ASPECTS OF SEA LEVEL VARIABILITY IN THE SOUTHWEST INDIAN OCEAN AND THE EAST COAST OF AFRICA - (LATITUDE 0 - 35°S AND FROM THE COAST TO 60°E).

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DECLARATION

Plagiarism is an offense and I know what it means. I hereby declare that the contents of this thesis are my own original work with the exception of the parts that are acknowledged. The subject matter of this thesis "Aspects of Sea level Variability in the Southwest Indian Ocean and the East coast of Africa" has not been presented at any University before for the award of any form of degree.

Name...Joseph Odhiambo Amollo...

Signature.... Signed by candidate ....

Signed on.......12/02/2013...

DEDICATION

I wish to dedicate this work to the two relevant Organizations in Kenya (Kenya Meteorological department and Kenya Maritime and Fisheries Research Institute) who are mandated to carry out sea level observations, analyses, interpretations and issuance of Marine related forecast for the benefit of the coastal population and the Country at large. Improvements on this work will do the Kenyan country and the East African region as a whole a lot of good in the future plan for the protection of the coastal environment, ecosystems and the population from the impacts of anticipated sea level changes.

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ACRONYMS

RSLR	Relative Sea Level Rise
Sa	Annual Tidal harmonic
Ssa	Semi-Annual Tidal Harmonic
IB	Inverted Barometer
MSL	Mean Sea Level
SWIO	South West Indian Ocean
SSH	Sea Surface Height
SLP	Sea Level Pressure
ENSO	El Nino Southern Oscillation
NAO	North Atlantic Oscillation
PDO	Pacific Decadal Oscillation
IOD	Indian Ocean Dipole
NCEP	National Centres for Environmental Prediction
NCAR	National Centres for Atmospheric Research
IPCC	Intergovernmental Panel on Climate Change
GRACE	Gravity and Recovery Climate Experiment
ICOADS	International Comprehensive Ocean Atmosphere Data Set
CLIMAP	Climate long range investigation Mapping and Prediction
EOF	Empirical Orthogonal Function
GIA	Glacial Isostatic Adjustments
ECMWF	European Centre for Medium Range Weather Forecasting

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Abstract

Analysis of tide gauge sea level observations of varying durations in the southwest Indian Ocean and the East coast of Africa (Lamu, Mombasa, Zanzibar, Durban, Port La Rue and Port Louis) show variability which are related to global, regional time scales, local weather and climatic changes, oceanographic and hydrological forcing that manifest in both short and long time scales. The investigations on the tide gauge sea level observations are conducted through the separation of the total sea level measurements into the contributing components (tides and residuals) using a Matlab in built software (t-tide).

Short time scale sea level variability in the southwest Indian Ocean is due to the effects of tides which exhibit tidal range variations with latitude and shelf width, storm surges resulting from tropical cyclones passage especially in the mid-latitude region, atmospheric pressure fluctuations over the surface of the sea and local wind fields. Sea surface temperature variations during summer and winter result in differential heating of the ocean surface and contribute to the observed sea level variability at seasonal time scale especially in the region 25°S and southwards where the temperature differences are large. The equatorial region is characterized by a near constant sea surface temperature that sustains thermal expansion of the upper layer of the ocean water throughout the year. Monsoon periods show significant and variable wind speeds that impact on sea level variability in the southwest Indian Ocean and the East coast of Africa and are greatest during the summer monsoon (from June to August). On longer time scales (Interannual and decadal), sea level variations in this region is mostly influenced by the El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). During the 1997/98 El Nino event, the sea levels are significantly higher than normal at the coast and the islands. During the 2000/2001 La Nina, the sea levels are significantly lower than normal at the coasts in the southwest Indian Ocean. Indian Ocean Dipole effects are significant in the southwest Indian Ocean during the period 2006 through to 2008 and are more enhanced in 2007. The annual highest sea levels in this region are influenced by the year to year changes in weather pattern and the perigean cycle of the tides on a 4.4 year period but their secular trends are not statistically significant.

Chapter One

Introduction

Sea level has changed and the changes will continue on all time scales in response to various factors which include tidal effects, atmospheric pressure variations, precipitation changes and wind effects on short time scales. On a global scale and longer time scales, temperature changes resulting from the changes in solar radiation that reach the surface of the earth due to variations in Earth’s orbit around the sun, mass addition into the ocean from glacier and ice melt and tectonic activities which alter the shape of the ocean basin are the main processes that influence sea level variations (Church et al 2010). Additional contributions to sea level change emanate from the water storage on land, in lakes, rivers, dams, wetlands, soil moisture, snow cover, permafrost and aquifers which are largely influenced by both climate variations and anthropogenic activities (Cazenave et al 2000, Milly et al 2003, Chambers et al 2004). Sea level investigations have encountered major challenges in the recent decades. These challenges include the inability to quantitatively describe the observed 20th century sea level rise which were more than the total estimated contributions on decadal time scale (IPCC 2007).

Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, AR4) estimated the global mean sea level rise during the 1993-2003 decade at 3.1±0.7 mm/yr with nearly half the rise being linked to thermal expansion and about 40 percent being associated with the contribution of ice melt (Bindoff et al 2007). More recent investigations (2003-2009) using datasets acquired through altimetry observations have estimated the global rise in sea level at 2.6±0.4 mm/yr (Ablain et al 2009) and indicated reduced level of contribution to sea level rise by ocean thermal expansion in comparison to the 1993-2003 decade. Mass addition into the ocean through accelerated ice melt due to increased global warming and steric change caused by the general warming are the reliable explanation for the observed differences in observed sea level change (Cazenave et al 2009; Peltier 2009; Cazenave and Llovel 2010).

Variability of sea level at regional scales is important because the impacts on the environment and the society are due to regional or local sea level rise and local land shifts. Regional variability in sea levels has been revealed by tide gauge and altimetry observations and is largely related to weather and climatic variations especially in the equatorial Pacific Ocean. The observed pattern in regional variability of the sea level is associated with the variable wind patterns that are related to climatic phenomena like the El Nino Southern Oscillation and manifest themselves in the regional pattern of ocean thermal expansion (Church et al 2010). Non-uniform heating of the ocean on regional scales and the subsequent thermal expansion of the sea water together with mass loss of the ice caps and glacier due to melting and dynamical response to warming climate has influenced sea level change on longer time scale and on a wide area. The contributions of ice sheets is not uniformly distributed and results to a lower relative sea level near decaying ice sheets and a larger than globally averaged rise (by about 20%) far from decaying ice sheets (Church et al 2008).

Sea Level observations along the coast are carried out with the aid of tide gauges located at specific sites along the coastal region and islands. The tide gauges measure the sea level changes relative to the level of the land. Sea level changes observed through tide gauges provide useful information regarding the fluctuations in the volume of the ocean waters as well as the changes in vertical movement of the crust relative to the Earth's centre of mass. Altimetry measurements of sea surface height trends regionally has led to improved understanding of the close relations between sea level variability on interannual to decadal time scales and climatic phenomena such as El Nino Southern Oscillation (ENSO), North Atlantic Oscillations (NAO) and Pacific Decadal Oscillation (PDO) among other climatic indices (Bindoff et al 2007).

Sea level rise has been projected for the period 2090 – 2100 decade in comparison to the period 1980 – 2000 by the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007, AR4). The model projections are composed of two parts where the first part estimates sea level rise at 18 – 15 cm by the year 2095 at 90% confidence range with the main contributions drawn from thermal expansion, glaciers and ice caps and modelled ice sheet. The second part of the projection is based on the possible rapid dynamic response of the Greenland and West Antarctic ice sheets and their subsequent accelerated contributions to sea level rise Rahmstorf (2007) and Velicogna (2009).

Continued sea level variability at the coasts and islands in the tropical oceans has major socio-economic, biological and geophysical impacts. Some of the major impacts that are associated with sea level rise when no proper defence measures are in place include coastal inundation, changes in the frequency of extreme events (flooding and tropical cyclones) and reduced resilience of coastal ecosystem and wetland loss. Other impacts on the coastal zone include salination of the freshwater due to salt water intrusion and loss of productive agricultural lands due to over fertilization by nutrients that are deposited to the sea through river discharge and stream flows. These impacts of sea level change on the coastal environment raise a lot of concern in planning coastal development which is characterized by high concentration of population, industrial and socio-economic investments. An improved understanding of sea level variability and its drivers is essential in reducing the level of uncertainties associated with future impacts on the coastal environment and also to contribute effectively in the planning and management of the coast. Several efforts have been directed towards understanding the various aspects of sea level variability on a global and regional scale at different time scales (Nicholls et al 2007a).

This study is primarily intended to investigate components that affect sea level variations across different time scales (short and long time scales) in the East coast of Africa and two Islands in the southwest Indian Ocean. The investigation is also aimed at determining how the highest water level amplitudes are changing and the contributing factors to the changes in amplitudes of the high water levels in the South West Indian Ocean and the East coast of Africa (Lamu, Mombasa, Zanzibar, Port Louis in Mauritius and Pt. La Rue in Seychelles and Durban) at longer time scales.

1.1 Sea Level Variability on a short time scales (hours, days and month).

Shorter time periodic variations in sea level observations are related to the changes in the local weather (air pressure changes, storm surges, and temperature fluctuations due to solar heating) and changes in local wind setup over the ocean. Wind driven waves cause impacts on sea levels on a relatively shorter time scale and affect wider areas. Tides have effect on sea level variability at semi-diurnal, diurnal, fortnightly, monthly and even longer time scales and on a wide extent. Fluctuations in the salinity distribution in the upper layer of the ocean of up to about 200 m which cause density changes also contribute to the seasonal fluctuations of the sea level (Gill and Niiler 1973; Pattullo et al 1955).

1.1.1 Astronomical aspects of Sea Level Variability (Tides)

Tides constitute the major component of high water levels and their long term characteristic variations are important in assessing the sea level variability at different time scales (daily, monthly, seasonal and even much longer periods). Information about tidal range and periods provide a useful framework for describing the fundamental forces responsible for the various cycles in tides at different locations. Tides are characterized by three kinds of oscillations, the diurnal, semidiurnal and long period. The diurnal tides are most effective when the moon's declination is furthest and reduced to zero when the moon crosses the equatorial plane (zero declination). Unlike the diurnal tides, the semidiurnal tides do not reduce to zero range at any latitude but are partially reduced during the period of neap tides and are greatest when the moon's declination is zero. Analyses of tide gauge data show regular movements which are reflected in the vertical rise and fall of the sea level and the forward and backward movements of the water currents. The main features of the tide in sea level records are the range which defines the height between successive high (low) levels and period which is the time difference between one high (low) level and the next high (low) level (Pugh 1987).

During the equinoxes in the months of March and September, the solar semi-diurnal forces are greatest with the consequence that spring tides are significantly larger than normal (equinoctial tides) and contribute to the distinctly elevated sea levels during this time. The higher tidal forces which are the major component of extreme water levels are significantly highest when the moon and the sun are in line with the Earth and are at their closest distance (Pugh 1987).

During certain times in the lunar month, the water levels are reported to be higher and lower than average in a successive manner and are most pronounced when the northward and southward declinations through the equatorial plane is greatest and is caused by the small additional tides with periods of one day which adds to one high water level and also subtracts from the next high water level (Pugh 1987).

Tides generated in the deep ocean are usually dissipated by friction on shallow continental shelves and also external tides over topography in the deep ocean. The tidal oscillations on the continental shelf depend on the size, shape and bathymetry of the shelf sea and determine the tides near shore and consequently the sea levels. Large tides are experienced when a natural mode of oscillation of a part of the shelf occurs at a frequency close to that of the ocean tide (near resonance) Pugh (1987).

Sea level variations at interannual and much longer time scales are influenced by tidal effects as a result of two important precessions (rotation of a plane relative to a reference plane) of the moon, notably, the 18.6-year lunar nodal cycle and the 8.8-year cycle of the lunar perigee. These modulations have significant implications on the analyses and interpretations of the sea level records that cover several years in terms of extreme value predictions (Menendez and Woodworth 2010). The lunar perigee influences sea level as a quasi- 4.4 year cycle (Woodworth and Blackman 2004). The influences of these modulations on highest water levels vary significantly in both magnitudes and phases of the tide constituents (Eliot 2010).

The 18.6 year lunar nodal precession has a significant effect on the moon's declination (angle south or north of the equator). Greatest declination is observed when the ascending node is zero (at the Equator) and is minimum when the ascending node is at 180° (Ray 2007). Changes in the moon's declination have influence on the characteristics of the lunar tidal forcing on the sea levels with a larger declination increasing diurnal forces at the expense of semi-diurnal forces and vice versa (Ray 2007). The significant influence of the 8.8 year periodic cycle of the lunar perigee on high tides occur as a quasi-4.4 year cycle in which nearly every four years, the sun coincides with the line of apsides (the line connecting two points of an orbit that are nearest and farthest from the centre of attraction, as the perigee and apogee of the moon or the perihelion and aphelion of a planet) and larger tidal ranges are developed especially around the time of equinox when the sun's declination is zero and the semi-diurnal forces are maximum (Cartwright 1974; Wood 2001a).

Both nodal and perigean influences are present in semi-diurnal and diurnal tidal forms. Perigean influence (8.8 year cycle) is significantly related to highest water levels in areas dominated by semi-diurnal tides while the nodal influence (18.6 year cycle) on highest water levels is associated with regions dominated by diurnal tides (Haigh 2011).

1.1.2 Weather introduced sea level variability (Storm surges and shelf Waves).

Storm surges together with the astronomical tides are classified as long waves but they present some significant differences. Whereas tides occur on the oceanic scale, storm surges are conspicuously a coastal phenomenon. Further, significant tides cannot occur in a completely closed small coastal or inland water body but storm surges can occur even in completely enclosed lakes, in canals and rivers (Gonnert et. al, 2001). The propagation of storm surges over water is much faster than the speed with which the weather systems move in the atmosphere. It is evident that as the surges draw near shallow waters at the shore, they move more slowly and the speed gradually matches the speed of movement of the weather system. When both the speeds of the surges and the weather systems match, resonance coupling takes place and energy is transferred from the weather system to the ocean surface leading to the development of the higher storm surge at the shore and subsequent sea level change (Pugh 1987).

Wave propagation from deep waters to the shores cause obvious changes in mean sea level which are linked to the close relations between atmospheric pressure, winds and sea level. The changes in sea levels due to changes in pressure (inverted barometer effect) are related to the wind stress and manifests in the variations of the theoretical 1 cm/mb change in sea levels (Pugh 1987). The fluctuations in the inverted barometer effect are influenced by the dynamic response of the shallow waters of the continental shelf to the movement of the atmospheric pressure fields, time scale and regional characteristics. Pressure changes are dominant at higher frequencies and at shorter time span due to their shorter time response but when longer time span of days to months are considered, wind stress effects on sea levels prevail primarily because of their longer time response to changes (Shillington 1984). Greatest responses of sea level variations at shorter time scales of days to months are associated with depressions which are characterized by small pressure changes and suggest high geostrophic winds. The description of the weather related components of sea level variations requires the consideration of the synoptic scale characteristics of a particular region (Searson 1995).

1.1.3 Resultant tide-Surge interaction

Shallow water dynamic processes that cause interaction between tide constituents and produce higher and lower harmonics also cause interaction of tide and surge components of the sea level. Tide-surge interaction is important because it occurs in shallow coastal water areas where large surges are experienced and influence the sea level variability. Shallow water interactions between tides and surges are probably responsible for the monthly variations of the tide constituents and hence sea level variations. The variations are caused by the loss of more energy from tides and surges when they travel together and interact than it would be if they travel separately (Amin 1982). There is also seasonal modulation of the Principle lunar constituent (M_2) and principle solar (S_2) amplitudes through the surge-tide interaction (Pugh and Vassie 1976).

The interaction between storm surges and tides causes modification of the tides while the tidal cycles produce alterations in the storm surge amplitude and contribute to the sea level variations at the coast. Tide-surge interaction is controlled by bottom friction and variations of the wave propagation speed which are depth dependent. Shallow water interaction produces a phase shift and modulations of tides and surges respectively. The phase shifts of the tidal signals represent the effects of the surge on the tide while the modulation of the surge represents the effects of the tide on the surge (Horsburgh and Wilson, 2007).

1.2 Long term Sea Level Variability.

Sea level variations at interannual to decadal time scales are due to atmospheric and oceanic interaction processes which are influenced by the fluctuations in atmospheric pressure systems and ocean circulation together with temperature changes at regional level (Church et al 2008).

One of the factors that have been widely considered to contribute to sea level variability at longer time scales is temperature fluctuations which initiate volume expansion and is dependent on the heat distributions within the ocean water column. A number of estimates of the contribution to sea level rise by thermal expansion are available and indicate that this process may be responsible for a fraction of the total sea level rise (Millar and Douglas 2004).

Sea level variations at longer time scales and on a wider area are also influenced by the processes that cause changes of the surface elevation of the Earth's crust by changing the shape of the basin and include glacial isostatic adjustments (GIA) and tectonic movements. It is believed that north hemisphere estimates of relative sea level rise were much greater than 10mm yr^{-1} after the last glacial maximum but decreased to 1-2mm yr^{-1} and less in recent millenia (Bloom and Yonekura 1985) due to GIA and vertical land adjustments.

Initially ice accumulations deformed the continental plate and the subsequent disintegration of glaciers reduced the weight on the land below and led to vertical and upward realignment of land surfaces that continues today. The offload of glaciers has continuously resulted to an upward push of land and hence lowering the sea level over large parts of the earth at longer time scales especially in the northern hemisphere (Rohling et al 2009). The impact of glaciations on sea level is not uniformly distributed because the weight of the ice also caused an upward fore-bulge towards the south limit of the glaciations which made the levels at the affected regions much less than today. In addition to the post glacial rebound are related effects of regional or local tectonic activities (Emery and Aubrey 1991; Flemming 1992) which are associated with plate uplifts or subsidence, earthquakes and volcanism that occur at widely different time and spatial scales.

Meteorological and climatic phenomena also contribute to the adjustments of sea level on both short term and long term periods. On longer time scales, El Nino Southern Oscillation, North Atlantic Oscillation and Indian Ocean Dipole events are some of the climatic phenomena that affect sea level variations. ENSO which is a global scale climatic phenomenon has its origin in the tropical Indo-Pacific as a result of anomalous sea surface temperature in the East and West tropical Pacific and manifests in both El Nino and La Nina events. Some regional tide gauge records have indicated periodic variations in trends of sea level change with significant interannual fluctuations which are attributed to the ENSO events (Johnston and Merrifield 1999; Wyrtki 1977).

The impact of ENSO in the Indian Ocean has been considered to be caused by the variations of the Indonesian Through flow (Meyer 1996) and large scale winds together with surface heat flux anomalies (Reason et al 2000; Xie et al 2002).

Indian Ocean Dipole (IOD) is absolutely an atmosphere-ocean interaction of the coupled climate of the tropical Indian Ocean and normally occurs during the months of September-

November (Behera et al 2008; Schott et al 2009). A positive Indian Ocean Dipole event results to a sea surface temperature anomaly in the east and west with warm/cold anomalies in the Western and Eastern Indian Ocean respectively (Saji et al 1999; Behera et al 2006). Easterly trade winds initiate eastward currents which cause upwelling off the Indonesian coast (Schott et al 2009) and bring to the surface cold water to fill the eastern Indian Ocean consequently triggering a positive IOD event. A negative IOD usually follows a positive IOD generating a quasi biennial oscillation in the IOD variability.

1.2.1 Large scale Sea Level variability due to ocean circulation pattern

Sea level change is closely linked to the ocean circulation system (Reid and Mantyla 1976) in the sense that they are significantly elevated in the central parts of the ocean's gyre as a result of the general geostrophic balance of the clockwise circulation of the current system (clockwise in the northern hemisphere and counter clockwise in the southern hemisphere). Significant trend pattern of increase (decrease) in the general circulation of the ocean can initiate changes in the central gyre and sea level at the coastal boundaries.

Local wind stress and wind forcing of the ocean circulation have a direct impact on the coastal sea level variations. Wind stress that acts parallel to a coastline or shelf initiates Ekman transport which in effect causes the development of water level disparity and controls the water movement resulting to changes in sea level (Schott et al 2008). Ekman transport describes the net movement of water to the left (right) of the wind stress in the southern (northern) hemisphere respectively and is controlled by several factors amongst which include wind strength, latitudinal variation (due to Coriolis effects) and water depth. The seasonal effect of wind fields on sea level is more significant along the continental shelves where the transfer of momentum and energy to the surface layer of the water produces sea surface slope and currents (Collins et al 2012).

Indian Ocean circulation pattern unlike in the other oceans (Pacific and Atlantic) is different in the northern and southern parts. The wind driven circulation of the Northern Indian Ocean is majorly influenced by the seasonal changes in the monsoon winds and reverses radically with the changing seasons unlike in the Southern Indian Ocean where the well known anti-cyclonic wind driven circulation is continuous throughout the year (Schott et al 2008).

The unique monsoonal gyre north of the equator is controlled by the north east (winter) monsoon winds from east to west and starts in the month of November with a peak between December and January and subsides around March-April. Past Somalia coast downwards, these winds are deflected to the south by the African continent and flow along the coast where they become the Equatorial Counter Current which is strongest during the month of December. The Equatorial Counter Current is located between 3ºN to 5ºS but changes position to about 10ºS from the month of January to April and influences variations in sea level around this part of the Indian Ocean. The general circulation during the North East Monsoon period is characterized by weakly developed mean monthly wind speeds along the African coast (Collins et al 2012).

Summer monsoon circulation is greatest during the month of July and is more energetic with greater mean monthly wind speeds along the East coast of Africa northwards. The Southwest monsoon flow domain is generally eastwards including the counter current. During the period of the southwest monsoon, most of the water of the south equatorial currents flows northwards along the African coast and impact on sea levels. This intensely wind driven system starts to diminish in October. The monsoon circulation patterns have a major impact on the amplitude and frequencies of the sea level variations along the coasts and the Islands of the Indian Ocean (Collins et al 2012).

The equatorial Indian Ocean is characterized by a strong and elaborate semi annual cycle of zonal wind component (Schott and Creary 2001) and during summer (winter), westerly (easterly) winds prevail on the equator (figure 1.0). The semi annual zonal wind variability is possibly caused by across equatorial momentum transfer due to lack of equivalence of the monsoon winds with the consequent variations in sea level at the equatorial and along the coasts.

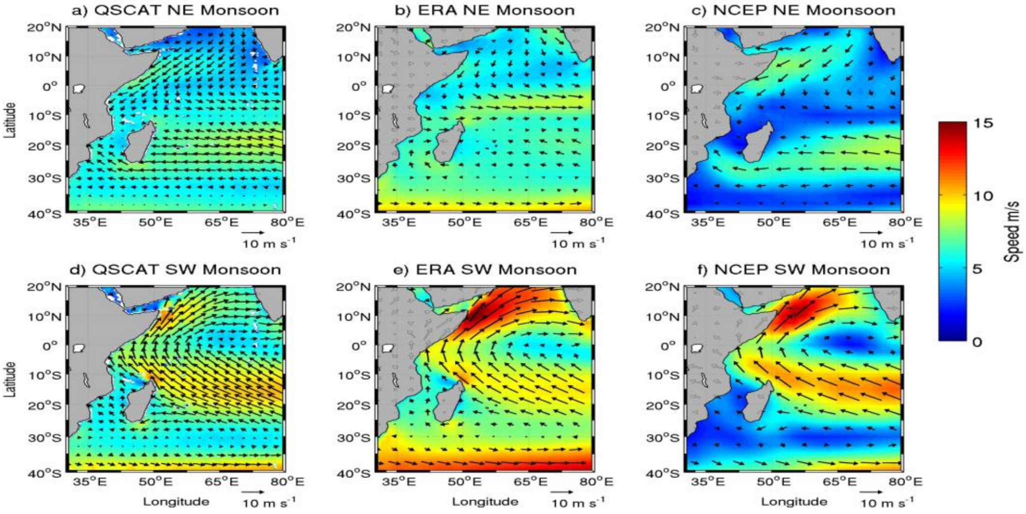


Figure 1.0**:** NE and SW Monsoon circulation patterns in Indian Ocean from QSCAT, ERA and NCEP (Collins et al 2012).

1.3 Secular Mean Sea Level trends

Mean Sea Level is regarded as the average level of the sea over a stated period of time relative to a fixed benchmark on land where tide gauge is located. Evidences for lower sea levels than at present include submerged eroded beaches and shorelines and deltas while evidence for upward land movements is seen in raised beaches, tidal flats and salt marshes. Secular changes describe long term mean sea level changes while eustatic changes describe the global mean sea level changes. The vertical land movements of regional extent are termed as eperigenic movements (IOC Manual and Guide No 14 vol 4).

Mean sea level is a good approximation to the geoid which is the undisturbed equipotential surface. The equipotential may change with time due to the continuous mass redistribution in the Earth’s system as a result of glacial isostatic adjustment (GIA) and hydrological flux into and out of the ocean (Farreld and Clerk 1976). Other changes to the equipotential of the sea surface my result from tectonic processes that operate over longer time scales (Barletta and Sabadini 2006) and alter the ocean basin.

Oceanographic effects such as water density variations, ocean circulation patterns and atmospheric effect (mean air pressure and winds) influence permanent displacement of the mean sea level from the geoid. Other influences on mean sea level change are caused by gravitational tides and the weather effects (Pugh 1987).

The direct and indirect effects of weather on mean sea level at seasonal and interannual time scales are due to wind fields changes and variations in solar heating on the surface of the ocean. Sea level heights observed from tide gauge globally have indicated considerable regional variations due to the effects of meteorological and oceanographic phenomena (Pattulo et al 1955; 1963 and Woodworth 1984 and Prandi et al 2009).

Chapter Two: Literature Review

2.1 Short term sea level Variability

Local variations in sea level have been explained in terms of the different tidal regimes and ranges of a particular region. Pugh (1987) reported variation of sea levels on short time as related to variations in the tide and weather. Meteorological disturbances are variable and greatest in winter and are significantly effective where they act on shallow seas. Total sea level as a result of combined effect of severe storms and high water during spring tides in shallow water areas is capable of producing huge coastal flooding (Lamb 1980; Murty 1984; Wood 1986).

Elevated sea levels are associated with both mid-latitude and tropical storms in which storm surges are generated by a combined effect of low atmospheric pressure and intense winds over the ocean. Synoptic scale extra tropical cyclones which are baroclinic systems and form in mid-latitudes are an important part of mid-latitude weather and climate (Chan 1983). The effects of tropical storms are significant when they track parallel to the coast (Pugh 1987). Tropical cyclones are in essence capable of generating devastating storm surges and elevated sea level events at the coasts.

Pittock et al (1996) found that changes in the characteristic aspects of a cyclone are important component of extreme sea level variations. Changes in cyclone numbers, tracks, intensities, sizes and frequencies together with fluctuations in the occurrence of sea level extreme amplitudes and changes in cyclone propagation velocities are important information in sea level variability investigations. Gulev et al (2001) clearly showed on the basis of storm tracking of National Centres for Environmental Prediction (NCEP) and National centre for atmospheric research (NCAR) reanalysis that some of the characteristics of the cyclones experienced significant changes in the last several decades particularly the growing number of rapidly intensifying extra-tropical cyclones in parts of the Northern Hemisphere.

Studies have revealed that short period fluctuations of the sea level are influenced by the surface wind whereby the onshore (offshore) winds raise (lower) the tidal levels respectively (Eugene 1974) and the component of the wind stress acting parallel to a coastline induces Ekman transport which creates water level differences. The wind flow pattern along the coast (offshore and onshore) can either remove or pile up water at the coast and contribute to the variability of the sea level at different locations within the coast.

Several studies have been conducted on sea level variability along the west coast of India on various time scales from seasonal to interannual and decades. The observations have indicated that the variations in sea level during winter and summer monsoons are connected to the coastal currents around India and to the circulation in the Arabian Sea (Banse 1968; Johannessen et al 1981; Shetye et al 1991; Shankar and Shetye 1997, 1999, 2001; Srinivas et al 2005a, b; Shetye et al 2008). It has also been specified that sea level variability could be determined partially by local forcing and partly by sea level variations induced from other regions of the ocean (Lighthill 1969).

Studies conducted by Young et al (2011) to investigate changes in wind speed for the period 1991-2008 and significant wave heights for the duration 1985-2008 found a generally increasing values for both the wind speed and wave heights. The wave heights increases were significant especially in the southern hemisphere. The results indicated an impact of waves on sea level at the coastal region through the modification of the long shore sediment transport and coastal evolution.

2.2 Long term sea level Variability.

Global sea levels have continued to vary during the past decades and the variations have been linked to various processes which include thermal expansion of the warming ocean and fresh water addition from melting continental ice caps and glaciers on long term scales. On regional scales, long term sea level variability is affected by oceanic and atmospheric circulation changes in addition to climatic influences. The rate of sea level change varies from relatively stable to naturally subsiding coasts which are experiencing glacial isostatic adjustment induced subsidence.

Wigley and Raper (1987) reported that global sea level rise is influenced by a number of processes within the earth system which include temperature and salinity changes resulting in density variations of seawater and eventually steric changes.

Past studies have suggested that thermal expansion majorly influences changes of the upper layer of the ocean and that the expansion of the upper layer of the ocean has a significant contribution to the steric effect on shorter time scales of months to season (figure 2.0). Heat exchange has been found to be much faster in the upper most layers of the ocean up to approximately 700 m and that thermal expansion in this upper layer takes place in a time scale of several months to years. Heat exchange within the deeper layer of the ocean is quite slow and takes much longer time (decades to century) as the deep ocean adapts to the mixing process (Hoffert et al 1980). The extent of sea water expansion is considered to be proportional to the quantity of heat that is absorbed by the ocean and the water temperature, with greater expansion evident in warmer water and at greater depth. Recent studies have indicated that ocean thermal expansion has contributed immensely to the 20th Century sea level rise and is projected to continue during the 21st Century and for centuries in the future (Bindoff et al 2007; Meehl et al 2007).

