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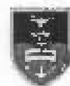
University of Cape Town

Sea Level and Climate Variability at Zanzibar

Mohammed K. Ngwali

Submitted in partial fulfilment of the requirements for the Masters Degree in Applied Marine Science



UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Department of Oceanography

May 2007

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DECLARATION

I do hereby declare that the entitled "Sea Level and Climate Variability in Zanzibar" submitted in partial of requirements of the degree of Master of Science in Applied Marine Sciences of the University of Cape Town is a record of research work. The subject matter embodied in this research is my own original work and has not been submitted at any University.

Name ...MOHAMMED KHAMIS NGWALI

Signature ..Signed by candidate

Signed this..25....day of April, 2007

DEDICATION

With Great love and appreciation, I dedicate this work first and foremost to the Almighty "*Allah*" for the very life and sustenance, and secondly to my mother who passed away at the time I was barely three months old.

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To the Almighty and merciful God (*Allah*), I am most grateful for your continuous guidance, protection and immense blessings throughout my academic career.

ABSTRACT

This study focuses on general features and variations of sea level at Zanzibar, and the relation of these to climate variability over the tropical western Indian Ocean during the 1997-1998 El Niño and the 2000-2001 La Niña periods. The sea level data used in this study has been collected over a period of nine years from 1996 to 2004.

Analyses have shown that the predominant type of tides at Zanzibar are semi-diurnal with two high and two low water levels in each tidal day. Over the monthly cycle, two spring and two neap tides with different tidal ranges are observed. The tidal range may vary depending on the season of the year. Long-term monthly mean sea level height data shows that there are two high water and two low water periods in a year. The variation of sea level height throughout the year is related to seasonal changes in solar heating, the prevailing winds (monsoon) and sea level pressure patterns over the tropical western Indian Ocean and the East African Coast.

On interannual time scales, variation of sea level at Zanzibar is related to large scale climate modes. Analysis of nine years of sea level data indicated that interannual variation of sea level in Zanzibar is linked to the impact of El Niño Southern Oscillation (ENSO) events in the tropical western Indian Ocean and the Indian Ocean Zonal Dipole Mode (IOZDM)

During the 1997/1998 El Niño and positive IOZDM, sea surface temperature began to slightly rise from July 1997 and strong positive sea surface temperatures were observed in the Indian Ocean from January to April 1998. The increase in sea surface temperature during the period was associated with thermal expansion of the ocean along the East African Coast, resulting in an increase of sea levels around Zanzibar. That situation enabled strong convection to develop leading to severe weather over the East African region.

The decrease in sea surface temperature and sea level height during the 2000/2001 La Niña and associated cold event in the tropical western Indian

Ocean caused a reduction of moist air from the ocean and stabilized the atmosphere, resulting in the development of relatively fine weather and reduced rainfall over the East African region.

Chapter 1

"Sea levels are always changing, for many reasons. Some changes are rapid while others take place very slowly. The changes can be local or can extend globally" (David Pugh 2004 page 1).

1 Introduction

This Introductory chapter will discuss the basic idea of sea level variations on various time scales and the major factors that cause these variations. It will also discuss the major factors that influence sea level variations and climate at Zanzibar before explaining in detail the various processes involved.

The major purposes of this study are to investigate and understand general features of sea level variations at Zanzibar on different time scales, to investigate factors that affect sea level variation around Zanzibar and to investigate and understand the impact of climate variability on sea level at Zanzibar.

Sea level is the height of the sea, with reference to a suitable reference surface (datum level). The most common method used to measure sea level is by tide gauges. Normally tide gauges are placed at the coast areas and island sites (Schwatz 1982). The average sea level around which variations occur is called the mean sea level. Mean sea level refers to water level observations which have been averaged over a long period of time, no matter how long a period of data has been averaged (Pugh 1987).

The change of mean sea level height with respect to the reference surface is called sea level variations (Church & Gregory 2001). Variations in sea level occurs hourly, daily and monthly but differs seasonally depending on the time and period of the year. It may also vary interannually due to the fluctuations of

various oceanic and climate parameters and the impact of large scale climate modes, and long time scales due to human induced climate change

1.1 Hourly to Monthly Mean Sea Level Variations

Daily mean sea level variation is the average height of the sea with reference to the land on a particular day. The daily mean sea value is obtained from hourly observed data (Ruby & Sete 2002). Normally, daily variations in sea level are associated with daily changes in local weather conditions which are influenced by the passage of synoptic weather system.

Usually sea level records are dominated by a twice-daily oscillation due to tides. While sea level fluctuates on a daily basis due to tides, weather conditions may cause change in the interval between high and low water or change in times of arrival of the tides (Pugh 1987). The hourly and daily mean sea level is mainly used for investigating the dynamics of events such as tsunamis and tropical cyclones on time scales of hours to several days.

The monthly mean sea level is calculated from daily mean sea level data. From the monthly mean sea level data, the average seasonal and annual cycle and the interannual variations may be derived. Monthly mean sea level data are useful for monitoring the linear trend of sea level variations at a particular place and its oceanic climate (Ruby & Sete 2002). The monthly mean sea level may be affected by variability in winds and pressure systems, sea surface temperature and ocean circulation, and by climate variability and changes

1.2 Seasonal and Interannual Sea Level Variability

Interannual sea level variations are caused by fluctuations in atmospheric and sea surface temperatures reflecting interactions between the ocean and atmosphere (Parker 1992). Those variations may be related to El Nino

Southern Oscillation (ENSO) events or to other climate modes such as the Indian Ocean Zonal Dipole Mode (IOZDM).

Initial research suggested that ENSO and IODZM were independent climate modes over the Indian Ocean although their associated sea surface temperature anomaly patterns were similar (Saji et al 1999). More recent result indicates that these phenomena may be related (Xie et al 2002; Loschnigg et al 2003) and have a significant impact on Indian Ocean sea level and climate variability on interannual time scales. The IODZM is a basin-scale event which occurs interannually in the tropical Indian Ocean (Ashok et al 2001) whereas ENSO is a global scale climate phenomenon that originates in the tropical Indo-Pacific. ENSO impacts in the Indian Ocean through both variations in the Indonesian Throughflow (Meyers 1996) and large scale wind and surface heat flux anomalies (Reason et al 2000, Xie et al 2002). In addition, ENSO generates Rossby waves in the Indian Ocean which propagate the signal to the West (Xie et al 2002).

Rossby waves are large-scale waves whose restoring force is the variation in the Coriolis effect with latitude. These waves are also known as planetary waves. Typically, they take a year (tropics) to a decade or more (middle latitude) to cross an ocean basin like the Indian Ocean. As they approach the land, Rossby waves deflect rightwards in the northern hemisphere and leftwards in the southern hemisphere (Capurro 1970). Rossby waves play a significant role in providing a mechanism for transmitting the climatic impacts of strong ENSO events (Webster at el 1999 and Yu and Rienecker 2000). They influence upper ocean temperatures, thermocline depths and cause variation in sea levels.

1.3 Major Factors Causing Sea Level Variation

There are two major factors controlling the sea level variation of a place. These factors are firstly astronomical, the gravitational forces of attraction

between the sun, the moon and the earth, and secondly, environmental or meteorological (weather systems and associated winds, climate variability).

1.3.1 Astronomical Factors

Astronomical factors are known as natural factors that control daily and seasonal variation of tides. These are combinations of the gravitational forces of attraction between the sun, the moon, and the earth. These forces of attraction create very predictable tides as the earth rotates.

Tides are defined as the periodic rise and fall of sea level with respect to the land. These periodic variations in sea level at a particular place are caused by the gravitational force of attraction of the sun and the moon on the earth and ocean. These forces create very predictable rises and falls in the sea level as the earth rotates on its axis (Bearman 1989). The gravitational attraction of the sun and the moon on the earth depends on the distance of these bodies from the earth (Mazumdar and Arima 2005). Because the moon is closer to the earth than the sun, it has a larger effect. The gravitational attraction of the moon on the earth causes the oceans to bulge out in the direction of the moon and another bulge occurs on the opposite side. The other force acting on these bulges is the centrifugal force. On the side closest to the moon, lunar attraction exceeds the centripetal forces while on the opposite side; the centrifugal force exceeds the lunar attraction (Lewis 1987).

These bulges would form a stable equilibrium tide, but because the earth is rotating on its own axis, the bulges have to move around the earth to keep themselves aligned with the moon (Pugh 1987). Since the earth rotates while this happens, two tides occur each day. The regular rise and fall of sea water twice a day is referred to as the semidiurnal tide. When the sea level is at its greatest height, the tide is said to be high and when sea level is at its lowest position, the tide is said to be low. Thus, sea level varies as the tidal bulge passes through each point on the surface of the earth (Pugh 1987). In order to keep up with the moon's position relative to the earth, these bulges travel around the earth every 24 hours 50 minutes (lunar day), and each day there

are two high and two low tides. There is about 12 hours 25 minutes between two high tides (Macmillan 1966).

The position of these bulges changes from time to time as the moon rotates around the earth and keeps the ocean constantly in movement. On average, it requires about 50 minutes longer each day for a sublunar point on the rotating earth to regain the position directly along the major axis of the moon's tidal force envelope, where the tide-rising influence is a maximum (Brussell and Macmillan 1954, Macmillan 1966).

The monthly tidal systems are influenced by the variability in the gravitational force on the earth due to the changing phases of the moon, declination of the moon and the changing earth-moon distance during the lunar orbit (Mazumdar and Arima 2005). Due to the changing phases of the moon, spring and neap tides can be formed.

Spring tides are especially strong tides (not related to the spring season). Normally, spring tides occur during full or new moon when the gravitational pull of the moon and sun are combined (Garrison 2002) as the earth, the sun, and the moon are in linear alignment. New moon occurs when the moon passes between the earth and the sun. Full moon occurs when the moon lies on the opposite side of the earth in relation to the sun. During the time of spring tide, the high tides are very high and the low tides are very low. Spring tides occur at two-week intervals during the full moon and the new moon.

Neap tides are especially weak tides. These occur when the gravitational forces of the moon and the sun are perpendicular, in other words they form a right angle to one another with respect to the earth (Garrison 2002). When the moon, earth, and sun form a right angle, the pulls of the moon and the sun act against each other. This makes the bulges cancel each other out, resulting in a smaller difference between high and low tide. These tides normally happen during the first and third quarter phases of the moon. During neap tides, high tides are not very high and low tides are not very low. Neap tides also occur one week after spring tides (Garrison 2002).

The moon has an influence on the time of arrival of tides of a given phase at any location due to the interaction between the tidal force envelopes of the moon and sun (Lewis 1987). Between new moon and first-quarter phase and between full moon and the third-quarter phase, a displacement of force components can be created which can cause acceleration in tidal arrival times resulting in the occurrence of high tides before the moon itself reaches the local meridian of the place (Brussell and Macmillan 1954). This is known as priming the tides. On the other hand, between first-quarter phase and full moon, and between third-quarter phase and new moon, an opposite displacement of force components can occur. Because of this placement, the arrival of high tides may occur after the moon has reached the place. This is called lagging of the tides (Brussell and Macmillan 1954).

1.3.2 Environmental Factors

Environmental factors are non-astronomical factors, sometimes known as meteorological factors, and include weather and climate. Weather can have a significant effect on tidal variations. The variations in tidal heights caused by prolonged winds and pressure are associated with different weather systems influencing a region (Pugh 2004). Climate variations on seasonal, interannual and decadal scales lead to sea level variations on these scales (Diane 1996). Variations in sea level can alter the transfer of the heat, moisture and momentum between the ocean and the atmosphere leading to regional changes in ocean and atmospheric circulations.

Weather conditions have a large impact on sea level variation. Conditions which differ from the average due to the passage of different weather systems will cause corresponding differences between the predicted daily tides and actual height of the sea level. Mainly sea level pressure changes and a strong or prolonged wind cause variations of sea levels from the predicted heights (Pugh 2004).

The sea level pressure, which acts upon the sea surface, has a relationship that can impact upon the variation of sea level. Theoretically, a sea level responds as an inverse barometer to a change in the atmospheric pressure. For a stationary ocean, sea levels increase by 1cm for every decrease of 1millibar in atmospheric pressure and vice versa (Robinson 1964, Chelton and Davis 1982).

Sea level at any given basin responds to atmospheric pressure and its variability. High pressure causes low tide, whereas low pressure raises the tidal level. However, the change takes time to develop and depends on the average pressure over a large area. Variations in atmospheric pressure are always associated with changes in the wind speed and direction (Brundrit 1984). Wind produces coastal waves, which are the most pronounced fluctuations in sea level around coastal and island areas.

Surface wind is the horizontal movement of air caused by a horizontal pressure gradient force. This change causes in fluctuations in sea level. Although the effect of the wind varies significantly as a result of local geographical features, the effect of the surface wind upon the sea surface always causes an increase or decrease in sea level. Wind creates waves which self-evidently influence the sea level fluctuations in coastal regions (Eugenie 1974). Strong winds blowing along the shore may cause storm surges. A surge is a marked change in water level caused by strong weather systems and typically travels more or less the same speed as the tides. Small surges are caused by the local weather, but large surges may be caused by tropical storms or cyclones some distance away.

