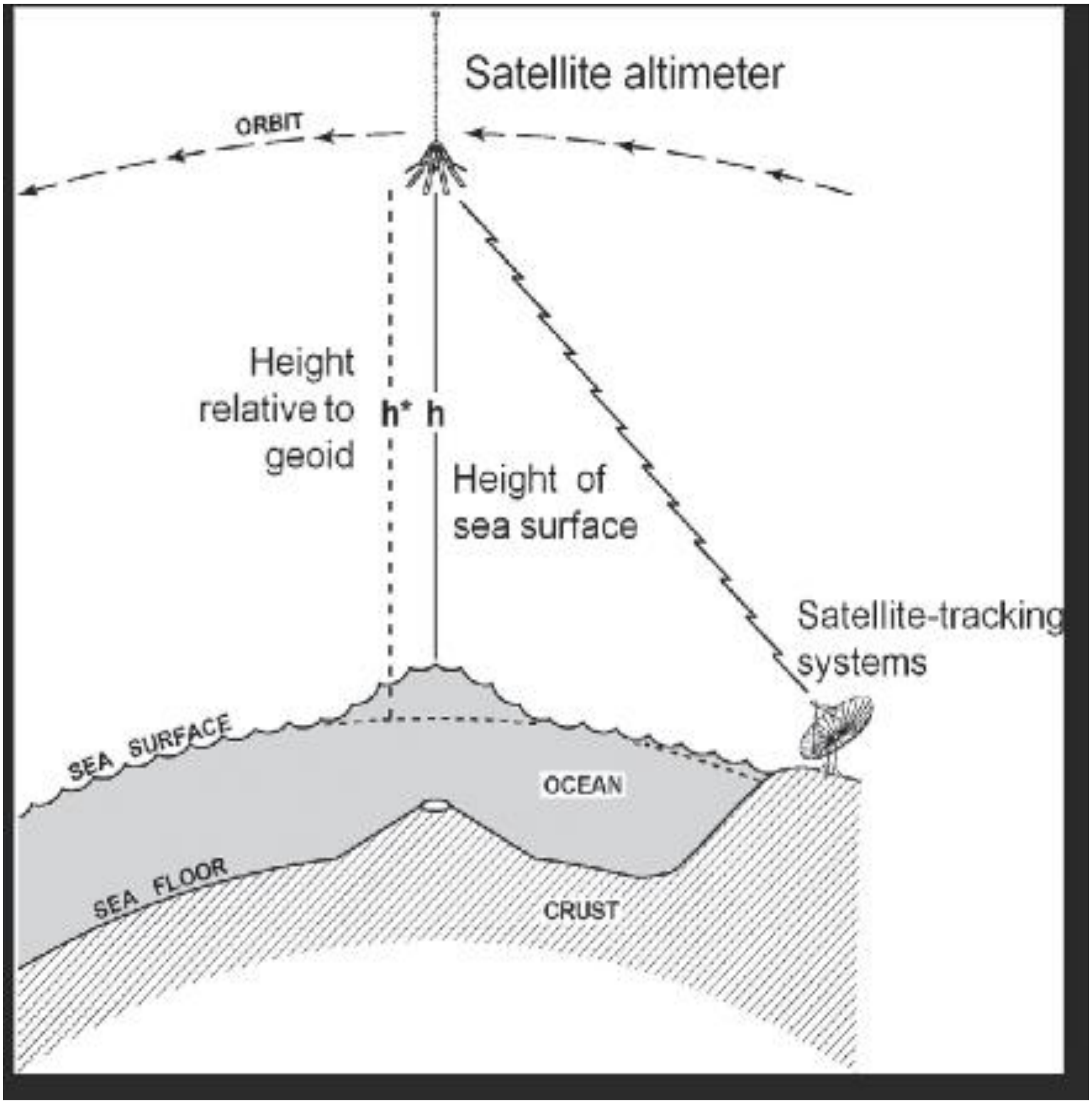

Figure 2-1: The principle of Satellite Altimetry (Ablain et al., 2016).

CHAPTER THREE

METHODOLOGY

This study aims at assessing the marine geoid variation due to sea level change and its impact on ocean mapping. Marine geoid, are thus determined and assessed. This section describes the Altimetric method (the mean sea surface height and mean dynamic topography) used in determining the marine geoid along the specific area of interest.

3.1 Computations of Marine geoids, the rates of change of marine geoids and the assessment of marine geoid models against TZG19

3.1.1 Marine geoids computations (N)

Mean dynamic topography of the ocean can be obtained direct as the residual surface between the mean sea surface height (MSSH) and the geoid height (N). Equation 3.1 below represents the formulae used to compute the marine geoids.

$$N = MSSH - MDT \tag{3.1}$$

To compute for the marine geoids of the years 2010, 2013, 2015, 2018 and 2020 from altimetry data, the following mathematical equations were used;

$$N_{10} = MSS\_CNES\_CLS10 - DTU10MDT \tag{3.2}$$

$$N_{13} = DTU13MSS - DTU13MDT \tag{3.3}$$

$$N_{15} = DTU15MSS - DTU15MDT \tag{3.4}$$

$$N_{18} = DTU18MSS - MDT\_CNES\_CLS2018 \tag{3.5}$$

$$N_{20} = DTU21MSS - MDT\_CNES\_CLS2020 \tag{3.6}$$

Where N_{10}, N_{13}, N_{15}, N_{18} and N_{20} are the marine geoids of 2010, 2013, 2015, 2018 and 2020 respectively.