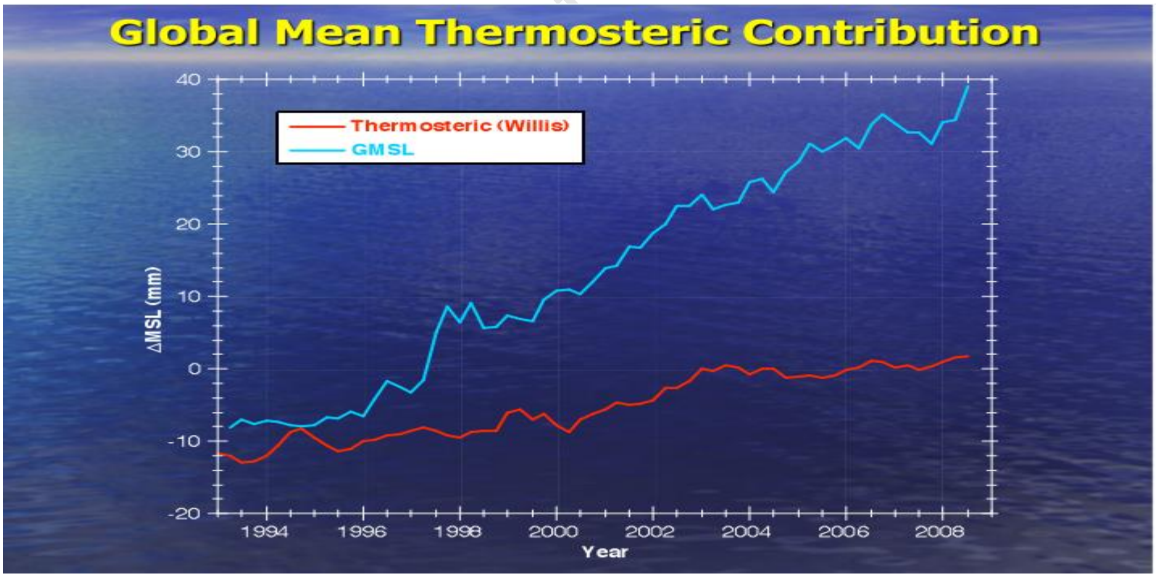


Figure 2.0: Thermosteric contributions to sea level rise (Willis et al 2008)

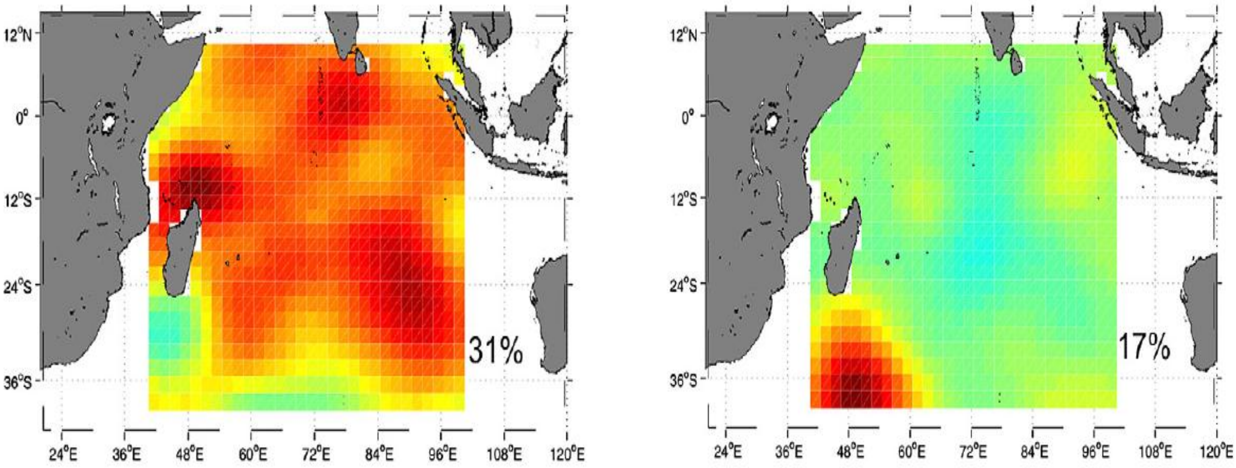
Density changes caused by salinity and temperature fluctuations within a column of seawater can cause volume changes that are reflected in the expansion or contraction of the water column and subsequent sea level change.

The increasing concentrations of CO_2 and other greenhouse gases in the atmosphere are expected to accelerate global warming by between 2-7ºc in the absence of efficient and proper mechanisms to reduce emissions (Hansen et al 1988; Bretherton et al 1990). Such warming could enhance both melting of glacier and thermal expansion of the sea water and subsequent sea level change (Meier 1984).

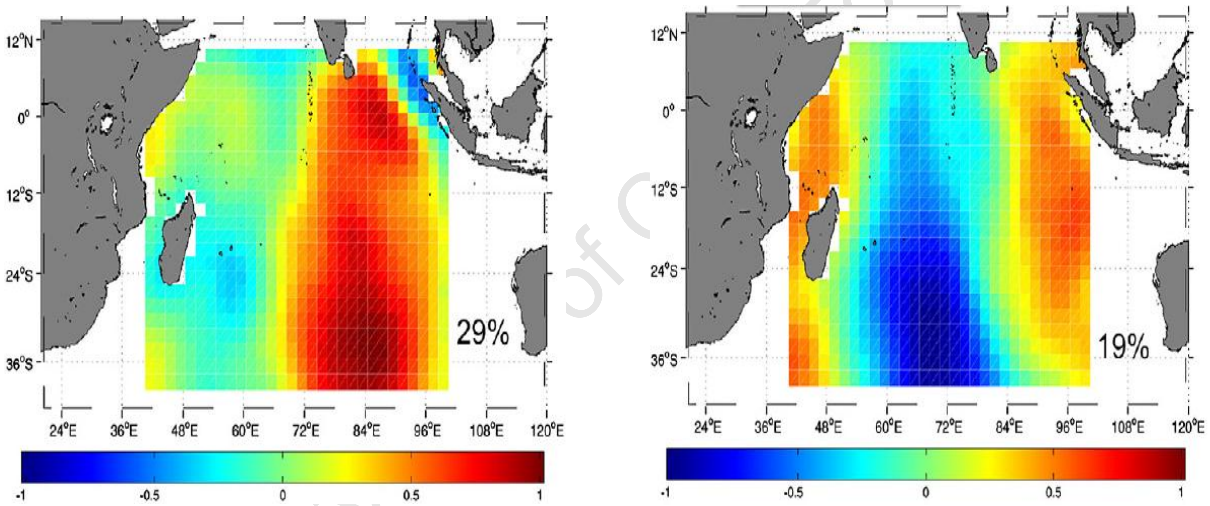
Glaciers and ice caps withdrawal have been observed to occur on a Global scale with large and significantt accelerations in the recent decades (Wahr 2009). Gravity and Recovery Climate experiment (GRACE) data analysis has revealed accelerated mass losses from Greenland and West Antarctic which have been linked to rapid outlet glacier flows along some margins of Greenland and ground line which is below sea level in West Antarctic (Wahr 2009). The imbalance between accumulations due to precipitation of snow and losses resulting from melting and runoff have also contributed to mass loss in Greenland while in Antarctic, mass loss has been occasioned by the instability of the ice dynamics (Stammer 2008). The mass addition to the ocean from the losses of glaciers and ice caps has been considered as a major cause of the observed regional mean sea level variations (figures 2.1, 2.2 & 2.3).

Long term trends comparisons of mass contributions and upper layer (up to about 700 m) thermosteric contributions to total sea level have been estimated at 1.1mm/year by Domingues et al (2008) and 1.3 mm/year by Ishii et al (2006) for mass contributions. Thermosteric contributions of the upper layer up to 700 m to sea level rise have been estimated at 0.52±0.08 mm/year by Domingues (2008) and 0.31±0.07 mm/year by Ishii et al (2006).

Significant differences in the above estimates have been explained by the assumptions made by Domingues that there is a linear increase in the rate of change of the contributions by Greenland and Antactic ice sheets. Also the inclusion of the deeper layer thermosteric contribution to sea level rise (which is approximately 0.2mm/year and is about 40 percent of the total thermosteric contribution) could have led to the difference in the estimates. Guinehut et al (2006) concluded in his observation that the deeper layer thermal expansion contributions were less important. Mass contribution is reported to be unsteady but could be the dominant contributor to regional sea level variation (Llovel et al 2010).



Figures2.1a, 2.1b: EOF1 and EOF2: Indian Ocean decomposition for steric - corrected altimetry contribution to regional Sea Level variability (Marcos et al 2011).



Figures2.2a and 2.2b: The EOF1 and EOF2 Mass contribution to regional Sea Level variability Indian Ocean GRACE data (M. Marcos et al 2011)

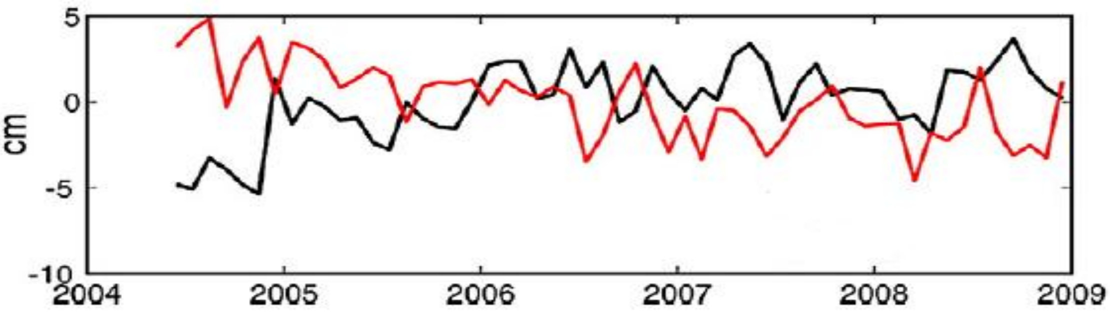


Figure 2.3: EOF1 amplitudes of regional sea level variability in Indian Ocean black lines represent altimetry-steric and red for GRACE (Marcos et al 2011).

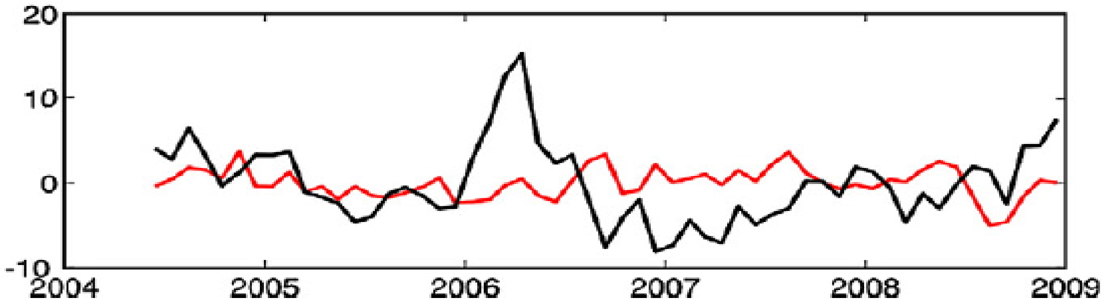


Figure 2.4: EOF2 amplitudes of sea level variability in Indian Ocean. Black lines represent altimetry-steric and red for GRACE (Marcos et al 2011).

Tropical pacific sea level variations have been reported to be related to El Nino Southern Oscillation phenomena. This was recognized by Wyrtki (1977) when he conducted a study on the response to the 1972 El Nino by sea level records from several islands and coastal stations and associated equatorial circulation. Unbalanced kind of variation of sea surface temperature and sea level was identified as having opposite phases between the western and eastern tropical regions.

The impacts of ENSO events on climate and sea level variability in the Indian Ocean and the surrounding countries have been observed. It has been shown that the most distinct climate variability in the Indian Ocean basin on interannual time scales could be linked to ENSO events (Reason et al 2000) and these ENSO events influence weather and climate patterns on a global scale. Allan et al (2003) recognized the influence of protracted ENSO events in the fluctuations of climate in Indian Ocean and droughts and floods are enhanced in severity during such events resulting to sea level changes.

ENSO events have been linked with the heat flux and wind stress anomalies over Indian Ocean and the related forced interannual variability (Yu et al 2002). The 1997/1998 enhanced warming over the tropical Indian Ocean region was related to the strong El Nino event. During this time, the unusual warming over the tropical Western Indian Ocean and subsequent high sea levels along the coast of East Africa region were related (Chamber et al 1999).

Indian Ocean Dipole is on most occasions triggered by ENSO but at times occur independently subject to eastern tropical preconditioning. It exhibits both strong positive and negative phases that are associated with regional changes in sea surface temperatures across the Indian Ocean with coupled wind and precipitation anomalies. The positive phases of the IOD events of varying durations and intensities have occurred during the periods 1961, 1963, 1967, 1972, 1994, 1997 and 2006 (Saji and Yamagata 2003; Behera et al 2008). Other positive IODs were realized in 2007 and 2008 (Cai et al 2009). The positive phases of IOD are related to the elevated sea surface temperatures in the Western Indian Ocean and lower sea surface temperatures in the east. The sea surface temperature anomalies induce winds that blow from east to west and increases sea level in the Western Indian Ocean.

2.3 Previous studies on Sea Level change and variability

Sea level rise has been investigated and found to threaten the densely populated coastal zone and low-lying areas since the time of emergence of human induced global warming around 1980s and the threat is expected to continue into the future (Barth and Titus, 1984; Milliman et al 1989; Warrick et al 1993). Continued settlement and concentration of population and investments which includes many major cities around the coast is expected to increase the risks of exposure to the multiple meteorological and geophysical hazards like storms and floods (Kron 2008).

The already exposed and vulnerable coastal and low-lying areas require flood risk management strategies and policies to provide defences for the impacts of floods at the coastal regions. The rising and variable sea level in association with mean sea level changes and the related frequent storms are expected to exacerbate the risks to the coastal environment and community. Nicholls (2010) estimated that on a global scale, millions of people currently live below normal high tide levels and several hundred million people are exposed to flooding risks majority of whom live in African coasts and the Asian region which are characterized by high population growth and low levels of developments. Most coastal regions and islands are in principle subjected to flooding as a result of relative and climate induced sea level rise (figure 2.5).

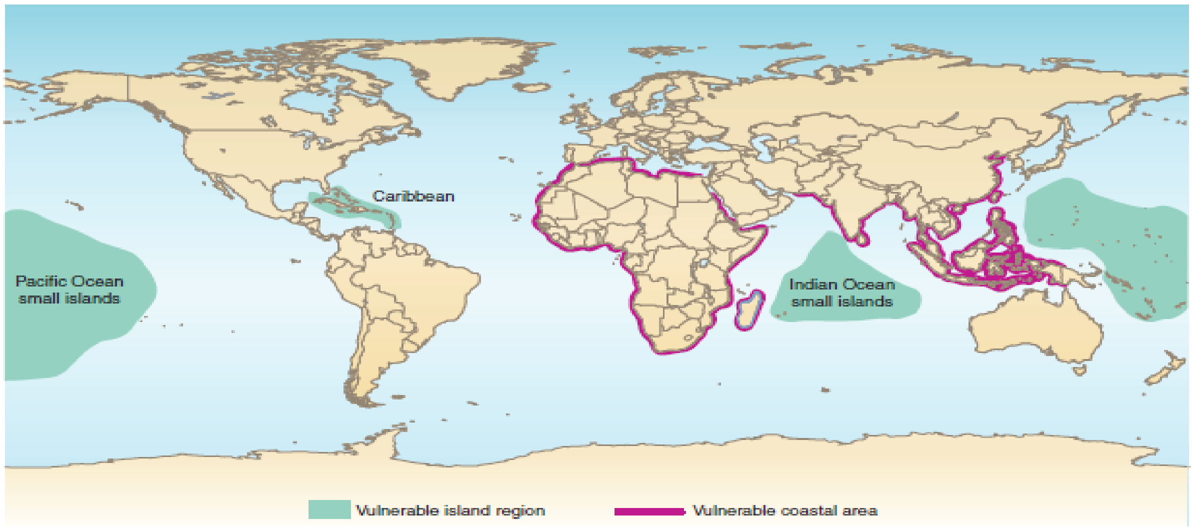
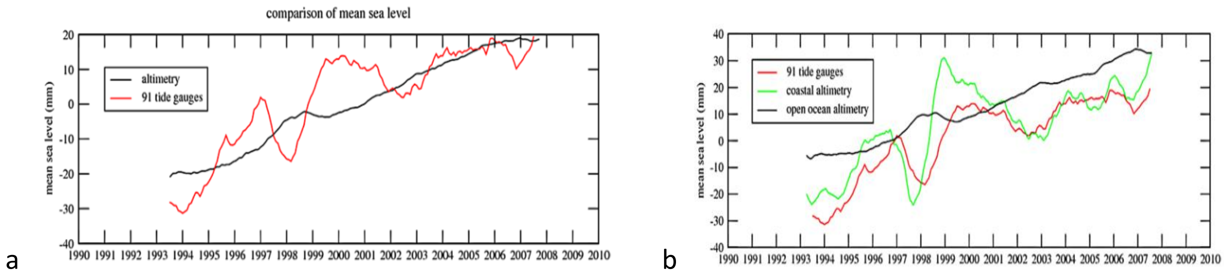


Figure 2.5: Vulnerability to sea level rise at the coastal zones and Islands (Robert Nicholls 2010).

Reliable and efficient levels of adaptation measures have been recommended to adequately address the anticipated impacts due to sea level rise. These measures range from implementations of efficient coastal management policies in the form of upgrade of defences and accurate and timely warning systems to proper land management practices. Regardless of the overwhelming evidence for global sea level rise, certain regions have been observed to experience sea level fall attributed majorly to surface cooling in climatologically upwelling zones, tectonic processes which raise the land on which tide gauges are located and glacial isostatic adjustment (GIA) induced rebounds in high latitude areas which were once sites of large glaciers during the last glacial maximum (Peltier 2001).

Comparison of regional and global variations of sea level trends (Fig 2.6a & b below) shows a possible influence of meteorological effects (non- uniform solar heating of the ocean and salinity variations), oceanographic in terms of circulation changes and hydrological forcing (water exchange between land and the ocean) on sea level variability (Prandi et al 2009).

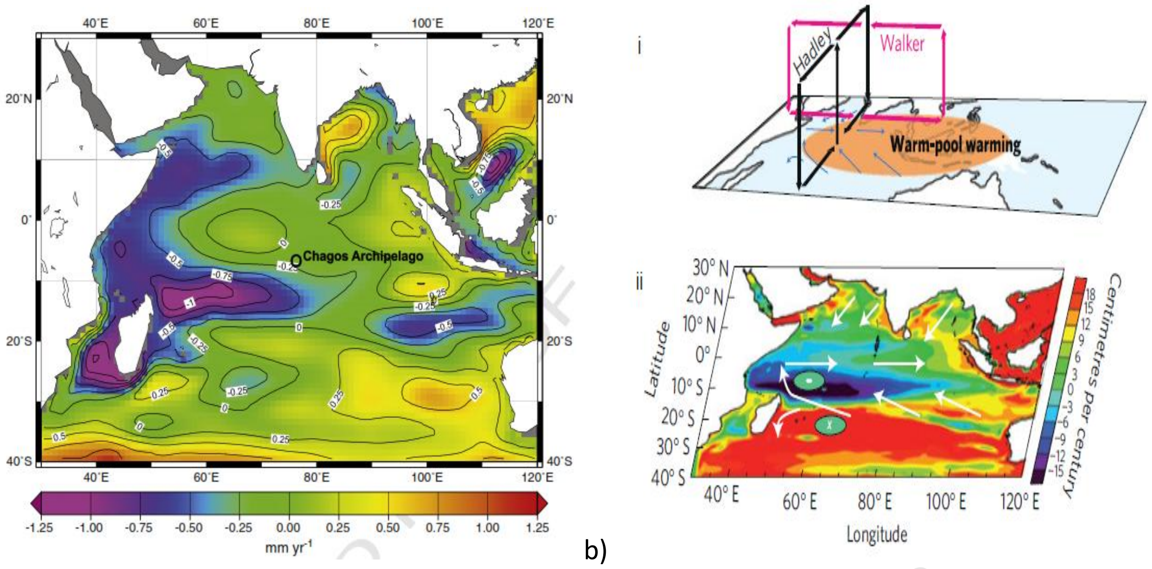


Figures 2.6a Global mean sea level derived from satellite altimetry (black curve) and averaged at 91 tide gauge sites over 1993 – 2007 (red curves) and b: coastal mean sea level calculated from tide gauges (red curve), compared with coastal altimetry mean sea level (green curves) and open ocean altimetry mean sea level (black curve) - Prandi et al (2009).

Indian Ocean sea level variability (especially South western Indian Ocean) has been linked to several factors which include human produced greenhouse gases and wind stress in association with Ekman pumping velocity in addition to other meteorological and climatic factors. Han et al (2010) reported that most regions in the South West Indian Ocean where sea level has dropped notably Zanzibar coast are in a region regarded to be climatologically upwelling zones where mean sea level is low in comparison to the surrounding areas.

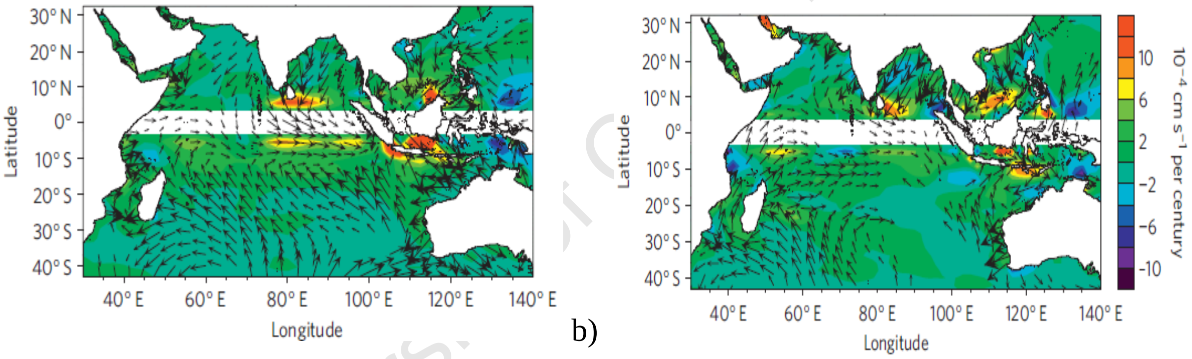
The constant trends of climatologically sea level fall and rise stretches southwards with a noticeable slight increase in mean sea level especially south of 25° S (Fig 2.7a below). The climatological effect is thought to be less effective in the north and west Arabian Sea level variations. It is thought that the enhancement of the inter-tropical convergent zone near the Equator is associated with the low level branch of the strengthened local Hadley cell averaged over the Indian Ocean while the enhanced equatorial westerly winds are associated with the strengthened Indian Ocean Walker cell which together influence the enhancement of upward air motion that occur in the central and eastern equatorial Indian Ocean (Han et al 2010). The strong intertropical convergent zone is conspicuous during both summer and winter periods while the strong equatorial westerly occurs mainly during the Asian summer monsoon and influence sea level variations.

In Figures 2.7 below, warming is considered to strengthen the Indian Ocean regional Hadley and Walker cells Fig 2.7b (i), which then combine to form a definite pattern of surface wind change indicated by the surface arrows in **i** and **ii** (Fig 2.7b) and together with the Ekman pumping velocity represented by positive-circle with dot and negative-circle with x (Fig 2.7b) control the distinct sea-level pattern (colour contours in ii).



a) b)

Figure 2.7a: Sea Level trend in Indian Ocean during 1961-2008, b: Indo-Pacific warm-pool warming cause of the Indian Ocean sea-level variations (ICOADS) - Dunne R.P. et al (2011).



a) b)

Figures 2.8a & b: European Center for Medium-Range Weather Forecasts and NCEP 40-year reanalysis winds (zonal and meridional wind stress) in Indian Ocean for 1961–2001 - Han et al 2010

The general flow of surface wind stress in Indian Ocean (Fig 2.8a & b) shows a characteristic convergence towards the equatorial region of the ocean due to the anomalous south-easterly (north-easterly) winds that originate from the southern (northern) hemispheres respectively (Han et al 2010). Westerly wind trend is dominant over easterly winds during the inter-monsoon periods along the equator and enhances the mean wind flow and forms the positive trends of the Ekman pumping velocity in the south tropical Indian Ocean which is associated with ocean mass divergence as was observed by Wyrtki (1973). The combined effects of these winds together with Ekman pumping is believed to either lower the sea level or enhance the upwelling of cold sub-surface water or influences both processes.

The cold water brought to the surface through the process of upwelling is denser and therefore contributes to the observed lower sea level (Yamagata et al 1996). The amplitude of sea level change consequently is reported to increase westwards when the Ekman pumping velocity keeps the same sign zonally. Conversely negative Ekman pumping velocity in the south sub-tropical mid Indian Ocean supports down welling and contributes to the sea level elevations. Near the equator, westerly wind anomalies are responsible for Ekman mass divergence to the equator and subsequence elevation of the sea level (Han et al 2010).

Climate and sea level are mutually related in some special ways in a manner that climate influences the process that control the variations in shape and mass of continental ice sheets which have direct consequences on sea level variability. Other physical mechanisms responsible for the alteration of the atmosphere-surface interface and hence create changes in the transfer of Momentum, heat and moisture between the surface and the atmosphere influence the variability of sea level at the coast (CLIMAP 1976). Atmospheric processes that remove or create geographical barriers in the ocean are also known to alter the ocean currents which are the major conveyors of heat from the tropics to the poles and as such responsible for climate modulation in some regions. Human induced climate change through increased CO_2 emissions and other processes have been identified to persistently cause significant changes which include rising sea level, rising sea surface temperatures and changes in storms and waves (Berner et al 1983).

Higher sea levels have been linked with direct and instant impact on coastal areas which are characterized by dense population, productive lands and increasing infrastructure development such as ports and harbours, industries and power stations as well as largely built environment (Suchs et al 2001 and Mc Granahan et al 2007). The coasts support important and productive ecosystems which are sensitive to sea level rise and changes in the climate and require protections from the impacts that are related to sea level change (Kremer et al. 2004 and Crossland et al 2005). An indirect link between increased volcanism, higher atmospheric carbon dioxide levels and higher global sea levels due to rapid sea floor spreading has also been revealed (Berner et al 1983).

Zhang et al (2000) reported a mean rise in sea levels which translate to a rise in extreme water levels and that changes in storm characteristics could also influence extreme water levels. Similar sentiments were also expressed by Von Storch and Woth (2008). Future increases in the intensity of tropical cyclones could be associated with increases in extreme water levels in the affected areas while changes in tracks, intensity and frequencies of extra-tropical storms were reported by Meehl et al, (2007) as being capable of modifying the occurrence of extreme water levels in mid-latitudes. The changes in mean sea level will also influence the propagation of tides and surges and this could have more effects on extreme water level.

Dronkers (1964), Wiegel (1964); Silvester (1974); Berkeley Thorn and Roberts (1981) and Wood and Flemming (1981) noted in their investigations the need for the design, construction and operations of maritime works and defence measure to provide resistance and protection against erosion and flooding occasioned by sea level rise. The expensive coastal protection against flooding through the construction of suitable and continuous sea-walls has raised concerns and it has been suggested that only the schemes which protect highly vulnerable (low-lying) populated areas and installations or valuable property are justified in terms of costs (Horner 1985).

The occurrence of extensive flooding has been in the past associated with overtopping of defence measures. Different designs of seawalls can be constructed with the primary aim of minimizing overtopping due to high water levels. The recommended and most appropriate design is a gradually slopping defence that progressively removes the energy of the incoming waves as opposed to the vertical wall which perfectly reflects the waves. This is due to the realization that the reflected waves easily interact with other incoming waves and can cause damage to the beach in the form of beach scours, lowering of the beach level and eventual undercutting of the foundations of the defence walls (Owen 1983). The probability of a combined sea level effects and wave impacts describe the areas that need protection. In addition, coastal regions can be efficiently protected through accurate forecasts of the estimated high sea levels and the provision and dissemination of early warnings of impending floods for people to relocate to higher grounds.

The fundamental components of flood forecasting system are a means of detecting and predicting coastal flooding potential and a reliable procedure for conveying the warnings information to the communities in the areas at risk (Horsburgh 2008).

A number of studies have been conducted to investigate the frequencies and trends of extreme sea level changes at specific locations over different time scales and it has been reported that these extreme sea level events cause immediate impacts in the form of flooding and loss of life in different locations and regions (Lowe et al., 2010) unlike the impacts resulting from changes in mean sea level which are much longer term.

Recent studies conducted on sea level extremes on global and regional scales have indicated no significant changes in storminess. Woodworth and Blackman (2004) and Marcos et al, (2009) showed in their respective reports that there is consistency in changes of extreme sea level in a similar manner to changes in Mean Sea Level and deduced that shifts in meteorological patterns particularly storm tracks, are likely to influence local changes in the distribution of extreme events in the absence of significant changes in storminess.

Tsimplis et al (1995) noted the existence of two distinctly different tidal regimes in the coast of southern Europe and reported that the tidal signals at Atlantic coast were much distinct during spring tides while in most locations within the Mediterranean Sea the tidal signals were an order of magnitude smaller with the important exceptions of Adriatic Sea and the Gulf of Gabes. Thus in most of the Mediterranean basin, sea level extremes is mainly caused by storm surges rather than by the combined effects of tides and surges (Marcos et al., 2009).

Searson and Brundrit (1995) carried out investigations on extreme high sea levels around the coast of South Africa and reported the tidal ranges of the order of two metres and classified the coast as a meso-tidal coastal environment. Their investigation also showed the occurrence of monthly extremes sea levels during spring tides and displayed seasonal variations as the weather related residuals.

Woodworth and Blackman (2004) reported in their investigation on global tide gauge observations that there was evidence for an increase in extreme high water levels worldwide and in a number of the case studies, the secular and interannual variability in the extremes were found to be similar to those in the Mean Sea Level (changes in extreme water levels were related to the changes in Mean Sea Level).

Investigation on flood and surge mechanisms along the French Atlantic coast reported a slight decrease in the main factors that contribute to surge development in the last half century (Bouligand and Pirazzoli (1999) and Pirazzoli 2000) while Pirazzoli et al (2006) reported that the medium term coastal flood risk due to high waters levels in the recent decades had increased on the English side of the channel as compared to the French coast.

Aruajo et al (2002) conducted a study on the trends of non-tidal variability at six channel sites and reported a small but significant trends in extreme sea levels at Brest and Newlyn for periods of 120 and 184 years respectively but investigations done at Trieste over the period 1939- 2001 by Raicich (2003) reported no significant evidence in trends for weak and moderate surges while the frequency of both the strong positive and negative surges were observed to decrease.

Investigations on non-tidal residuals by Bromirski et al (2003) at San Francisco since 1958 reported that winter residuals had exhibited a significant increasing trend while D' Onofrio et al (1999, 2008) observed a trend of extreme levels at Buenos Aires similar to those in Mean Sea Level. Significant changes in extreme sea levels for an extended period in a number of Autralian locations have been reported and the high water levels due to a combined effect of storm surge and Mean Sea Level of two longest records (Fort Denison in Sydney, New south Wales, and Freemantle western Australia) have been observed to increase and is consistent with increased regional coastal flooding during the 20th Century (Church et al 2006).

Differences between observed sea levels and those expected from tides can arise from a wide range of ocean processes in addition to storm surges (Pugh 1987). In a related investigation of extreme sea levels caused by ocean eddies, Firing and Merrified (2004) found long term increases in the number and heights of extreme daily mean sea level values at Honolulu in relation to a fixed datum but no evidence was found for an increase in connection to the underlying upward trend in mean sea level.

Zhang et al (2000) carried out a study to determine the magnitude of floods in US west coast and reported no significant increase in modern storms over the US west coast during the last century and concluded that the flooding events was exacerbated by the effect of increased Mean Sea Level. Bernier and Thompson (2006) observed a small reduction in extreme events in the North West Atlantic between 1960 and 1999 and related the changes to alterations in atmospheric conditions.

These revelations could be important with regards to coastal impact studies since the uncertainties about future projections of extreme sea level and mean sea level are likely to be the same for the next few decades.

Zhang et al (2000) and Woodworth and Blackman (2004) found in their respective investigations that global sea level has risen by approximately 18cm through the 20th century which they indicated was faster than during the 19th century. This estimate seems small but has had various significant implications particularly in the estimation of return periods of extreme water levels and has contributed to accelerated erosive characteristic tendency of the coasts as was widely observed by Bird (1985, 2000) and Vellinga and Leatherman (1989). It is however not logical to associate global sea level rise directly to impacts at the coast because the coastal zones have been subjected to multiple drivers of changes over the 20th century Rosenzweig et al (2007).

The rate of shoreline recession and long term rate of relative Sea Level Rise (RSLR) away from inlets and engineered shores support the concept of Brunn Rule, where the shoreline receding rate is between 50 to 100 times the rate of Relative Sea Level Rise (Zhang et al 2004). Mimura and Nobuoka (1996) also found a similar relationship on a subsiding coastal plain in Japan. However, near inlets, indirect effects of sea level rise which causes the associated estuaries or lagoons to trap beach sized sediments can have much larger erosion effects on the neighbouring open coasts than predicted by Brunn rule (Stive 2004).

Lack of continental wide study that can provide information and comparable results for all African countries has made the vulnerability assessment a major challenge. It is on global scale assessments like in the case of Deltas and relative sea level (Ericson et al 2006), and coastal flooding and wetland loss due to global sea level rise (Nicholls 2004) and port cities and exposure to coastal flooding (Nicholls et al. 2008) that African interests have been considered. Africa compared with other global regions has been found to be limited in continuous historical sea level data to facilitate the research in sea level rise (Woodworth et al (2007), PSMSL (2007) and Menendez and Woodworth (2010)). The limitations prevent desirable assessments of coastal impacts and vulnerability as uncertainties still surround the sea level change rate in this region with respect to other global regions. There is also little quantitative data concerning local uplift and subsidence.