1.4 Sea Level Variation around Zanzibar

In addition to the astronomical forces, variations of sea levels differ from one place to another due to geographical location, seasonal change and the general circulation of ocean and atmosphere at a particular place (Douglas & Ramizes, 2001). Geographically, Zanzibar Island is located in the western

Indian Ocean just 35 kilometres off the northern coast of Tanzania. Zanzibar has two major islands, Unguja with an area of 1,554 km^2 and Pemba with an area of 980 km^2. Pemba is about 50 kilometres to the north of Unguja (see Figure 1.1 below). Due to the location, variation of sea level around Zanzibar depends on the annual cycle in oceanic and atmospheric circulations over the Indian Ocean, and particularly over the tropical western Indian Ocean.

Figure 1.1 map showing Zanzibar Isles

The climate at Zanzibar can be divided into four main seasons. The warmest season is from January to early March, the long rain season known as "Masika" normally starts in the middle of March and lasts until the end of May or early June, the coolest months are June, July, August and early September and the short rainy season occurs during October to December. At times, the short rains may continue up to early January. The peak of the long rains is usually in April and for the short rains is usually in November.

The climate and its variability of the Zanzibar Isles are similar to the northern coast of Tanzania. Because of its geographical location and maritime exposure, the climate of Zanzibar is of the warm, humid tropical type with a strong oceanic influence. According to Reynolds Sea Surface Temperature Version 2 (SST V2) reanalysis data (see Figures 1.2 below), the maximum

sea surface temperatures in the tropical western Indian Ocean and East African coastal waters are observed from December to April and may exceed 27^{0}C. The minimum is observed from July to September, when sea surface temperature may be less than 26^{0}C.

For the most part, seasonal changes in sea surface temperature over the western Indian Ocean and the along East African coast play a major role in climate variability of Zanzibar. Above all, seasonal changes in sea surface temperature may influence major atmospheric circulation systems and winds over the East African region.

The major circulation systems that control the climate of Zanzibar are related to changes in the position of the Intertropical Convergence Zone (ITCZ), the monsoon circulations and tropical cyclones. The ITCZ is an area where the northeast trade winds converge with the southeast trade winds in the tropical region (Grant 1996). Usually, the ITCZ is associated with a tropical low pressure belt with horizontal low- level convergence, which causes uplift of moist air masses in that zone, resulting in occasions of heavy rain and frequent thunderstorms in that region.

The ITCZ tends to shift with the seasons, migrating southward during the southern summer and then northward during southern winter. The position of the ITCZ fluctuates during the different seasons and passes over Zanzibar twice a year, firstly, during October when the ITCZ moves from the northern to the southern hemisphere and, secondly, around March when it moves back from the southern to the northern hemisphere.

Zanzibar experiences northerly to northeasterly wind from December to February when the ITCZ is in southern hemisphere, and from April to August south to southeasterly wind when the ITCZ is in northern hemisphere. When there is a tropical cyclone within the vicinity, strong winds may be experienced. Tropical cyclones are the primary cause of storm surges along the Tanzanian coast and Zanzibar islands. The typical tropical cyclone season in the western Indian Ocean is from November to April.

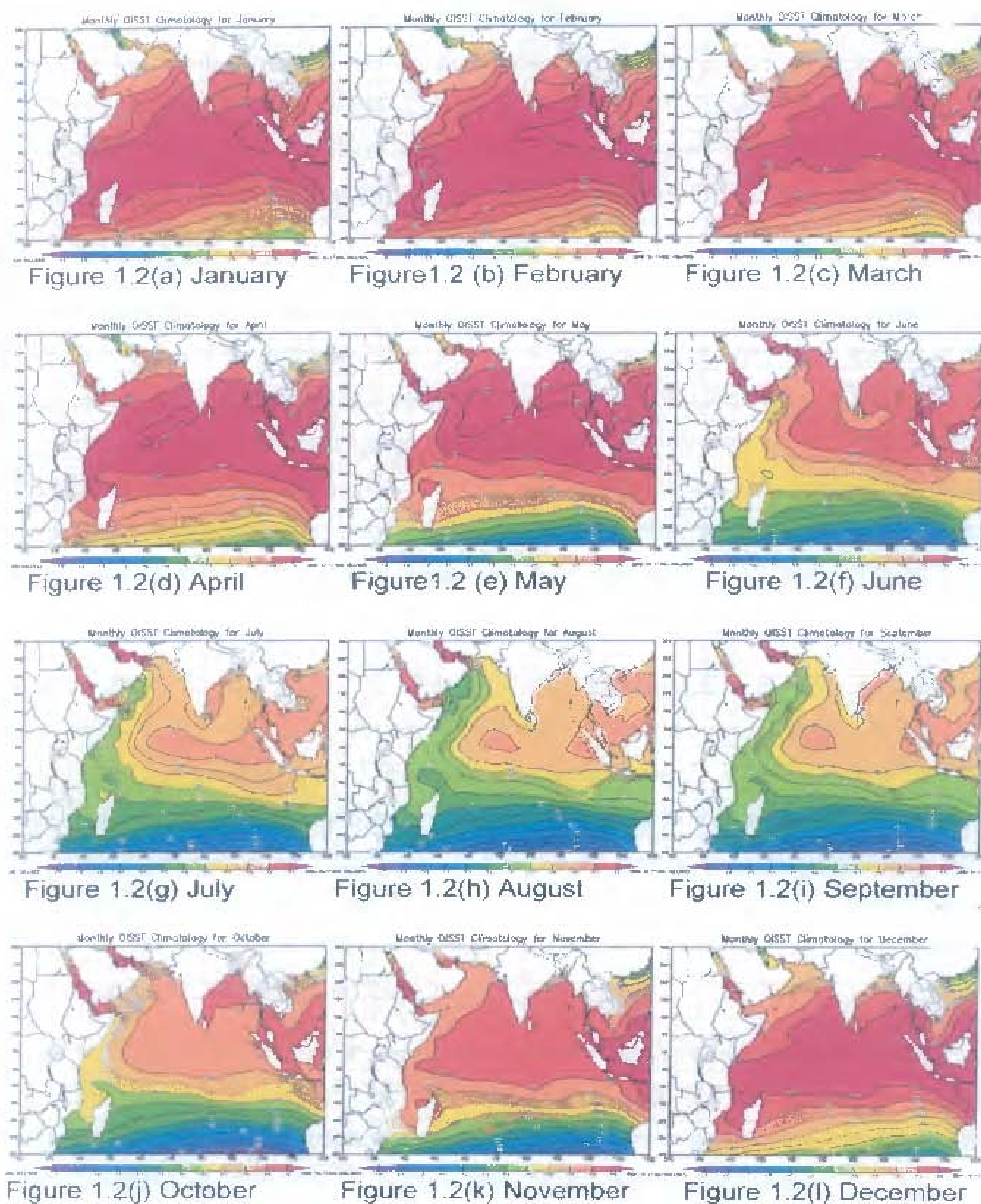


Figure 1.2(a) January Figure1.2 (b) February Figure 1.2(c) March

Figure 1.2(d) April Figure1.2 (e) May Figure 1.2(f) June

Figure 1.2(g) July Figure 1.2(h) August Figure 1.2(i) September

Figure 1.2(j) October Figure 1.2(k) November Figure 1.2(l) December

Figures (1.2a-1.2 l) Long-term sea surface temperature (climatology) from January to December

Besides the astronomical factors that cause sea level variation, the major factors that influence variations of sea level around Zanzibar are related to various changes in atmospheric and oceanic processes over the tropical western Indian Ocean. Therefore, it is very important to understand various atmospheric and oceanic processes in the Indian Ocean on different time scales.

The Indian Ocean is bounded by Asia in the northern hemisphere, while in the South it is open to the Southern Ocean. To the west is Africa. To the east, the Indian Ocean is connected with the Equatorial Pacific Ocean through the Indonesian Throughflow (Fieux & Reverdin 2001). Nearly all the Throughflow moves westward across the Indian Ocean and into the South Equatorial Current. The volume transport of Throughflow varies, with larger than average transport during La Nina and less than average during El Niño (Clark & Liu 1994).

The Indian Ocean is the third largest ocean after the Pacific Ocean and Atlantic Ocean, with a large part of the basin in the southern hemisphere. The northern Indian Ocean includes the Arabian Sea. The major difference between the Indian and Atlantic or Pacific oceans is the seasonal reversal of the monsoon winds and its effect on the ocean currents in the northern part of the Indian Ocean (Tomczak & Godfrey 1994) which in turn is related to the pressure of Asia. Due to the location of Asia, there is no temperate zone or polar region in North Indian Ocean.

The Indian Ocean circulation is a large-scale system which transfers heat and salinity from one region to another (Wells 2001).The major processes controlling circulation of the ocean are wind and density differences, the latter produced by the differences in buoyancy fluxes within the ocean.

The Indian Ocean circulation plays an important role in climate variability in the region. This involves the relationship between sea surface temperature, upper ocean heat content and sea level variation, and oceanic and atmospheric circulation on different time scales (Schneider 1996). Over the

tropical ocean regions, there is a particularly fast response to surface wind stress and this allows strong coupling between the ocean and atmosphere to occur which is important for development of the Indian Ocean Zonal Dipole Mode.

The Indian Ocean circulation includes horizontal and vertical flows. Horizontal flow leads to the horizontal advection of heat on a large scale from one region to another while vertical flow includes upwelling and the overturning in the ocean. Both horizontal and vertical flows may be induced by the wind acting on the sea surface between the ocean and atmosphere by the surface heat and freshwater fluxes. The horizontal layer of less than 100m in depth which is directly affected by the winds is known as the Ekman layer (Wells 2001). The Ekman layer is fundamentally important for the large scale southward export of heat in the Indian Ocean (Godfrey 1996*)*.

Where the Ekman flow converges, it produces downwelling transport into the interior of the ocean, and where it diverges, it produces an upwelling transport from the interior into the surface layer. Ekman transport does not develop a divergence near the equator, and therefore, unlike the Pacific and Atlantic, there is no upwelling in the equatorial Indian Ocean (Tomczak & Godfrey 1994). Strong equatorial downwelling occurs during monsoon transition periods, when winds turn eastward at the equator, providing Ekman transport convergence. Areas of strong upwelling in the Indian Ocean develop off the Somali coast and the Arabian Peninsular as well as Java / Sumatra during the southwest monsoon and in the thermocline ridge northwest of Madagascar, particularly during austral summer (Schott & McCreary 2001).

1.4.1 Monsoon Circulation over the Indian Ocean

The Monsoon is a seasonal change in direction of the prevailing surface wind between summer and winter. The word monsoon appears to have originated from the Arabic word "*mausim*" which means seasonal changes (Krishnamurti 1996). Sometimes the name monsoon is used to denote the main rainy season, and a spectacular change in the monsoon rains occurs during the

beginning of both the summer and winter monsoons. In fact, monsoon relates to both extremes of the annual cycle.

Basically, the monsoon flow is caused by large pressure gradients created by differential heating of land and ocean on large scales. The pressure gradient leads to regional circulation of wind, which is steady and sustained (Slingo 2003). During the summer, the continent heats up rapidly and warm air rises while the cool air from the ocean flows onto the land. During winter, the reverse is the case.

The critical factor that determines the generation of the monsoon is the geographical orientation of the ocean and landmass. The northern hemisphere part of the Indian Ocean as well as the equatorial Indian Ocean is characterized by seasonal changes in monsoons. The most obvious monsoonal affect is the seasonal reversal of the wind direction over the northern part of the Indian Ocean, particularly the Arabian Sea (Tomczak & Godfrey 1994). The monsoon blows from the southwest during one half of the year and from the northeast during the other half of the year.

Over the Subtropical South Indian Ocean, the atmospheric circulations undergo only a slight meridional shift (Parker 1980). The meridional shift is determined by the pressure gradient between the equatorial trough and the subtropical high-pressure belts.

Over East Africa, monsoon winds have a large impact on coastal regions because they are associated with the seasonal shift of the ITCZ (Waliser 2002). In January, the ITCZ is located at about 15^0S and most of East Africa is under the influence of northeasterly winds, which become northwesterlies south of the equator. In July, the ITCZ is situated around 25^0N and most of East African coast is under the influence of southeasterly and southerly winds (see Figures 1.3a – 1.3l below).