3.1.2 Rate of change of marine geoids

Rates of the change in marine geoids was computed basing on specific time periods of 2010-2013, 2010-2015, 2010-2018, 2010-2020, 2013-2015, 2013-2018, 2013-2020, 2015-2018, 2015-2020 and 2018-2020. Rate was obtained by the formula hereunder;

$$R_{10-13} = Mean\ \Delta N / T_{10-13} \tag{3.7}$$

$$R_{10-15} = Mean\ \Delta N / T_{10-15} \tag{3.8}$$

$$R_{10-18} = Mean\ \Delta N / T_{10-18} \tag{3.9}$$

$$R_{10-20} = Mean\ \Delta N / T_{10-20} \tag{3.10}$$

$$R_{13-15} = Mean\ \Delta N / T_{13-15} \tag{3.11}$$

$$R_{13-18} = Mean\ \Delta N / T_{13-18} \tag{3.12}$$

$$R_{13-20} = Mean\ \Delta N / T_{13-20} \tag{3.13}$$

$$R_{15-18} = Mean\ \Delta N / T_{15-18} \tag{3.14}$$

$$R_{15-20} = Mean\ \Delta / T_{15-20} \tag{3.15}$$

$$R_{18-20} = Mean\ \Delta N / T_{18-20} \tag{3.16}$$

Where R is the rate and T is the time interval of the specific years.

3.1.3 Assessment of marine geoid models against TZG19

The assessment was done by taking the difference between the geoidal height from TZG19 and that of the marine geoid models, the difference is determined by the mathematical formula hereunder;

$$\Delta N = N_{TZG19} - N_i \tag{3.17}$$

Where, NTZG19 is the geoidal height from TZG19 and N_i is the Marine geoid model from MSSH and MDT models.

The differences of the geoidal heights from the marine geoid models and the TZG19 model were used in determination of statistics for the assessment of the marine geoid models. The statistics are obtained as follows;

i. Mean difference (ΔN_{mean})

   This is the average of the geoidal heights difference between the geoidal models.

$$\Delta N_{mean} = \frac{1}{N} \sum_{i=1}^{n} \Delta N_{2i}^{n} \tag{3.18}$$

ii. Standard deviation (σ) of geoidal height differences

$$\sigma_i = \pm\sqrt{\sum_{i=1}^{n}\frac{(\Delta N_{2i}^{n} - \Delta N_{mean})^2}{n-1}} \tag{3.19}$$

iii. Root mean square (RMS) of the height differences

$$RMS = \sqrt{\sum_{i=1}^{n}\frac{(\Delta N_{2i}^{n})^2}{n}} \tag{3.20}$$

3.2 Data sources

The types of data used in this research are the mean sea surface heights and mean dynamic topography based on altimetric modelling technique.

3.2.1 Description of the MSS and MDT dataset.

The MSS and MDT global models (the CNES_CLS) used in this study were made available by the AVISO space research Centre (http://ww.aviso.altimetry.fr or/and Email:aviso@altimetry.fr and) and for DTU, MDT and MSS global models were made available by Prof. O. B. Andersen (via email communication) of the Technical University of Denmark (DTU-Space).These models are found in Topex/Poseidon ellipsoid but to meet the requirements of the study, they are to be made available in WGS84 which is very close to GRS80.

3.2.2 Steps in downloading the MSS and MDT models.

i. Open the Data access page from AVISO website or using the link http://www.aviso.altimetry.fr directly from any web browser, Figure 3-1 below shows the AVISO web page.

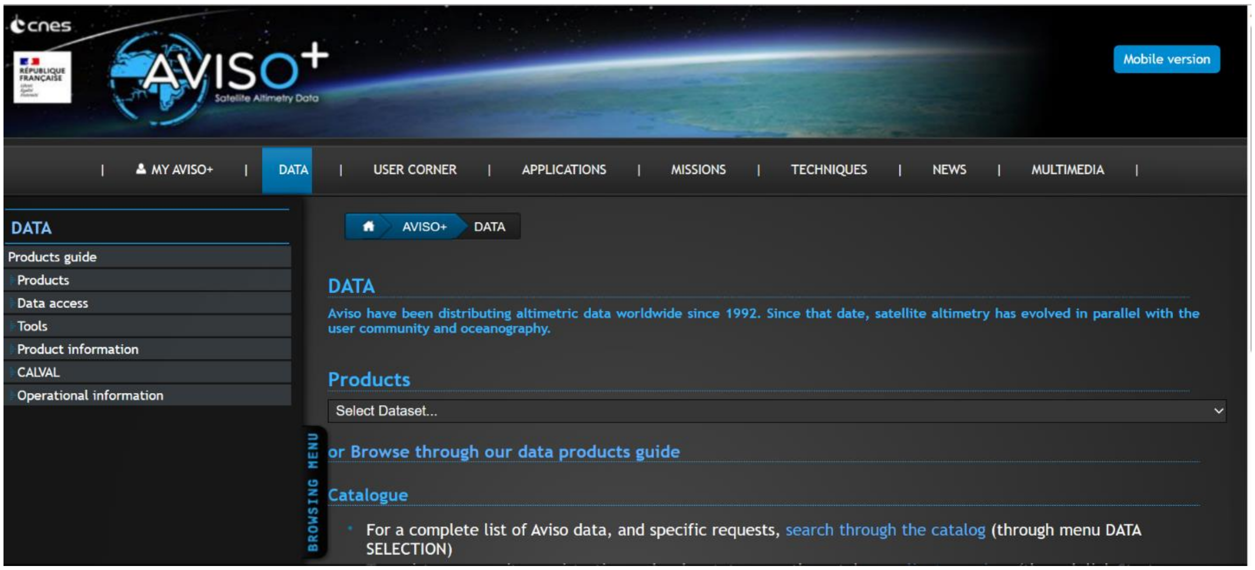

Figure 3-1: AVISO web page

ii. Open the registration form in the Aviso page, which will be used to request for data and get direct link to the data. This form requires necessary information such as the email address as well as the type of data requested, here the user can also specify the boundary of the data such as the latitude and longitude. The data access registration form is shown in Figure 3-2 below.