Studies have revealed that a number of coastal African communities are highly vulnerable to climate change and sea level rise leading to increased rates of coastal erosion and flooding of low-lying coasts (Ibe and Awosika (1991) and de la Vega-Leinert et al (2000)). Other related studies by Nicholls et al (1999) showed that, a mean global sea level rise of about 0.38m in combination with population growth scenario and inadequate protection upgrade will increase the average number of people that experience annual coastal flooding in Africa from one million per year in 1990 to about seventy million per year in 2080's.

UN-HABITAT (2008) vulnerability assessment in Africa indicated that many of the major coastal cities around the African continent will be affected by the rising sea level and sea level extremes, and the impacts could be severe due to lack of adequate information and preparedness and adaptation through adequate drainage developments and soft engineering to withstand severe and extreme weather conditions.

Nicholls (2006) reported that about 30 million people around African Atlantic and Indian Ocean live within the flood hazard zones and are likely to be impacted by storm surges in coastal areas (potentially exposed population) and about 2 million people per year could potentially be flooded in the 2020's.

Von Storch and Reichardt (1997) carried out study of storm surges in the shelf sea around Western Europe and found that the changes in storm surge amplitude (relative to mean sea level) resulting from changes in climate related to a doubling of atmospheric carbon dioxide fell within the limit of natural variability. Flather and Smith (1998) used ECHAM3 climate model in the European shelf region to derive storm surge model for present day and future climate time slice and found that the surge extremes were different for future and present day simulations but the differences were mostly within the natural variability as estimated from longer storm surge simulation driven by surface forcing from a meteorological reanalysis of the period 1955-94.

Lower et al (2001) investigated the projected 21st century changes in extreme water levels using 20-years and 30-years' time slice from the Hadley Centre Global Ocean-Atmosphere coupled climate model (Had CM2) and downscaled these to 50km using the atmospheric regional model HadRM2 and reported significant changes in extreme sea levels at some locations in the European shelf region. Studies conducted on the extreme sea level around the coastline of Australia by McInnes et al (2003) found that the inclusion of estimates of climate change to 2050 (changes in cyclone characteristics and mean sea level rise considered) led to an increase in the area inundated by most severe 5 percent of storms.

Inundation levels caused by the projected future one in every 100-year extreme events around coastal township within Corner Inlet along the southern eastern of Victoria in Australia were found to increase by 15 and 30 percent (relative to land level) under a 2070 worst case scenario. However approximately 100 km stretch along the coast to the northeast in Gippsland lakes, inundation levels due to sea level rise were found to increase by 166 percent under the same scenario (McInnes et al (2006)).

Searson and Brundrit (1995) in their investigation of extreme sea levels around the coast of South Africa pointed out the influence of waves on sea levels and reported that smaller waves built on a higher background sea level can produce similar effects as large waves on a lower background level. In their investigation, they noted the possible negative impacts of extreme sea levels to the coastal environment and community, infrastructure and economic activities.

Mean Sea Level which is described as the average level of the sea over a defined period relative to a fixed bench mark on land near the tide gauge has generally increased globally during the last century due to the thermal expansion of sea water, the melting of ice sheets and glaciers and the hydrological exchanges between the land and the Ocean (Bindoff et al., 2007). However in certain locations the MSL (relative to land) is falling due to vertical rise of the land on which tide gauges are situated. High tide heights contribute to the occurrence of extreme high water levels and astronomical modulations such as the equinoctial spring tides, the inter-annual perigean influence and the nodal cycle can increase the risks of flooding at specific times Pugh (1987). Combined changes in storminess and Mean Sea Level have the potential to modify the frequency and magnitude of extreme water levels.

Extreme water levels pose increased risk resulting from floods which impact coastal and flood plains areas characterized by fertile soil and dense population. Many cities also develop at the coast and coastal property may be very vulnerable to extreme sea levels (Hinton et al. (2007)). Driven by projected increases of sea levels, more intense rainfall, stronger wind speeds, and inundation, coastal and low-lying areas are subject to more risks which are estimated to increase in the future (Hall et al, 2007).

The East coast of Africa has been observed to undergo much faster growth in terms of population due to its fast growing industrial infrastructure, rapid development of fishing, the seaports and tourism (Boko et al. 2007) and many agricultural areas are situated in the coastal zone and are threatened by floods, salination and inundations resulting from extreme water levels. This has far reaching impacts on food supply and industrial products like wood and oil as was expressed by Nyong (2005). City ports are also highly exposed to coastal flooding due to storm surges and given the low wealth and poor development of flood management, the existing exposure is of concern.

Chapter Three: Data and Methodology

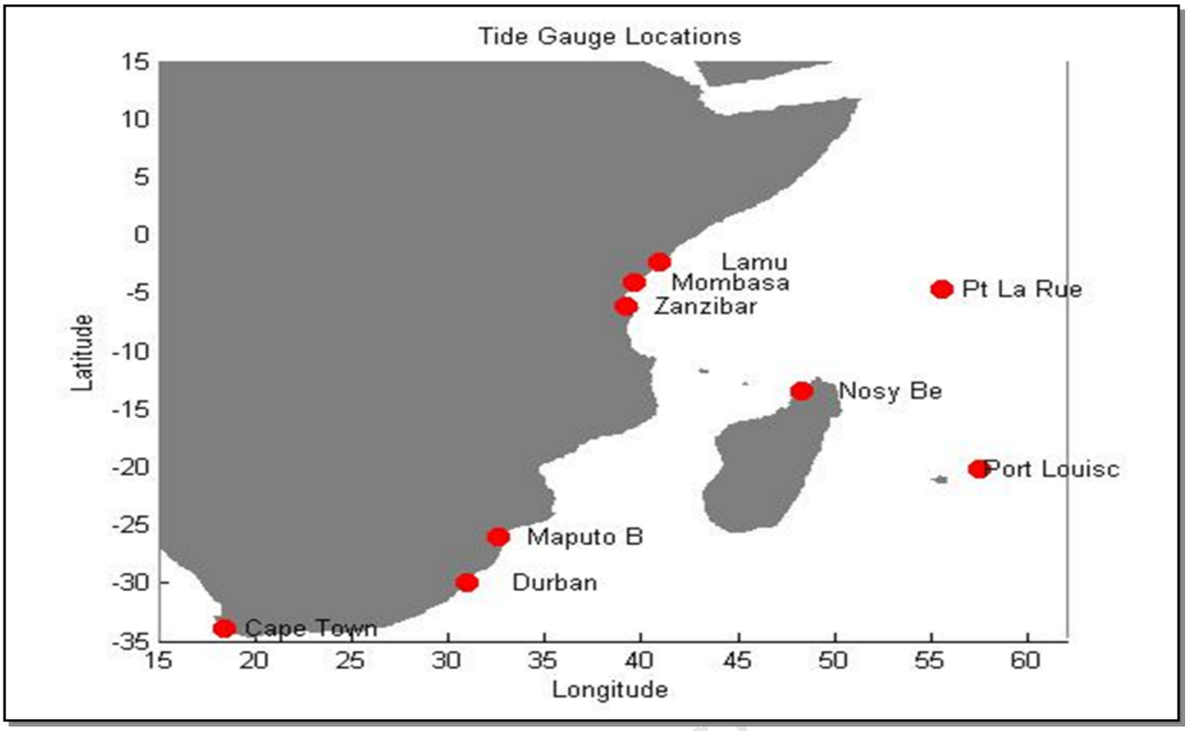


Figure 3.0: Location of tide gauges considered for this study (stations are labelled with their names).

No.	**STN**	**Longitude**	**Latitude**	**Period(years)**
1	Lamu	40.54E	02.16S	1996-2008
2	Mombasa	39.39E	04.04S	1991-2009
3	Zanzibar	39.11E	06.09S	1984-2006
4	Port Louis C	57.30E	20.09S	1986-2008
5	Pt La Rue	55.32E	04.40S	1993-2004
6	Durban	31.03E	29.52S	1979-2007

Table 1: Tide gauges location and data duration.

3.1 DATA

Sea Level data from four tide gauge stations along the East coast of Africa (Lamu, Mombasa, Zanzibar and Durban) and two adjacent Islands (Port Louis c and Pt La Rue) are available at the University of Hawaii Sea Level Center (http://www.uhslc.soest.hawaii.edu) and are research quality datasets. Altimetry sea surface height datasets are available at http://sealevel.colorado.edu/ and http://www.aviso.oceanobs.com. Other data records (wind fields and sea surface temperatures) were obtained from NCEP/NCAR Reanalysis 1 and http://climexp.knmi.nl respectively.

Several corrections and quality control measures have been applied to the hourly sea level data sets acquired from the University of Hawaii sea level center and they include:

a. Gaps or obvious wrong data points identified in the observations which span less than 25 hours are filled with the predicted tide method (Foreman 1977).

b. Timing errors of equal increments of an hour are corrected by shifting the data while reference level shifts are corrected using information from the station and also comparing readings with a fixed benchmark in order to verify that the shifts are not due to natural events (http://www.uhslc.soest.hawaii.edu). These quality control measures applied to the hourly sea level observations are to ensure that the disseminated datasets are of good quality for research.

Hourly values of sea level observations from the four tide gauges located along the East Coast of Africa (Lamu, Mombasa, Zanzibar and Durban) and two from adjacent Islands (Port Louis C and Pt. La Rue) were considered for this study. Each complete normal year comprised of approximately 8760 values of hourly sea level observations which are measured relative to the local tide gauge bench mark. The length of the data records for each station varies from a minimum of 11 years at Pt. La Rue in Seychelles to about 39 years of records at Durban tide station at the coast of South Africa. A summary of the data records is represented in table 1 above.

Most of the sea level records were fairly complete during the considered periods of the study except for some duration when gaps were observed in the records. Stations which had very short records and approximately more than 40 percent gaps in the records were omitted from the study (Nosy Be and Maputo B). The presence of the gaps which are not systematic but fairly distributed throughout sea level records has no major consequences to an analysis procedure (Tsimplis and Shaw 2010). The study was primarily intended to determine the components and variability of the high water levels and trends but not the return periods of the maxima events which are affected by the presence of gaps in the records.

3.2 Methodology

A visual examination of the data sets was carried out by plotting the data using computer in built software and checking for timing errors and datum shifts. There are various problems that are associated with tide gauge datasets along the East coast of Africa and the adjacent islands. The major problems are related to the quality control that is apparent in the residuals, and lack of continuous and long period records for confident time series analysis. It is therefore important that the quality of data for sea level investigations be given priority in order to achieve better results for more accurate and reliable interpretation.

3.2.1 Classical Harmonic Analysis

Tidal constituents with a signal-to-noise ratio equal to or larger than three are fitted to the time series by harmonic analysis using the standard program t-tide (written in MATLAB) developed by Pawlowicz et al (2002). This package is applicable in classical harmonic analysis for periods of one year or less of sea level data to generate the tidal constituents in terms of the amplitudes and phases. The generated constituents are then recombined for the generation of time series of the astronomical tide at a particular site as was also applied by Brundrit (1995) in sea level investigation around the coast of South Africa. Filtering is carried out to remove the unwanted high frequency component and retain the low frequency with nearly zero phase shifts in the time series for the determination of both short term and long term variability of the oceanographic signals.

T-tide package can be used to perform classical harmonic analysis with nodal corrections and infer valid conclusions from the data and make predictions using the analyzed constituents. Other advantages of using t-tide package include the fact that it is implemented in Matlab which is an analysis package widely used by oceanographers and therefore allows for efficient use within the software framework and a complete analysis involving plotting of raw data (Pawlowicz 2002). The basis of harmonic analysis is the assumption that the tidal variations can be represented by a determined number of harmonic terms. Usually for a period of one year, 60 constituents are considered but in shallow water, more than a hundred constituents may be applicable (Pugh 1987). The estimation of the amplitude and phase can be represented by the following expression (Eq. 3.1):

$$A_n \mathrm{Cos}\,(\sigma_n t - g_n) \qquad (3:1)$$

Where:

A_n is amplitude, g_n is phase lag on equilibrium tide at Greenwich time and σ_n is an angular speed. In tidal notations, the phase lag g_n is expressed in degrees.

Harmonic method of analysis entails least square fitting of the tidal function which is performed rapidly by finding the solution for the system of equations using computer matrix inversion where gaps in the data are permissible and the fitting is confined to the period when the observations were taken. The least squares harmonic analysis has a variety of attractive features that allow the resolution of hundreds of tidal constituents of which about 45 are astronomical in nature and are specific frequency related in the tidal potential (Pugh 1987). The other constituents include shallow water coefficients which are related to bottom frictional effects and non linear terms in the equation of motion and are also related to radiational constituents due to atmospheric effects. The tidal constituents are then used to reconstruct a time series of the form represented by (Eq. 3.2):

$$T(t) = Z_0 + \Sigma A_n f_n \cos[\sigma_n t - g_n + (V_n + u_n)] \qquad (3:2)$$

Where Z_0 represents mean sea level and f_n and u_n are the nodal adjustments (nodal factor and nodal angle respectively). The term $\sigma_n t$ and V_n represent the equilibrium angular speed and phase angle for the constituents at arbitrary time origin and together determine the phase angle of the equilibrium constituent. The nodal factors influence certain lunar constituents notably L_2 which is affected by the 8.8-year cycle while all the lunar constituents are affected by the 18.6-year nodal cycle. These modulations (f_n and u_n) cannot separately be determined from a year of data and therefore should be represented in some way as in equation 3:2 to eliminate the errors related to their effects on tides (Pugh 2004).

The time series of the combined tidal constituents is used to predict, at hourly intervals the contributions of tides to the total water level. When the predicted tidal time series is subtracted from the corresponding total observed water level, time series of hourly residuals which describe the meteorological contributions (storm surge elevations) to sea level heights is obtained. The general and fundamental principle of this analysis is that at a particular time (t), the total sea level (η) can be considered to be the sum of tidal component (x), surge component (y) and mean sea level (z_o) which can be expressed as follows (Eq. 3.3)

$$\eta(t) = x(t) + y(t) + z_o \qquad (3.3)$$

Time series analysis defines the variability of the data in terms of the distinct periodic functions and the shape of the spectrum. The oceanic variability that occurs at the low frequency end of the spectrum is dominated by fluctuations which occur at short time scales and also at seasonal, annual and decadal time periods. Due of the presence of noise in real data, and for accurate resolution of periodic behaviour, data series should include a few repeat cycles of the time scale of interest for better results.

3.2.2 Percentile Analysis:

Percentile method of analysis is applicable in investigating and describing the trends of high water levels caused by changes in storminess or Mean Sea Level. It determines the changes in the distribution and variability at interannual or longer time scales of observed maxima water levels and has been widely used in sea level research. Woodworth and Blackman (2002) applied the percentile method in their investigation of changes in high water levels at Liverpool and Hunter (2002) applied a similar method in determining the cause of flooding at Funafuti, Tuvalu in the central tropical pacific.

The fluctuations in interannual maxima sea levels are assessed by determining percentile changes which is considered to be non parametric and only requires the ranking of the observations and identifying the value that correspond to a particular percentile. The application of higher percentiles is capable of providing reliable solution to the problem of biases in the annual maxima due to incorrectly measured hourly values. Percentile requires only the timing of extreme sea level events and avoids the possible errors in height of the higher water level measurements.

In a normal year with no gaps, 8760 hourly sea level measurements are available and can be ranked in terms of their observed sea levels and used to compute percentile levels for each year. The median corresponds to 50th percentile and is taken to be approximately the same as the mean value (Woodworth and Blackman 2002, 2004). The trends for the annual values are determined for 99.9 percentile for both observed levels and residuals. This study distinguishes between observed annual extremes and the extremes derived after tides have been subtracted (non-tidal residuals).

3.2.3 Statistical Analysis.

A summary and interpretation of the hourly residuals at all the tide gauge stations under investigations in the South West Indian Ocean and the East coast of Africa is necessary for the comparison to be made between the various sites. In order to determine the distributions of the residuals which are weather related, normal probability distribution which describe the spread of data and of the mean residual at specific standard deviations was investigated. The spread of the residuals is a measure of the variability of meteorological effect on sea levels where larger spread shows minimal variability and narrow spread with pronounced peaks indicate significant variability of the meteorological contributions which in effect causes variations of the local sea level.

Chapter Four: Results

4.1 Tidal Pattern and range in the East Coast of Africa and Islands

Tides in the Southwest Indian Ocean are generated by the oceanic response to the gravitational attraction of the moon and the sun and the solar radiation. Tides are usually the pronounced signals in sea level observations and are easy to distinguish from other components of the sea level variation because of their well-defined periods. Tidal characteristics in the SWIO vary in accordance to the nature of and length of coast shelf (regimes) and latitude. Some regions are dominated by semi-diurnal form of tides while other areas are predominantly diurnal. Mixed regimes (where diurnal and semi-diurnal components display comparable magnitudes) are also associated with some areas in this region of SWIO. Tidal analysis was considered important for this research to generate the tide constituents in the form of tide tables which is lacking for the East African region (refer to appendices B).

Figures 4.0 show significant variations in tidal ranges in the East coast of Africa and adjacent islands. The spring ranges are greatest in the East African coast where Lamu (Fig 4a) is about 3.8m, Mombasa (Fig 4b) is 3.8m and Zanzibar (Fig 4c) is approximately 4.0m and reduces with increasing latitude south and north of the Equator as in the case of the southern stations where Durban (Fig 4d) is approximately 2.0m and the Island stations (Pt. La Rue (Fig 4f) is about 1.5m and Port Louis C (Fig 4e) is approximately 0.8m).

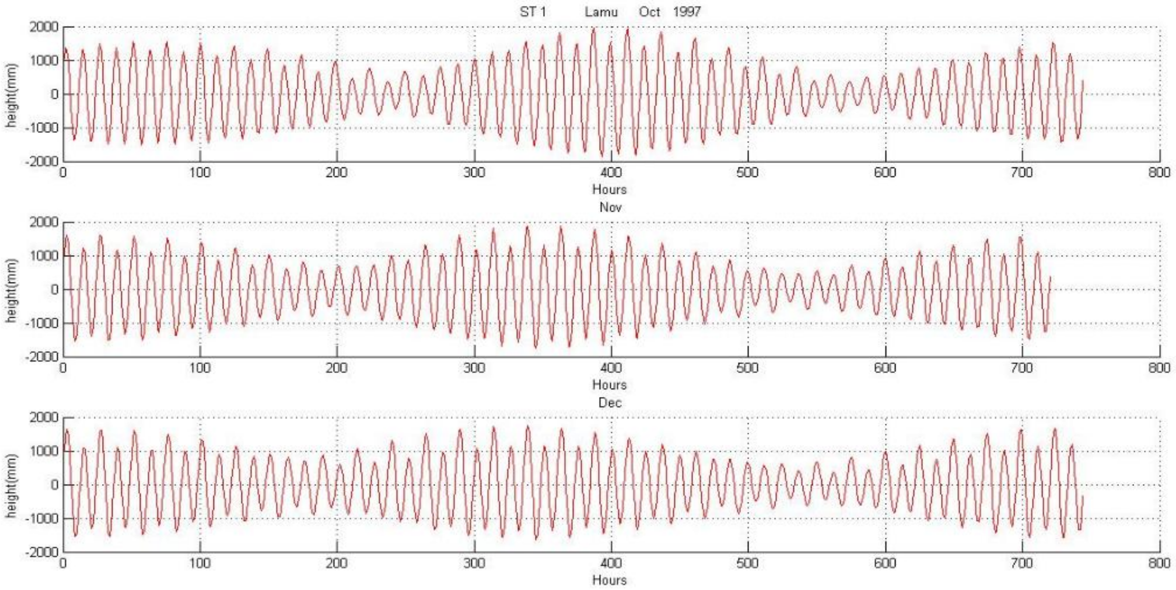


Figure 4a: Semi-diurnal tidal heights and range in Lamu during Oct- Dec 1997

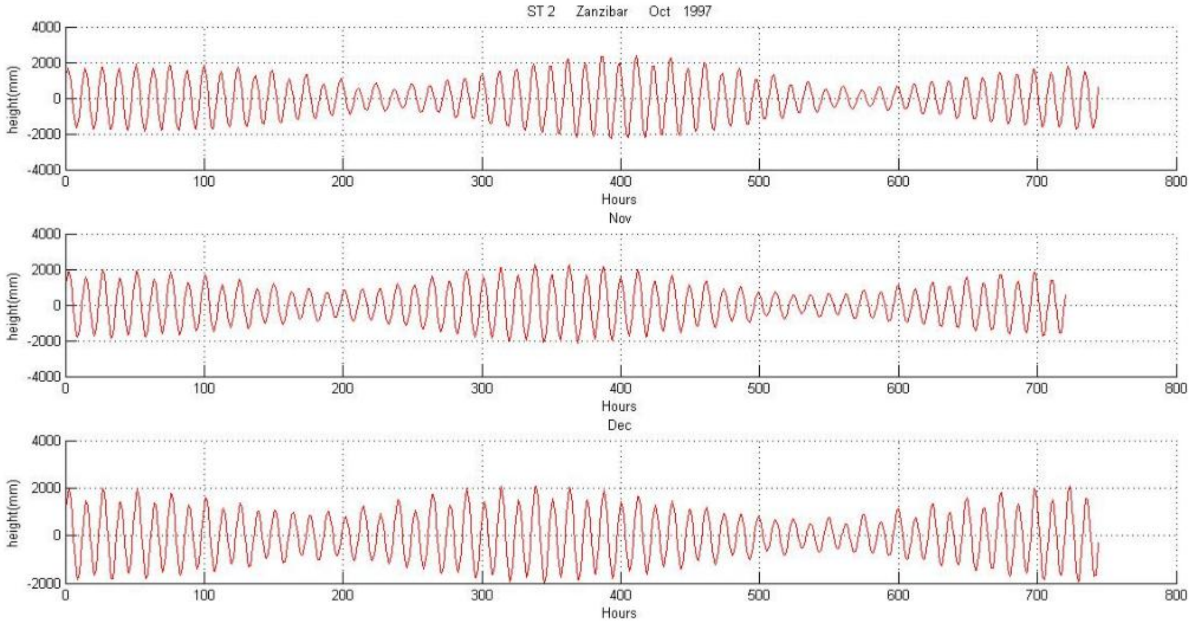


Figure 4b: Semi-diurnal tidal heights and range in Zanzibar during Oct- Dec 1997

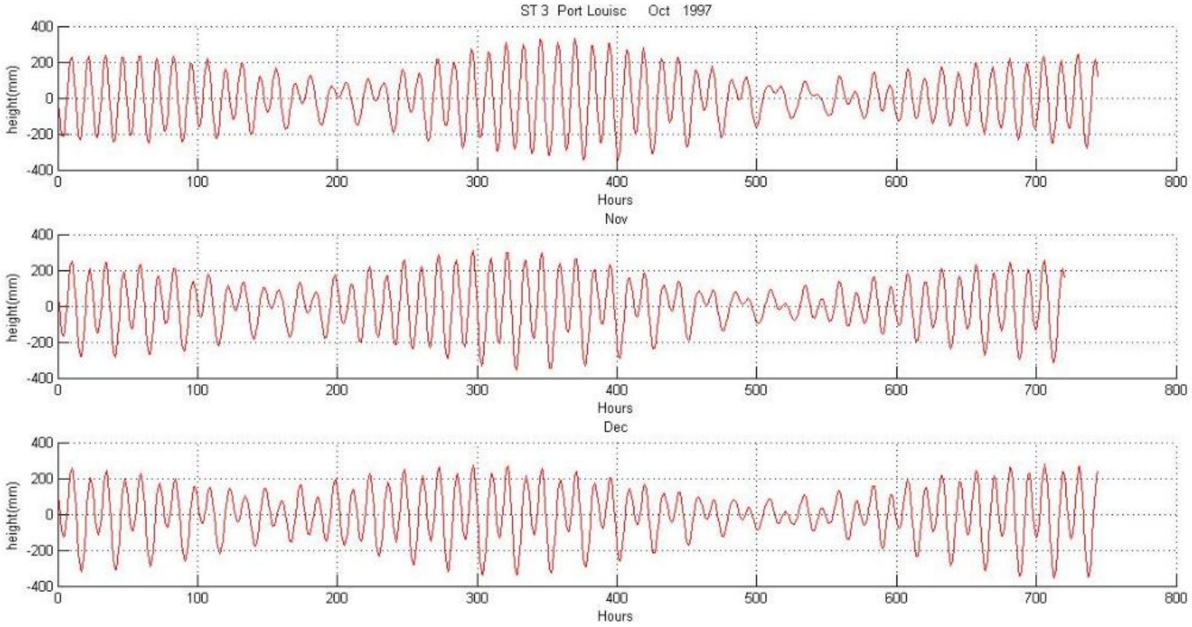


Figure 4c: Semi-diurnal tidal heights and range in Port Louis in Mauritius during Oct- Dec 1997

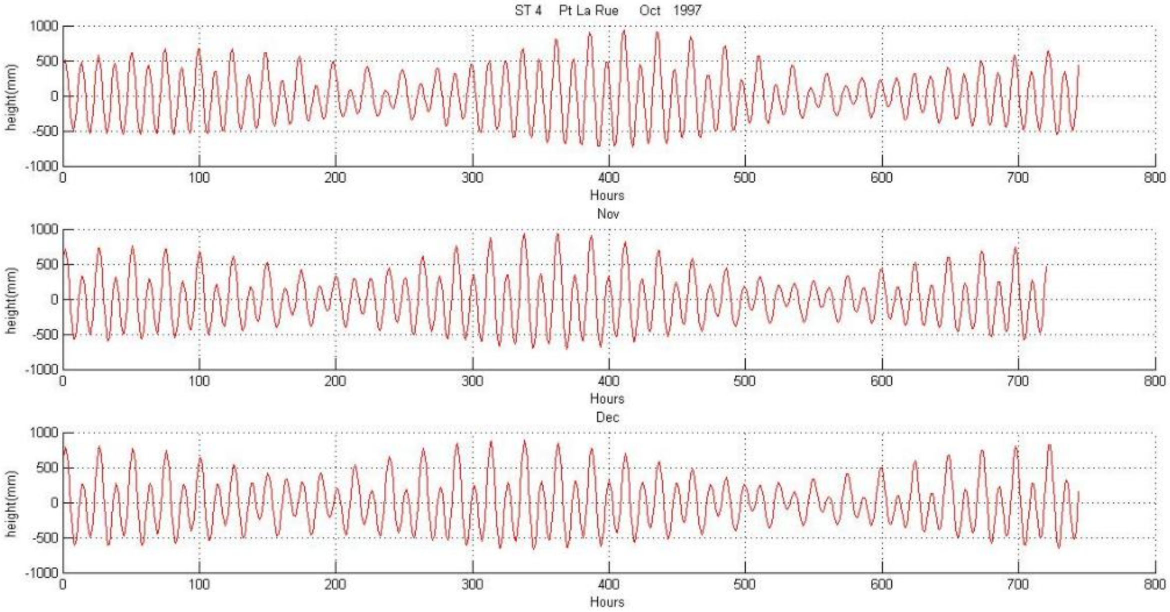


Figure 4d: Semi-diurnal tidal heights and range in Pt La Rue during Oct- Dec 1997

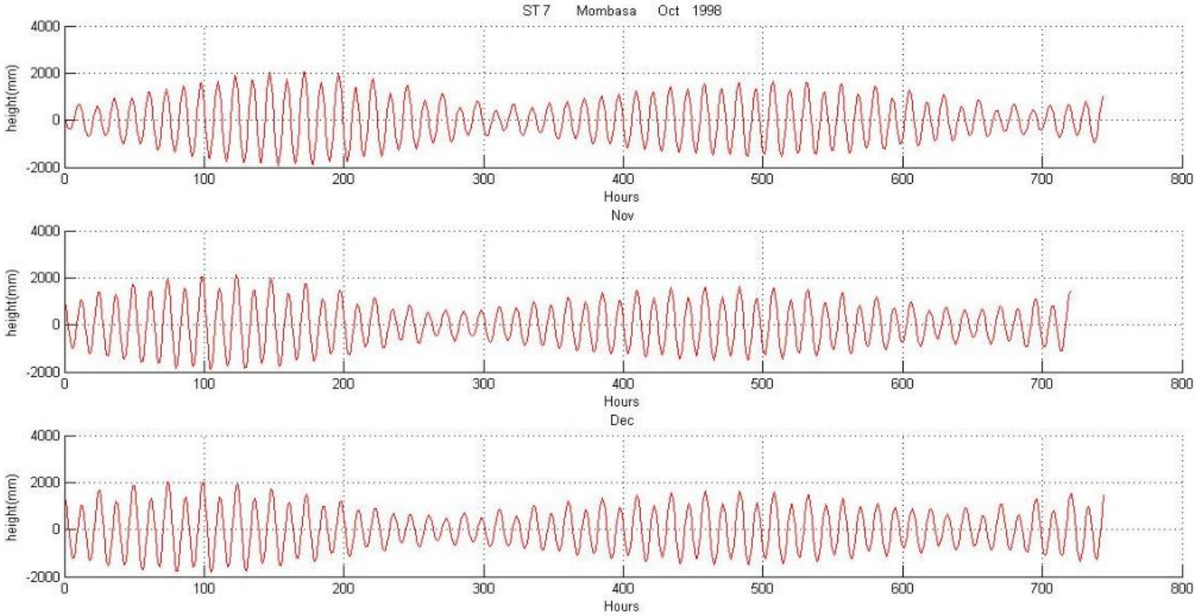


Figure 4e: Semi-diurnal tidal heights and range in Mombasa during Oct - Dec 1998

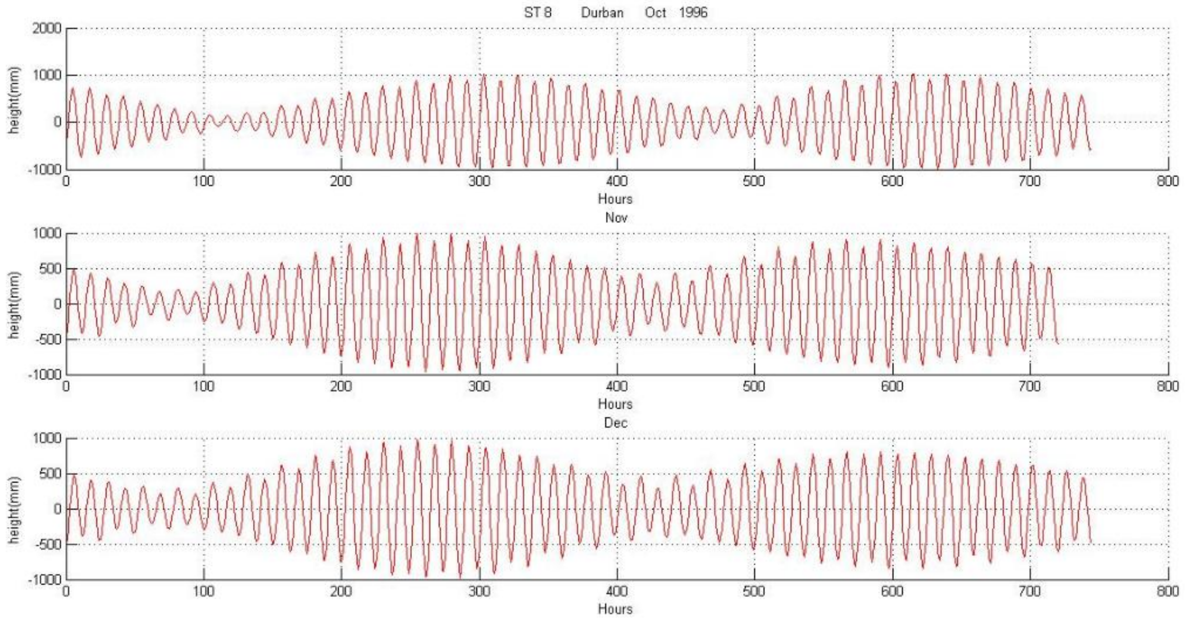


Figure 4f: Semi-diurnal tidal heights and range in Durban during Oct- Dec 1996

The East coast of Africa is dominated by tidal oscillations which are semi-diurnal in nature which manifest in the sea level observations. The semi-diurnal pattern of the tides observed at the East Coast of Africa tide gauge stations can be explained by the lunar and solar declination relation. The varying tidal ranges observed at the East coast of Africa are related to the latitudinal relationship of semidiurnal tides and the continental shelf width with larger ranges associated with zero declination and wide shelf width. This finding is consistent with the global tide models (FES (2004), Munk et al (1965) and Ray and Mitchum (1997)) which show that stations near ocean coastline are sensitive to precise ocean-land boundary with the resultant higher tide at the coast than in deeper sections of the sea. The models also show that near strong western boundary currents (example the Agulhas current) and other sources of strong meso-scale variability, the tidal error are significantly large.