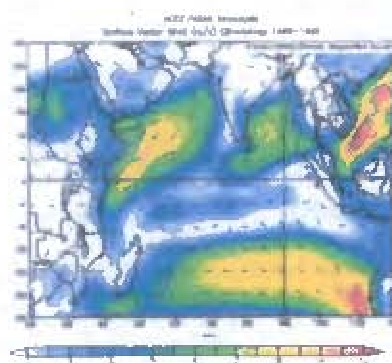


Figure 1.3a January

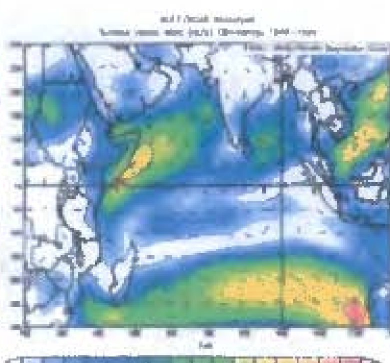


Figure 1.3b February

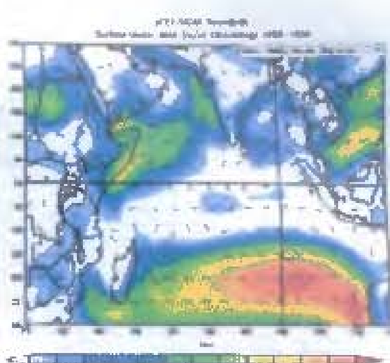


Figure 1.3c March

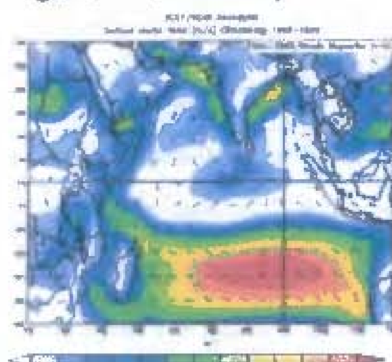
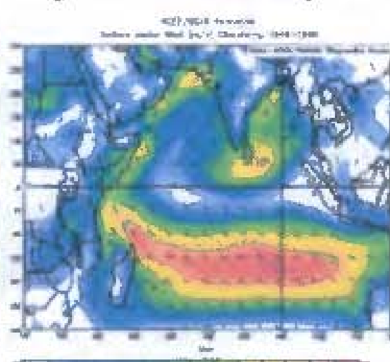


Figure 1.3d April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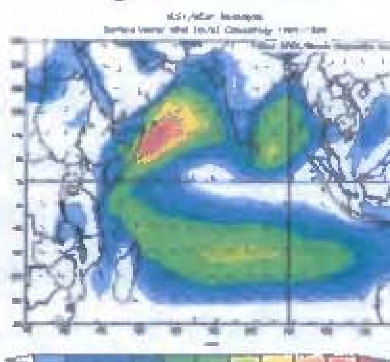
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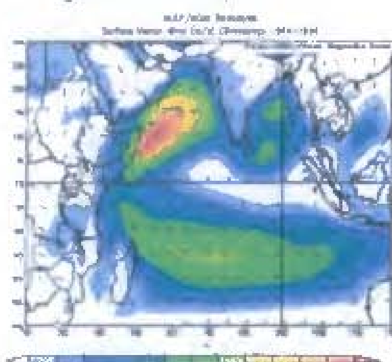
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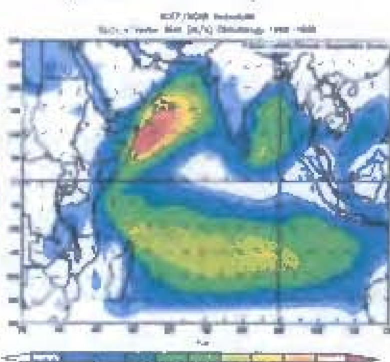
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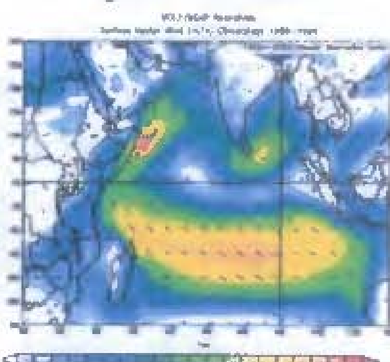
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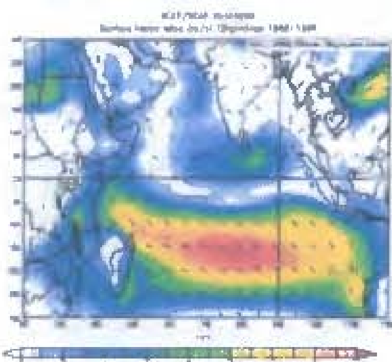
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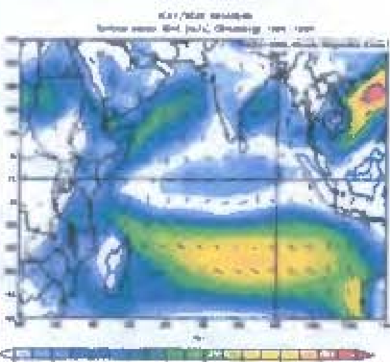
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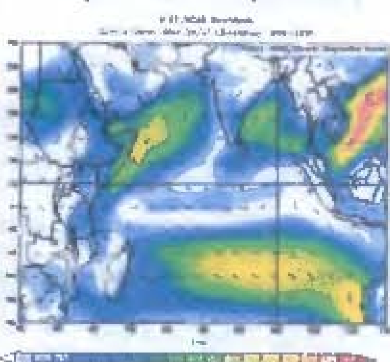


Figure 1.3l December

Figures (1.3a – 1.3l) Long-term surface wind (climatology) from January to December

Over coastal East Africa, these two monsoon winds differ only in direction, and the air masses that they bring are similar. At the equator, the monsoon winds change direction and remain weak throughout the year (Tomczak & Godfrey 1994). Monsoon winds over the East African coast always have an influence on sea level variation.

1.4.2 Tropical Cyclones

Tropical cyclone is a general term, and is used to denote an intensive tropical low pressure system that originates over the tropical oceans. In this tropical weather system, winds move in a circular direction around a warmer centre low-pressure area (Longhore 2000). Favourable conditions for the formation of tropical cyclones occur over tropical oceans at latitudes of 5°-20° away from the equator. When sea surface temperature exceeds 26°C, and a pre-existing weather disturbance occurs, with light winds aloft and high relative humidity may develop into a tropical cyclone (Byers 1974). Due to the Coriolis force, tropical cyclones generally do not form within 3 degrees latitude of the Equator.

Tropical storms may be classified into three main phases depending on their intensity. These phases are tropical depression, tropical storms and tropical cyclone. When there is an organized system of clouds and thunderstorms with surface circulation and maximum sustained winds of less than 17metres per second (33 knots), the system is known as a tropical depression. During the second phase (tropical storm), the organized system has well defined surface circulation and maximum sustained winds between 17 and 33 meters per second (33-63 knots). The third phase occurs when the surface circulation intensifies and maximum sustained winds exceed 33 metre per second (63 knots, the weather pattern is known as tropical cyclone (Asinani 1993).

Structurally, the tropical cyclone is a large, rotating area of clouds, winds and thunderstorm activity and usually contains a central region, known as the

'eye'. The diameter of the eye is tens of kilometres with light winds and cloudless conditions, surrounded by the eyewall, which contains dense convective cloud and the strongest winds of the storm (Huschkle 1959). The eyewall produces the most violent wind often combined with heavy rain and storm surge.

Storm surges are generated by wind stress acting over the sea surface and by variations in surface atmospheric pressure (Flather & Khandker 1993). Extreme storm surge events may occur during the tropical cyclone season. When storm surges occasionally coincide with the high tide phase of the normal tidal cycle, they may cause an increase in sea level height around Zanzibar and other coastal areas in the region (Doswell 1996).

1.4.3 Indian Ocean Tsunami

A Tsunami is a natural phenomenon which can be defined as a series of large gravity waves in the ocean triggered by underwater earthquakes, volcanic activities or landslides. A tsunami can be generated anywhere in the ocean, an inland sea or in a large body of water. The most destructive tsunamis are generated from large earthquakes on the ocean floor. Usually a tsunami occurs along the boundaries of the tectonic plates in the regions of the earth which are characterized by these features. When these plates move past each other, they cause large earthquakes which displace large areas of the ocean floor (Bryant 2001). The sudden displacements of large volumes of water over such large areas disturb the surface of the ocean, the mean sea level of a specified area and generate destructive tsunami waves.

Tsunami waves can travel great distances with very high speed from their origin, as a series of long gravity waves with an average wave speed of about 700km/h. The tsunami speed is directly related to the depth of the water. The maximum speed of a tsunami wave for the ocean depth is $\sqrt{gh}$, where g is the acceleration to the gravity and h is the depth of the ocean. The wave speed of

a tsunami decreases as it approaches shallow water but the force and amplitude increase as they move toward the coast (Knauss 1977).

The maximum height of the tsunami is reached on the shore at runup. The runup can be explained as the maximum height reached by the water on the shore (Bryant 2001).The tsunami runup at the particular point of impact normally depends on how the energy is focused, the coastal configuration and offshore topography. On the continental shelf, tsunamis lose energy through frictional dissipation with the seabed.

By identifying the location of the earthquake, the depth of the ocean and the distance between the source and any possible target, one can predict the time of arrival of a tsunami and the possible point. The devastating Indian Ocean tsunami occurred on 26 December 2004 at 00h 58m 53s (universal time) near the Sumatra coast (Indonesia). The first tsunami wave reached Zanzibar after 10h 44m (universal time) .The tsunami wave took 09h 45m to cross the Indian Ocean from the source point to Zanzibar (Merrifield et al 2005).The first indication of the arrival of a tsunami is an abnormal variation of sea level and may appear as either rapidly rising or falling sea level.

1.4.4 El Nino Southern Oscillation (ENSO)

El Niño is the term used to describe an anomalous increase of sea surface temperatures in the eastern tropical Pacific Ocean. The formation of an El Niño is linked with the variation of a Pacific Ocean circulation pattern known as Southern Oscillation. The Southern Oscillation is the seesaw variation of sea surface pressure patterns between the eastern and western tropical Pacific. When the surface pressure is high in the eastern tropical Pacific, it tends to be low in the western tropical Pacific, and vice-versa. It can be stated that there is a relationship between El Niño and the pressure change across the Pacific Ocean (Southern Ocean Oscillation). These two events together are known as El Niño/ Southern Oscillation (ENSO). The ENSO cycle is defined by anomaly in the oceanic and atmospheric conditions, which in turn

affects circulation, rainfall and weather patterns throughout most of the world (Philander 2001).

ENSO is a global-scale climate phenomenon, which is naturally caused by the large-scale interactions between the ocean and atmosphere although its origin lies in the tropical Indo-Pacific Ocean (Diaz & Markgraf 2000). It can be said that this climate phenomenon is caused by interactions between the ocean and the atmosphere in the tropical ocean which has important consequences for weather in the tropical regions and around the globe.

Among the many changes in oceanic and atmospheric conditions related to ENSO are the changing of patterns of the sea surface temperatures, sea level pressure and sea level height and winds. These changes influence ocean and atmospheric circulation patterns over the tropical Pacific and then to the Indian Ocean basin and elsewhere (Nicholls et al 2003). The changing of sea surface temperature leads to variations in atmospheric pressure and wind flow, which affect the ocean current circulation and sea level over the equatorial and tropical Indian Ocean.

Sea level variation is determined by various factors that operate on different time scales. On a long time-scale, climate and climatic processes influence variations of sea level. These processes have focused mainly on the relationship between the interannual variability and ENSO.

The ENSO warm phase is also known as an El Niño event. A warm phase event of ENSO refers to the anomalous warming of sea surface temperatures and an increase in sea level height in the central and eastern equatorial Pacific and Indian Oceans. During El Nino events, warming of tropical regions of the Pacific and Indian oceans leads to displacement of major rainfall producing systems causing massive redistribution of climate regimes. La Nina is generally the opposite conditions of El Niño, and is termed the cold phase of ENSO. During the cold phase event of ENSO, sea surface temperatures become anomalously colder compared to the long-term average for the central and eastern Pacific Ocean and tropical Indian Ocean and sea level

height decreases (Glantz 1996) in these regions. Over the Indian Ocean basin, ENSO also has a large impact on sea surface temperatures, the ocean and monsoon circulations (Reason et al 2000) as well as weather systems such as tropical cyclones and their tracks.

1.4.5 Indian Ocean Zonal Dipole Mode (IOZDM)

The Indian Ocean Dipole (IOZDM) is a major oscillation in the climate system that occurs interannually in the tropical parts of the Indian Ocean (Saji and Yamagata 2003). The IOZDM involves a self-sustaining coupled ocean-atmosphere-land interaction over the tropical Indian Ocean region (Webster et al 1999, Yu and Rienecker 2000) that usually leads to rapid change in circulation patterns of the coupled ocean atmosphere system change rapidly.

Initially, the Indian Ocean Zonal Dipole Mode was thought to be independent from ENSO (Saji et al 1999), and when IOZDM positive phase, is characterized positive sea surface temperatures anomalies over the western side of the Indian Ocean and negative sea surface temperature anomalies over the eastern side of the basin. The positive sea surface temperature anomalies over the western side of the Indian Ocean (positive IODZM) cause the atmosphere to be unstable leading to heavy rain over East Africa and negative sea surface temperature anomalies over the eastern side of the basin, cause stability of atmosphere and dryness over southeast Asia. During a negative phase of IODZM, the reverse anomalies tend to develop (Behera and Yamagata 2001) and the increased rainfall shift to the eastern side of the tropical Indian Ocean.

IODZM events may occur in the presence and absence of ENSO activity, and ENSO phenomena may also occur in the presence and absence of IODZM. When IODZM coincides with ENSO, high positive sea surface temperature and sea level height anomalies are observed in the tropical western Indian Ocean associated as co-occurred in 1997/98 (Saji and Yamagata 2003). During IOZDM events, the surface wind field shows abrupt changes,

particularly in its zonal component over the equatorial region (Saji et al 1999). Significant anomalies tend to appear around June and intensify in the following months whereas the maximum is observed around October.

The IOZDM strongly depends on the conditions set by monsoonal circulation (Loschnigg et al 2003). In fact the variability of the monsoons significantly affects this mode although the relationship of the IODZM to Indian monsoon variability is still not clear (Saji et al 1999).

Behera and Yamagata (2001) showed evidence of a dipole – like feature in sea surface temperature of the South Indian Ocean that evolves during the austral summer months every few years or so. This phenomenon is not considered in this thesis as it seems to affect the subtropics and mid-latitudes of the South Indian Ocean with little evidence of an impact in the Tanzanian region or tropical Indian Ocean (Behera and Yamagata, 2001; Reason,2001; Hermes & Reason, 2005).

Chapter 2

2. Literature Review

This chapter reviews the literature on sea level and the basic reasons for its variation in different time scales. These variations in sea level may be in either short time (local) or long time (regional) scales.