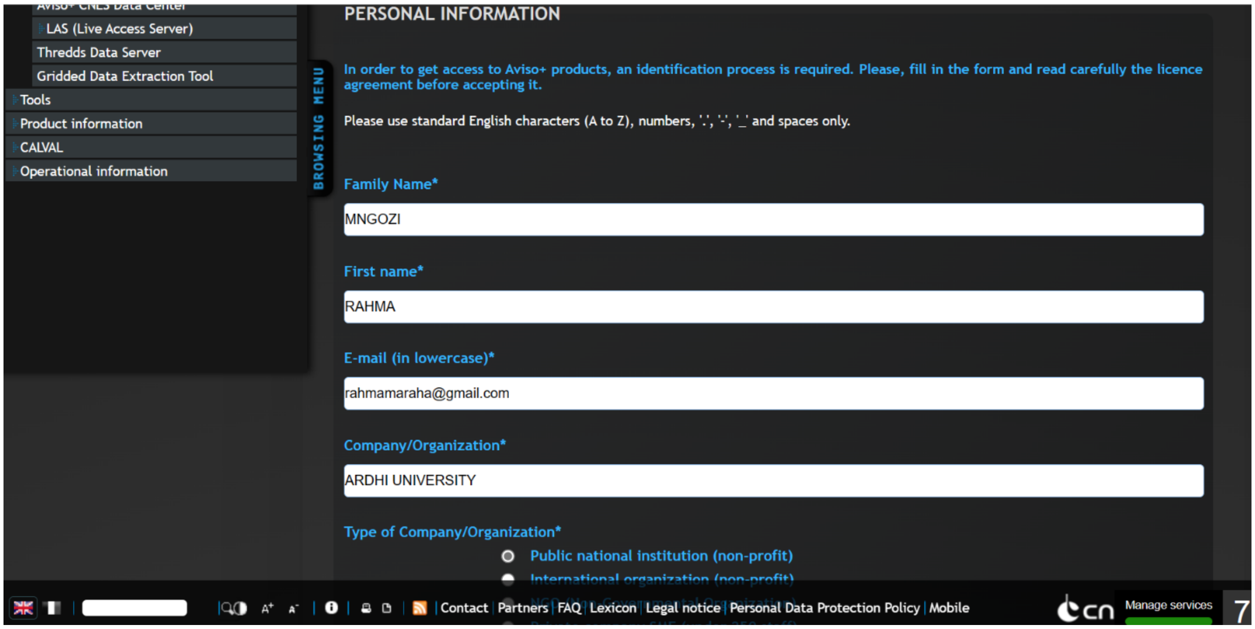

Figure 3-2: Registration window form from Aviso

iii. After completion of registration, confirmation link will be sent to the user's email address, with a username and password that will directly lead the user to the requested data.

iv. Following the link, the user will be able to locate the data and by selecting download option the downloading process will start.

v. After downloading the data files which are found in Netcdf format, the data will be opened in an appropriate software such as the Golden Surfer software for easy extraction.

3.2.3 Steps in extraction of the MSS and MDT data.

i. Open the preferred software (Golden Surfer software version 20), go to grid then extract data. Here the user will be required to specify the boundary of the data that is the latitude and longitude. In this study the boundary was between 1°N to -12°S latitude and 39°E to 43°E longitude, Figure 3-3 below shows the extraction window for MDT data in Surfer software.