4.2 Residual variability in the SWIO and East Coast of Africa

Figures 4.1 show the variability of residuals in the South West Indian Ocean and the adjacent islands. The results show that surges are more pronounced and variable (maximum of about 25 cm) at the stations in the mid and high latitudes in this region (for example Durban in fig. 4.1d). In the East African coast, Lamu (Fig 4.1a), Mombasa (Fig. 4.1b) and Zanzibar (Fig. 4.1c) surges are characterized by low heights in the range of 15-20 cm and are less variable. It has been established in previous investigations that no two surge events are exactly the same due to small variations in weather patterns which produce different responses in the body of water in regions where there is a tendency for local water-mass resonance and oscillations (Pugh 1987). This is evident in the East Coast of Africa sea level residuals.

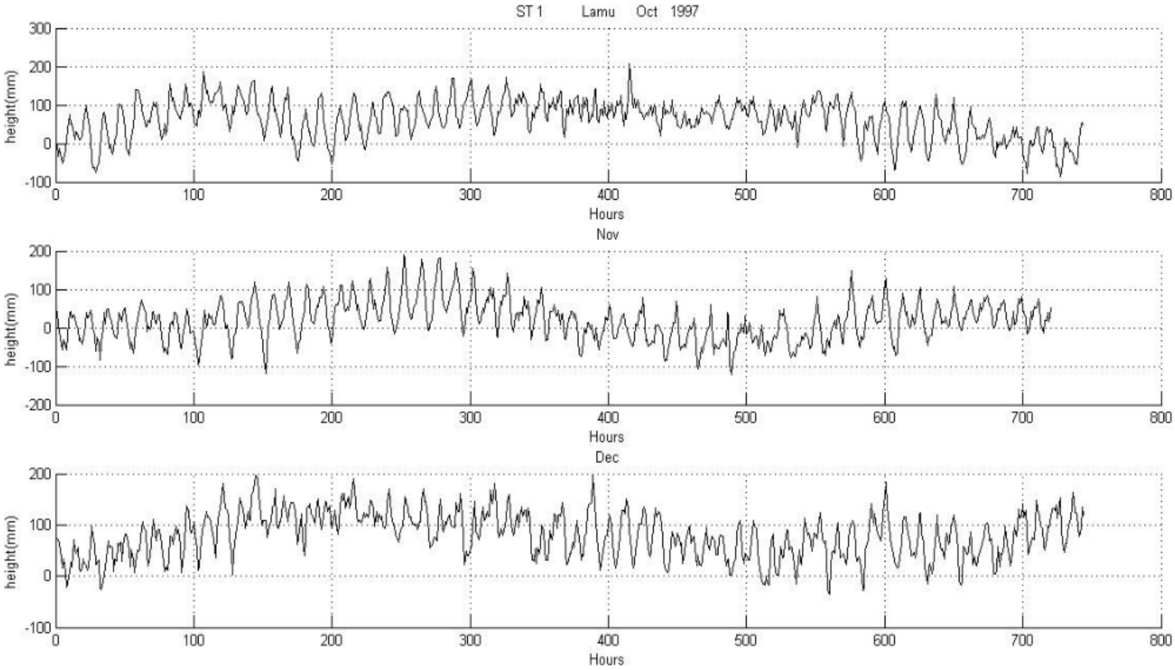


Figure 4.1a: Residual variability in Lamu during Oct- Dec 1997

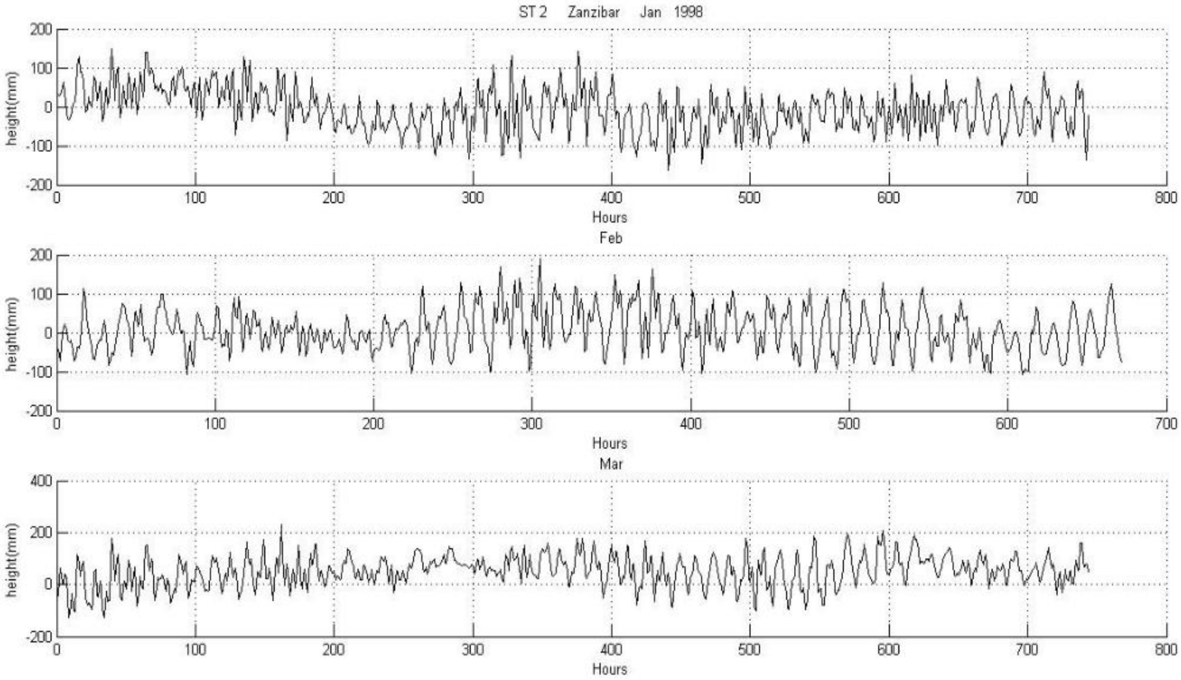


Figure 4.1b: Residual variability in Zanzibar during Jan- March 1998

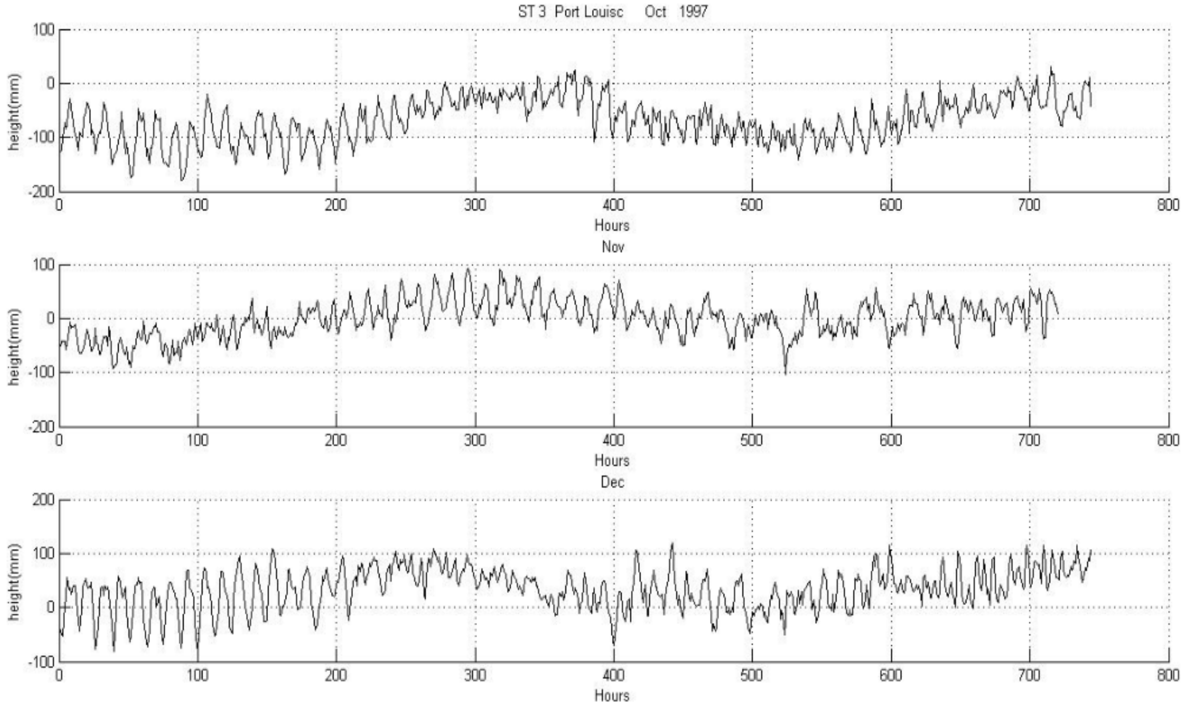


Figure 4.1c: Residual variability in Port Louis during Oct- Dec 1997

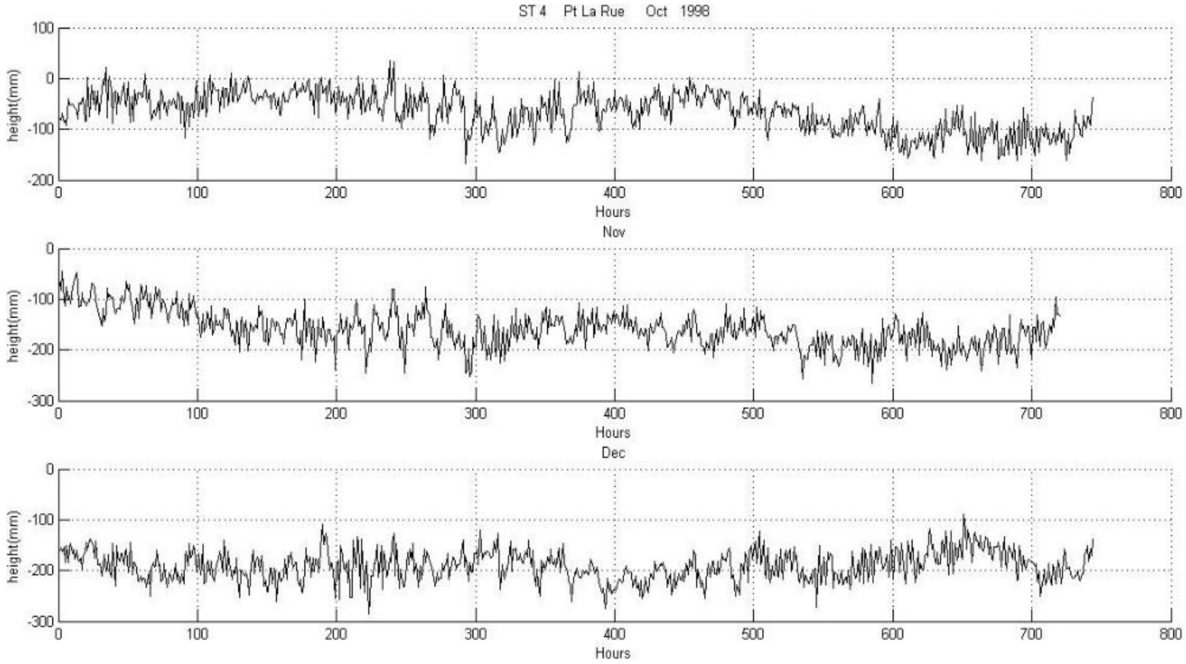


Figure 4.1d: Residual variability in Pt. La Rue Oct- Dec 1998

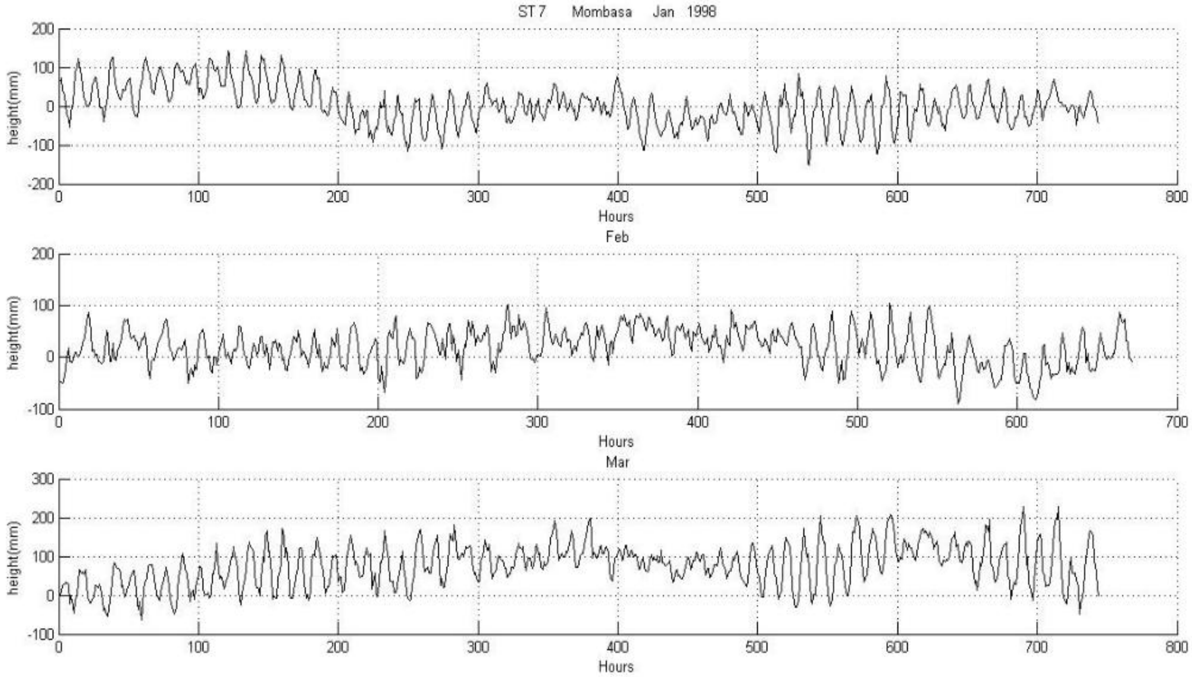


Figure 4.1e: Residual variability in Mombasa during Jan- March 1998

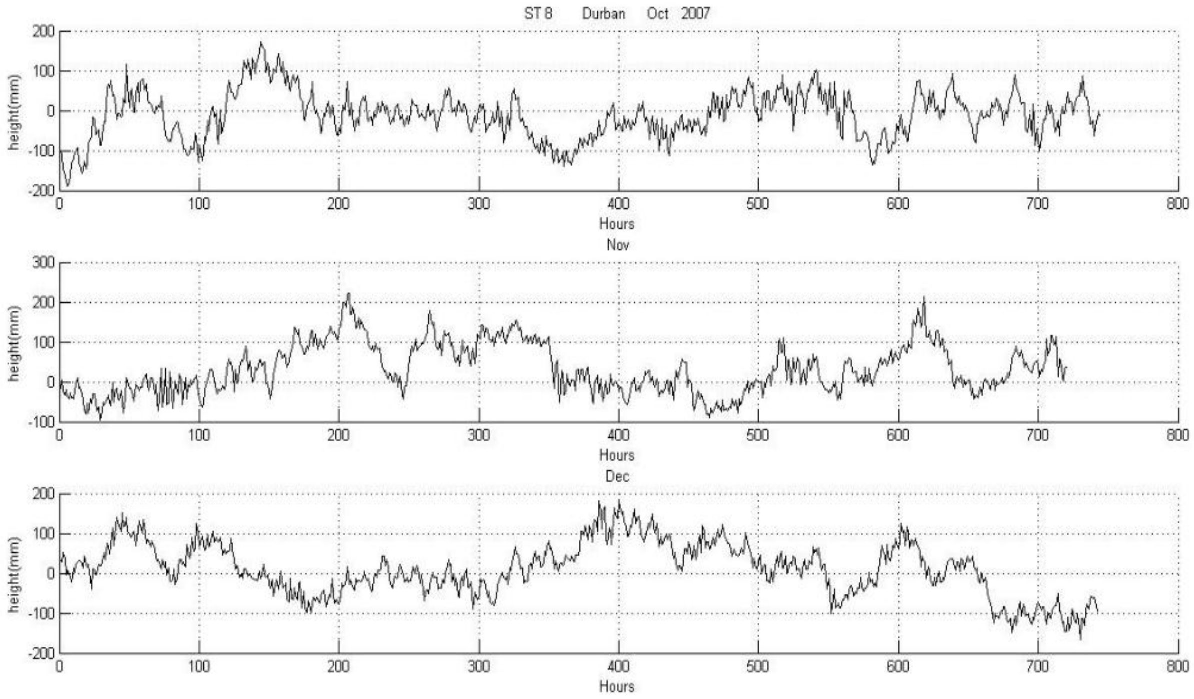


Figure 4.1f: Residual variability in Durban during Oct- Dec 1997

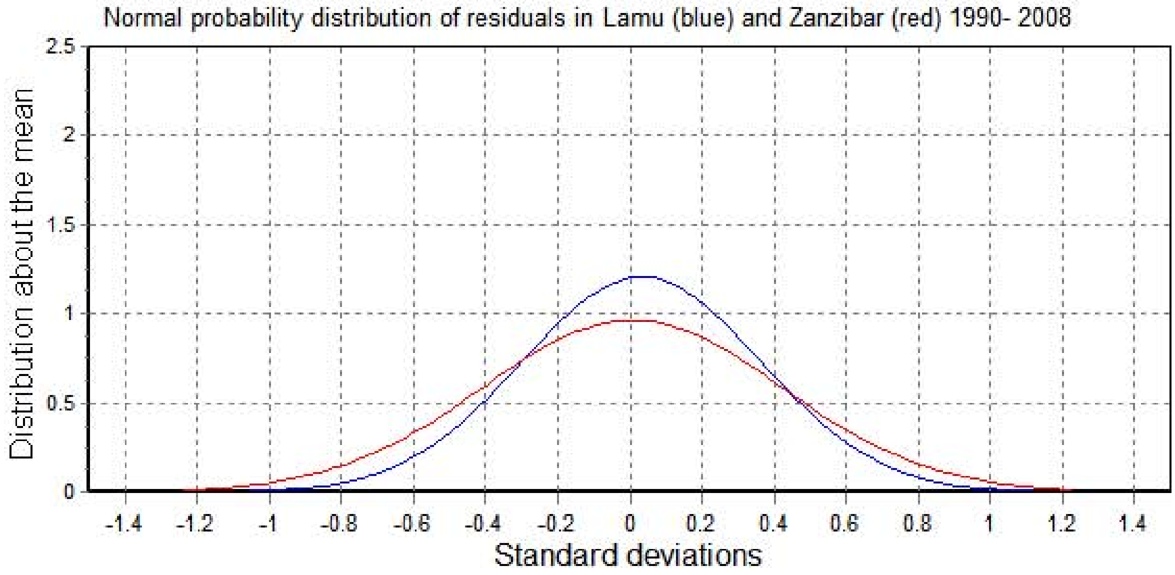
The high and variable surge elevation in Durban (figure 4.1d) could be due to the influence of tropical and extra-tropical storms which affect large areas over extended periods of several days as they pass in this region**.** It is also possible that the interaction between tides and surges is weak in the East African coast leading to incomplete separations of the surges from tide constituents hence the observed weak surge signals (Pugh 1987).

4.3 Probability distribution of Residuals.

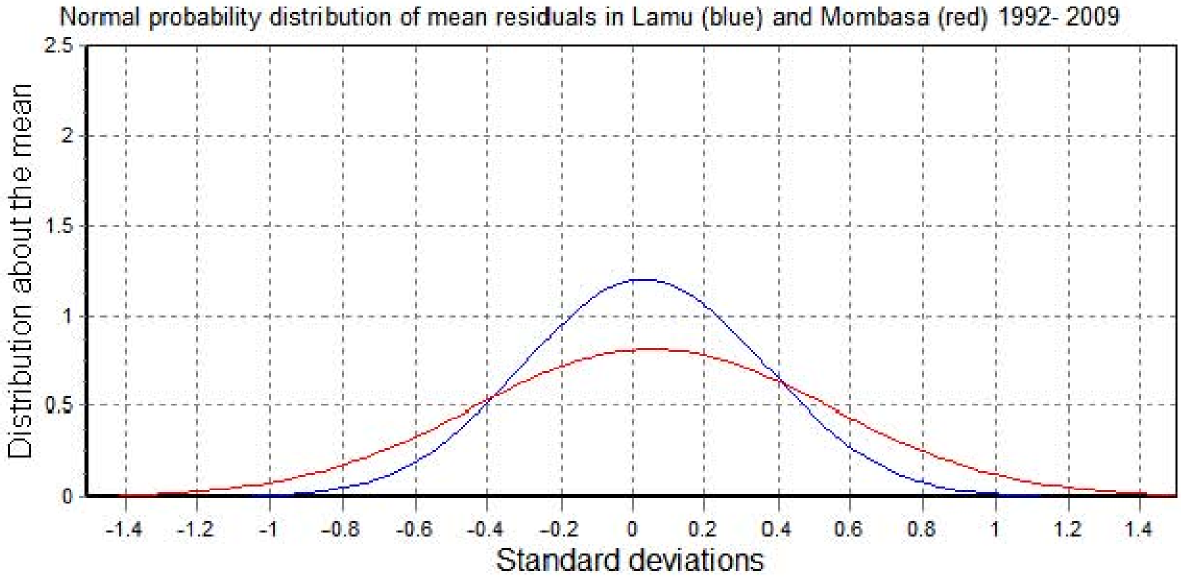
Figures 4.2 represent probability distributions of residuals for selected tide gauge stations in the South West Indian Ocean. Residuals along the East coast of Africa are well spread in the distribution curve. The standard deviations ranges from -1.5 to 1.5 in the East Africa coastal stations (Fig. 4.2 a, b and c) while in Durban the spread is in the range of -0.9 to +0.9 and is well represented in figure 4.2h (red curve). The island stations have the narrowest spread in the distribution curve and ranges from -0.6 to +0.6 but with pronounced peaks (Fig. 4.2g). The distributions of residuals in most of the sea level observations from tide gauge stations under review are uniform indicating that positive and negative surges are to a good approximation symmetrical in the South West Indian Ocean and the East coast of Africa.

The following figures 4.2 show a comparison of the distribution of surges at different tide gauge stations in the South West Indian Ocean and the East coast of Africa. Negative surges are conspicuously dominant in Port Louis where the distribution is skewed to the negative (Fig. 4.2g blue curve)

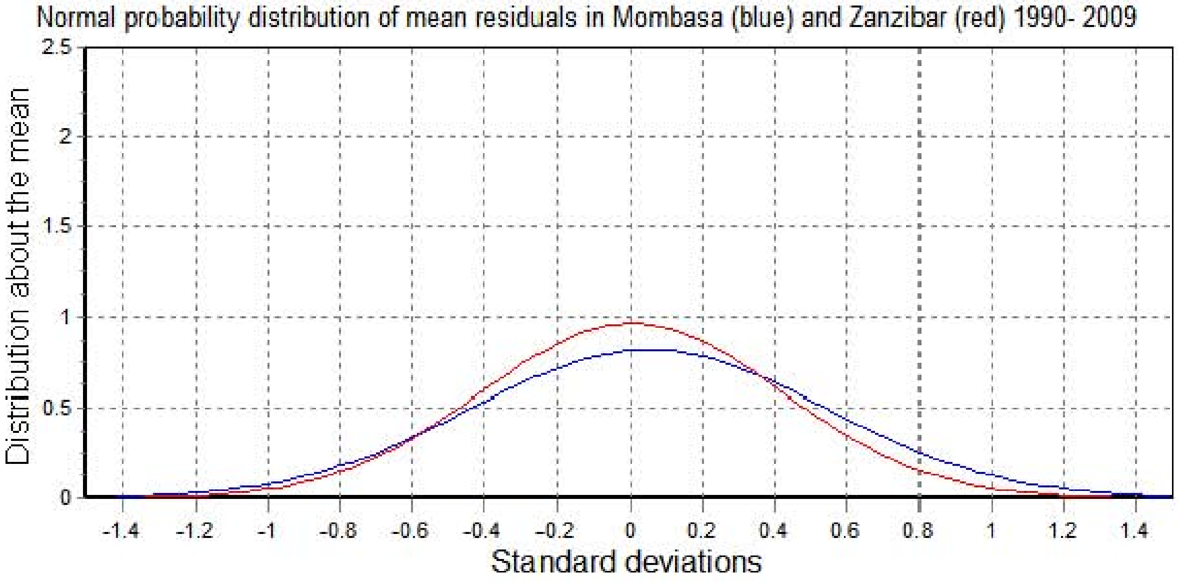
a)



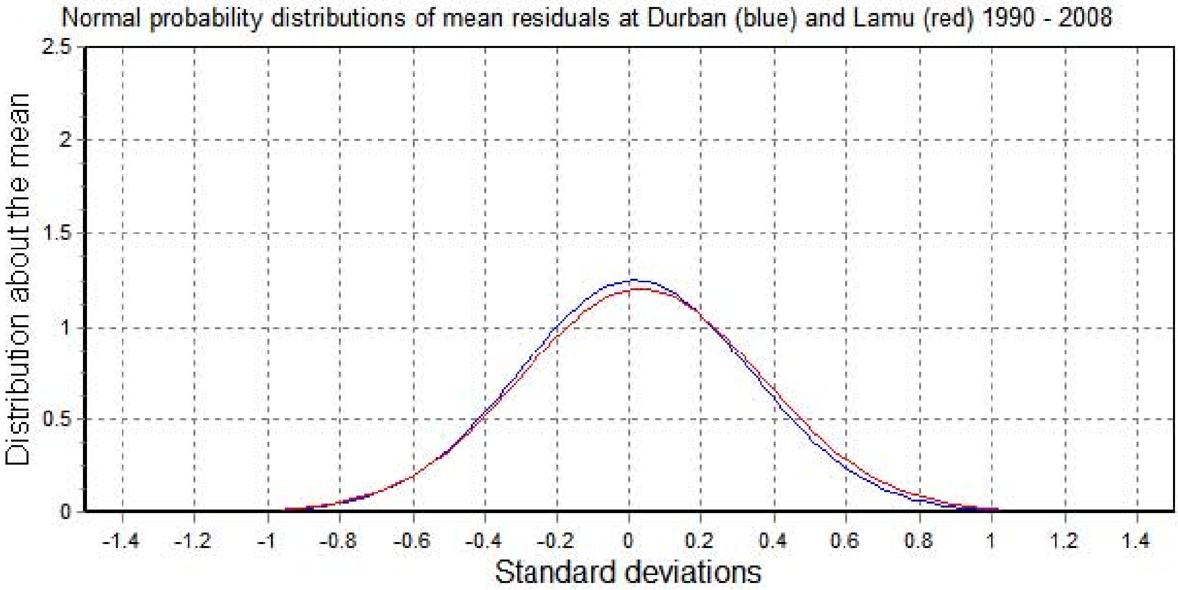
b)



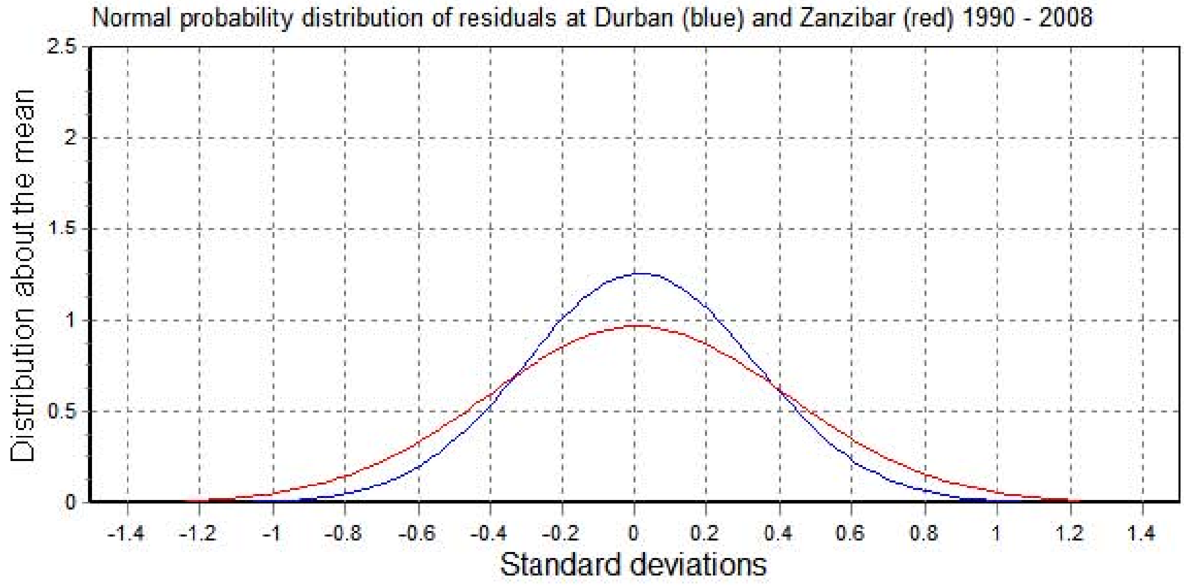
c)


Normal probability distribution of mean residuals in Mombasa (blue) and Zanzibar (red) 1990- 2009
Distribution about the mean
Standard deviations
2.5
2
1.5
1
0.5
0
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4

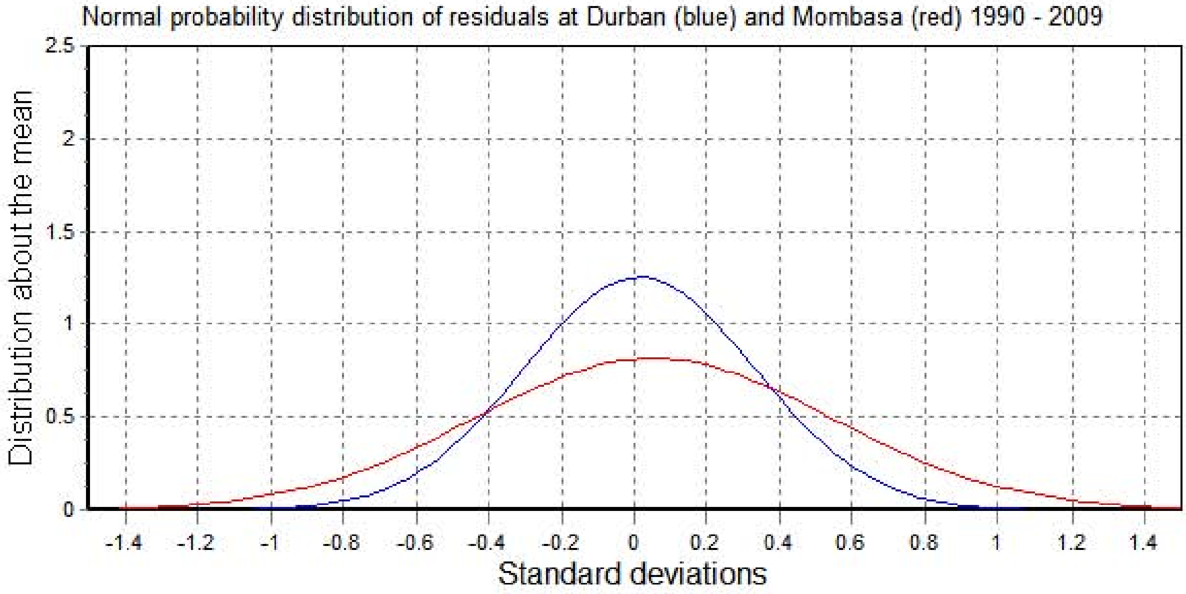
d)