2.1 Sea Level Variations on Short Time Scales

Short time scale variation of sea level, which is normally influenced by local weather, is associated with synoptic weather systems (Brundrit 1984). Pugh (1987) stated that short time scale (local) variation of sea levels is due to tidal variation and weather. Diane (1996) indicated that the short period variations of sea levels are due to atmospheric pressure changes relating to atmospheric disturbances.

The most important weather parameters that influence short time scale variation of sea level are surface winds and sea level pressures. June (1980) noted that short term variation of sea level is caused by fluctuations in, and movement of, synoptic systems. It has been shown that as a low-pressure system moves toward the coast, the sea level will increase. When it moves away from the coast, sea level tends to decrease.

Surface winds play a significant role in the short period fluctuation of sea levels along the coastal region. Eugenie (1974) maintained that offshore wind lowers tidal levels and onshore winds raise the tidal levels. As a strong wind blows onshore, it may pile up the water near the coast and cause high waters to be higher than predicted. If the strong wind blows offshore, there will be a reverse effect. Another phenomenon which persists for a short period and causes fluctuations of sea level height are storm surges.

A storm surge is a long-period surface gravity wave caused by storm winds, or tropical cyclones in the tropical ocean regions. Principally, storm surges are generated by wind stress acting over the surface and by variations of atmospheric pressure (Flather & Khandker 1993). Changes in storm surge height would result from occurring alterations of strong winds and low pressure. The combination of strong wind and low pressure associated with storms may create a pronounced increase in sea level.

The most serious impacts are caused by changes of sea levels during storm surges, and exceptionally high waves are due to severe weather. Individual storms can produce localised changes in the sea level, which persist for a short period. These cause an extra-tidal fluctuation in sea level of coastal regions, which are associated with weather conditions (Huyer et al 1979). A significant change in storm surge activity is influenced by synoptic weather systems. Even ocean waves generated by the storm can produce a set up along the coasts and raise sea level heights along the coast and around islands (Searson & Brundrit 1995).

Pittock et al (1996) articulated that changes in frequency and intensity of tropical cyclones could result from alterations in sea surface temperature and large-scale atmospheric circulation. In general, the highest maximum sea level is associated with maximum gust and lower sea level pressure. This normally happens when there is a tropical cyclone in the vicinity (Chan 1983).

2.2 Sea Level Variations on Long Time Scales

In additional to geographical location, the variation of sea level on a large scale is caused by seasonal and interannual changes of various climate elements. Variation of sea level on a regional scale is largely caused by anomalies in sea surface temperatures, seasonal winds, and ocean currents (Parker 1992). Phinn & Hastings (1992) discussed how large-scale prevailing wind and sea surface temperatures are important climate parameters affecting

sea level variation in a particular region. Seasonal changes in wind and solar heating also leads to large-scale variations of sea levels (Pugh 1987).

The major factor that influences large scale variation of sea level over the tropical oceans is prevailing winds (Yamagi & Akaki (1994). In the tropical region of the Indian Ocean, Kumar (2001) indicated that variation of sea levels at Cochin on the southwest coast of India is caused by prevailing seasonal change of monsoon winds. Singh et al (2001) highlighted one of the major sources of sea level variations along the Maldives coast as being seasonal change in the monsoon winds. In their study of the recent sea levels and sea surface temperature changes along the Maldives coast, they concluded that the maximum rise in sea level is observed when there is a predominance of South West monsoon winds. Similarly, Singh (2002) described that the variation of sea levels along the coast of Bangladesh is caused by variations of monsoon winds. He documented that, among all seasons in Bangladesh, the most abrupt increase of sea levels occurred during the period of the South West monsoon when sea surface temperatures over the equatorial region and the Northern Indian Ocean are significantly high (Singh 2002).

The thermal expansion of the ocean is an important influence on the variation of sea levels (Church & Gregory 2001). One of the most important climate parameters that reflect thermal expansion of the ocean is sea surface temperature (Singh et al, 2001). Upper ocean temperatures are related to the density and volume of the mixed layer. When the ocean warms, its density decreases and its volume also increase (Louis 1970). The largest change in sea surface temperature normally takes place at the surface and reflects thermal expansion of the ocean. Pugh (1987) stated that the increasing volume due to climate change might cause expansion of the ocean or change the shape of the ocean basins resulting in a variation of sea levels.

In recent years, variations in sea level have become a hot topic because of its relation to global warming and climate variability (Cohen 1996). Changes in sea level due to global warming can be greater in some places than others

because the ocean circulation will adapt to accommodate the new climate regime. Evans (2004) demonstrated that global warming may accelerate sea level rise by adding water to the oceans from glaciers and land ice, but the main contributor is thermal expansion of the ocean, which causes a rise in sea level due to rising sea surface temperature.

As mentioned earlier in this study, the ENSO cycle has a large impact on oceanic and atmospheric conditions, which in turn affect climate variability (Parker 1992). Among many changes in oceanic and atmospheric conditions related to El Niño is the variation in sea level and sea surface temperature in the tropical oceans (Phinn & Hastings, 1992).

Variations of sea level and sea surface temperature related to El Niño have been noted and discussed by Bjerknes (1966), Hickey (1975), Ropelewski and Halpert (1987), Philander (1990). Wyrtki and Meyers (1975) found good correlations between the strength of trade winds in the tropical Indo–Pacific Ocean and the occurrence of El Niño. They concluded that high sea surface temperature and sea levels related to El Niño in the Eastern Pacific were caused by equatorial Kelvin waves excited by the weakening of the trade winds. McCreary (1976) indicated that a weakening of the Equatorial Zonal trade wind field causes a rise in sea level height in the eastern tropical Pacific Ocean, which then spreads to higher latitudes along the eastern boundary as coastal trapped Kelvin waves.

Wyrtki (1977) noted that tropical Pacific sea level variations are associated with El Niño. He used several sea level records from numerous islands and coastal stations in the equatorial Pacific to study their response and that of associated equatorial circulation to the 1972 El Niño. He found that the most distinct phenomenon is seesaw-like variation of sea surface temperature and sea level, having opposite phases between western and eastern tropical regions.

Chelton & Davis (1982) explained that on the west coast of North and South America, the large interannual variations of sea level can be caused by El

Niño /La Niña events. They further indicated that once an ENSO event has started, the reversal of pressure gradients causes surface trade winds and equatorial currents to change their normal directions. Warmer water flowing from west to east causes local sea levels to rise and leads to relatively water upwelling along the west coast of North and South America. Pizarro et al (2001) reported that the coastal ocean circulation off western South America is driven by interannual alongshore wind stress and an interannual alongshore pressure gradient resulting from El Niño / La Niña pressure fluctuations at the Equator. Much of the ocean variability near the western coast of South America is caused by equatorial Kelvin waves impinging upon their coast.

Over the Indian Ocean, ENSO events have a large impact on climate variability of the ocean and various countries surrounding the Indian Ocean basin. Reason et al (2000) showed that the most prominent climatic variability in the Indian Ocean basin on interannual time scales may linked to ENSO events. They noted that during El Niño (La Niña) events, enhanced (reduced) cloudiness and convective activity tends to be found in the western and central Indian Ocean as sea surface temperature anomalies are positive (negative).Kijazi and Reason (2005) showed that increased rainfall over northern coast of Tanzania is observed during El Niño years (warm phase of ENSO), and that La Niña years (cold phase of ENSO) tend to show the reverse.

An ENSO event influences weather and climate patterns on the global scales. Allan et al (2003) explained that fluctuations of climate in the Indian Ocean (climatic extremes) which lead to flooding or drought are magnified during strong protracted ENSO events. Yu et al (2002) reported that sea surface temperature anomalies which often appear in the Indian Ocean during ENSO events tend to evolve during the austral winter and spring following the first appearance of anomalous sea surface temperature in the tropical Pacific. They also noted that ENSO affects heat flux and wind stress anomalies, which then actively force much of the interannual variability in the Indian Ocean during the ENSO cycle.

During 1997/98, unusual warming in the tropical Indian Ocean occurred in associated with a strong El Niño event. Chambers et al (1999) explained that the great warming over tropical western Indian Ocean and increased sea level height over East Africa region during 1997 and 1998 was associated with El Niño. However, Saji et al (1999) and Webster et al (1999) suggest that the strong anomalies in sea surface temperatures, sea surface height, precipitation and winds that occurred in the Indian Ocean region in 1997/98 were associated with another type of mode, the Indian Ocean Zonal Dipole Mode.

The Indian Ocean Zonal Dipole Mode has strong consequences for climate variability not only in East African and Indonesian regions, but in other areas surrounding the tropical Indian Ocean. Lareef et al (2003) showed that the positive phase of the Indian Ocean Zonal Dipole induces large-scale convergence in the lower level tropical western Indian Ocean extending to Sri Lanka leading to heavy rainfall in that area. In their study of modulation of Sri Lankan Maha rainfall by the Indian Ocean Zonal Dipole Mode, they found that there is high correlation between this rainfall and occurrence of the positive Indian Ocean Dipole Mode. They concluded that interannual variation of Maha rainfall indicates the strong relation between the Indian Ocean Zonal Dipole Mode Index and rainfall during both wet and dry years.

Ashok et al (2001) agreed with previous authors like Saji et al (1999) that the Indian Ocean Zonal Dipole Mode events affect the India summer monsoon on its own and as a result it influences Indian summer monsoon rainfall. They noted that due to the existence of negative and positive events in the IOZDM and ENSO phenomena, the influence on India summer monsoon rainfall depends on the phase and amplitude of IOZDM and ENSO. These authors concluded that the IOZDM is the major coupled mode in the tropical Indian Ocean that influences Indian summer monsoon rainfall.

2.3 Previous Studies on Sea Level in the Indian Ocean

A number of research studies on sea level have been conducted in various regions of the oceans. Most of these studies are based on an investigation of climate variability or monitoring the trend of sea level variation in a particular place.

Several authors have used various methods to study the sea level variation over the Indian Ocean region. The most recent studies used single tide gauge station data to represent a large area. For instance, in India, Kumar (2001) used tide data (sea level data) from Port Cochin to study monthly mean sea level variations at Cochin on the Southwest Coast of India. He found that tide type was mixed but predominantly is semi-diurnal type with unequal tidal amplitudes. The highest and lowest level occurs during spring and neap tides; during November and December, high tides are found to be unusually high. He concluded that monthly variation of sea level at Cochin is due to seasonal change. Sea level is lowest during May to September, when the region experiences southwest monsoonal wind associated with upwelling.

Another study mentioned previously was conducted in Maldives Isles, where Singh et al (2001) used sea level data from Maldives and sea surface temperature (from satellite) in their study of recent sea level and sea surface temperature changes along the Maldives Coast. They described that sea surface temperature is the major factor leading to the sea level variations along the Maldives Coast. There is a lag correlation of about two months for the maximum influence of sea surface temperature on the sea level. Variations of sea level are due to seasonal changes and the highest is observed during the premonsoon (March-May) season, particularly in April when sea surface temperature is above 30 ^{0}C.

In Pakistan, Khan et al (2002) conducted their research on sea level variation and geomorphological changes in the coastal belt of Pakistan using sea level data (tide data) from Karachi harbour as a basic reference and sea surface temperature data (from satellite NOAA) for their study. They concluded that

tides are semidiurnal and the main factor determining sea level variations at Karachi is sea surface temperature, the higher rate of sea level rise coincides with higher rates of increase of sea surface temperature. Variation of sea levels along the coast of Pakistan is due to seasonal change and river discharge.

In Mozambique, Ruby & Sete (2002) used tide gauge data at Maputo harbour to represent the coast of Mozambique in their study of sea level variation. They noted that tides along the coast of Mozambique are of semi-diurnal type, and the tidal range varies between extreme neap tides and extreme spring tides. Variation of sea levels around Mozambique is caused by seasonal changes and is influenced by river discharge. The maximum is observed during November to April and minimum from May to October which corresponds to wet and dry seasons.

Tiwari et al (2004) used monthly tide gauge data from the Bombay tide gauge station located (18^0 55'N, 72^0 50' E) on the west coast of India, sea surface temperature and satellite data in their study of correlation of interannual sea level variations in the Indian Ocean from Topex/Poseidon altimetry, temperature data and tide gauges with ENSO. They concluded that there is a significant correlation of sea level changes in the Indian Ocean with ENSO events indicating external forcing on interannual sea level variations in the Indian Ocean.

The intention of this work is to study sea level variations over Zanzibar and the influence of climate variability on regional sea level. This area has not yet been researched and therefore there is a dearth of literature to refer to. The study is intended to focus mainly on monthly variations using correlation methods as previously used in India by Tiwari et al 2004), by Singh et al (2001) in the Maldives and that used by Ruby & Sete (2002) in the Mozambique. The data and methodology of this study will be discussed in the next chapter.

Chapter 3

3. Data and Methodology

This chapter explores the data collected from different sources and discusses the methods that have been used in this study.

3.1 Data

The data used can be divided into three groups. These are sea level data (tide data) from Zanzibar and Lamu, meteorological data from Zanzibar and satellite data.