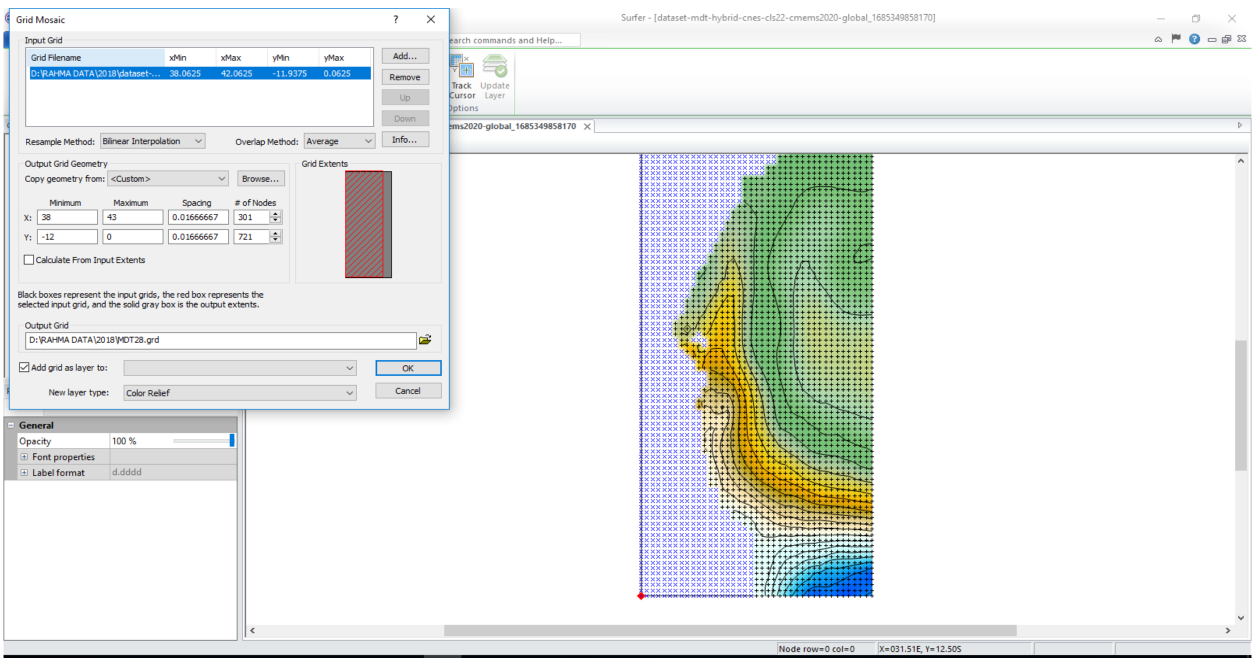

Figure 1: Extraction window for MDT data.

ii. Upon extraction the user is required to select the directory of the extracted data plus the format of which in this study it was XYZ format. After the specifications the data will be extracted and saved.

iii. Open the file (DAT file) in Golden Surfer software to view the data in XYZ format, the data will be displayed with the latitude, longitude and height information.

NB: The procedures for downloading and extraction for the mean sea surface (MSS) and mean dynamic topography (MDT) are the same.

iv. Sorting of data is required to remove the large fill values or no data values (2.15e+09). After sorting out data the scale factor is applied of which in these data, scale factor for MSSH is 0.001 and scale factor for MDT is 0.0001.

3.2.4 The MSSH and MDT models

To be able to conduct the marine geoid computation and assessment, the altimetric models were downloaded that is, the mean sea surface heights (MSSH) and the mean dynamic topography (MDT) from their respective websites. The MSSH_CNES were downloaded from http://www.aviso.altimetry.fr in Netcdf format. The DTU models were made available by Prof. O.B. Andersen of DTU-Space (via email) in XYZ format. All these data have the longitude, latitude and height information. The Golden Surfer 13 software was used to read and extract the data and covert to DAT (xyz) format. The downloaded and extracted data ranges from 0°N to 12°S and 38°E to 43°E.

3.2.5 Mean Sea Surface (MSS).

The mean sea surface represents the average of all sea surface heights observed over appropriate time period to remove fictitious sea surface signals. It is the height above reference ellipsoid (Picot, 2003). It is obtained from the difference between the sea level anomaly and the sea surface height. The principle of the satellite in determining the sea surface height is based on the emission of a radar pulse and measurement of the two-way time travel (to and from) of the signal, i.e., from the radar to the sea surface and then reflected back to the radar (Ntambila, 2012). It corresponds to the sum of the geoid undulations N and the MDT averaged over a selected time period. MSSH models are essentially based on satellite altimetry data. They are used for various purposes, such as the computation of SLA and to provide a common reference for different satellite missions (Limpach, 2010). The MSS models used in this study to determine the marine geoid model are the MSS_CNES_CLS10, DTU15MSS, DTU13MSS, DTU18MSS and DTU21MSS, all based on satellite altimetry technique.

Table 3-1 and Table 3-2 represents sample of MSS_CNES_CLS2010 and DTU15MSS datasets respectively.

Table 3-1: Sample of MSS_CNES_CLS2010 dataset

Longitudes (degrees)	Latitudes (degrees)	MSSH (meters)
40.583	-11.917	-23.005
40.6	-11.917	-23.086
40.612	-11.917	-23.168
40.633	-11.917	-23.254
40.65	-11.917	-23.345
40.667	-11.917	-23.44
40.683	-11.917	-23.539
40.7	-11.917	-23.64
40.712	-11.917	-23.745
40.733	-11.917	-23.847
40.75	-11.917	-23.941
40.767	-11.917	-24.028
40.783	-11.917	-24.109
40.8	-11.917	-24.186
40.812	-11.917	-24.255

Table 3-2: Sample of DTU15MSS dataset

Longitudes (degrees)	Latitudes (degrees)	MSSH (meters)
40.583	-11.917	-23.212
40.6	-11.917	-23.289
40.612	-11.917	-23.358
40.633	-11.917	-23.42
40.65	-11.917	-23.485
40.667	-11.917	-23.554
40.683	-11.917	-23.625
40.7	-11.917	-23.702
40.717	-11.917	-23.787
40.733	-11.917	-23.872
40.75	-11.917	-23.954
40.767	-11.917	-24.036

3.2.6 Mean Dynamic Topography

The MDT can be obtained indirectly or by synthetic technique by subtracting the sea level anomaly (SLA) from the dynamic topography (DT). The mean dynamic topography used in this study in determination of marine geoids are DTU10MDT, DTU13MDT, DTU15MDT, MDT_CNES_CLS2018 and the MDT_CNES_CLS2020 based on satellite altimetry technique. The global MDT and MSSH data used in this research were obtained from the space research Centre CNES (AVISO) and the technical University of Denmark (DTU).

Tables 3-3 and 3-4 represents sample of MDT_CNES_CLS2018 and MDT_CNES_CLS2020 respectively.