Normal probability distributions of mean residuals at Durban (blue) and Lamu (red) 1990 - 2008
Distribution about the mean
Standard deviations
2.5
2
1.5
1
0.5
0
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4

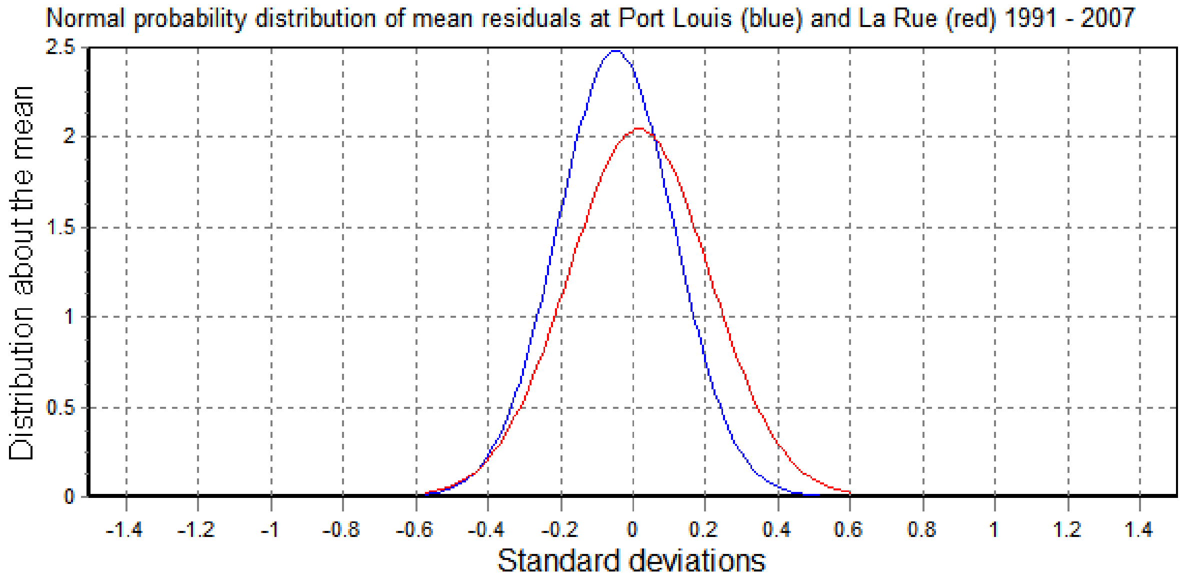
e)


Normal probability distribution of residuals at Durban (blue) and Zanzibar (red) 1990 - 2008

f)


Normal probability distribution of residuals at Durban (blue) and Mombasa (red) 1990 - 2009

g)



h)

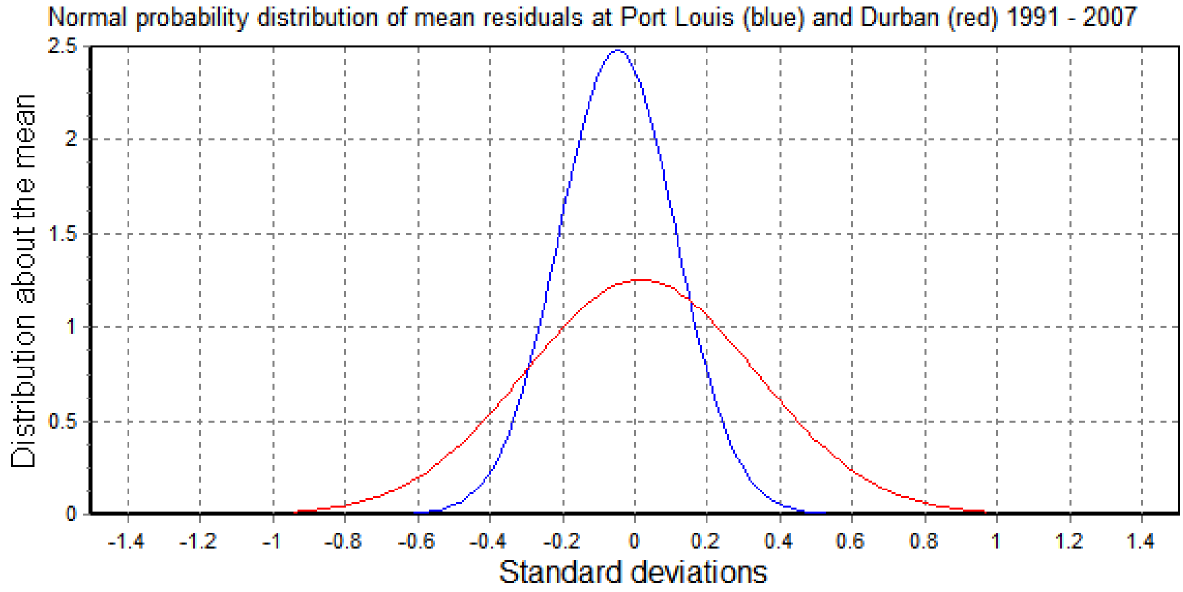


Figure 4.2a -h: Comparison of the spread of residuals at the six tide gauge stations along the East coast of Africa. The normal distribution curve with standard deviations in the range of -1.5 to +1.5 show variability of weather effects.

The distributions of the mean residual at each of the standard deviations (samples) in the above figures diminishes and tend to zero towards both positive and negative infinities and implies low frequencies of extreme meteorological events in the East coast of Africa and the islands under investigation (Pt La Rue in Seychelles and Port Louis in Mauritius).

4.4 Sea surface height and Sea level Pressure Relations in the SWIO and the East Coast of Africa (Inverted barometer effect).

Inverted barometer effect represents the inverse relationship between atmospheric pressure and sea surface height. Monthly mean analysis of the sea surface height in East African coast and the South East Africa coastal regions and Sea level pressure in these two regions (data obtained from http://climexp.knmi, NCEP Reanalysis 1) were compared and the results indicate that sea surface heights are higher in the East African and South east African coastal regions from the month of January to April. Atmospheric pressure tends to manifest in an opposite manner and is lowest during these months (January to April). The inverse relationship between sea surface height and the atmospheric pressure (an increase of pressure by 1mb lowers the sea level by about 1cm and the reverse is true) is significant in the following results (Fig 4.3).

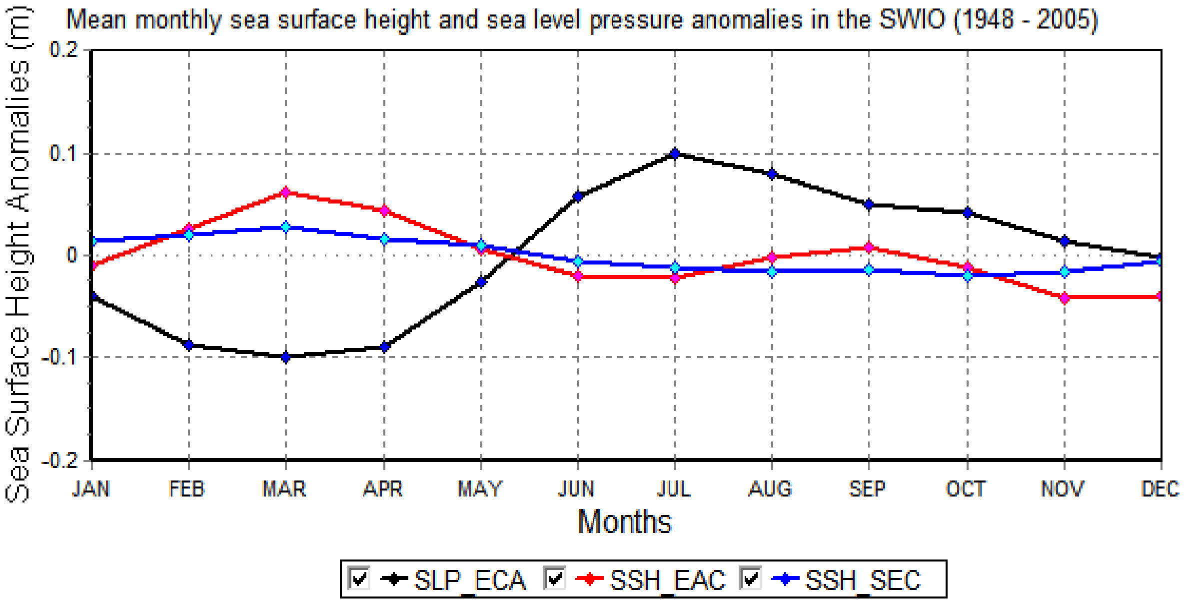


Figure 4.3: Monthly Mean Sea Surface height in the East Africa coast (SSH_EAC- red line), south east coast of Africa (SSH_SEC- blue line) and Sea Level Pressure (SLP_ECA – black line) variations in the South West Indian Ocean and East coast of Africa.

4.5 Tide Gauges Monthly Mean Sea Level Variations in the SWIO and the East coast of Africa

Figures 4.4 – 4.8 show bi-modal peaks of elevated sea level anomalies in the Monthly mean analysis of tide gauge sea level observations in almost all the stations under review in the East coast of Africa and the Islands except for Port Louis in Mauritius. March to May and September months are characterized by higher sea level anomalies over the region of South West Indian Ocean. Between the two peaks of maxima sea levels are the Months of July and August when the anomalies are significantly low. November through to February is characterized by lower sea level. It is also significant that the peak during March to May is greater than September peak and could be related to the influence of varying meteorological effects during these months and also the contributions of equinoctial spring tides.

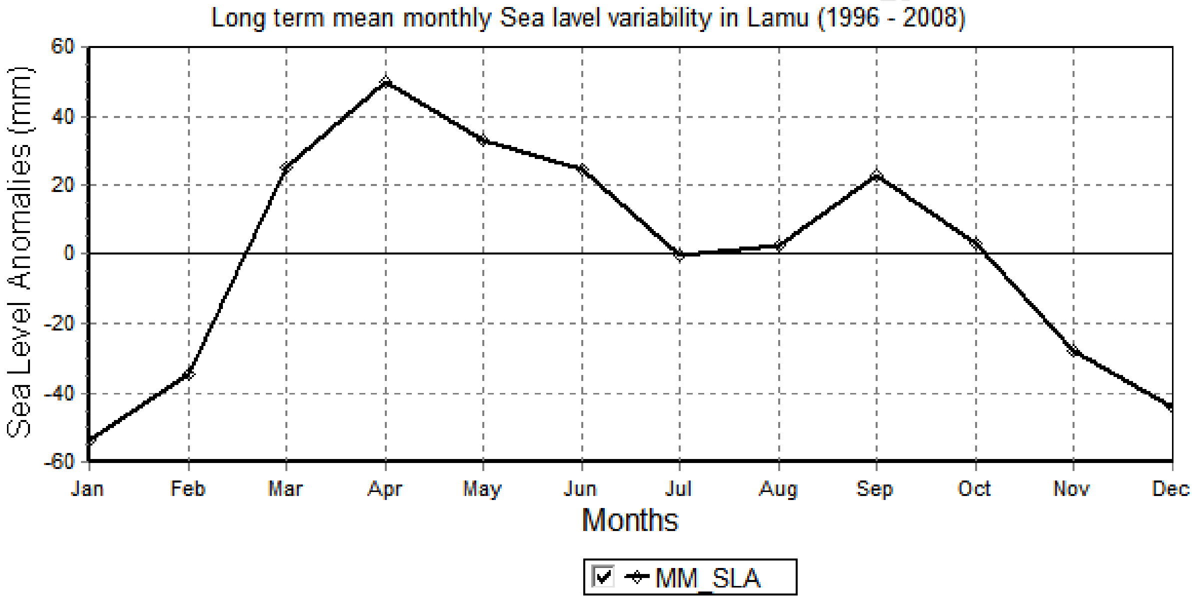


Figure 4.4: Observed monthly mean sea level variations in Lamu tide gauge station.

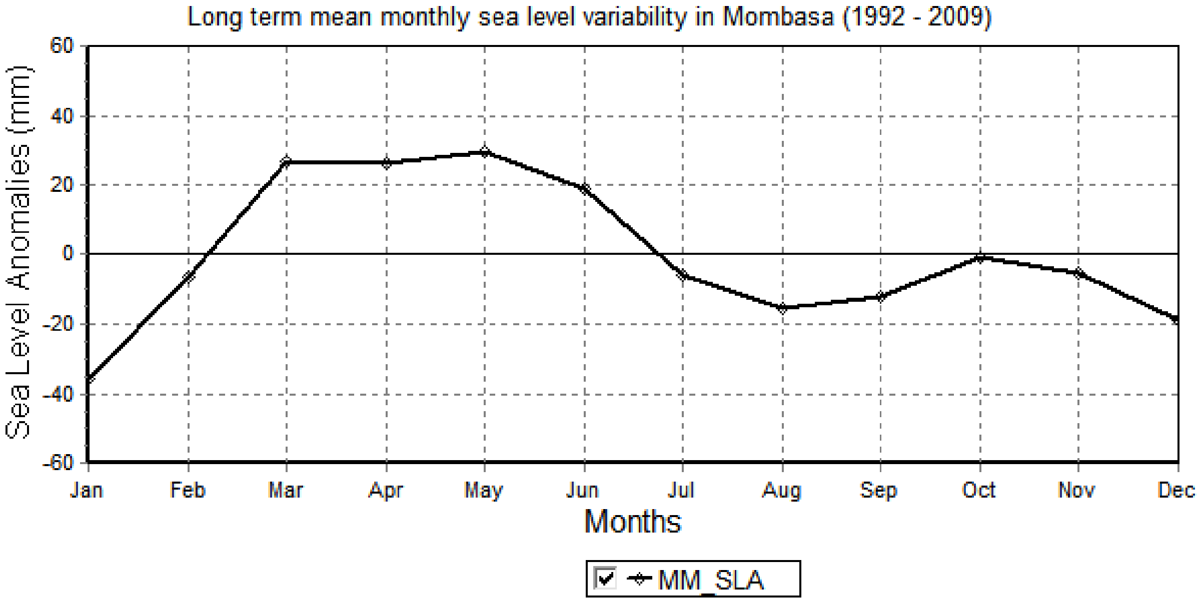


Figure 4.5: Observed monthly mean sea level variations in Mombasa tide gauge station

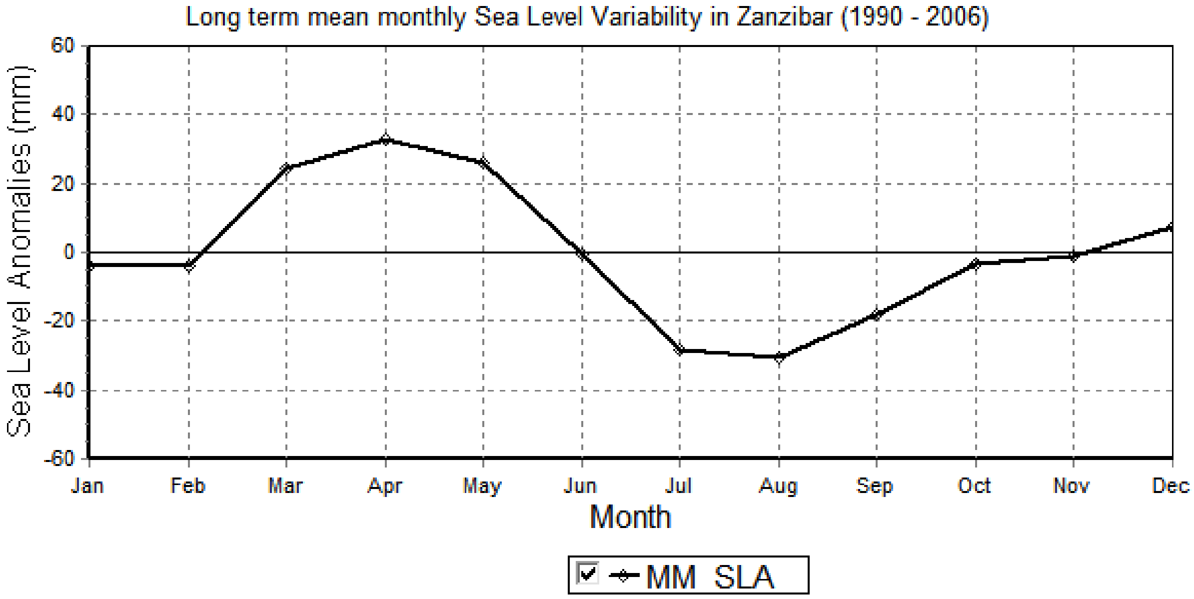


Figure 4.6: Observed monthly mean sea level variations in Zanzibar tide gauge station.

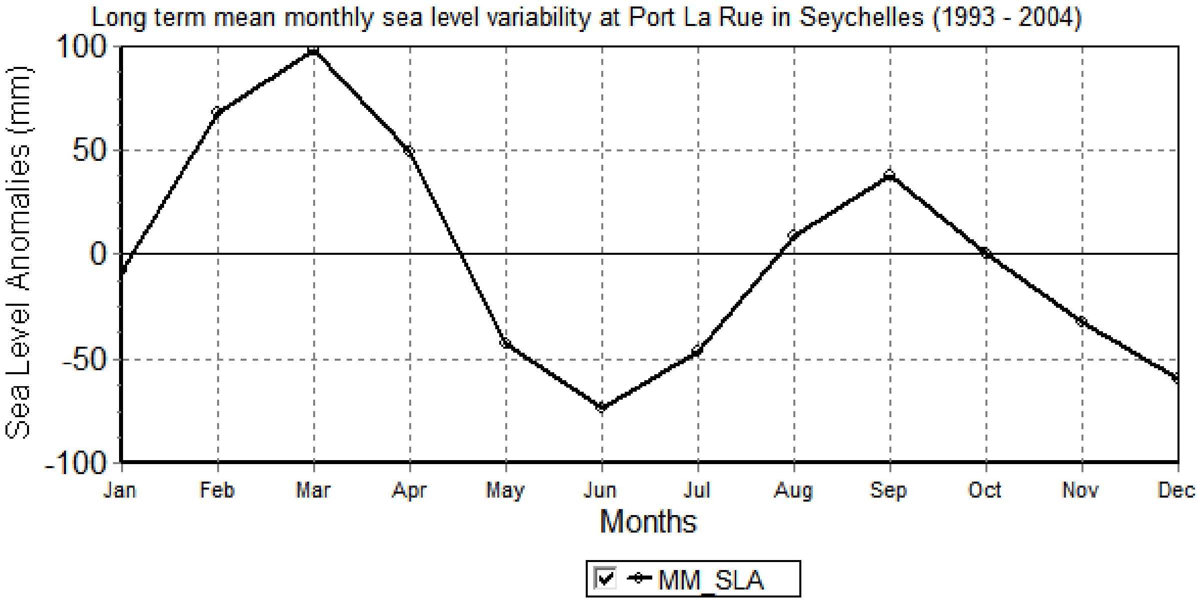


Figure 4.7: Observed monthly mean sea level variations in Port La Rue tide gauge station.

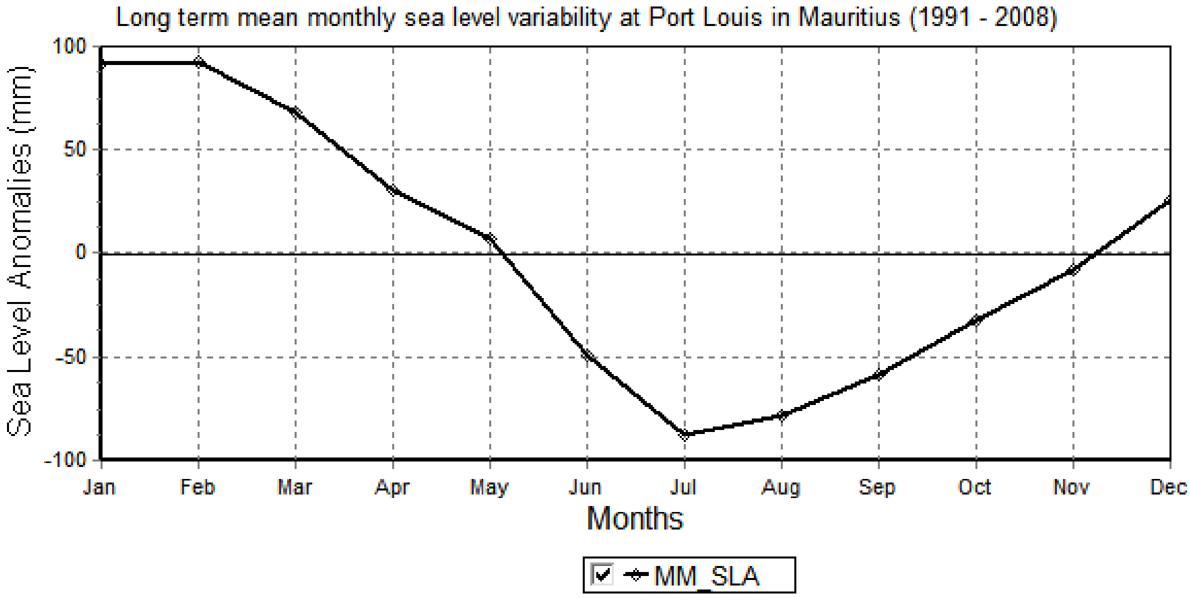


Figure 4.8: Observed monthly mean sea level variations in Port Louis tide gauge station.

Port Louis station (figure 4.8) experiences higher sea levels from December to February. After February there is a continuous and significant drop till the month of July after which it again starts to rise progressively. Lowest anomalies during the months of July and August at Port Louis coincide with the periods of SW monsoon (Fig. 4.18) and it is possible that sea level variations during these months (July and August) are influenced by summer monsoon.

It is appropriate to deduce from the observations made on monthly sea level variability at the stations under consideration that there is a significant influence of variable meteorological factors at different times of the year and is consistent with observations made over this region by Camberlin and Philippon (2002); Williams and Funk (2011). Also of greater influence on sea level at monthly to seasonal time scales are the spring tides during the equinoxes and wind which also vary with season.

4.6 Tide gauge and Altimetry Interannual Sea Level variability, correlations and Trend Pattern in the SWIO and East Coast of Africa

Tide gauge data of sea level observations along the East coast of Africa and the adjacent islands (Port La Rue and Port Louis) and Altimetry observations of sea sea surface heights obtained from http://www.aviso.oceanobs.com were analyzed and their correlations investigated. It is worth noting that Aviso data are IB corrected (air pressure corrections have been applied to the data) while the tide gauge sea level observations are not corrected for air pressure effects.

The following results (Fig. 4.9 – 4.14) show similarity in interannual patterns of the sea level variability btween tide gauges and altimetry observations. Altimetry variations are more pronounced in positive amplitudes in the Southwest Indian Ocean and along the East coast of Africa except for Port La Rue in Seychelles (Fig. 4.14) where tide gauge anomalies are much higher than altimetry measurements. Positive and negative anomalies are distinct during the 1997/1998 and 2000/2001 periods respectively. There are also significant positive signals during the period 2006 and 2007 in both the altimetry and tide gauge observations.

The data correlations of the tide gauge and altimetry (from aviso) at 95% confidence level are: Lamu 0.93, Mombasa 0.92, Zanzibar 0.92, Pt La Rue 0.898, Port Louis 0.893 and Durban -0.104. Durban correlation value is unique (Fig. 4.12) and could be due to the large number of missing data from the tide gauge station and also the 1997 event recorded by tide gauge which needs further investigations. The trend patterns observed in the altimetry and tide gauge sea level anomalies are similar except in Zanzibar where tide gauge shows a significant falling trend of mean sea level (Fig. 4.9) probably due to the effects of land movements on tide gauge.

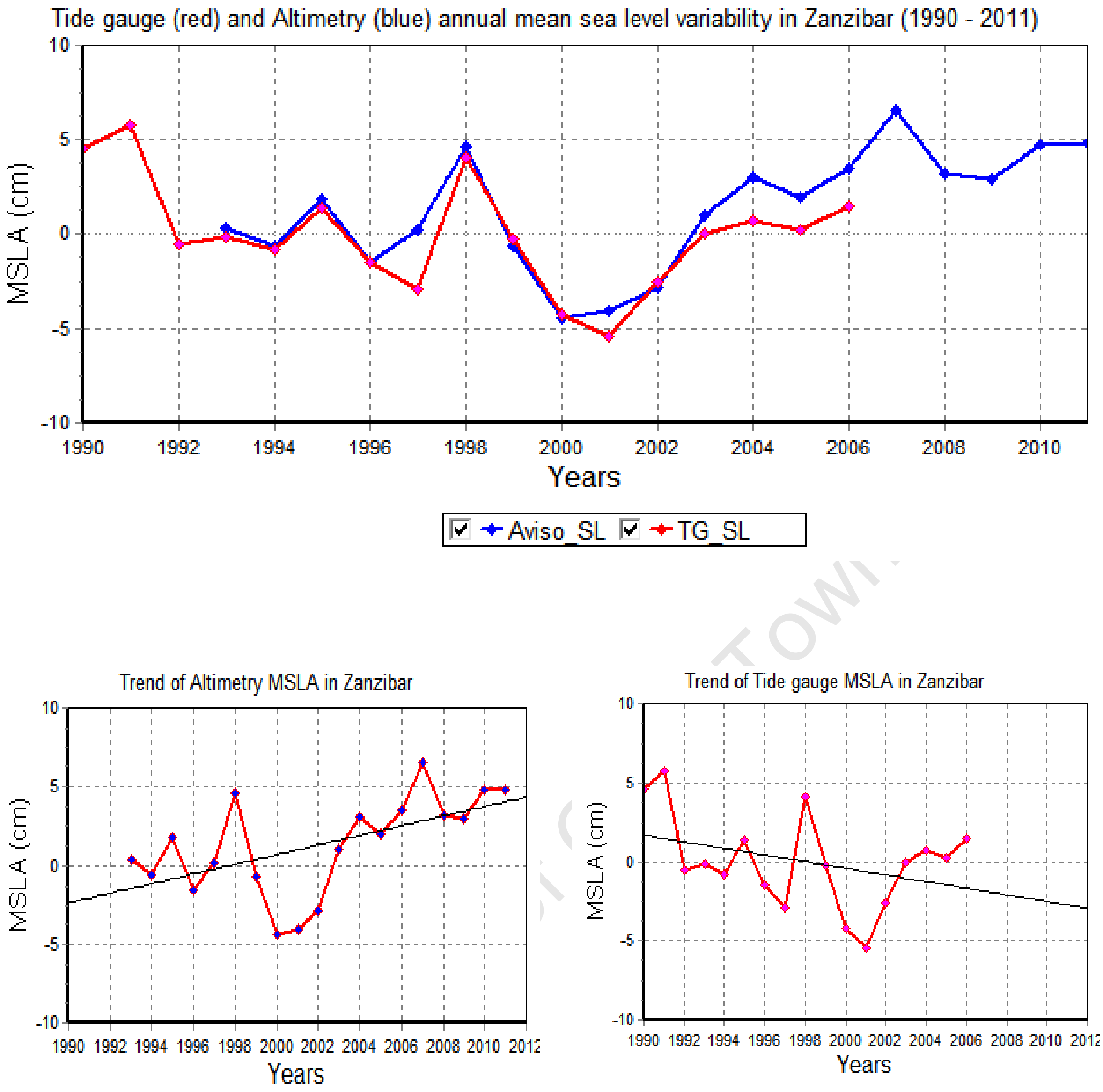


Figure 4.9: Altimetry and Tide gauge correlations of interannual sea level variability and Trends patterns in Zanzibar (tide gauge data from 1990 – 2006 and altimetry data from 1993 - 2011)

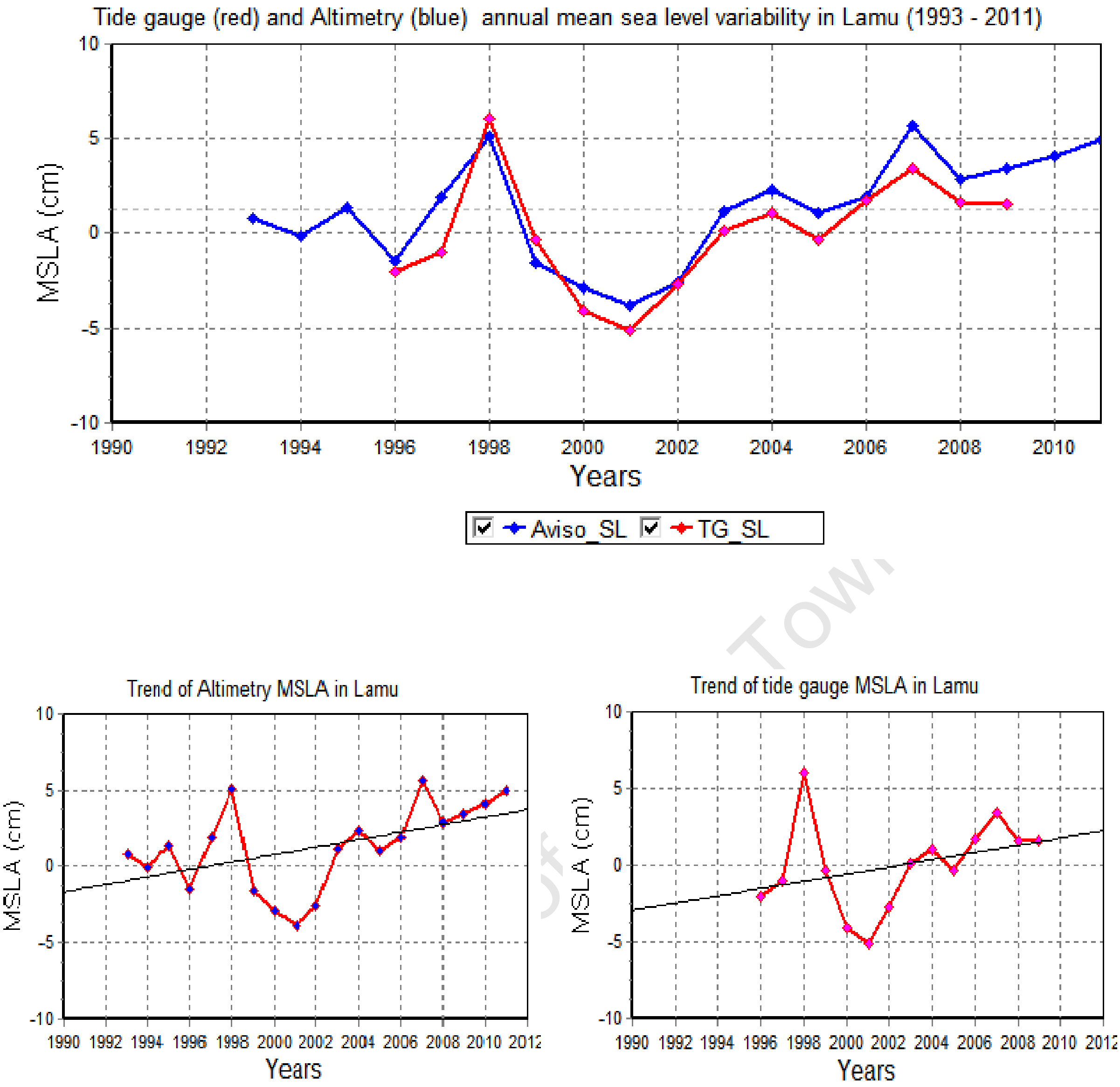


Figure 4.10: Altimetry and Tide gauge correlations of interannual sea level variability and trends patterns in Lamu (tide gauge data from 1996 – 2009 and altimetry data from 1993 - 2011)