Sea level data from Zanzibar tide gauge station was available on an hourly, daily and monthly basis for the period of nine (9) years from 1996 to 2004. This data was obtained from the University of Hawaii, Sea Level Centre (http://ilikai.soest.hawaii.edu/uhslc/). Zanzibar Tide Gauge Station is under the Commission of Land and Environment of Zanzibar, in collaboration with the University of Hawaii Sea Level Centre. This tide gauge station is situated at the seaward end of the main jetty in Zanzibar harbour at Latitude 06^0 09' South and Longitude 39^{0}11' East. The adjacent tide gauge station used in this study is that of Lamu (Kenya). This station is situated at latitude 02^0 16' South and Longitude 40^0 54' East and is operated by Kenya Marine and Fisheries Institute. The tide gauge data obtained from this station was on a monthly basis for a period of 9 years from 1996 to 2004. The Lamu data have used together with that from Zanzibar in order to provide a more complete picture of the variability in Zanzibar region. Both Zanzibar and Lamu tide gauge stations are equipped with satellite transmission facilities to enable real time data acquisition.

The meteorological data used are mean sea level pressure and surface wind. Mean sea level data is monthly mean sea level pressure, which is for the

period of 9 years from 1996 to 2004, collected from the Zanzibar Meteorological Office, under the auspices of Tanzania Meteorological Agency. Sea level pressure and mean surface anomalies were obtained from the National Centre for Environmental Prediction (NCEP).

The surface temperature data used are Reynolds optimally interpolated monthly sea surface temperature anomalies from May 1997 to July 1998 and from May 2000 to July 2001. These data were obtained from the PO.DAAC Ocean ESIP Tool (POET) through http://paet.jpl.nasa.gov/. Other data are monthly sea surface height anomalies from May 1997 to July 1998 and from May 2000 to July 2001 which was provided by the Climate Explorer (KNMI) through *http://climexp.knmi.nl/* and monthly mean wind (Climatology) and Surface Zonal wind anomalies were supplied by the National Centre for Environmental Prediction (NCEP) via http://www.cdc.noaa.gov/.

3.2 Methodology

In general, the method used in this study focuses on an investigation and examination of sea level height and sea level pressure data, calculating monthly sea level height and sea level pressure anomalies, and comparing with monthly sea surface temperature anomalies and sea level height anomalies (tide gauge and satellite data).

Hourly, daily and monthly sea level data were analysed and examined in order to identify general features and characteristics of sea levels in Zanzibar. This anomaly allows this work to arrive at an understanding of the variation of sea levels around Zanzibar on hourly, daily, monthly and seasonal time scales.

The monthly mean sea level pressure and monthly sea level heights were also analysed and examined in order to determine long-term monthly mean variations and the annual cycle. By using long-term mean values, sea level height and monthly sea level pressure anomalies can be computed. The monthly anomalies can be defined as the difference between long-term

average and monthly mean for a given or particular month (deviation from the mean).

Interannual variation of sea levels at Zanzibar and Lamu were computed and examined in relation to the occurrence of large scale climate variability over Zanzibar and the East African coast. The interannual variations are anomalies of annual or seasonal develop in sea level, pressure and other parameters which can reach extremes during some years.

The second part of this work is to study sea level variation and climate variability around Zanzibar during the great warming over the tropical western Indian Ocean from 1997 to 1998, and the period of cold anomalies from 2000 to 2001.

A comparison of monthly sea surface temperature anomalies with monthly sea surface height anomalies from satellite and monthly sea level height monthly anomalies of Zanzibar and Lamu is made in order to know their relationship for the period 1997/1998 and 2000/ 2001. Furthermore, a comparison is made between monthly anomalies of sea level height and sea level pressure over the same period around Zanzibar.

Chapter 4

4. Results and Discussion

This chapter will discuss the results obtained from the analyses, and is divided into two major parts. The first part focuses on general features of sea level variations. These include hourly, daily, monthly and interannual variations whereas the second part focuses on variation of sea level in relation to climate variability around Zanzibar during the anomalous years of 1997/1998 and 2000/2001.

4.1 Features of Sea Level Variation

The most predominant type of tide observed at Zanzibar is a semi-diurnal oscillation, with two high water levels and two low water levels in each tidal cycle. For example, the hourly mean variation of sea levels on 1 December 2004 shows that there are two high water and two low water levels at different times with intervals of 12 hours between two high water levels or between the two low water levels (see Figure 4.1 below).

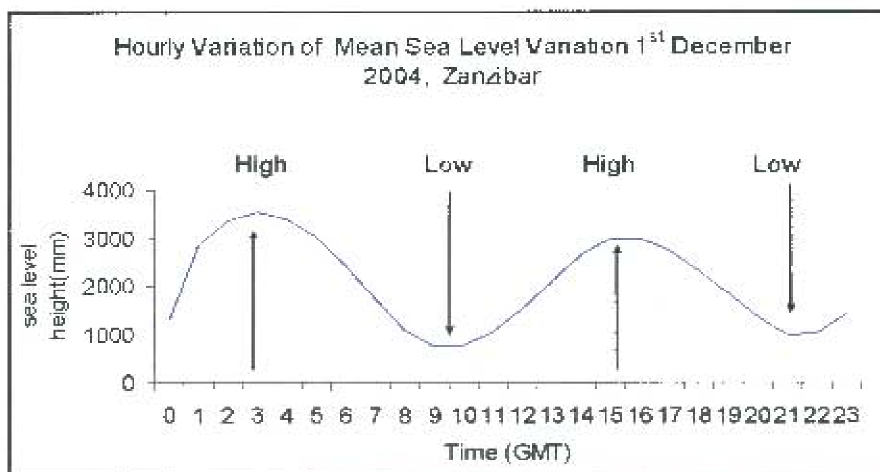


Figure 4.1 Hourly sea level variations (high and low water) at Zanzibar 1December 2004

The first high water level observed was approximately at 03 hours and the second high water level was approximately at 15 hours while low water levels were observed approximately at 0930 and 2130 hours.

Every month Zanzibar experiences two spring tides and two neap tides. These spring and neap tides may differ in their ranges depending on declination of the sun and the moon. The highest spring tide and lowest neap tides occur around March and September, when the moon and the sun are at or near equinoxes with zero degree (0°) declination (Macmillan 1966). During that period, the combined forces of the sun and moon on the earth are greater.

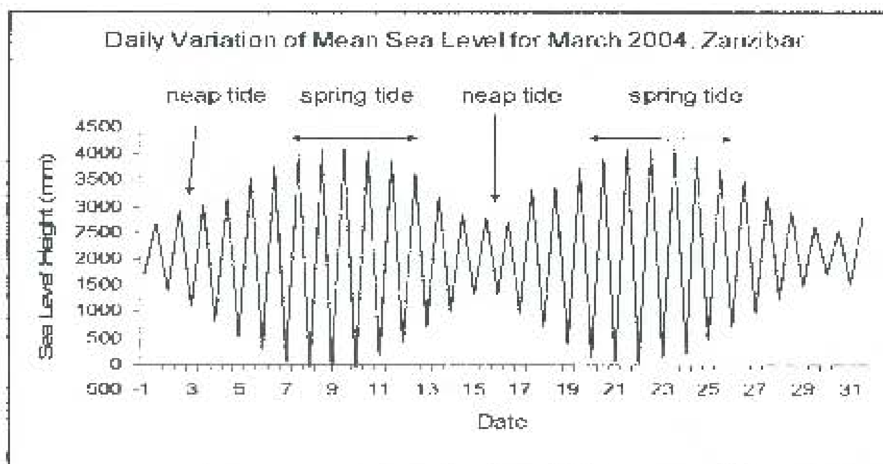


Figure 4.2 daily sea level variations (springs and neap tides March 2004) Zanzibar

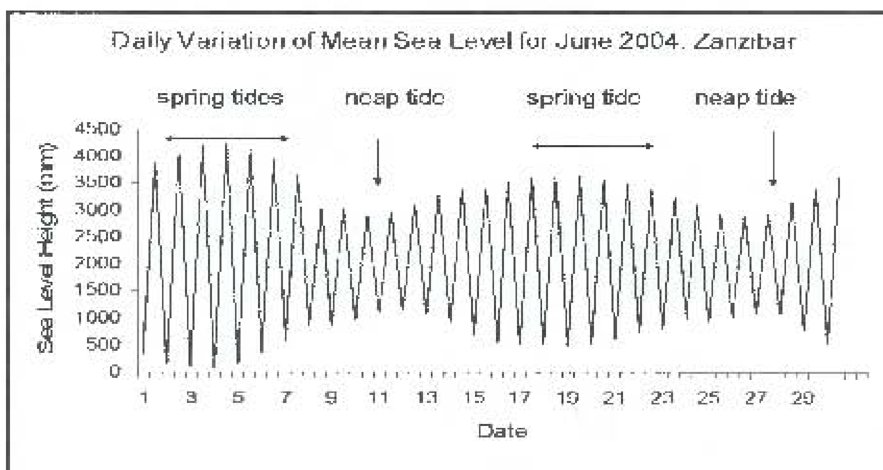


Figure 4.3 daily sea level variations (springs and neap tides June 2004) Zanzibar

When the sun is overhead at the tropics (23.5° south or north of equator) in June and December, the gravitational forces are reduced. During that time, lower spring tide and higher neap tide may be experienced.

The results obtained from the analyses for March and June 2004 show that there were two spring tides and two neap tides but they differ in their tidal range. In March 2004, the first spring tide occurred between 7th and 12th, with high tidal range from -108 to 4112 mm (see Figure 4.2 above) while the neap tide occurred between 13th and 19th with tidal range from 1724 to 2529mm.

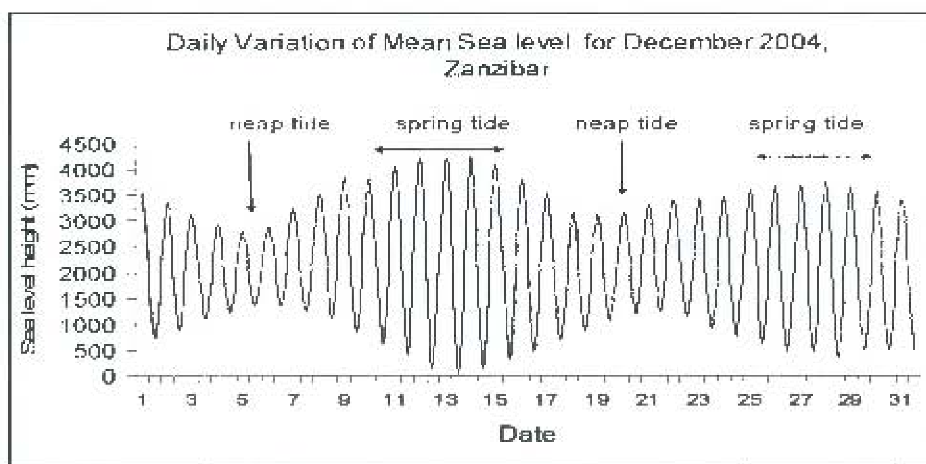


Figure 4.4a Daily sea level variation spring and neap tides, December 2004, Zanzibar

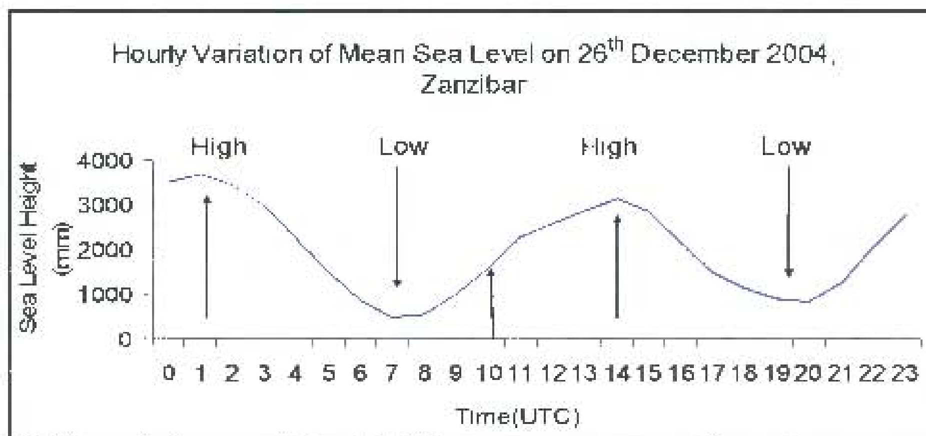


Figure 4.4b Hourly sea level variations, 26 December 2004 (high and low water), Zanzibar

During the first spring tide in June 2004, the tidal range was from 78 to 4226 mm, followed by a neap tide from 8th to 15th with neap tidal range from 1134 to 2904 mm (see Figure 4.3 above). Comparing spring and neap tidal ranges between March and June showed that spring tide during March was higher and neap tide was lower.

Hourly and daily mean sea level variations are normally used for investigating the dynamics of events on short time scales. An example is the Indian Ocean tsunami, which occurred during December 2004. The Indian Ocean tsunami occurred on 26th December, at 00h 58m 53s (universal time) near the Sumatra coast (Indonesia). The first tsunami wave reached Zanzibar at 10h 44m (Merrifield et al 2005). Figures 4.4a and 4.4b show that 26thDecember 2004 occurred during the period of spring tide, and the time of occurrence of the first gravity wave (tsunami wave) in Zanzibar was at a time when the low tide was changing toward the high tide(See Figures 4.4a and 4.4b above).

Sometimes tsunamis are called tidal waves (Harinarayana & Hirata 2005) but they have no relation with astronomical tides. Astronomical tides are due to the gravitational pull of the moon and tsunami waves are influenced by the gravity of the earth. As previously described, the major indication of an arriving tsunami wave at the coastal region is a rapid rise and fall of sea level. Abrupt rising of sea level due to tsunamis cause destruction at the coastal area and may be modulated by the behaviour of the astronomical tide. Due to relatively low tides (low water) when the tsunami waves reached Zanzibar, the coastal environmental damage was not great compared with other areas of the Indian Ocean. Normally, extreme damage to coastal infrastructure and flooding over low-lying areas occurs when tsunami waves coincide with high tides (high water).