Table 3-3: Sample of MDT_CNES_CLS2018 dataset

Longitude (degrees)	Latitude (degrees)	MDT (meters)
40.58333	-11.9167	0.918375
40.6	-11.9167	0.919182
40.61667	-11.9167	0.919988
40.63333	-11.9167	0.920795
40.65	-11.9167	0.921602
40.66667	-11.9167	0.922408
40.68333	-11.9167	0.923215
40.7	-11.9167	0.925562
40.71667	-11.9167	0.928422
40.73333	-11.9167	0.931282
40.75	-11.9167	0.934142
40.76667	-11.9167	0.937002
40.78333	-11.9167	0.939862
40.8	-11.9167	0.942722
40.81667	-11.9167	0.945609

Table 3-4: Sample dataset of MDT_CNES_CLS2021

Longitude (degrees)	Latitude (degrees)	MDT (meters)
40.56667	-11.9333	0.929183
40.58333	-11.9333	0.929808
40.6	-11.9333	0.930434
40.61667	-11.9333	0.931059
40.63333	-11.9333	0.931684
40.65	-11.9333	0.93231
40.66667	-11.9333	0.932935
40.68333	-11.9333	0.93356
40.7	-11.9333	0.934987
40.71667	-11.9333	0.936681
40.73333	-11.9333	0.938375
40.75	-11.9333	0.940068

3.3 Device and software used

In this study the computer device was used, equipped with the software which are useful in computation and processing of these models. The software used are the Golden surfer version 20 and both the Microsoft excel and word 2013.

3.3.1 The Golden surfer Software Version 20

Surfer in this research was used for manipulation of MSS and MDT which includes gridding and extraction of the models in the AOI for easy processing. It was also used for digitization to obtain the Indian Ocean base map of the AOI, as well as blanking of the area outside the AOI.

3.3.2 The Microsoft excel 2016

This software was used for computation of marine geoid models from the height differences of the models such as the MSS and MDT in the whole preparation of the dissertation report, it was also used to draw the N and MSSH graphs and computing the MDT, MSSH and marine geoids rates.

3.3.3 The Microsoft word 2016

This software was used for writing the actual contents of the dissertation report.

CHAPTER FOUR

RESULTS AND ANALYSIS

This chapter present the results of the involved data acquired in the last part of Chapter 3 based on satellite altimetry technique (MSSH and MDT). It involved difference between the MSSH and MDT models (equation 3.1) which were obtained from different source provider covering the area of interest of the research and the discussion of the results obtained in this research dissertation.

4.1 Results

4.1.1 Marine Geoid models obtained from the MSSH and MDT models.

The marine geoids in this study were computed using the Equations 3.2, 3.3, 3.4, 3.5 and 3.6 from the models MSS_CNES_CLS2010, DTU13MSS, DTU15MSS, DTU18 and MSS_CNES_CLS2021 as MSSH models and DTU10MDT, DTU13MDT, DTU15MDT, MSS_CNES_CLS2018 and the MDT_CNES_CLS2020 as MDT models and results are presented in Table 4-1 below;

Table 4-1: Showing marine geoid computed from MSS and MDT models of 2010, 2013, 2015, 2018 and 2020 respectively.

N10(m)	N13(m)	N15(m)	N18(m)	N20 (m)
-23.101	-23.270	-23.309	-24.156	-24.238
-23.182	-23.355	-23.387	-24.229	-24.302
-23.264	-23.433	-23.456	-24.293	-24.367
-23.35	-23.502	-23.518	-24.356	-24.427
-23.441	-23.571	-23.583	-24.42	-24.486
-23.537	-23.641	-23.651	-24.487	-24.545
-23.636	-23.712	-23.722	-24.556	-24.603
-23.737	-23.792	-23.800	-24.633	-24.666
-23.842	-23.879	-23.885	-24.717	-24.733
-23.944	-23.966	-23.97	-24.803	-24.803
-24.038	-24.05	-24.052	-24.887	-24.878
-24.125	-24.134	-24.134	-24.972	-24.961
-24.207	-24.217	-24.215	-25.057	-25.046

4.1.2 Rates of change in marine geoids (N) and trends

The rates of changes in N were computed using Equations 3.7, 3.8, 3.9, 3.10, 3.11, 3.12, 3.13, 3.14, 3.15 and 3.16 together with their mean, standard deviations and the respective rates were also obtained as shown in Table 4-2;

Table 4-2: Statistics of the rate/year (R) of N for the past 10 years.

N	Years	Min	Max	Mean	STD	R
	2010- 2013	-0.17377	0.106722	-0.01581	0.018761	-0.00395
	2010-2015	-0.22031	0.129958	-0.02275	0.021866	-0.00379
	2010-2018	-1.07811	-0.52818	-0.75867	0.078611	0.0843
	2010-2020	-1.13912	-0.39196	-0.74045	0.085415	-0.06731
	2013-2015	-0.05254	0.039062	-0.00694	0.007561	0.00231
	2013-2018	-0.97033	-0.60365	-0.74286	0.065795	0.12381
	2013-2020	-1.03945	-0.46964	-0.72464	0.072654	0.09058
	2015-2018	-0.95616	-0.6208	-0.73592	0.065175	0.18398
	2015-2020	-1.0415	-0.4947	-0.7177	0.071732	0.01196
	2018-2020	-0.14848	0.228573	0.018222	0.02343	0.00607