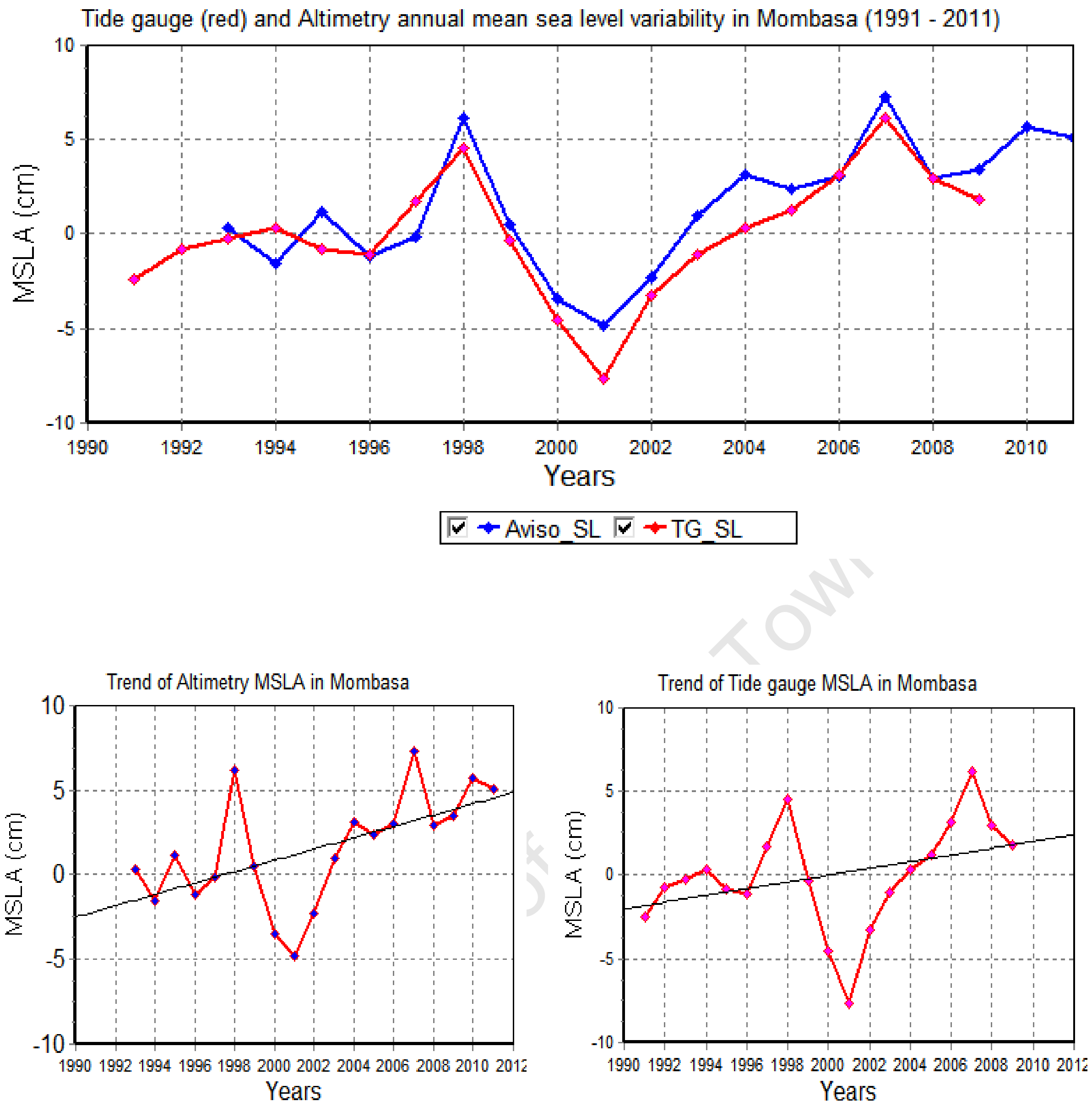


Figure 4.11: Altimetry and Tide gauge correlations of interannual sea level variability and Trends patterns in Mombasa (tide gauge data from 1991 – 2009, altimetry data from 1993 - 2011)

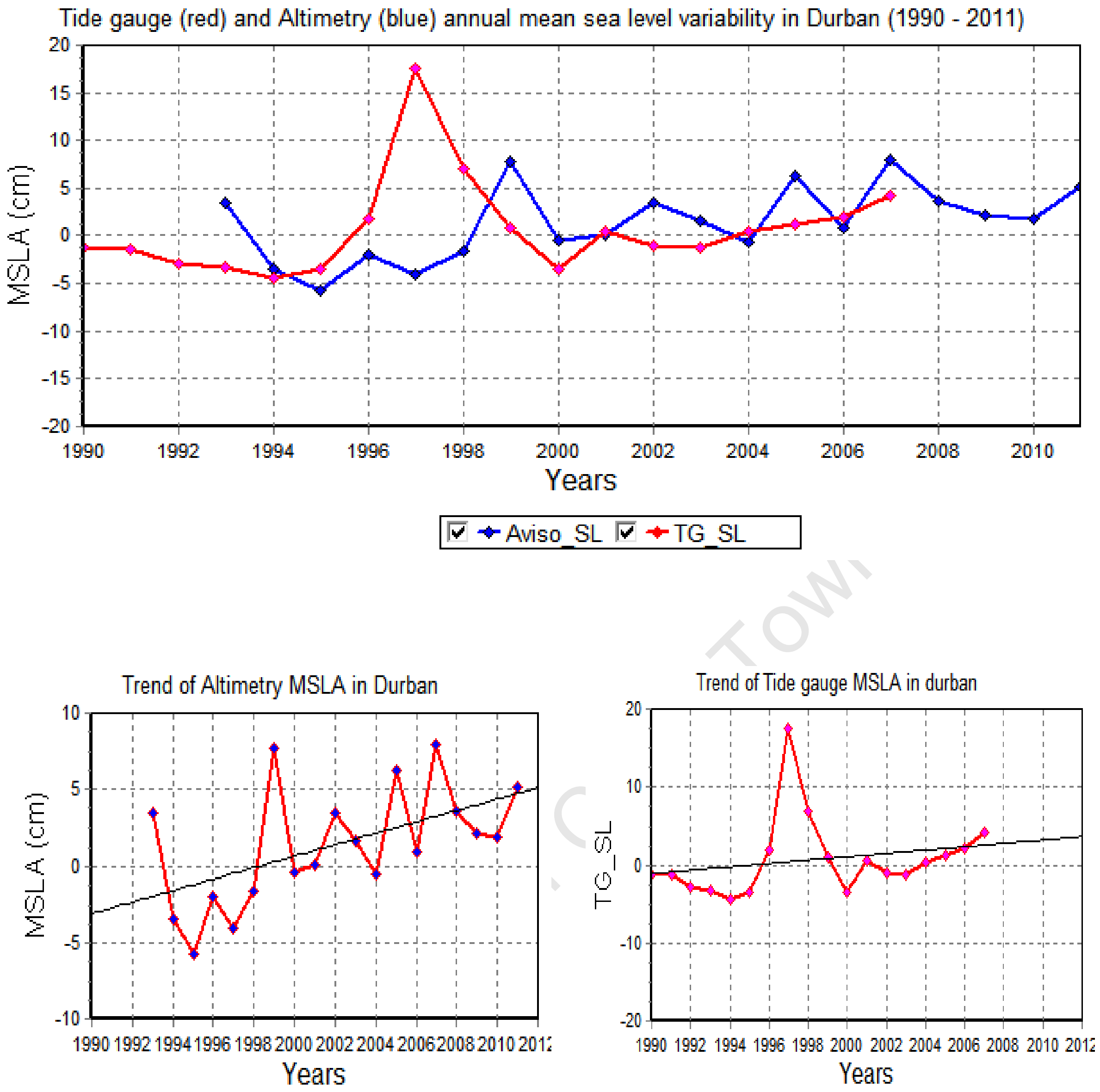


Figure 4.12: Altimetry and Tide gauge correlations of Interannual sea level variability and trends patterns in Durban (tide gauge data from 1990 – 2007, altimetry data from 1993 - 2011)

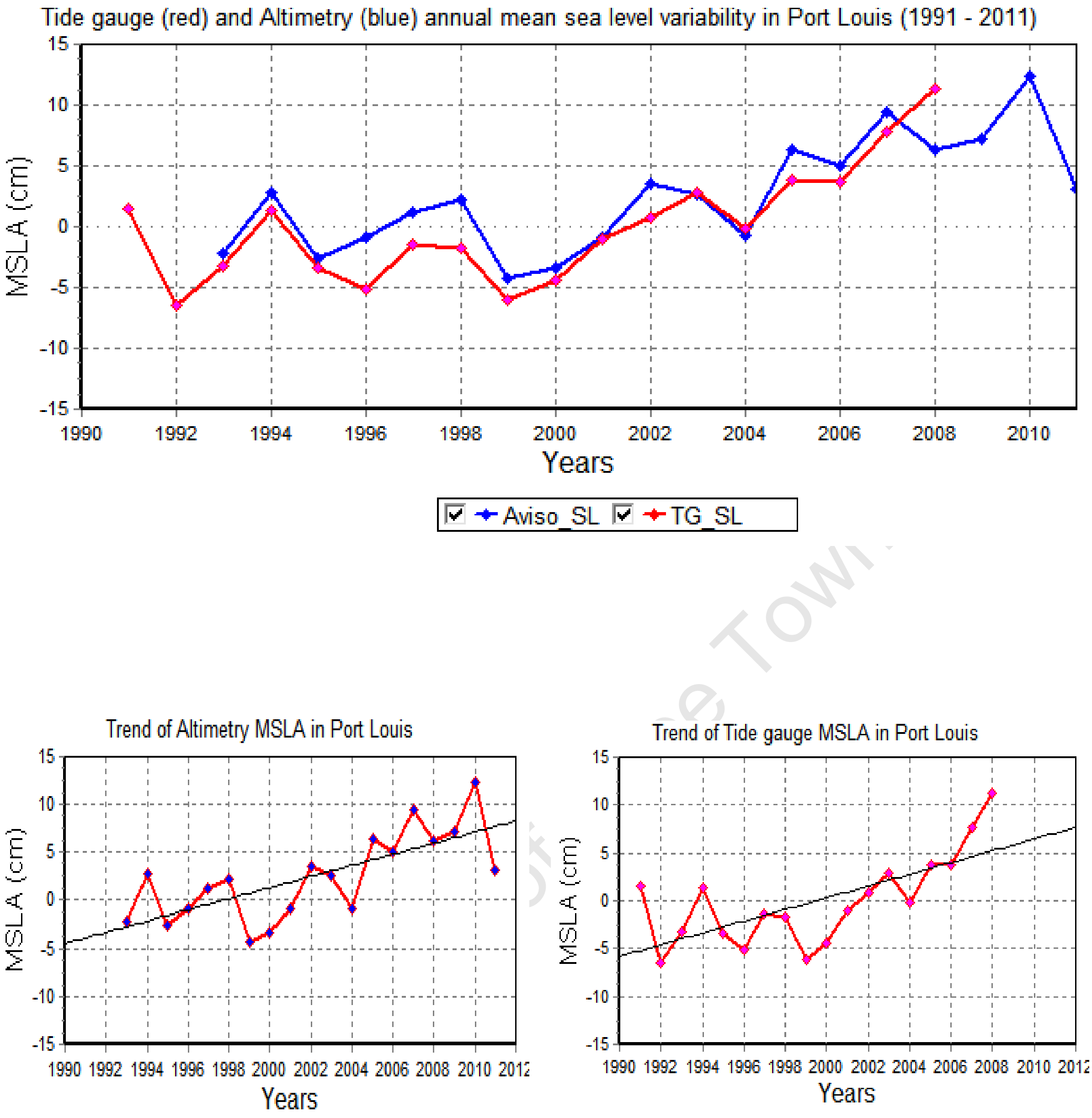


Figure 4.13: Altimetry and Tide gauge correlations of Interannual sea level variability and Trends patterns in Port Louis (tide gauge data from 1991 – 2008, altimetry data from 1993 - 2011)

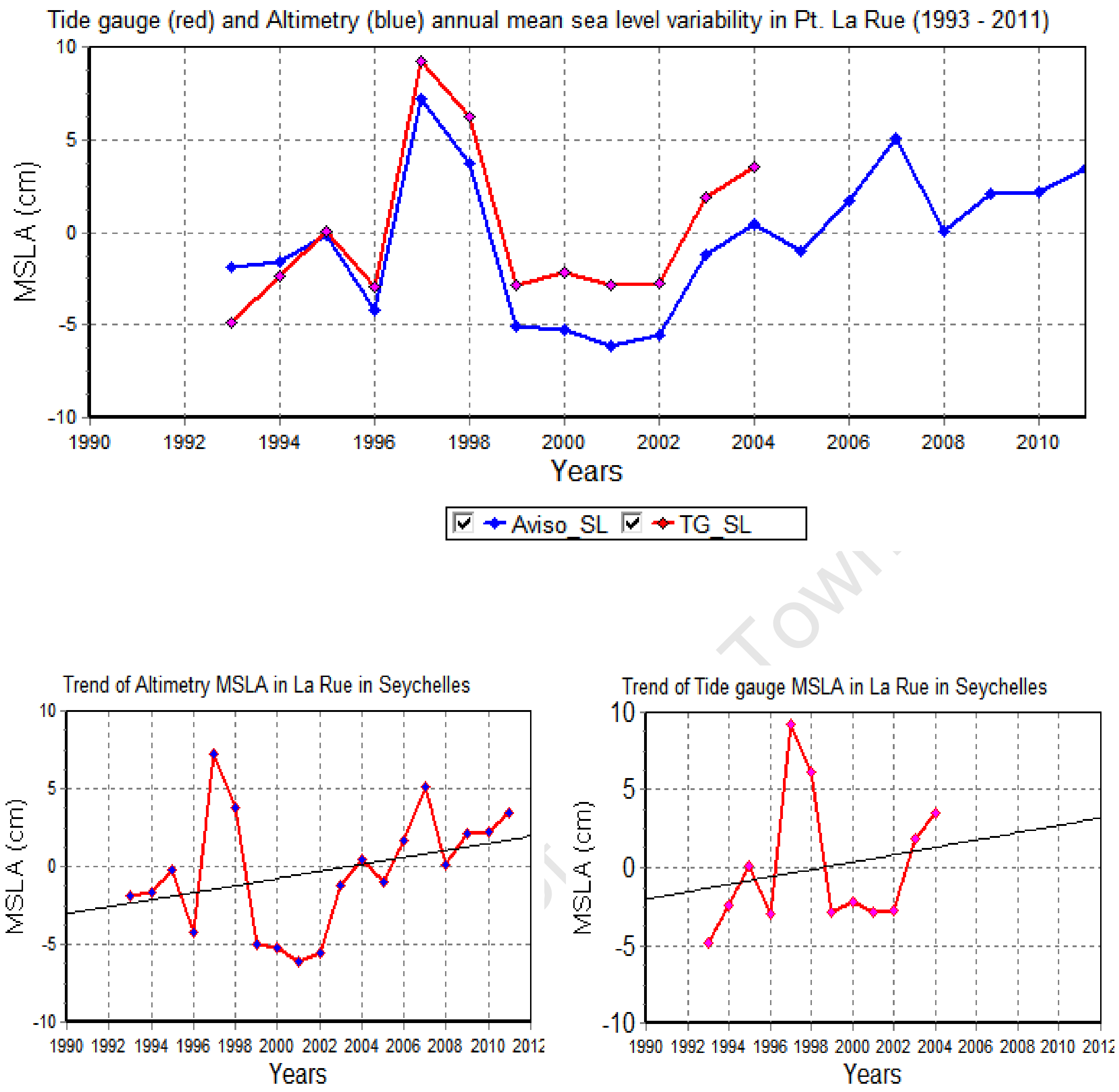
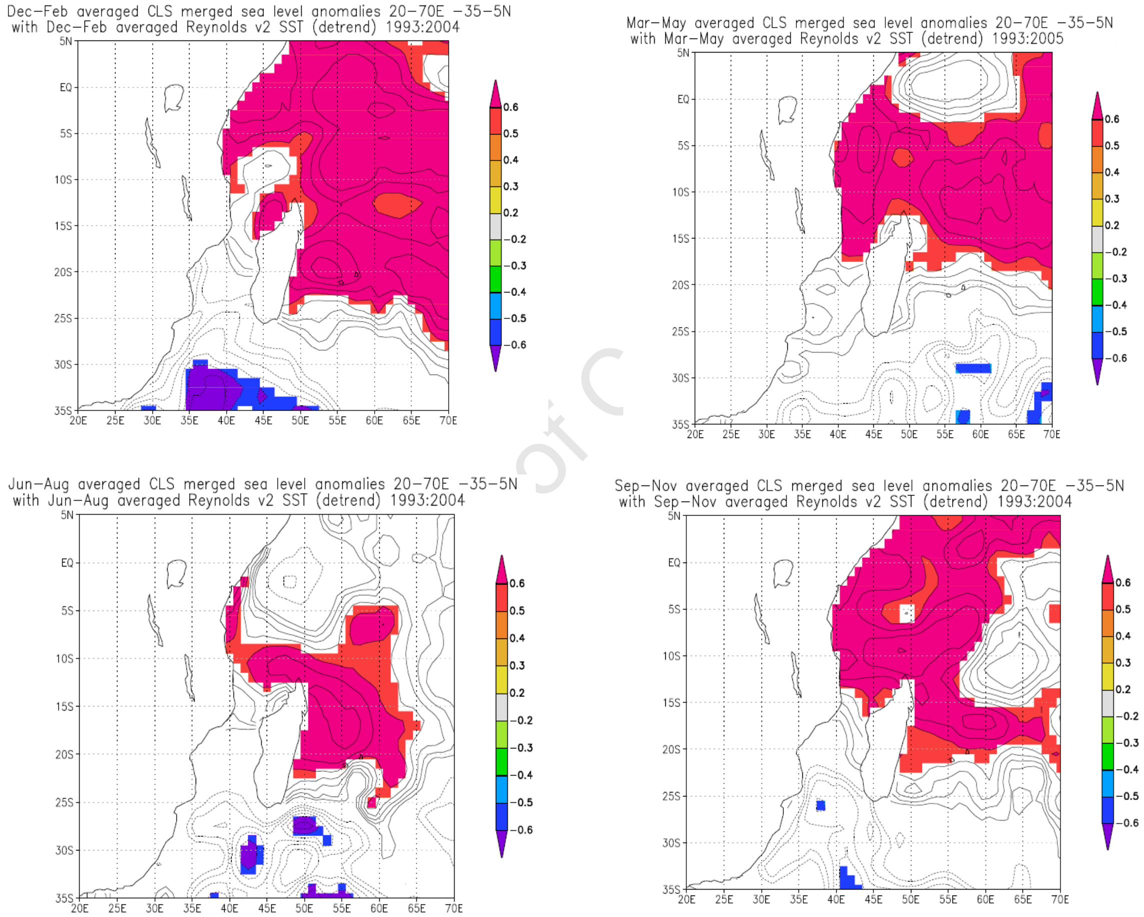


Figure 4.14: Altimetry and Tide gauge correlations of Interannual sea level variability and Trend patterns in Pt La Rue (tide gauge data from 1993 – 2004, altimetry data from 1993 - 2011)

Significant climatic mode that influences sea level variability in this region at interannual and on a wider regional scale is the El Nino-Southern Oscillation (ENSO). There is also evidence of the influence of the positive phases of the Indian Ocean Dipole (IOD) during 2006, 2007 and 2008 which is useful in describing sea level variability along the East coast of Africa.

4.7 Correlations of Sea Surface Temperature and Sea Level Height

Seasonal (three monthly average) correlations of the sea level (CLS merged sea level) and sea surface temperatures (Reynolds SST) for the period 1993 – 2004 (data available at http://climexp.knmi.nl) was examined over the South West Indian Ocean. The following results (Fig. 4.15) show significant positive relationship around tropical equatorial regions up to about 25°S where there is little temperature fluctuations. The rest of the region especially the southern part of the East coast of Africa shows negative or no relationship between sea surface temperature and sea surface height variations.



Figures 4.15a-d: Seasonal correlations of Sea Level anomalies with Sea surface temperatures over South West Indian Ocean (http://climexp.knmi.nl) data from 1993 - 2004

4.8 Wind Circulation pattern over Southwest Indian Ocean and the East coast of Africa

Long term mean monthly wind data acquired from NCEP Reanalysis 1 for the period 1981-2010 at 0.995 sigma level was investigated to determine the influence of wind fields on sea level variability in this region of the southwest Indian Ocean and the East coast of Africa. The trend of the surface wind shows a convergence near the equatorial region due to anomalous southeasterly (northeasterly) winds from south (north) hemisphere and subsequent eastward flow during the NE (winter) monsoon in December to February (Fig. 4.16). During the summer monsoon (Fig. 4.18), the south-easterly winds change direction eastwards near African continent and flow along the coast northwards and are likely to impact on sea level variations along the coast and Islands.

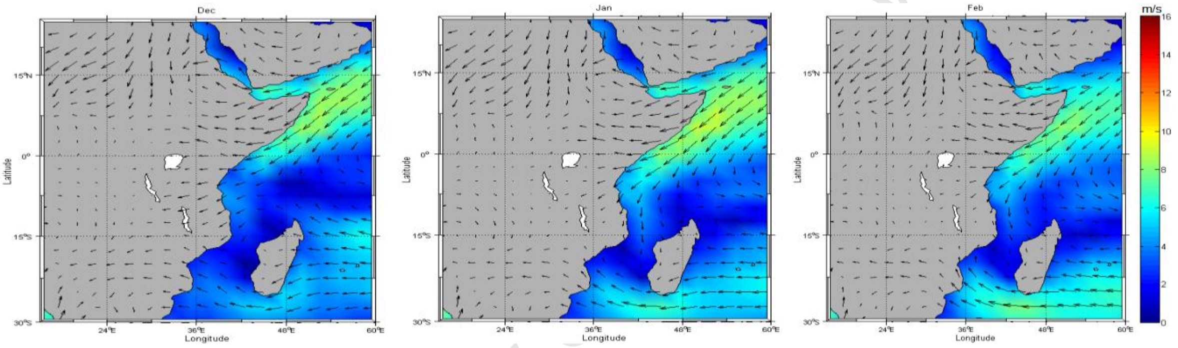


Figure 4.16: NE monsoon (Dec- Feb) wind vector over SWIO and along the East coast of Africa

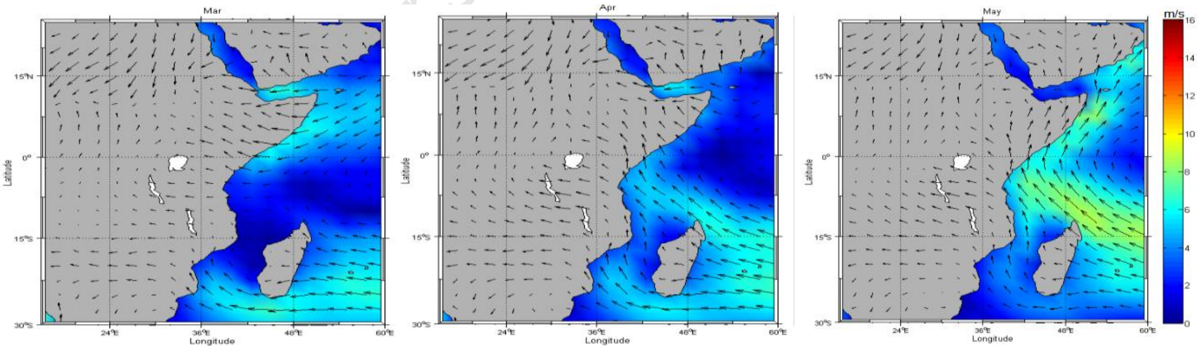


Figure 4.17: Intermonsoon (March- May) wind vector in SWIO and along the East coast of Africa

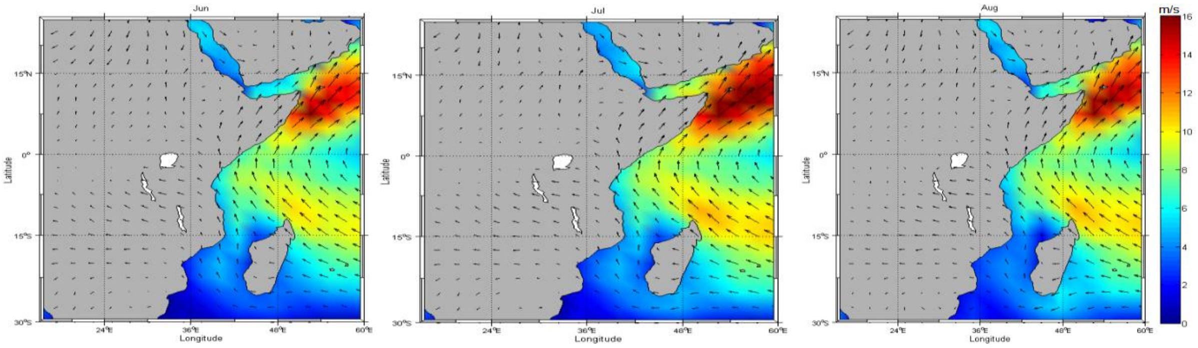


Figure 4.18: SW monsoon (Jun- August) wind vector in SWIO and along the East coast of Africa

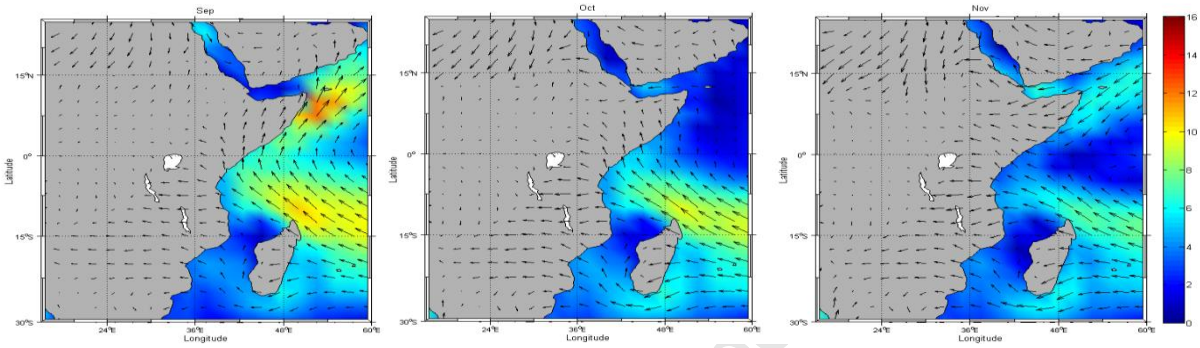


Figure 4.19: Intermonsoon (Sep- Nov) wind vector in SWIO and along the East coast of Africa

The wind speeds along the East coast of Africa vary in relation to the monsoon and inter-monsoon periods and are greatest during the southwest monsoon (June – September) but lowest during the northeast monsoon (December – March) and inter-monsoons consistent with the Hastenrath and Lamb (1979) conclusion that coastal winds in the region of western India from November to February are weak with a lower monthly mean. The region around the Somali jet is observed to experience quite intense winds during the SW monsoon (Fig 4.18 from June to August) which is highest in the month of July and could influence the sea levels around that region consistent with the findings by Collins et al (2012).

4.9 Trends of Annual Maxima Sea Level Observations and Residuals.

Two variables were investigated in this section, the total sea level elevation and the surge component at each station. In investigating and estimating the trends of annual maxima water levels, the 99.9 percentile value for each year’s hourly data was determined for the whole period of the data coverage at each individual tide gauge station under investigation. This value represents the highest sea level observation in a year. Similar procedure was used to determine the highest residual value in each year (Tables 1- 6) in the appendices A.

The slopes for observations (red dots) and residuals (blue dots) are indicated in the following plots (Fig. 4.20 – 4.25): Lamu 0±7 mm/year, Mombasa 1±8 mm/year, Zanzibar 1±6 mm/year, Port Louis C -3±5 mm/year and Pt. La Rue 3±14 mm/year. The trends are not statistically significant except for Durban sea level observation which shows a slightly significant positive trend of 3±2 mm/year. The residual trends are similar to those of observations and are statistically not significant. It can be interpreted that there is no significant increase in storms in this region of South West Indian Ocean.

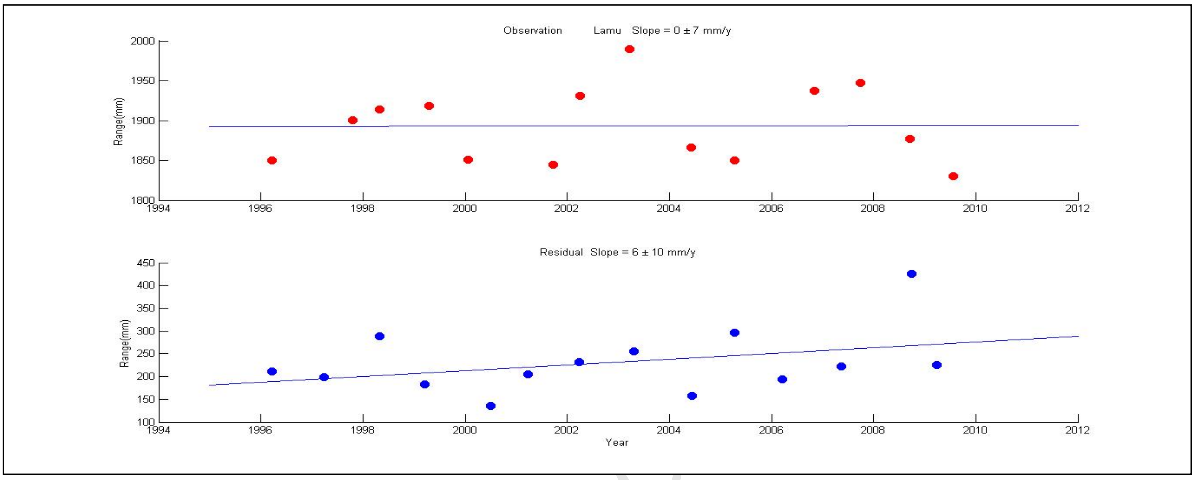


Figure 4.20: Trends of annual maxima Sea Level observations and residuals at Lamu tide gauge.

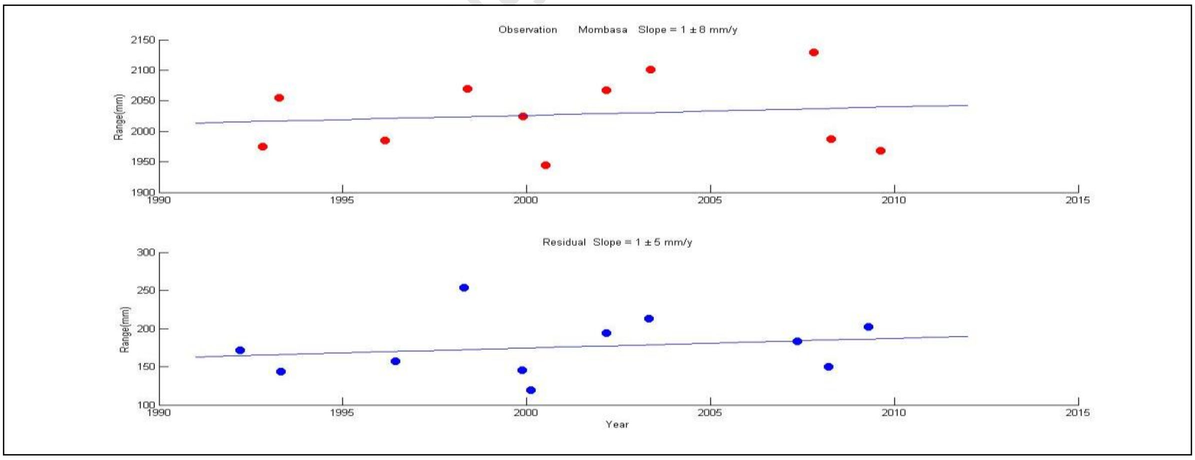


Figure 4.21: Trends of annual maxima Sea Level observations and residuals at Mombasa tide gauge.