Regarding the annual cycle, the long-term monthly mean sea level curve shows that, on average, there are two high water and two low water level periods. The first high level water period observed is from March to May and

the second period is from October to November. The low water periods are observed from July to August and January to February (see Figure 4.5 below).

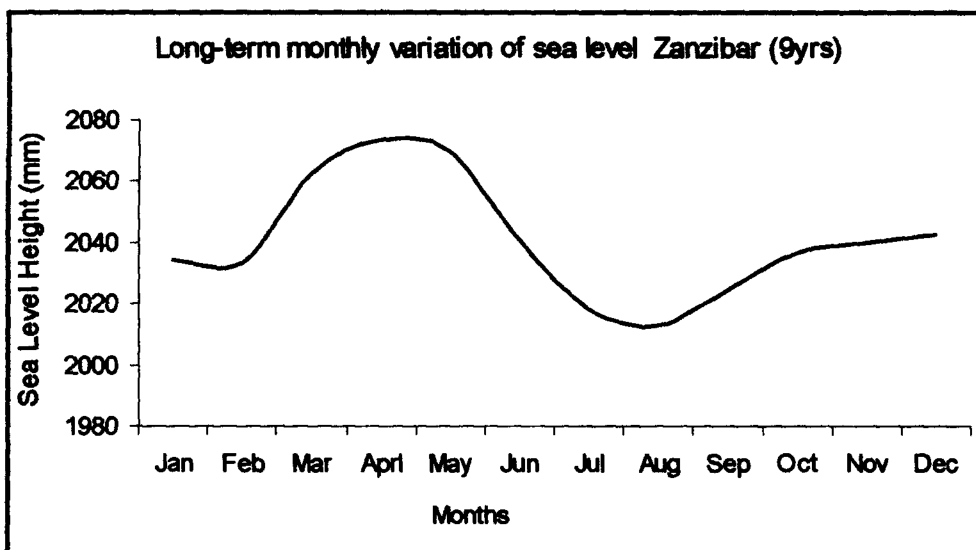


Figure 4.5 Long-term monthly mean sea levels (annual circle) at Zanzibar

The high water periods during March to May and October to November are associated with the southeast and northeast monsoon winds over the East African coast. These prevailing winds bring an abundance of waves impinging upon the coast, resulting in an increase in sea level height (see Figure 4.5 and Figures 1.3a - 1.3l above). Although both monsoonal wind systems play an important role in raising sea levels over the East African coast, the highest sea level period occurs during the middle of the southeast monsoon (April).

Sea level pressure is another source that influences variation of sea level. Seasonal changes in sea level pressure over the East African region may be another factor that causes monthly and seasonal variation of sea levels at Zanzibar. The monthly mean sea level pressure curve of Zanzibar indicates that a low-pressure period is observed during summer as the ITCZ moves into the southern hemisphere, particularly during December to March, and high-pressure is observed during winter, particularly in July and August (see Figure 4.6 below).

From a theoretical point of view, when seasonal sea level pressure is low, the sea level height is increased and vice versa. For this reason, the possible low sea level period observed from July- August and high water level period observed from March-May at Zanzibar may be associated with seasonal pressure changes over the East African region.

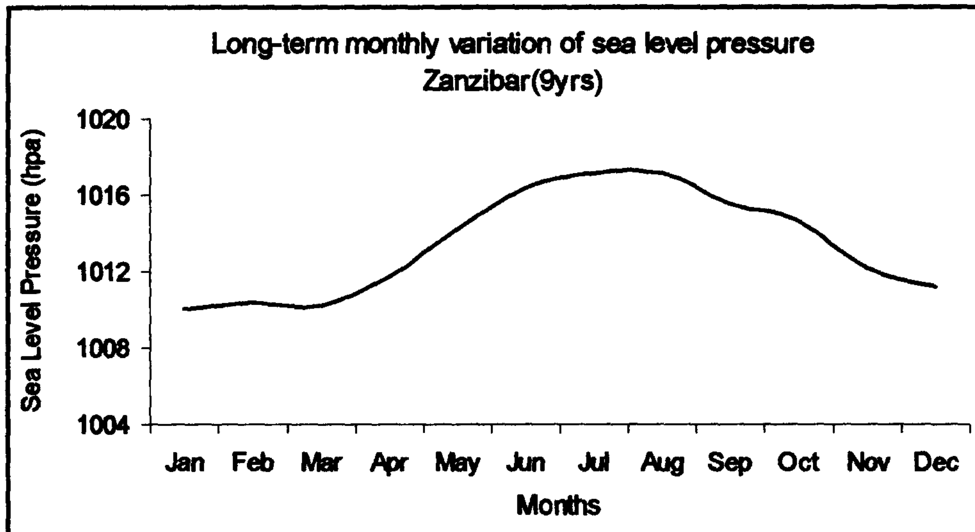


Figure 4.6 Long-term monthly mean sea level pressures at Zanzibar

Another possible source that may cause monthly variation of sea level height in Zanzibar is seasonal solar heating over the tropical western Indian Ocean. The heating and cooling of the western Indian Ocean and neighbouring landmass due to insolation changes through the year leads to the monthly shift in monsoonal wind and seasonal variations of sea levels over the East African coast. This causes an increase in sea level height during March to May and a decrease in sea level height from July to September (see Figure 4.5 and Figures 1.2a -1.2l above).

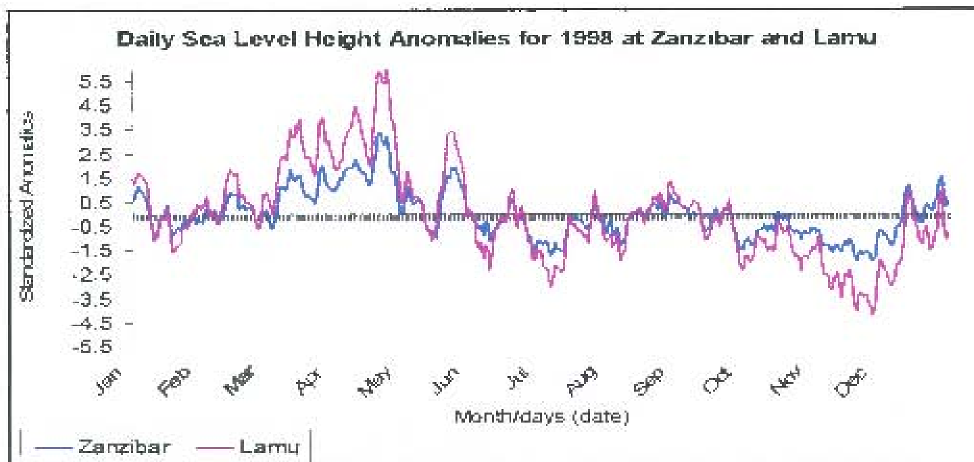


Figure 4.7 Daily variations of sea level height anomalies at Zanzibar and Lamu for 1998

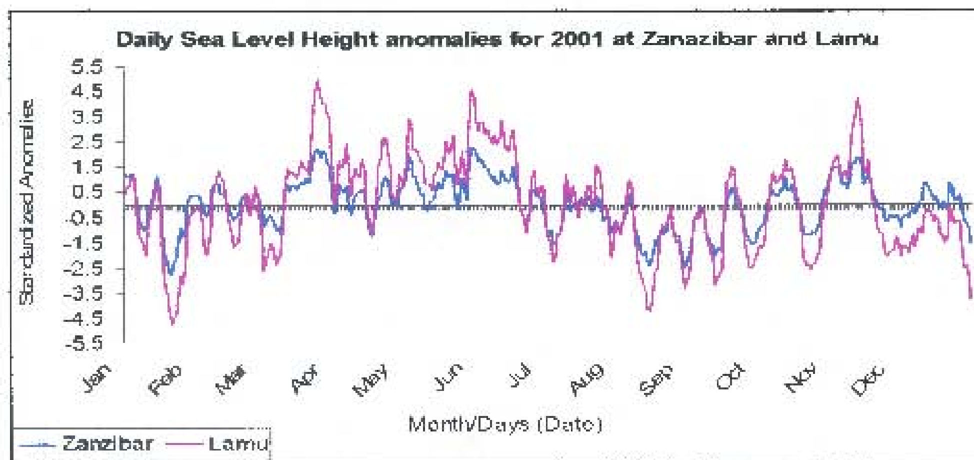


Figure 4.8 Daily variations of sea level height anomalies at Zanzibar and Lamu for 2001

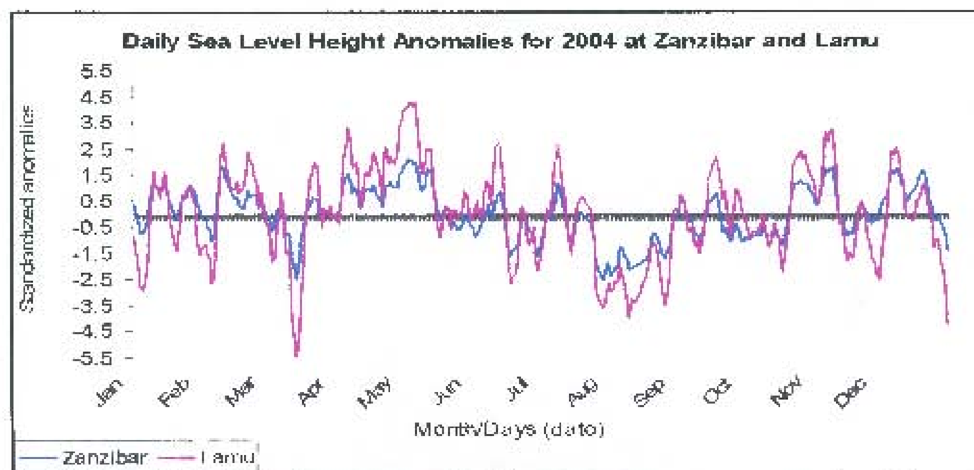


Figure 4.9 Daily variations of sea level height anomalies at Zanzibar and Lamu for 2004

The amplitude of the annual cycle at Zanzibar has also been compared to that at Lamu which is about 300 kilometres north of Zanzibar. Daily mean sea level data from the extreme warm year 1998, the extreme cold year 2001 and neutral year 2004 has also been examined.

Daily mean sea level curves obtained from three different years (named above) indicate that the annual cycle shows similar features of amplitude variability and relationship between Zanzibar and Lamu even though they differ in their magnitude (see Figures 4.7, 4.8 & 4.9 above and refer to Appendix 12 page 82). However, Zanzibar has lower daily amplitude variability compared to Lamu. Geographically, both are influenced by similar changes in weather systems and in ocean and atmospheric circulation over East Africa and the tropical western Indian Ocean. The analyses indicate that the variability of the annual cycle amplitude at Zanzibar and Lamu are closely related during both normal and extreme years.

Figure 4.9 above indicates that during March 2004 there was a significant negative sea level height anomaly at both Zanzibar and Lamu. It is probable that this anomaly was caused by abrupt increases of sea level pressure around East Africa through February as observed in figure 4.10b below.

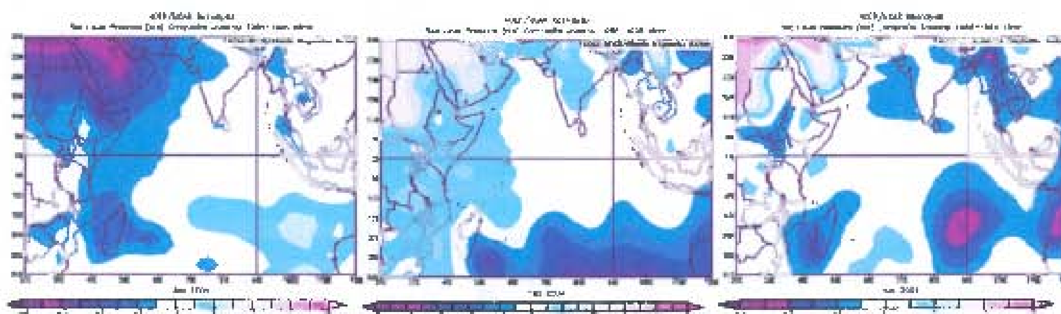


Figure 4.10a Jan 2004 Figure 4.10b Feb 2004 Figure 4.10c Mar 2004

Figures (4.10a, 4.10b and 4.10c), Sea level pressure anomalies for January, February and March 2004

In addition to the sea level pressure increasing during February 2004 (Figure 4.10 b) and sea level height decreasing in March 2004 (Figure 4.9), there

were significant changes in the surface zonal wind over East African region (see Figures 4.11a, 4.11b and 4.11c below).