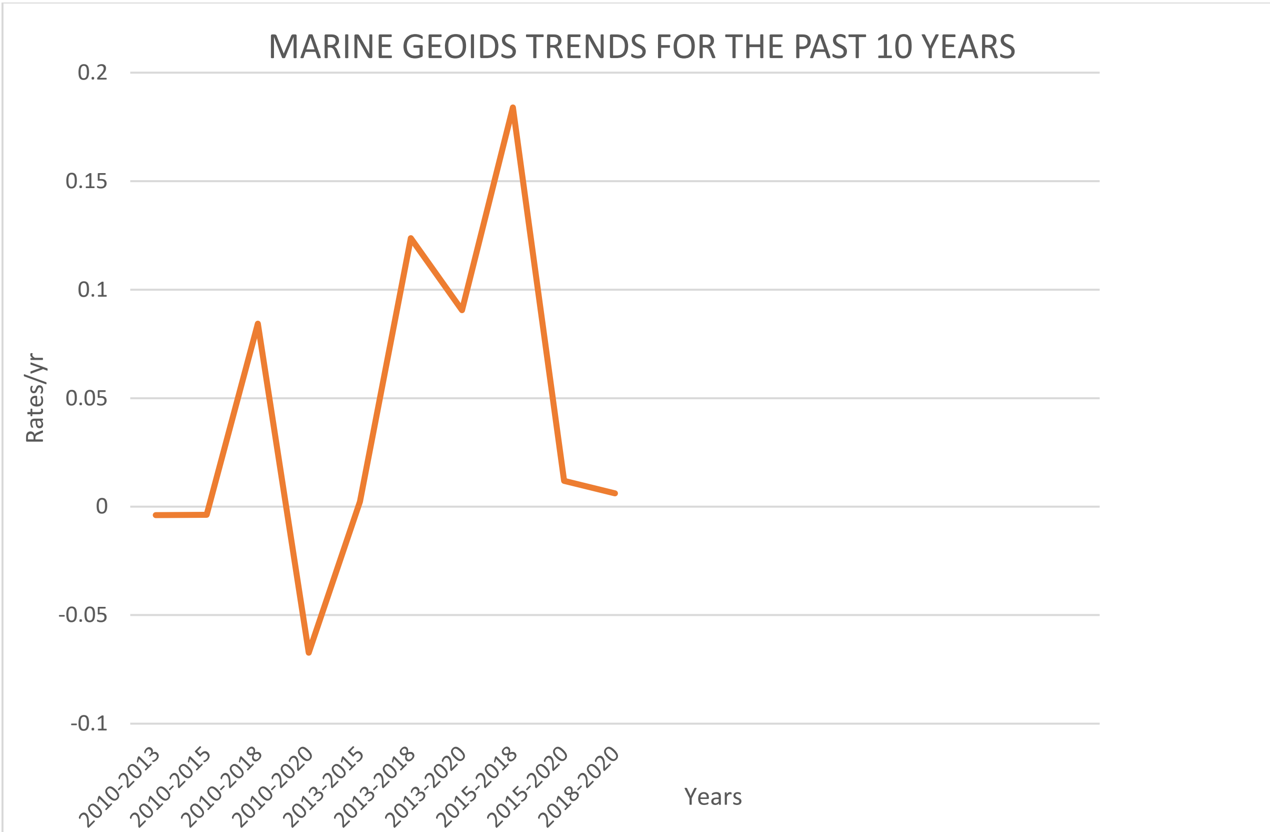

Figure 4-1: Trends of rate of marine geoid

4.1.3 Impacts of marine geoid on Ocean mapping

i. Bathymetric Mapping: The marine geoid, when combined with precise satellite altimetry data, can be used to derive accurate bathymetric maps of the ocean floor. Bathymetry refers to the measurement of ocean depths and underwater topography. By subtracting the height of the marine geoid from satellite altimetry measurements of the ocean surface, scientists can determine the depth of the ocean at various locations. This helps to create detailed bathymetry maps that are essential for navigation, marine resource exploration and oceanographic research. The marine geoid provides a reference surface for measuring depth of the ocean floor as it takes into account the shape of the Earth's surface. As a result, bathymetric maps need to be updated periodically to reflect the changes in the marine geoid.

ii. Precise sea level measurements: understanding the marine geoid's shape and changes allows scientists to determine variations in sea level with high precision. Satellite altimetry, which measures the height of the ocean surface relative to the geoid, is used to monitor sea level changes over time. This information is critical for assessing the impacts of climate change, understanding ocean circulation and planning for coastal management.

iii. Geophysical Studies: The marine geoid reflects variations in the Earth's gravity field caused by differences in the distribution of mass within the Earth. As a result, studying the marine geoid can provide valuable information about the Earth's internal structure, such as the density distribution of rocks and the presence of subsurface features like seamounts and ocean trenches. This information aids geophysical studies and enhances the understanding of Earth's geological processes.

iv. Coastal Mapping: Coastal mapping is important for understanding the relationship between the land and the sea. Coastal maps show the location of the shoreline, the elevation of the land and the depth of the ocean floor. Sea level rise and fall directly impact coastal areas, leading to shoreline changes and coastal erosion. Mapping coastal zones requires considering sea level variations to accurately represent the extent and dynamics of coastal features, such as beaches, cliffs, and tidal zones. Also, marine geoid provides a reference for measuring the elevation of the coastline because it takes into account the shape of the Earth's surface. Understanding these changes aids in coastal management, hazard assessment, and adaptation planning.

v. Ocean Circulation Studies: Oceanographers use the marine geoid to study ocean currents and circulation patterns. Variation in the geoid's shape is related to changes in ocean mass distribution, which in turn, are influenced by ocean currents. The marine geoid is affected by ocean circulation and currents. Changes in ocean circulation can cause variations in the Earth's gravitational field, which can affect the shape of the marine geoid. This can affect the elevation measurements accuracy. By understanding these variations, scientists can gain insights into ocean circulation patterns, ocean-atmosphere interactions and transport of heat and nutrients throughout the global ocean.

vi. Climate Change Monitoring: Sea level rise is one of the primary indicators of climate change. Mapping sea level variations over time helps monitor long-term changes and provides valuable data for climate change research and modeling. The marine geoid serves as a reference for quantifying sea level rise and its spatial distribution, contributing to a better understanding of global climate dynamics.