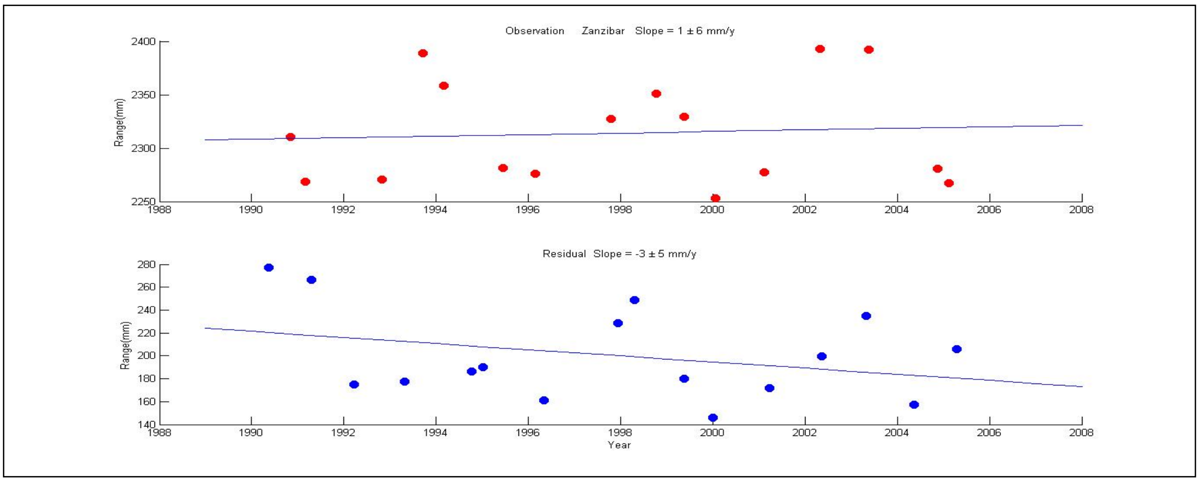


Figure 4.22: Trends of annual maxima Sea Level observations and residuals at Zanzibar tide gauge.

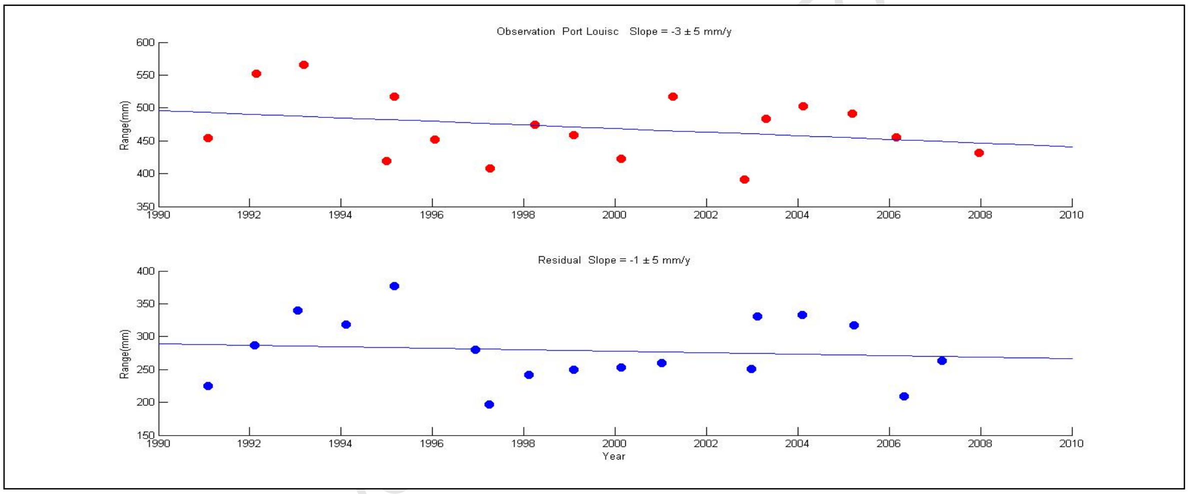


Figure 4.23: Trends of annual maxima Sea Level observations and residuals at Port Louis tide gauge.

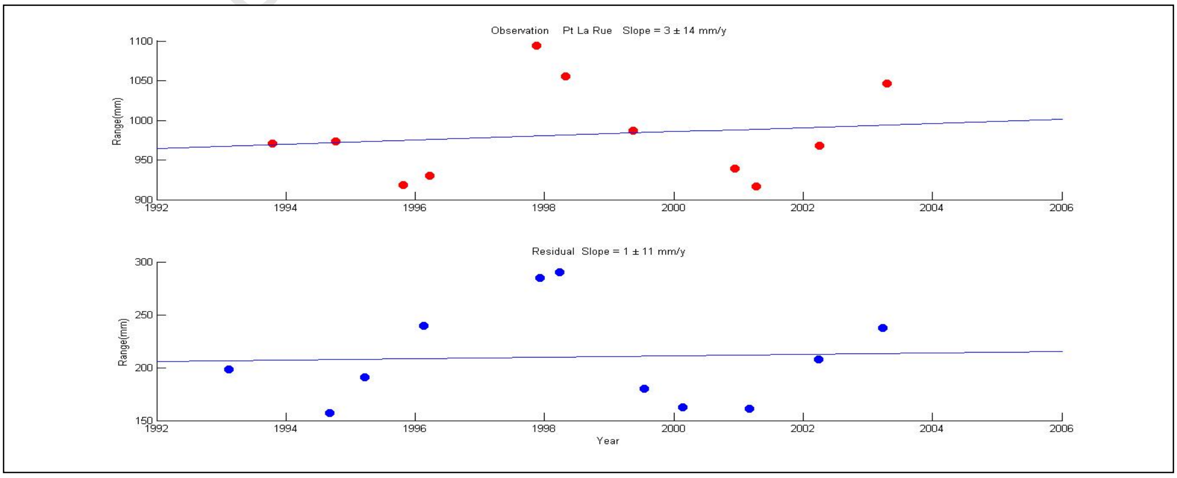


Figure 4.24: Trends of annual maxima Sea Level observations and residuals at La Rue tide gauge.

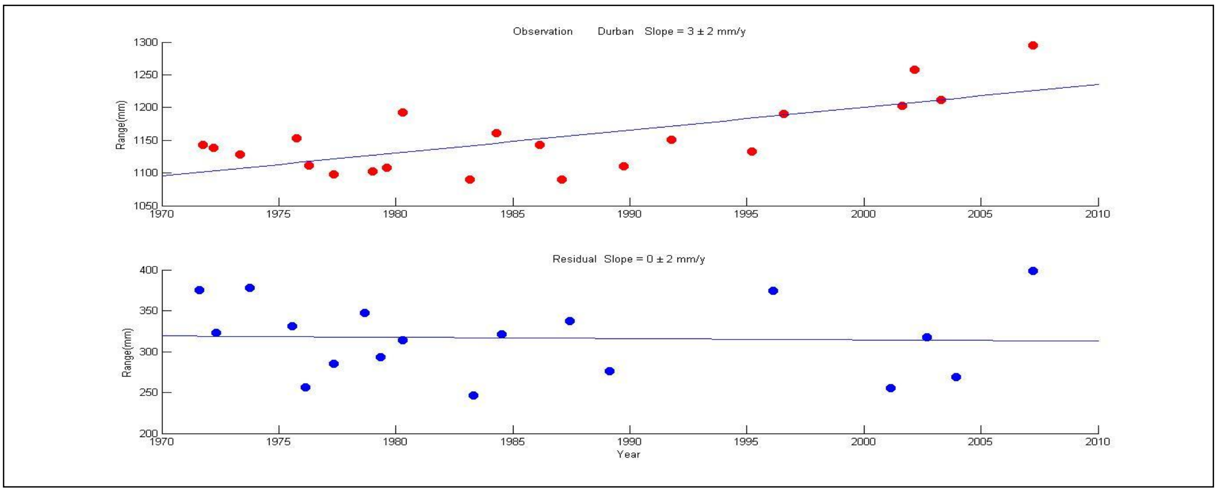


Figure 4.25: Trends of annual maxima Sea Level observations and residuals at Durban tide gauge.

The annual pattern and variations observed in the higher percentile water levels in the East coast of African tide gauge could be related to the influence of perigean cycle which exhibits a quasi 4.4 year periodicity and is evident in almost all records consistent with findings by Woodworth and Blackman (2004) who reported similar perigean influence in higher percentile series for the Tuvalu tide gauge.

The residual trends are similar to those of the higher sea level annual maxima and it is appropriate to suggest that the annual high water levels are significantly dependent on changes in meteorological factors caused by year to year fluctuations in weather. In additions there is a strong interannual variability in the extreme sea levels and residuals in the South West Indian Ocean tide gauges which can be explained by the regional climate pattern represented by the El Nino Southern Oscillation Index (ENSO) and the Indian Ocean Dipole (IOD) among other large scale climatic influences from other oceans.

Chapter Five: Discussions

Tide gauge and Altimetry Sea level observations in the South West Indian Ocean and the East coast of Africa have shown significant variability which is influenced by a number of contributions related to meteorological and climatic and oceanographic phenomena on all time scales.

On shorter time scales, sea level variability is mainly driven by tides, atmospheric pressure fluctuations and precipitations during the time when the ocean and atmosphere exchange water and also by storm surges. Tidal regimes vary a great deal at different coastal locations in the southwest Indian Ocean and the East coast of Africa and are characterized by semi-diurnal form of tidal oscillations which exhibit varying ranges (Fig 4.0).

The variations in temporal and spatial characteristics of tides in the East African coast (figures 4.0) are related to the influence of equinoxes, dynamical response to the ocean basin and the varying length of the continental shelves. By comparing figures 4.0 a, b, c at the coast of Africa and figures 4.0 e & f at the islands, it is clear that tides in the deeper ocean are characterized by small amplitudes of typically about 1m or less which is considerably lower than the amplitudes at coastal shelf where local resonance may result to larger amplitudes.

Tides in the Southwest Indian Ocean have significant contributions to the sea level variations at short time scales (fortnightly, monthly, seasonal) and even longer periods but their contributions in comparison to other numerical factors that define sea level variability at longer (interannual and decadal) time scales such as ocean circulation patterns, climatic indices (ENSO) seems less. This observation is similar to observations made by (Shankar 2000).

The variations in the declination of the moon and the sun are probably responsible for the modulations produced by the semi-diurnal forces with maximum forces at the equatorial plane and reduce with increasing latitude north and south and manifest themselves in the sea level by either raising or lowering the levels. The results of this study (Fig. 4.0) agree well with the latitudinal variation of the semidiurnal tides principle where the stations near the equator (Fig 4.0 a, b and c) exhibit higher tidal ranges than those further away from the equator (Fig. 4.0 d, e and f) and influences total sea levels elevations.

The analyses of the tides were carried out separately for each year of data to generate tidal constituent for each of the stations under investigation and to minimize the long term dependence of individual constituents on the 1 year, 8.8 years perigee and 18.6 years nodal cycles. Previous studies by (Doodson and Warburg 1941) reported the variation in amplitude of M_2 in equilibrium tides as modified by ± 3.7% over the nodal cycle while in shallow parts of the ocean, the nodal dependence can be significantly minimized because of the bottom frictional effects.

Residuals which are the components of sea level after tides have been removed exhibit random variability (Fig 4.1) and are majorly influenced by coastline configuration and cyclone track among other varying influences like storms, wind fields, pressure fluctuations and sea floor topography in this region of the Southwest Indian Ocean. On shorter time scale of approximately one month or less, surges in the SWIO seems not to be significantly effective in a number of location due to the random phase where most of the surge energy is likely to appear in the harmonic constituents and get depleted from the surge component due to weak interaction with the tides. East Africa coastal region (Fig 4.1a, b and c) significantly represents a region of weak interaction between surges and tides which results to low surge amplitude.

Larger variability in the residuals (meteorological effects) in the Southwest Indian Ocean is likely to be influenced by eddies generated by the western boundary current (Agulhas current) and the passage of tropical storms in the mid and higher latitudes. Previous investigations notably by Thompson (1986) observed enhanced residual variance in western boundary currents (south Atlantic Bight and fluctuations in the Gulf Stream) on the EOF split at Cape Hatteras. The distinctly variable residuals in Durban (Fig. 4.1d) could also be related to the effects of eddies generated by Agulhas current. Tropical cyclone development near Madagascar and their track down the Mozambique Channel and possible land fall at the coast around Durban as was observed by (Searson 1995) could also be a reason for the observed higher and variable residuals around Durban coast.

Local Sea level variability in the Southwest Indian Ocean is significantly influenced on shorter time scales (days to month) by the action of the atmosphere on the surface of the sea which manifests in two distinct ways; the ‘Inverse Barometer (IB) effect where short time sea level changes are influenced by the action of atmospheric pressure on the surface of the sea.

An increase in the downward atmospheric force on the sea surface depresses sea levels and a decrease in the downward force on the surface of the ocean elevates the sea levels and is evident in the results shown in figures 4.3. Other possible manifestation of the atmosphere on the Southwest Indian Ocean sea level variability on shorter time scales is through wind stress that causes a drag which is directly related to the square of the wind speed on the ocean surface as was noted by Pugh (1987). The drag over the ocean sets up sea level gradients and when the wind flow is towards the coast, it results to increased surge amplitudes in shallow water regions at the coast and subsequent sea level elevations.

A large percentage of seasonal and interannual variability in sea level in the Southwest Indian Ocean are due to atmospheric and oceanographic processes. Seasonal characteristics of sea levels play a major role in sea level variability especially in this region of Southwest Indian Ocean which is dominated by small tidal amplitudes. The observed monthly sea level patterns in the East coast of Africa stations and the islands (figures 4.4 – 4.8) are due to a number of local forcing which include weather changes, fluctuations in air pressure, wind stress, oceanographic circulations patterns and temperature fluctuations which have been identified in the past as part of the high frequency signals present in the tide gauge observations of the sea levels.

Southwest Indian Ocean region is characterized by temperature fluctuations and salinity variations in sea water which together with water mass exchange between land and ocean contribute to sea level variability at seasonal time scale. Chan et al 1998, (2000); Minster et al (1999); Cazenave et al (2000) and Milly et al (2003) found similar relationship in the northern hemisphere seasonal sea level variations. At seasonal time scales, temperature effects in this region of SWIO are majorly concentrated in the upper layer of the ocean surface and are more effective at the equatorial region (Fig 4.15). On regional scales, steric height changes are the likely cause of the observed sea level variations on seasonal time scales in the Southwest Indian Ocean and agree well with the existing Indo- pacific warm pool warming ocean model which causes Indian Ocean sea level variations (Fig. 2.7b). Varations in the thermocline depth influences upwelling and impacts on the sea surface temperature. Upwelling (down welling) of the cold (warm) water is confined to regions where thermocline is shallow (deep) and as a result influence sea level variability.

Monthly and seasonal variations in meteorological aspects in the Indian Ocean and the surrounding environment are to a greater extent responsible for the major changes in the sea level. The bi-annual cycle of sea level elevations observed in East African coast (Fig 4.4 – 4.8) can be attributed to the strong semi-annual cycle of two strong wet seasons which occur between March to May as was also noted by Camberlin and Philippon (2002); Willian and Funk (2011) and between September and December, similar to a report by Hutchinson (1992) and are caused by the northward (southward) movement of the Indian Ocean ITCZ and impact on sea levels variability. During these months, the higher sea level anomalies observed in this region of SWIO at different tide gauge locations could be as a result of river discharge and stream flow contributions to the ocean caused by the possible intense and long duration storms in the region.

The South West Indian Ocean is characterized by semi-annual cycle of wind fields with significant differences in wind speeds during the monsoon and inter-monsoon periods (Fig 4.16- 4.19). The south easterly is dominant during the southwest monsoon in the southwest Indian Ocean while the easterly prevail during the northeast monsoon period (Fig 4.16 and 4.18). Sea levels are significantly low in the East African coast (Lamu, Mombasa) and Port La Rue in Seychelles from the month of December through to February (Fig 4.4, 4.5 and 4.7) coincidence with the NE (winter) monsoon period (Fig 4.16).

During the NE (SW) monsoon (Fig. 4.16 & 4.18) periods, sea levels are distinctly high (low) in Zanzibar and Port Louis (Fig 4.6 and 4.8) respectively and shows the possible influence of monsoon winds in elevating (depressing) sea levels in the southwest Indian Ocean and the East coast of Africa. Wind stress acting alongshore or on the coastal shelf impact on the sea level and in coastal regions, seasonal winds are significantly important in describing sea level variability (Eugene 1974). Ocean models for example the NCEP 40- year reanalysis winds in Indian Ocean for the period 1961 – 2001 (Fig. 2.8) have shown how wind fields are responsible for sea level variability along the coast and equatorial regions.

Significant evidence of strong interannual variability of sea level in the South West Indian Ocean (Fig 4.9 – 4.14) could be related to the climatic pattern in this region. The persistent characteristic change of Indian Ocean dynamics is affected by El Nino Southern Oscillation and Indian Ocean Dipole (Saji et al 1999; Webster et al 1999) and to some extent by the North Atlantic Oscillation (NAO).

The interannual sea level variability in the South West Indian Ocean and along the Eastern coast of the African continent shows a strong relationship with ENSO events of 1997/1998 and 2000/2001.

Tropical Indian Ocean has been observed to experience progressive warming during ENSO years (Nigam and Shen 1993; Klein et al 1999 and Liu and Alexander 2007). During El Nino, the atmospheric heat transfer by massive fluid motion over the Indian Ocean is restrained and the subsequent increases in solar radiation enhance warming over this region (Schott et al 2008). The enhanced precipitation during ENSO events in the South West Indian Ocean is also associated with anomalous cyclonic circulation in the lower troposphere in the region and increased tropical cyclones events (Xie et al 2002) which are capable of influencing variations of the sea level due to low pressure and high wind speeds over the ocean surface.

Indian Ocean Dipole (IOD) is influenced by the combined ocean-atmospheric instability and induces fluid movement over the Indian Ocean. Cooling of the eastern Indian Ocean initiates an eastward wind flow in the central basin that drives the westward currents at the equatorial region and lifts the thermocline leading to the cooling of the surface in the east and strengthens the anomaly (Schott et al 2008). Such interlinked feedbacks can lead to distinct cold anomaly in the east and anomalous westward winds in the central basin and subsequent sea level variations.

Indian Ocean Dipole is capable of initiating strong sea level anomalies and hence variability at different time and spatial scales. The significant interannual sea level variability during the years (2006, 2007 and 2008) along the East coast of African and the islands (Fig 4.9-4.14) indicate the effects of IOD in this region of the South West Indian Ocean. The positive phases of the IOD during these periods over Southwest Indian Ocean could have initiated a build up of wind fields across the Indian Ocean with the easterly pushing water towards the West Indian Ocean and resulting in higher sea levels. This relationship was also observed during periods of sea level elevations and depression in the Eastern Indian Ocean at Phuket Thailand by Brown et al (2011).

Indian Ocean Dipole and El Nino Southern Oscillations initiate the propagation of Rossby waves and thermocline variation that subsequently lead to cooling or warming of the upper Ocean layer and the resultant sea level variability in this region of Southwest Indian Ocean.

The trends of annual maxima sea levels are influenced by a number of factor on global, regional and local scales which include tides and storms on time scale of days to weeks and months, steric changes and meteorological effects on seasonal scales and climatic and tectonic effects on interannual to decadal time scales.

The annual highest water level in the southwest Indian Ocean and the East coast of Africa could be under the influence of the varying storms which can be attributed to the variations in the year to year weather phenomena. Figures (4.20- 4.25) show the contributions of the storms to the annual highest water levels in this region. It is unlikely that the variations in the annual high water levels are due to mean sea level changes but are probably due to the changes in meteorological events. There is also evidence of perigean influence on a 4.4-year cycle on the trends of extreme highest annual water levels in this region of the southwest Indian Ocean and the trends of the high water levels annually are statistically not significant.

Observations on annual monthly highest water levels in a year reveal that sea levels are significantly high during the months of February, March and April and again in the months of September and October an indication of spring tide influence during the equinoxes. Highest sea levels in the Southwest Indian Ocean and along the East coast of Africa are also observed during the times when storm surges coincide with high tides (Appendices A tables 1-6) especially during spring tides.

Chapter Six: Summary and Recommendations

Analysis and interpretation of sea level observations acquired through tide gauge and altimetry observations of sea surface heights are important for the assessment of the coastal and low-lying Islands which are subjected to the impacts of rising sea levels. The short term risks of the low-lying areas is due to the extreme surges which are driven by meteorological phenomena and are more destructive to the environment when they coincide with high tides during the equinoxes. The combined effects of storm surges and spring tides determine the amplitude and the month within a year during which highest sea levels occur. This information is relevant and useful for coastal planning and management.

Understanding and modelling of sea level variability on the basis of the contributing aspects is important for coastal planning and protection as well as forecasting the possible flood impact areas at specific regions in the coast. Tides and surges have been identified in this study as the major components of sea level height observations by tide gauges located along the coastal areas of the southwest Indian Ocean and the islands. Significant variations due to mean sea level change, crustal motion and geographical changes locally can also be represented in the total sea level elevation (Woodworth and Blackman 2004).

Investigations of regional sea level variability are capable of revealing the relationship with meteorological and oceanographic processes and promote the understanding of changes in regional climate. From this investigation, it has been found that storm surges are more effective in the mid latitude regions and their effectiveness reduces with decreasing latitude due to the significant absence of tropical cyclones at low latitudes. Surges are also capable of causing massive destructions to property along the coast during stormy events in the presence of strong wind and in the absence of proper coastal protections.

Semi-diurnal tides are important in defining the structure of sea level variability along the East coast of Africa because of their variations with latitude and the shelf width which modify tides and the major harmonic constituents (M_2 and S_2). The highest ranges of tides occur shortly after the times of first and last quarters of the moon and when the moon’s declination is zero (at the equator) and enhance the sea level elevations (Pugh 1987).

Sea level variability at shorter time scales of days is related to the atmospheric pressure changes which manifests in an inverse relationship with sea level height. Increases of atmospheric pressure over the surface of the sea translate to lower sea levels locally if the far field pressure remains constant. The inverse relationship between sea level and atmospheric pressure is clearly evident in the results of this study (Fig 4.3). It is expected that increases of atmospheric pressure by one millibar produces a decrease in sea level by one centimetre. This exact inverted barometer response is rarely achieved in practice and is because of the dynamic response of the shallow waters of the continental shelf to the movement of atmospheric pressure field (Pugh 1987).

At seasonal time scales and even longer time scales, wind fields play a major role in sea level variability in the southwest Indian Ocean and the East coast of Africa. The seasonal reversals of monsoon winds and flow along the East coast of Africa impact on the sea levels at the coast. The southwest monsoon winds are much stronger (with a maximum of about 16 m/s) than the northeast component (maximum of about 10m/s) and this intense wind speeds over the surface of the ocean cause drag and subsequent sea level variations.

Changes in the intensity of western boundary currents are also known to influence sea levels fluctuations at different time scales (Thompson 1986). It is therefore probable that the Agulhas current contributes significantly to the periodic sea level variations in Durban coast and the surrounding.

Sea levels in the southwest Indian Ocean and the East coast of Africa display important regional variability which is driven at interannual time scales by ENSO events. ENSO has a strong regulating impact on sea levels with a characteristic likelihood of high sea levels during the El Nino periods and lower sea levels during the La Nina events. Indian Ocean Dipole also has significant impacts on sea level variability with positive phases responsible for elevated levels and negative phases influence lower sea levels in the southwest Indian Ocean due to significant temperature anomalies.

The trends of the sea level extremes in East coast of Africa and the adjacent islands (Port La Rue in Seychelles and Port Louis in Mauritius) appear to be associated with the year to year changes in meteorological extremes and are also influenced by the perigean cycle of the tides on a 4.4 year period.

Recommendations

There is a need to develop the capability to provide present rates and predict future estimates of variations in sea levels on local and regional scales which will enable accurate and effective assessment of the impact on the coastal regions. Long and precise tide gauge records are required and will continue to play a major role together with satellite data in determining the rate of sea level change regionally. The establishment of more tide gauges and proper maintenance of the existing ones is a key to the realization of well protected coastal environment from sea level change impacts.

Given the present uncertainty about the rate of sea level rise especially in Africa coasts together with the inadequate research in this region and the shortage of continuous and long period dataset for research, it would be appropriate to develop regional models for the key locations to provide information about sea level and climate related impacts. Detailed vulnerability assessments with the primary aim of developing efficient adaptive capacity measures to the impacts of sea level rise should be conducted at the vulnerable locations.

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APPENDICES

A. Months in a Year of highest Observed Sea Levels and Residuals.

Tables 1 – 6 shows the months of highest observed sea levels and residuals in a year at the tide gauge stations located in the East coast of Africa and the adjacent islands of Port La Rue in Seychelles and Port Louis in Mauritius.

Year	Month	Day	Time(GMT)	**Observed Level (mm)**	Month	Day	Time (GMT)	**Residual Level (mm)**
1996	3	19	14	**1850.13**	3	21	19	**211.1**
1997	10	19	03	**1900.7**	3	28	19	**198.13**
1998	4	26	13	**1913.57**	4	27	18	**287.99**
1999	4	17	14	**1918.83**	3	19	19	**183.2**
2000	1	22	02	**1850.47**	7	3	18	**135.16**
2001	9	20	03	**1844.6**	3	27	19	**204.39**
2002	3	31	16	**1930.75**	3	28	18	**231.9**
2003	3	21	16	**1989.63**	4	19	19	**255.09**
2004	6	4	14	**1866.14**	6	11	11	**157.05**
2005	4	9	15	**1849.6**	4	9	17	**296.02**
2006	11	6	02	**1937.37**	3	17	06	**193.83**
2007	9	28	02	**1947.24**	5	13	19	**221.92**
2008	9	17	02	**1876.75**	10	1	01	**425.43**
2009	7	23	15	**1830.05**	3	30	20	**224.68**

Table 1: Months of highest sea level observations and residuals in a year at Lamu.

Year	Month	Day	Time (GMT)	**Observed Level (mm)**	Month	Day	Time (GMT)	**Residual Level (mm)**
1990	11	5	02	**2310.58**	5	11	18	**277.22**
1991	3	2	14	**2268.39**	4	14	16	**266.37**
1992	10	27	01	**2270.93**	3	17	22	**175.15**
1993	9	18	02	**2388.58**	4	26	18	**177.43**
1994	2	28	15	**2358.27**	10	9	22	**186.36**
1995	6	14	14	**2281.1**	1	7	14	**190.24**
1996	2	21	15	**2276.08**	5	3	16	**161.01**
1997	10	19	03	**2327.33**	12	8	13	**228.78**
1998	10	8	02	**2351**	4	21	06	**248.82**
1999	5	17	15	**2329.08**	5	14	19	**180.08**
2000	1	23	03	**2253.29**	1	1	15	**146.09**
2001	2	9	02	**2277.39**	3	23	18	**171.72**
2002	4	27	13	**2392.91**	5	12	20	**199.62**
2003	5	16	13	**2392.14**	4	30	17	**234.99**
2004	11	14	02	**2281.02**	5	11	22	**157.04**
2005	2	10	02	**2267.5**	4	13	06	**205.73**

Table 2: Months of highest sea level observations and residuals in a year at Zanzibar

Year	Month	Day	Time (GMT)	**Observed Level (mm)**	Month	Day	Time (GMT)	**Residual Level (mm)**
1992	10	26	01	**1974.82**	3	16	21	**171.37**
1993	4	6	13	**2054.41**	4	26	04	**143.87**
1996	2	20	02	**1985.02**	6	6	09	**157.08**
1998	5	26	14	**2069.06**	4	22	17	**253.2**
1999	11	25	02	**2024.74**	11	20	00	**145.82**
2000	7	3	14	**1944.32**	2	10	06	**119.74**
2002	2	28	02	**2066.81**	3	3	16	**194.14**
2003	5	16	13	**2100.75**	4	28	18	**212.92**
2007	10	27	02	**2129.44**	5	14	22	**182.94**
2008	4	8	14	**1986.81**	3	20	16	**150.11**
2009	8	21	14	**1967.94**	4	15	18	**202.02**

Table 3: Months of highest sea level and residuals in a year at Mombasa

Year	Month	Day	Time (GMT)	**Observed Level (mm)**	Month	Day	Time	**Residual Level (mm)**
1991	2	1	10	**453.99**	1	31	19	**225.34**
1992	2	18	22	**552.47**	2	9	23	**286.72**
1993	3	8	09	**565.56**	1	19	20	**339.49**
1994	12	31	21	**419.78**	2	10	18	**317.9**
1995	2	27	07	**517.66**	2	26	12	**377.23**
1996	1	20	21	**452.32**	12	8	09	**280.31**
1997	4	7	09	**407.8**	4	1	10	**196.23**
1998	3	27	21	**474.04**	2	11	07	**241.46**
1999	1	31	22	**458.15**	2	4	00	**249.51**
2000	2	19	08	**422.19**	2	15	11	**252.6**
2001	4	5	20	**517.44**	1	6	03	**259.59**
2002	11	3	08	**391.57**	12	27	01	**250.29**
2003	4	18	10	**483.99**	2	13	06	**330.47**
2004	2	8	10	**502.81**	2	5	09	**333.42**
2005	3	10	09	**491.64**	3	24	07	**316.82**
2006	2	28	09	**455.7**	4	29	14	**209.65**
2007	12	23	08	**431.93**	2	27	12	**263.73**

Table 4: Months of highest sea level observations and residuals in a year at Port Louis

Year	Month	Day	Time (GMT)	**Observed Level (mm)**	Month	Day	Time (GMT)	**Residual Level (mm)**
1993	10	17	02	**970.55**	2	13	16	**198.24**
1994	10	7	01	**973**	9	2	22	**156.95**
1995	10	26	01	**918.3**	3	20	14	**191.08**
1996	3	22	15	**930.2**	2	15	08	**239.62**
1997	11	14	00	**1094.58**	12	6	23	**284.63**
1998	4	27	13	**1055.09**	3	25	04	**290**
1999	5	16	13	**986.77**	7	14	17	**180.26**
2000	12	12	01	**938.98**	2	17	21	**162.78**
2001	4	10	14	**916.89**	3	3	13	**161.21**
2002	3	31	14	**967.67**	3	26	16	**207.74**
2003	4	20	15	**1046.81**	3	27	05	**237.16**

Table 5: Months of highest sea level observations and residuals in a year at Pt La Rue

Year	Month	Day	Time (GMT)	**Observed Level (mm)**	Month	Day	Time (GMT)	**Residual Level (mm)**
1971	10	5	15	**1142.41**	8	7	19	**375.4**
1972	3	18	03	**1138.39**	5	3	23	**322.96**
1973	5	5	03	**1128.49**	10	9	16	**377.82**
1975	10	5	13	**1152.94**	7	20	23	**330.84**
1976	4	15	03	**1111.38**	2	22	02	**256.28**
1977	5	4	02	**1097.99**	5	8	14	**285.37**
1978	12	30	14	**1102.09**	9	4	00	**347.03**
1979	8	9	15	**1107.65**	5	3	07	**293.59**
1980	4	15	14	**1193.01**	4	20	01	**314.14**
1983	3	2	04	**1089.66**	4	18	06	**246.76**
1984	4	16	01	**1160.76**	7	5	08	**320.9**
1986	2	25	14	**1142.69**	-	-	-	-
1987	2	1	03	**1089.74**	6	5	12	**337.13**
1989	9	18	16	**1110.72**	2	17	09	**276.07**
1991	10	7	13	**1151.18**	-	-	-	-
1995	3	18	03	**1132.69**	-	-	-	-
1996	7	31	15	**1189.85**	2	13	14	**373.99**
2001	8	20	15	**1202.7**	2	16	19	**255.54**
2002	2	28	02	**1258.18**	9	12	05	**317.67**
2003	4	18	02	**1211.08**	12	11	14	**269.15**
2007	3	20	04	**1295.13**	3	20	03	**398.75**