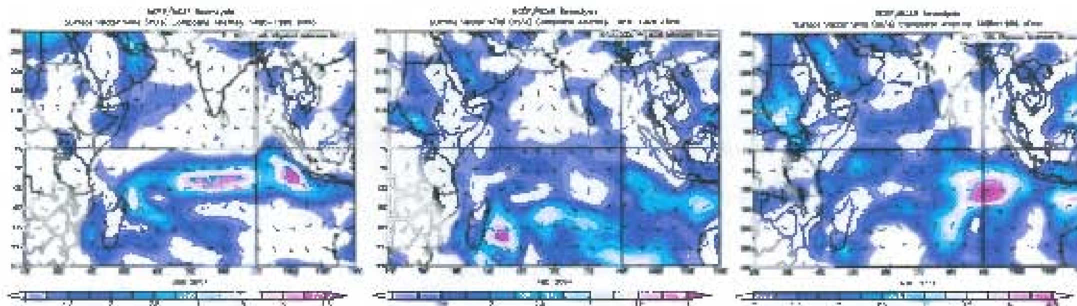


Figure 4.11a Jan 204 Figure 4.11b Feb 204 Figure 4.11c Mar 204

Figures (4.11) surface zonal wind anomalies for January, February and March 2004

4.1.2 Interannual Variations in Sea Level

The most prominent interannual ocean climate variability in the tropical Indian Ocean is linked to IOZDM and ENSO events (Yu and Rienecker 2000). As previously described, IODZM and ENSO are two different climate modes manifest in tropical Indian Ocean and in some years they coincide. During the second half of 1997(July to December) a positive phase IOZDM occurred together with an El Niño event, and the latter lasted through January to May 1998. Co-occurrence of IOZDM and ENSO in 1997/98 caused significant impacts in sea surface temperature, wind, rainfall and sea level over both western and eastern part of tropical Indian Ocean region (East Africa and Indonesia). Drought developed over Indonesia (Hendon 2003) whereas over the western Indian Ocean and East African region there was unusual warming resulting in heavy rainfall and severe flooding (Latif at el 1999, Webster at el 1999).

IOZDM and ENSO events not only affect regional rainfall and atmosphere circulation but also sea level. This section discusses the interannual variation of sea level related to ENSO and IOZDM. On interannual time scales, variation of sea level at Zanzibar is examined in relation to the occurrence of positive IOZDM and El Niño in 1997/1998, and La Niña conditions in 2000/2001 (see Figure 4.12 below). These two seasons show the strongest

deviations in sea level for this period. Note that these years correspond to the strongest ENSO events during the 1996-2004 period in which 1997/98 and 2002/2003 can be termed El Niño years, and 1995/96, 1998/99, 1999/2000, 2000/2001, La Niña years. The nearest station to Zanzibar is Lamu (Kenya), and this station also shows a similar tendency in interannual sea level variability to that of Zanzibar (see Figure 4.13 below).

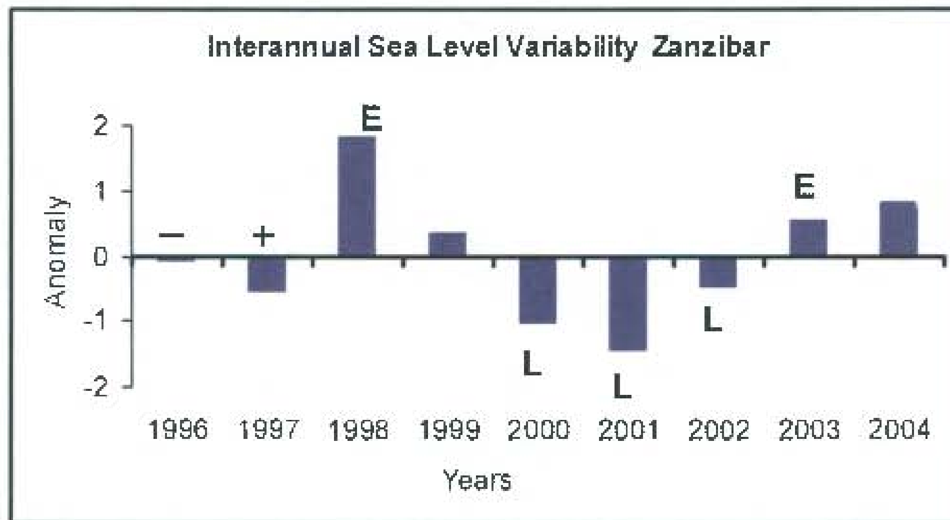


Figure 4.12 Interannual sea level variations Zanzibar (E= El Niño and L = La Niña + and – positive and negative phase of IOZDM)

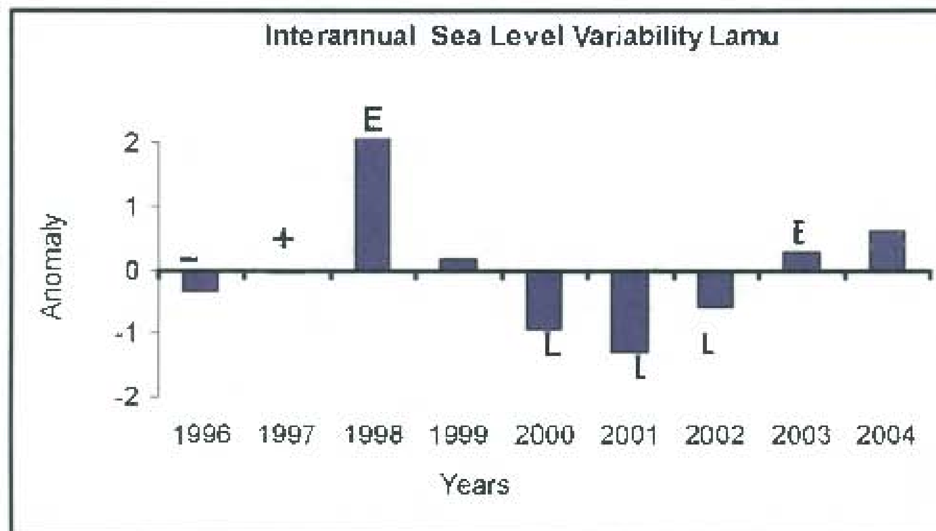


Figure 4.13 Interannual sea level variations Lamu (E= El Niño and L = La Niña, + and – positive and negative phase of IOZDM)

Both Zanzibar and Lamu show that in 1998, strong positive sea level height anomalies coincided with an El Niño year whereas 2000/2001 showed negative anomalies coinciding with La Niña years. Considering Figures 4.12 and 4.13 above, it can be concluded that interannual variation of sea levels at Zanzibar and Lamu (East Africa) is mainly related to the impact of ENSO on the tropical western Indian Ocean, which cause abnormal fluctuations of the climate system on interannual time scales and changes in weather patterns. By contrast, the IOZDM signal is less obvious.

ENSO typically leads to large-scale changes in winds, sea surface temperatures and ocean currents and this creates conditions that influences rainfall over the Indian Ocean region (Reason et al 2000, Yu and Rienecker 2000). During the El Niño years (e.g; 1997/1998), the East African region tends to receive abundant rain particularly during the short rainy (October, November and December- OND) season (Webster et al 1999, Kijazi and Reason 2005). During the La Nina, the East African region experiences relatively clear weather, with less rain during the short rain season (OND).

ENSO induced changes in winds, sea level pressure and sea surface temperatures suggest that there is a coherent relationship between ENSO and the interannual variations of sea level on the western Indian Ocean and East African coast. Furthermore, interannual variability in sea levels may be used as an indicator of climate variability in the region.

4.2 Variation of Sea Level during 1997/1998 and 2000 / 2001

Sea surface temperature appears to be one of the main factors that is related to variations in sea level over the tropical Indian Ocean and along the East African coast. The variation of sea surface temperatures over the East African coast and tropical Indian Ocean is connected with the impact of ENSO events leading to a coupled interaction between the atmosphere and ocean system in that region (Reason et al 2000, Yu and Rienecker 2000), as occurred in 1997/1998 and 2000/2001.

In 1997/1998, there was unusual warming over the tropical western Indian Ocean and East African coastal region partly caused by Rossby waves that propagated to the East African coast (Webster et al, 1999). The Rossby waves move westward in the ocean, transporting heat to the Indian Ocean from the western Pacific (Chambers et al 1999 and Yu and Rienecker 2000). These waves were created by strong easterly wind anomalies over the western Indian Ocean and reflect the positive phase of the Indian Ocean Zonal Dipole Mode events (Saji et al 1999, Webster et al 1999) that occurred in the second half of 1997 and amplified the ENSO signal over the Indian Ocean.

During the second half of 1997 (positive phase of IOZDM), both sea surface temperature and sea level height decrease on the eastern and increase on the western side of the basin and extreme sea surface temperature and sea level height anomalies were observed in October and November. In October and November, the lowest negative sea surface temperature and sea level height anomalies were observed off the coast of Indonesia and greatest positive anomalies occurred in the western side of the basin (sea figures 4.14f & 4.14g and 4.19f & 4.19g below)

Sea surface temperature over tropical western Indian Ocean began to rise from July 1997 as seen in Reynolds monthly sea surface temperature anomalies. The strongest positive anomaly was observed between January and April 1998, when sea surface temperature anomalies exceeded 1.2 ^{0}C (see Figures 4.14a – 4.14o below). Near the East African, coast sea surface temperatures began to rise from September 1997.The highest sea surface temperature anomalies observed at Zanzibar during March and April 1998 exceeded 1.2 ^{0}C (see Figures 4.15a and 4.15b below). At Lamu, the highest anomaly was observed in April 1998 when sea surface temperature was more 1.8 ^{0}C above average (see Figures 4.16a and 4.16b below).

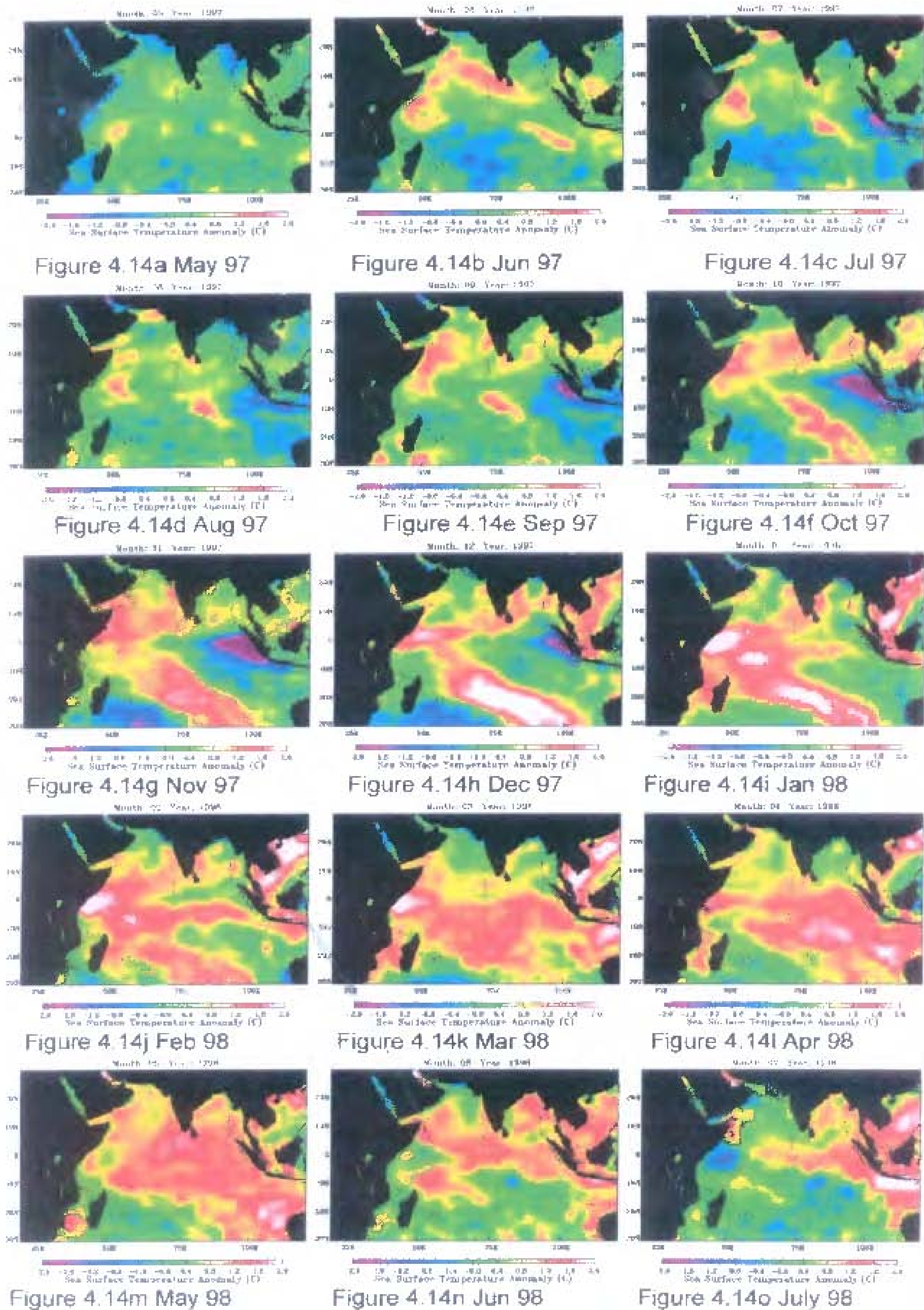


Figure 4.14a May 97 Figure 4.14b Jun 97 Figure 4.14c Jul 97

Figure 4.14d Aug 97 Figure 4.14e Sep 97 Figure 4.14f Oct 97

Figure 4.14g Nov 97 Figure 4.14h Dec 97 Figure 4.14i Jan 98

Figure 4.14j Feb 98 Figure 4.14k Mar 98 Figure 4.14l Apr 98

Figure 4.14m May 98 Figure 4.14n Jun 98 Figure 4.14o July 98

Figures (4.14a - 4.14o) Monthly sea surface Temperature anomalies over Tropical Indian Ocean from May 1997 to July 1998