4.1.4 Assessment of Marine Geoid from MSSH and MDT models by Tanzania Gravimetric Geoid Model along the Indian Ocean

The TZG19 geoid model used to assess the resulted marine geoid models from the satellite altimetry (the MSSH and MDT) models. The assessment is done by subtracting the obtained marine geoid models from the marine geoid of TZG19 as given in Equation 3.17.

where; N is the marine geoid model from a pair of MSSH and MDT, and i is a number of models such as from 2010-2020. Tables 4-3 and 4-4 showing the geoidal heights differences of the marine geoid models with the TZG19 geoid model as well as their statistics of minimum, maximum, mean, standard deviation and the root mean square (RMS).

Table 4-3: Assessment height differences of marine geoid models against TZG19 geoid model according to the Equation 4.1

ΔN10	ΔN13	ΔN15	ΔN18	ΔN20
-0.842	-0.673	-0.634	0.213	0.2947
-0.800	-0.627	-0.595	0.247	0.3198
-0.763	-0.594	-0.571	0.265	0.3396
-0.723	-0.571	-0.555	0.2828	0.3543
-0.682	-0.552	-0.54	0.2969	0.3633
-0.644	-0.540	-0.53	0.3059	0.3641
-0.609	-0.533	-0.523	0.3114	0.3582
-0.57	-0.515	-0.507	0.3262	0.3590
-0.555	-0.518	-0.512	0.3201	0.336
-0.544	-0.522	-0.518	0.3145	0.315
-0.548	-0.536	-0.534	0.301	0.2925

Table 4-4: Statistics of the comparison of Marine geoid models against NTZG19 in meter units

Models	Number of values	Minimum	Maximum	Mean	STD	RMS
ΔN10	12447	-0.476	0.900	-0.061	0.110	0.236
ΔN13	12447	-0.495	0.871	-0.049	0.103	0.234
ΔN15	50820	-1.403	0.349	-0.870	0.340	0.934
ΔN18	30420	-0.727	0.440	-0.283	0.070	0.292
ΔN20	12749	-0.634	1.142	-0.161	0.353	0.388

4.2 Analysis of results

From the results obtained in Table 4-4 of the assessment of the marine geoid models with the TZG19 geoid model, it is shown that the marine geoid models obtained are closer to TZG19.

Also, basing on the obtained line graph above in section 4.1.2 of the Marine geoid trends, it has been shown that;

- Considering years 2010-2013, 2010-2015 and 2010-2020, it has shown that the marine geoid has dropped to a rate of -0.00395m/yr, -0.00379m/yr and -0.06731m/yr respectively from the graph, implying that the marine geoid has dropped or submerged over that particular time. The decrease of marine geoid rate can be due to sea level rise as it suggests that sea levels are rising at a faster rate than previously observed. So, it is important to take cautions on the accelerating sea level rise since it highlights the urgency for coastal measures.
- Also, for the years 2010-2018, 2013-2018, 2013-2020 and 2015-2018 showing similar trends in change of marine geoid as they tend to have raised much to about 0.00843m/yr, 0.12381m/yr, 0.09058m/yr and 0.18398m/yr are influenced by various factors such as the oceanographic processes including ocean currents, upwelling and downwelling, like changes in ocean circulation patterns, regional climate phenomena (e.g., El Niño/ La Niña) and natural climate oscillations can contribute to short-term and long-term variations in marine geoid. Also, the local and regional can play a role in the observed differences in rates factors like

variation in ocean currents, tectonic activity, subsidence and uplift of land and regional patterns of sea level change and the mass redistribution, since within the Earth's system it affects the gravitational field and, consequently, the marine geoid. Factors such as ocean currents, variation of mass due to water temperature and salinity all contribute to mass redistribution, which affect the marine geoid.

- Moreover, in the years 2013-2015, 2015-2020 and 2018-2020 with the rates 0.003231, 0.01196 and 0.00607 respectively, it has been shown that the rates of marine geoid raised to smaller values compared to other years. This implies that the mentioned factors that contributed to the rate of the rise in marine geoid were available to minimal extents which caused the rise in marine geoid rates to be minimum compared to the other years. It is essential to consider both the short-term and the long-term fluctuations in the marine geoid are important to consider.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study on the assessment of marine geoid variation due to sea level change and its impact on ocean mapping has provided valuable insights into the relationship between marine geoid and sea level changes. From the assessment of the marine geoid models with the TZG19 geoid model, it is shown that the marine geoid models obtained are closer to TZG19.These findings have significant implications for understanding and improving ocean mapping efforts. The rates of the marine geoid for the past ten years were evaluated using the satellite altimetry data along the parts of the Indian ocean from 2010- 2020 which lies between -0.00395m/yr to 0.18398m/yr. From the analysis, result showed that marine geoid along the Indian ocean is mostly ascending in the recent years.

Since, according to the Intergovernmental Panel on Climate Change (IPCC) sea level can rise to 4.8 – 8.8 inches and considering years 2010 – 2020, it is shown that the marine geoid is ascending together with the rise in sea levels.

The positive correlation observed between the sea level and its impact on ocean mapping highlights the dynamic nature of the coastal and marine environments. The sea level change influences the marine geoid, bathymetry and coastal zone management. It necessitates the regular updating of mapping data and the consideration of sea level change in coastal planning, navigation and climate change monitoring.