Table 6: Months of highest sea level observations and residuals in a year at Durban

B. Tidal Constituents

Table 8: Tide Constituents Lamu station

tide	Frequencies (cycles/day)	Amplitudes (cm)	amplitude_error (cm)	Phases (deg)	pha_error (deg)
SA	Inf	0	0	0	0
SIG1	27.85	6.12	2.92	18.08	24.50
Q1	26.87	29.83	2.47	6.41	4.55
RHO1	26.72	4.73	2.32	339.49	28.84
O1	25.82	116.30	2.71	4.71	1.20
TAU1	25.67	3.14	1.64	45.52	34.31
NO1	24.83	11.07	2.60	309.40	11.01
P1	24.07	55.85	2.00	0.03	1.83
S1	24	27.26	2.71	317.79	6.50
K1	23.93	199.75	2.31	358.23	0.75
J1	23.10	14.54	2.53	8.47	9.65
SO1	22.42	6.63	2.29	112.56	21.73
OO1	22.31	10.84	4.02	44.53	22.07
EPS2	13.13	8.32	3.31	58.24	21.63
2N2	12.90	24.89	3.49	346.74	7.75
MU2	12.87	28.15	3.61	69.97	7.09
N2	12.66	176.59	3.05	13.64	1.13
NU2	12.63	37.88	3.01	10.76	5.20
H1	12.44	8.02	2.93	77.44	22.23
M2	12.42	982.48	3.08	31.28	0.18
LDA2	12.22	15.46	3.80	16.18	12.71
L2	12.19	35.02	3.07	35.15	4.35
T2	12.02	34.55	3.62	73.35	5.39
S2	12	488.0	3.55	73.42	0.35
R2	11.98	5.75	2.62	72.27	28.96
K2	11.97	135.91	4.21	71.83	1.85
MO3	8.39	8.53	1.56	178.43	12.45
SO3	8.19	6.86	1.66	214.39	13.51
MK3	8.18	7.06	1.58	161.10	13.20
SK3	7.99	4.94	1.59	218.29	17.98
MN4	6.27	9.34	1.63	160.03	10.40
M4	6.21	23.65	1.59	183.16	3.78
SN4	6.16	5.53	1.74	240.46	16.77
MS4	6.10	19.18	1.67	224.78	5.50
MK4	6.09	6.57	2.05	242.14	18.95
S4	6	7.57	1.78	285.40	13.35
2MK5	4.93	2.33	0.67	353.12	18.36
2MN6	4.17	3.37	0.90	49.17	15.89
M6	4.14	5.53	0.97	69.60	8.87
2MS6	4.09	10.31	0.93	121.74	5.93

Table 9: Tide Constituents Zanzibar station

tide	Frequencies (cycles/day)	Amplitudes (cm)	amplitude_error (cm)	Phases (deg)	phase_error (deg)
SSA	Inf	0	0	0	0
MF	327.86	21.87	11.55	23.35	29.56
2Q1	28.01	6.52	2.88	328.99	27.23
SIG1	27.85	4.88	2.74	344.10	32.50
Q1	26.87	27.70	2.85	356.61	6.00
RHO1	26.72	4.80	2.53	347.96	30.55
O1	25.82	110.28	2.77	0.73	1.57
NO1	24.83	9.11	3.21	329.57	17.32
P1	24.07	55.13	3.21	353.40	3.44
K1	23.93	184.98	3.18	355.72	0.92
J1	23.10	15.84	3.40	5.36	11.29
OO1	22.31	10.72	1.84	22.99	10.03
2N2	12.91	29.74	8.01	343.60	16.58
MU2	12.87	18.11	7.89	6.79	25.49
N2	12.66	221.96	6.96	6.57	1.89
NU2	12.63	45.61	6.78	8.21	10.31
M2	12.42	1205.70	7.42	25.29	0.35
LDA2	12.22	14.34	6.34	44.17	31.79
L2	12.19	36.76	6.38	37.94	9.85
S2	12	607.35	8.28	64.47	0.68
K2	11.97	166.91	5.35	60.99	1.72
MO3	8.39	1.77	1.00	202.71	49.18
M3	8.28	3.72	1.73	128.88	23.94
SK3	7.99	4.18	1.24	333.45	18.38
MN4	6.27	6.06	1.05	112.36	10.49
M4	6.21	15.21	1.18	180.77	4.43
MS4	6.10	10.34	1.03	276.06	6.55
MK4	6.09	2.11	0.78	279.80	25.13
2SK5	4.79	2.45	1.12	307.42	29.35
2MN6	4.17	11.73	3.42	348.37	14.29
M6	4.14	24.40	3.60	43.48	8.01
2MS6	4.09	15.94	3.53	109.62	13.51

Table 10: Tide Constituents Port Louis (Mauritius).

tide	Frequencies (cycles/day)	Amplitudes (cm)	amplitude_error (cm)	Phases (deg)	phase_error (deg)
Q1	26.87	8.00	1.22	20.80	9.46
O1	25.82	41.55	1.27	36.01	1.75
NO1	24.83	2.73	1.05	34.02	22.02
P1	24.07	19.33	1.52	62.45	4.34
K1	23.93	63.41	1.42	66.73	1.88
PHI1	23.80	2.80	1.47	72.16	33.45
J1	23.10	3.21	1.11	52.92	22.92
OO1	22.31	2.83	0.81	83.29	15.36
2N2	12.91	8.06	3.49	242.56	24.18
N2	12.66	43.76	3.69	275.57	4.95
NU2	12.63	8.05	3.37	268.78	26.04
M2	12.42	153.98	3.60	274.07	1.37
MKS2	12.39	5.69	2.75	180.77	25.70
L2	12.19	6.39	3.35	224.68	38.97
S2	12	100.21	3.68	279.36	1.96
K2	11.97	29.74	2.68	276.43	5.20
M3	8.28	6.05	1.03	22.97	10.94
M4	6.21	4.63	2.12	126.12	31.05
MS4	6.10	3.87	1.95	169.57	31.46
M6	4.14	2.08	1.11	82.86	28.01

Table 11: Tide Constituents at Pt. La Rue (Seychelles)

tide	Frequencies (cycles/day)	Amplitudes(cm)	amplitude_error (cm)	Phases (deg)	phase_error(deg)
SSA	Inf	0	0	0	0
2Q1	28.01	4.37	1.91	327.33	26.72
SIG1	27.85	3.94	1.82	355.72	24.62
Q1	26.87	26.07	1.97	353.90	4.28
RHO1	26.72	5.02	1.76	3.78	19.38
O1	25.82	103.46	1.67	4.90	1.25
NO1	24.83	5.07	1.55	33.12	16.94
P1	24.07	55.75	2.18	0.70	2.00
K1	23.93	182.36	1.54	0.12	0.57
J1	23.10	13.35	2.14	24.90	8.46
OO1	22.31	8.77	1.23	27.79	7.31
2N2	12.91	10.78	2.60	289.25	13.30
MU2	12.87	6.50	2.40	325.83	19.55
N2	12.66	85.68	2.35	349.65	1.53
NU2	12.63	16.30	2.23	352.08	8.04
M2	12.42	401.56	2.44	14.08	0.34
L2	12.19	14.80	2.50	30.06	10.45
S2	12	178.09	2.40	52.06	0.76
K2	11.97	47.74	2.03	49.20	2.30
ETA2	11.75	3.35	1.79	36.23	36.32
MO3	8.39	1.17	0.56	204.42	34.24
M3	8.28	3.28	0.82	333.08	12.77
SK3	7.99	2.61	0.78	116.71	16.81
MN4	6.27	1.20	0.66	234.46	36.75
M4	6.21	1.74	0.73	254.90	24.43

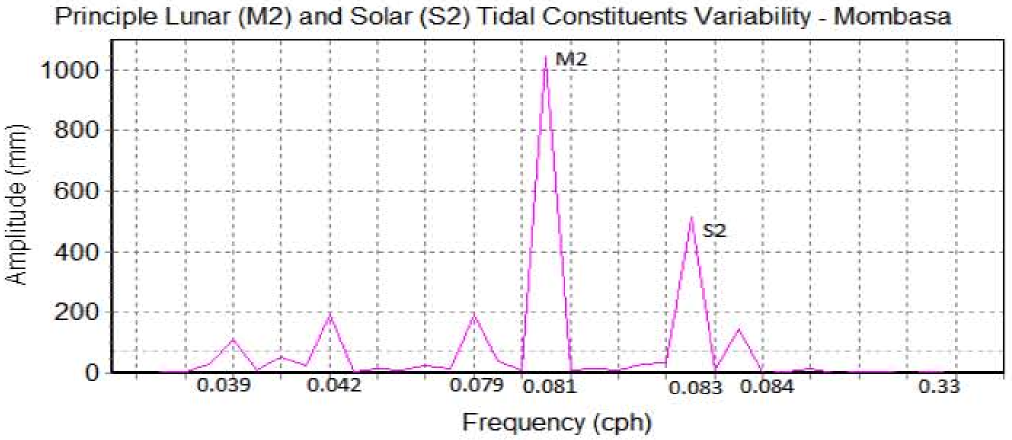
Table 12: Tide Constituents Mombasa Station

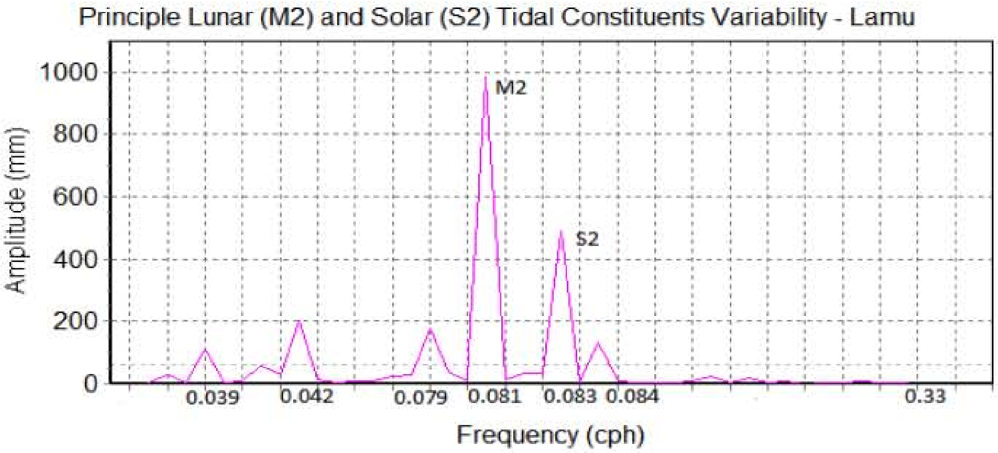
tide	frequencies	Amplitudes	amplitude_error	phases	phase_error
2Q1	28.01	2.48	1.35	317.45	39.38
SIG1	27.85	5.62	1.64	341.13	18.94
Q1	26.87	22.40	1.65	356.24	4.14
RHO1	26.72	5.42	1.75	346.35	17.28
O1	25.82	112.41	1.49	359.19	0.80
BET1	24.97	2.64	1.49	343.35	37.24
NO1	24.83	17.45	2.54	356.40	7.58
P1	24.07	54.76	1.91	354.37	1.97
S1	24	28.87	2.55	312.58	5.26
K1	23.93	189.97	1.46	354.27	0.54
PHI1	23.80	3.59	1.93	335.46	32.01
J1	23.10	11.11	1.73	353.76	8.38
OO1	22.31	10.16	1.11	29.83	6.69
UPS1	21.58	2.25	1.18	30.93	31.41
2N2	12.91	16.28	3.26	317.20	11.40
MU2	12.87	14.83	3,57	17.94	13.18
N2	12.66	183.74	3.65	5.03	1.21
NU2	12.63	40.89	3.23	7.15	5.84
H1	12.43	6.59	3.70	30.06	33.08
M2	12.42	1042.28	3.96	25.65	0.23
H2	12.40	6.89	3.75	353.86	27.21
LDA2	12.22	14.40	4.25	40.56	17.07
L2	12.19	34.82	2.89	45.16	4.59
T2	12.02	28.20	3.71	56.70	7.31
S2	12	514.03	3.91	64.73	0.41
R2	11.98	7.31	2.94	36.98	23.04
K2	11.97	143.69	2.99	60.74	1.22
ETA2	11.75	6.23	2.58	73.98	25.83
MO3	8.39	2.97	1.08	134.26	19.78
M3	8.28	3.03	1.44	136.74	24.03
MN4	6.27	5.42	1.20	104.66	13.11
M4	6.21	13.41	1.18	136.08	5.47
MS4	6.10	6.81	1.16	161.69	10.41
MK4	6.09	1.89	0.94	170.59	29.89
S4	6	3.36	1.10	196.38	18.83
SK4	5.99	1.84	0.95	195.98	29.62
2SK5	4.80	1.23	0.64	297.77	27.35
2MS6	4.09	2.67	0.88	138.42	16.61
2SM6	4.05	1.25	0.64	228.34	30.50

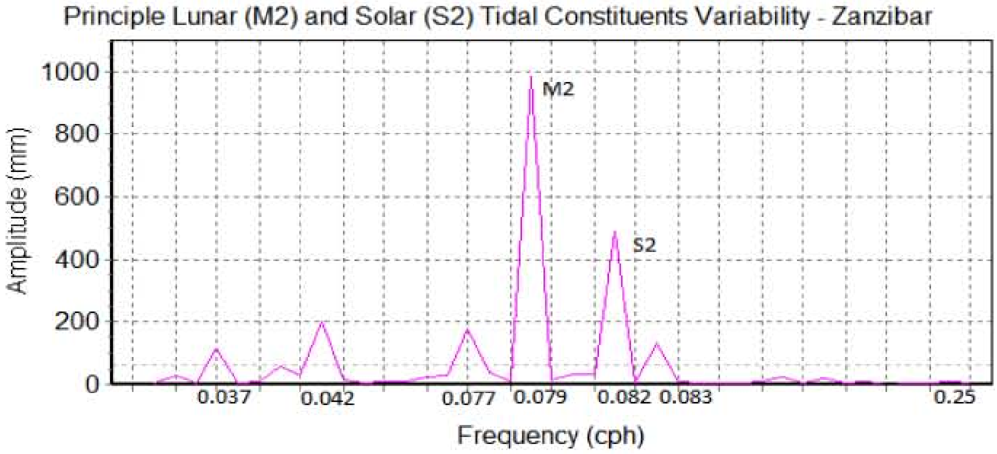
Table 13: Tide Constituents at Durban Station

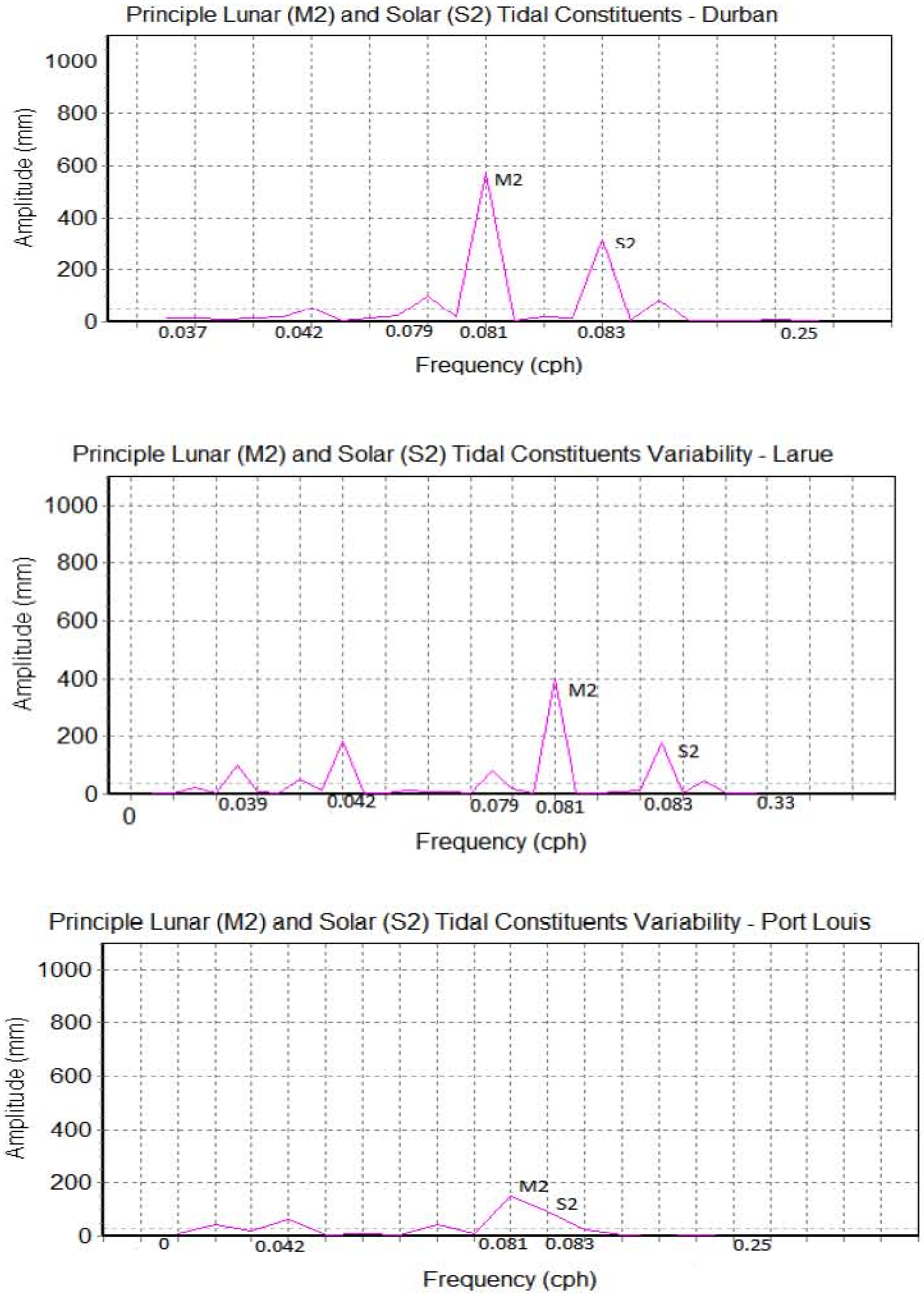
tide	Frequencies (cycles/day)	Amplitudes (cm)	amplitude_error (cm)	Phases (deg)	phase_error (deg)
Q1	26.87	9.30	1.76	294.11	11.05
O1	25.82	16.73	1.71	303.86	7.13
P1	24.07	15.51	2.43	139.42	7.88
K1	23.93	53.17	1.82	147.25	2.14
J1	23.10	5.29	1.95	172.97	21.45
OO1	22.31	3.41	1.36	217.17	18.90
2N2	12.91	11.90	3.01	44.76	14.88
MU2	12.87	18.03	3.10	40.41	9.91
N2	12.66	100.23	3.18	40.07	1.65
NU2	12.63	19.84	3.28	33.84	8.79
M2	12.42	562.92	3.34	44.03	0.30
LDA2	12.22	5.73	2.85	24.73	35.01
L2	12.19	23.88	3.32	37.75	9.29
S2	12	313.20	3.09	75.86	0.55
K2	11.97	88.65	2.41	72.11	1.59
ETA2	11.75	3.89	2.04	83.72	27.68
M3	8.28	3.14	1.27	349.45	19.47
SK3	7.99	4.48	1.03	139.54	12.74
MN4	6.27	4.01	0.64	133.75	8.87
M4	6.21	5.21	0.53	180.26	5.67
MS4	6.10	1.55	0.57	266.66	22.23
M6	4.14	1.19	0.65	110.83	34.21
2MS6	4.09	1.51	0.70	177.19	25.73

C. Variations of principle semidiurnal constituents (M_2 and L_2)



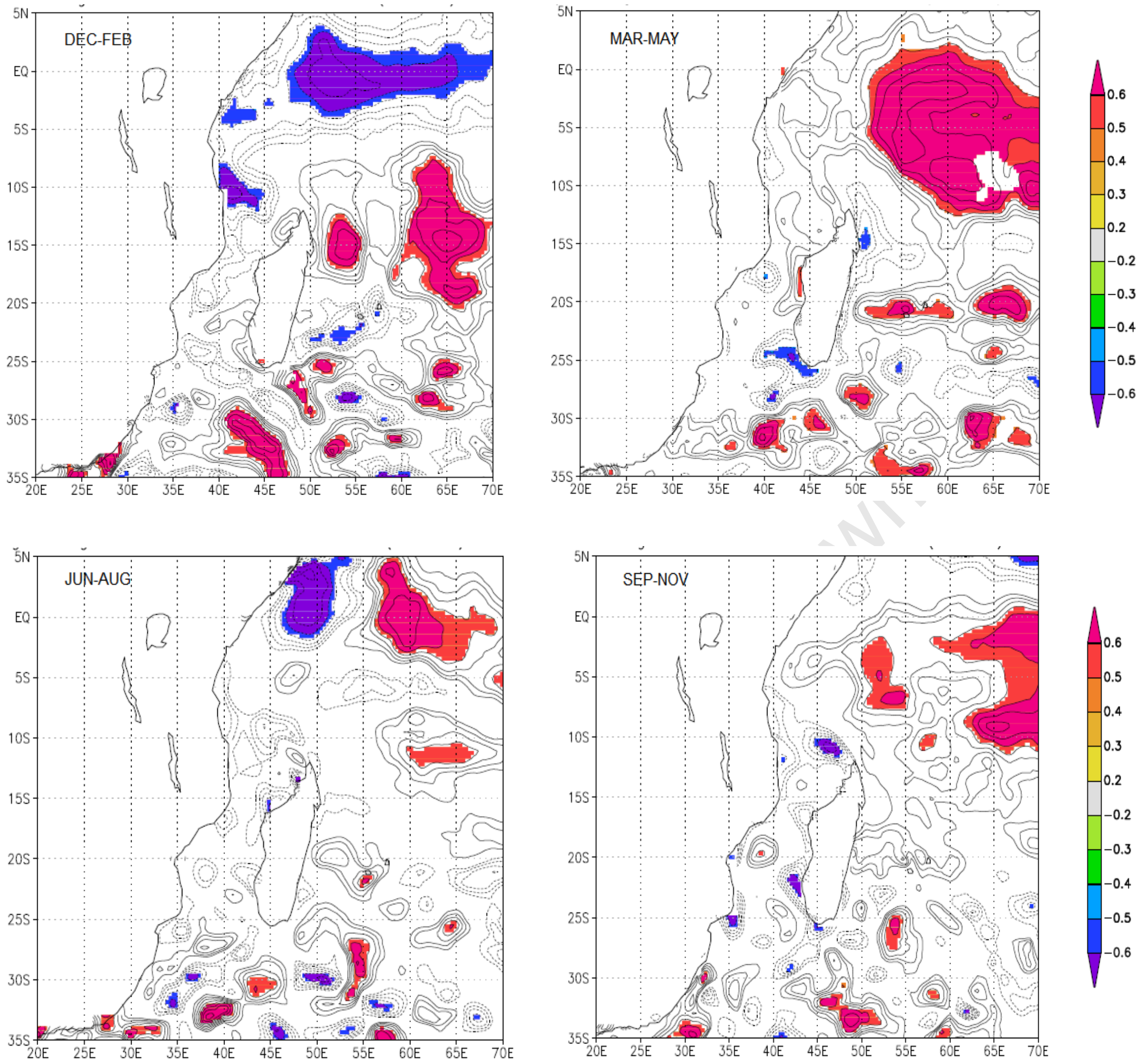






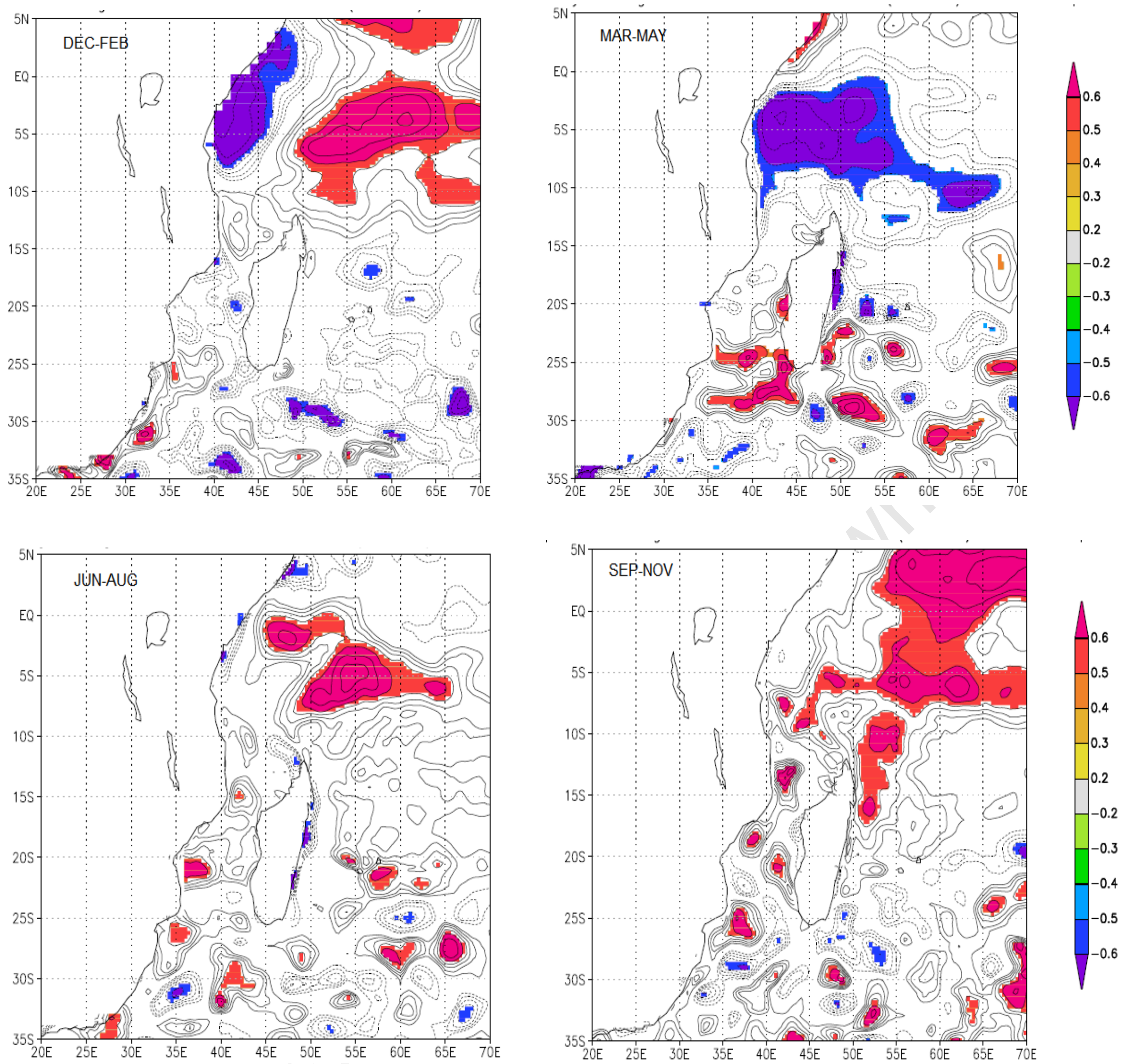
Variations of M_2 and S_2 tide constituents in the East coast of Africa and islands

D. Correlations of Meridional wind stress and Merged Sea Level Anomaly



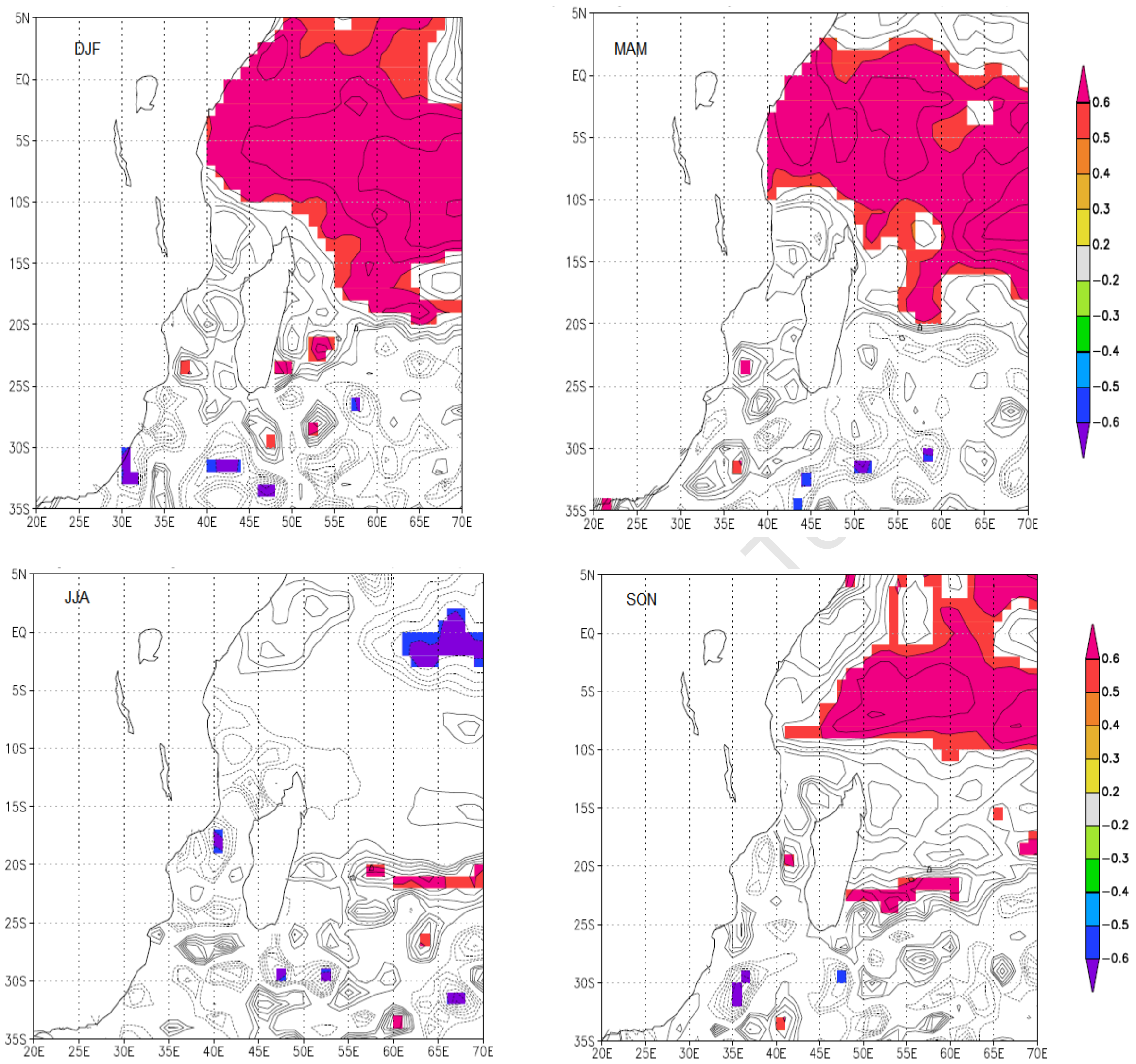
Long term Seasonal Meridional wind stress and merged sea level anomalies (1993-2004) http://climex.knmi.nl.

E. Correlations of Zonal wind stress and Merged Sea Level Anomaly



Long term seasonal zonal wind stress with merged sea level anomalies (1993-2004) http://climex.knmi.nl.

F. Correlations of NINO 3.4 Index and Merged Sea Level Anomaly



Seasonal averaged NINO 3.4 and CLS merged sea level anomalies (1993-2004) http://climex.knmi.nl.