5.2 Recommendations

From the study, the following recommendations are made;

- It is recommended that, since a 10-year record of observations and the assessment of marine geoids due to sea level variability using the satellite altimetry is not precise as their records is not as long as that of the tide gauges, so no definite conclusion can be drawn with respect to long-term predictions of the sea level variations thus, the future researcher can opt for the tide gauge data to perform the assessment and come up with precise results for the long-term variations.

References

Ablain, M., Legeais, J., Dieng, H., & Cazenave, A. (2016). Satellite Altimetry-Based Sea Level at Global and Regional Scales. *Surveys in Geophysics 38,* 7-31.

Andersen, O. (2004). Sea Level Determination from Satellite Altimetry-Recent development. *Observing and understanding Sea level variations*, 36.

Andersen, O. B., & Knudsen, P. (2000). The role of in gravity satellite altimetry in gravity field modelling in coastal areas. *Physics and Chemistry of the Earth 25(1),* 17-24.

Baker, T. F. (1993). Absolute sea level mesurements, climate change and vertical crustal movements. *Global Planet Change 8*, 149-159.

Cabanes, C., Cazenave, A., & Le Provost, C. (2001). Sea level rise during past 40 years determined from satellite and in situ observations. *Science 294*, 840.

Dixon, T., Naraghi, M., McNutt, M., & Smith, S. (1983). Bathymetry predictions from SEASAT altimeter data. *Journal of Geophysics 88,* 1563-1571.

FitzGerald, D., Fenster, M., Argow, B., & Buynevich, I. (2008). Coastal impacts due to sea level rise. *Annual Review of Earth and Planetary Science 36*, 601-647.

Forseberg, R., & Olesen, A. (2013). *Conduct aerial gravity survey countrywide for height component of the geodetic network*. Retrieved from DTU-Space, National Space Institute: www.space.dtu.dk

Garcia, E. (2014). Retracking Cryosat-2, Envsat and Jason-1 radar altimetry waveforms for improved gravity field recovery. *Geophysical Journal International, 21*, doi: 10.1093/gji/ggt469.

Gornitz, V., Rosenzweig, C., & Hillel, D. (1997). Effects of anthropogenic intervention in the land hydrological cycle on global sea level rise. *Global and Planetary Change 14*, 147-161.

Hannah, J. (2004). An updated analysis of long-term sea level change. *School of Surveying*, 60-68.

Heiskanen, W., & Moritz, H. (1967). Physical Geodesy. *W.H Freeman & Co, San Francisco*, 364.

Hoffmann-Wellenhof, B., & Moritz, H. (2006). *Physical Geodesy.* . Springer Wien, New York.

Houghton, J., Ding, Y., Griggs, D. J., & Noguer, M. (2001). *Climate Change.* New York: The Press Syndicate Of The University Of Cambridge.

Kasala, E. (2016). *Marine geoid on the easten coast of Tanzania from MSS and MDT and its evaluation by TZG13.* Dar-es-salaam, Tanzania: A dissertation for Bsc.in Geomatics Ardhi University.

Limpach, P. (2010). *Sea Surface Topography and Marine Geoid by AIrborne Laser Alimetry and Shipborne Ultrasound Altimetry.* (Vol. vol 80). Zurich, Switzerland: Institute of Geodesy and Photogrametry. ISBN 978-3-908440-24-6.

Meela, C. (2018). *Assessment for the best Tanzania marine geoid model from possible global MSSH and MDT satellite models using TZG13 gravimetric model as a reference.* Dar-es-salaam,Tanzania: A dissertation of Bsc in Geomatics Ardhi University.

Nicholls, R., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science 328*, 1517-1520.

Ntambila, D. (2012). *Validation of the recent geoid models for Tanzania.* Dar-es-salaam, Tanzania: Thesis of the Ardhi University.

Osward, A. (2018). *Rate of sea level change and its impact along th coast of Tanzania over the past 20 years.* Dar-es-salaam, Tanzania: A dissertation of Bsc in Geomatics Ardhi University.

Shija, J. (2017). *Optimal Marine Geoid from combination of of different combination of MSS and MDT models.* Dar-es-salaam, Tanzania: A dissertation for Bsc. in Geomatics of Ardhi University.

Sideris, M. (1997). Marine gravity and geoid determination by optimal combination of satellite altimetry and shipborne gravimetry data. *Journal of Geodesy*, 10.1007/S001900050088.

Sideris, M. (2012). Determination of sea level changes by combining Altimetric,Tide gauge, Satellite Gravity and Atmospheric Observations. *Geodesy For Planet Earth 21*, 299-317.

Siegismund, F., Kohl, A., Rummel, R., & Stammer, D. (2020). Temporal variations of the marine geoid. *Journal of Geophysical Research*, 125.

Smith, W. H. (2010). The marine Geoid and Satellite Altimetry. *Laboratory for Satellite Altimetry, National oceanic and Atmospheric Administration, 217-231*, doi: 10.1007/978-90-481-8681-5_11.

Smith, W. H., & Sandwell, D. (1997). Global seafloor topography from satellite altimetry and ship depth soundings. *Science 277*, 1957-1962.

Stammer, C. W. (2006). Satellite Altimetry, th marine geoid and the Oceanic General Circulation. *Department of Earth, Atmospheric and Planetary Sciences, Massachussets Institute of Technoology*, 219-250.

Torge, W. (2001). *Geodesy, third edition, Walter de Gruyter.* Berlin, New York.

Williams, S., Gutierrez, B., Titus, J., Gill, S., Cahoon, D., Thieler, E., & Anderson, K. (2009). *Sea-level rise and its effects on the coast.*