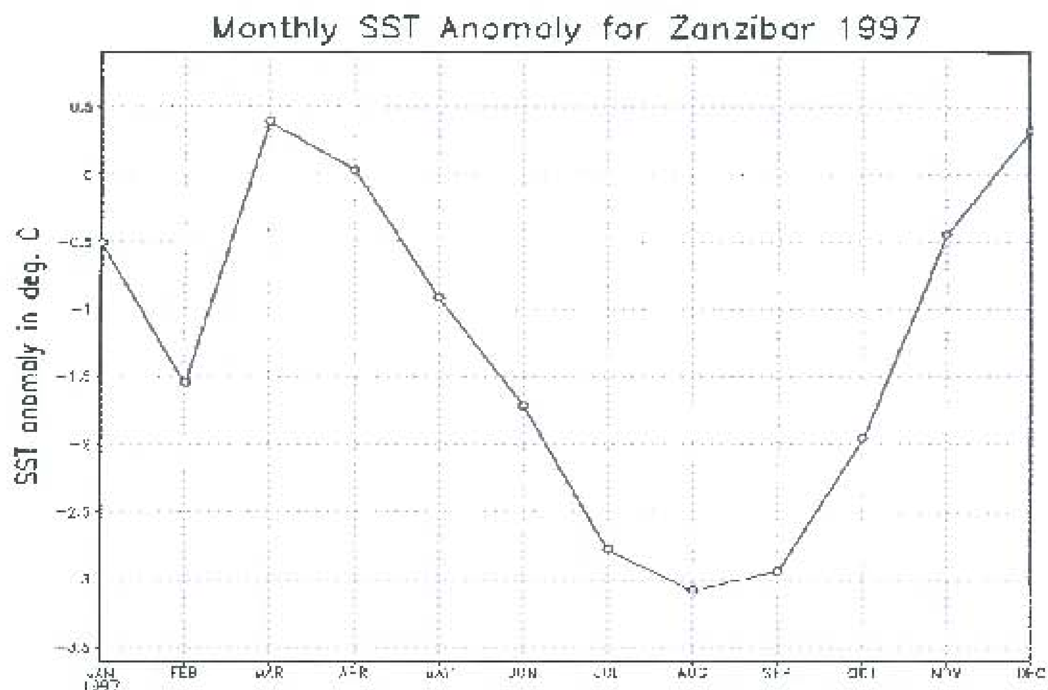


Figure 4.15a Monthly SST anomalies (^{o}C) at Zanzibar for 1997

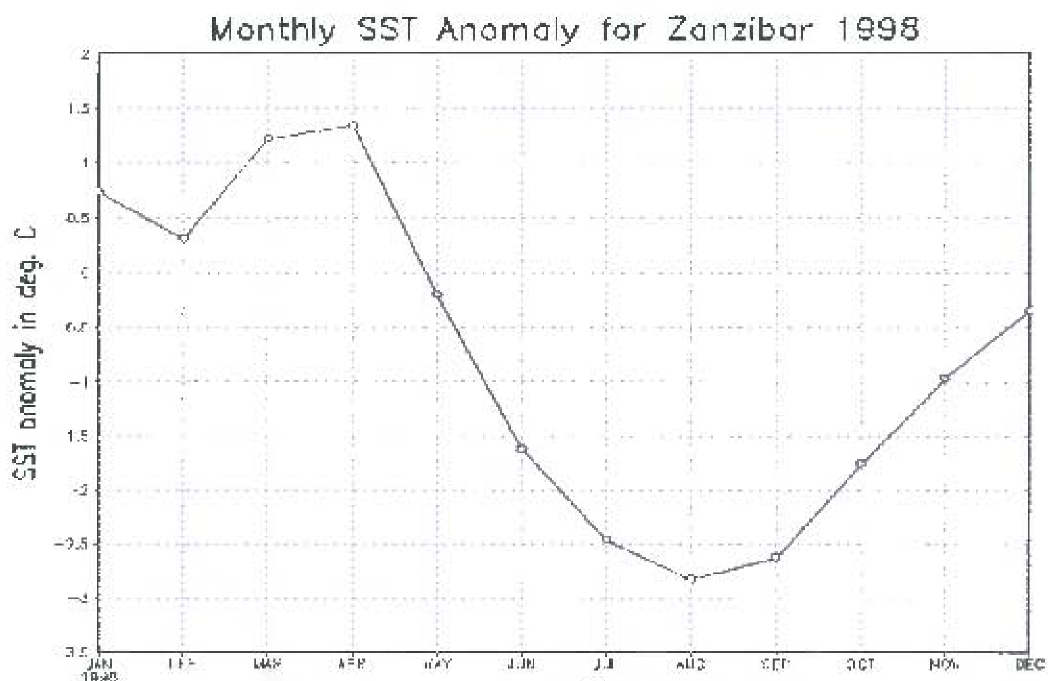


Figure 4.15b Monthly SST anomalies (^{o}C) at Zanzibar for 1998

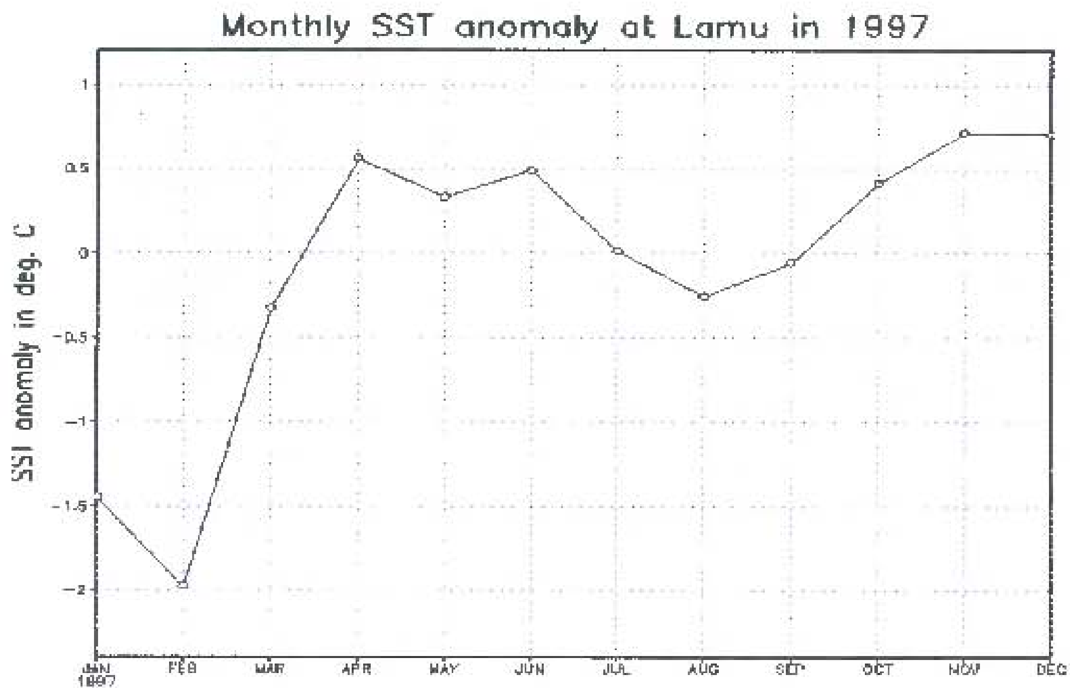


Figure 4.16a Monthly SST anomalies (^{O}C) around at for 1997

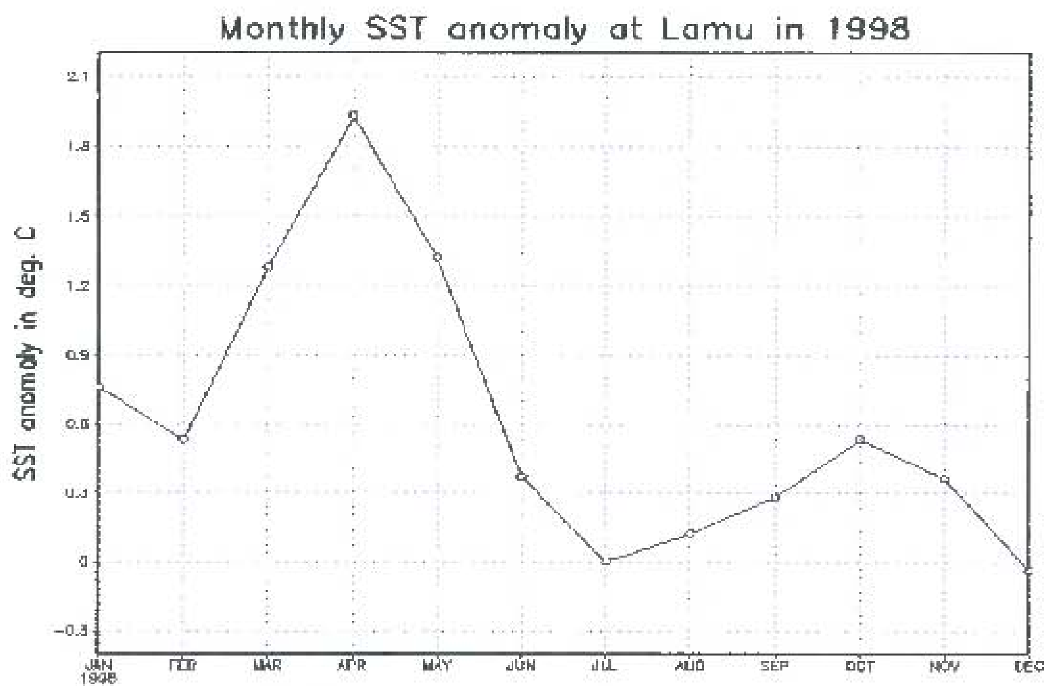


Figure 4.16b Monthly SST anomalies (^{O}C) at Lamu for 1998

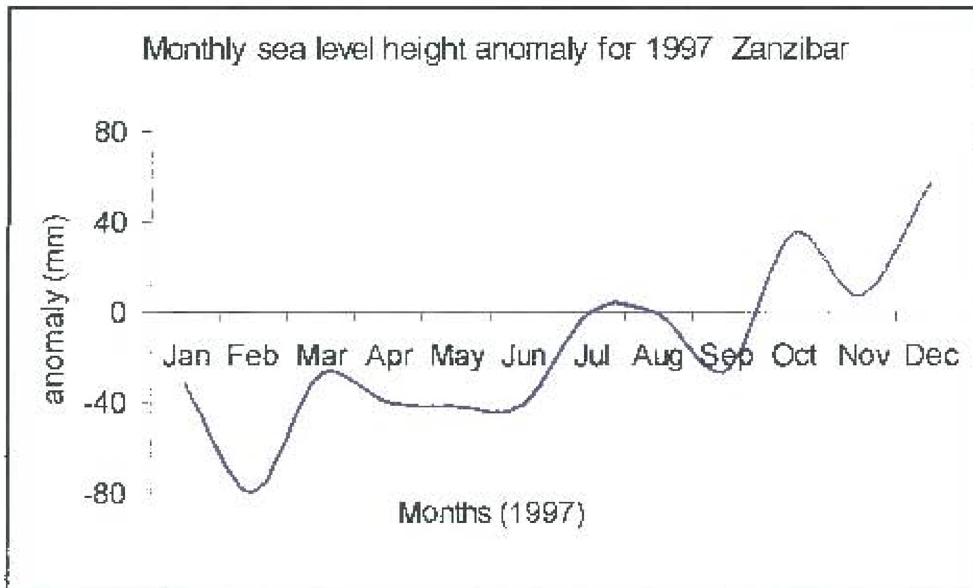


Figure 4.17a Monthly Sea level height anomalies (mm) 1997, Zanzibar.

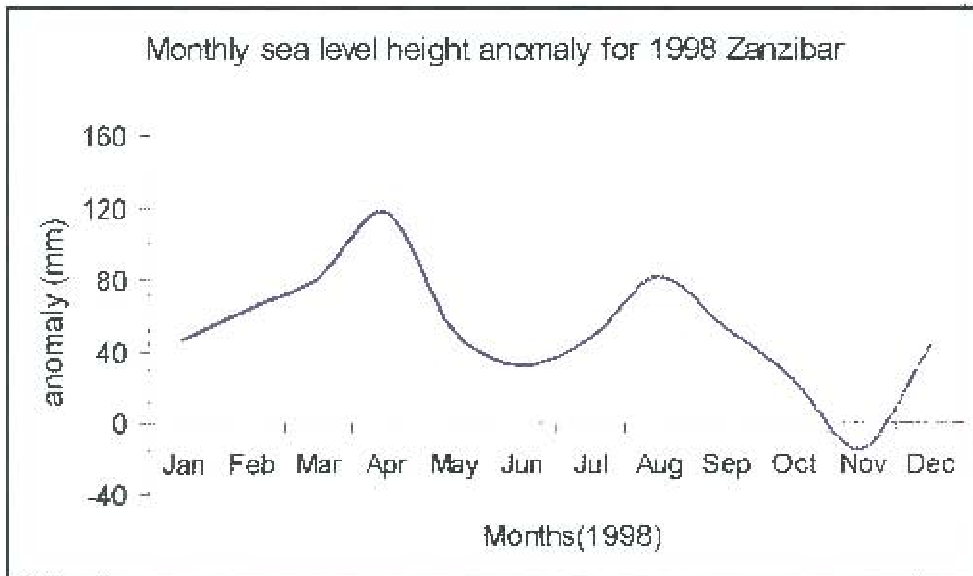


Figure 4.17b Monthly Sea level height anomalies (mm) 1998 Zanzibar

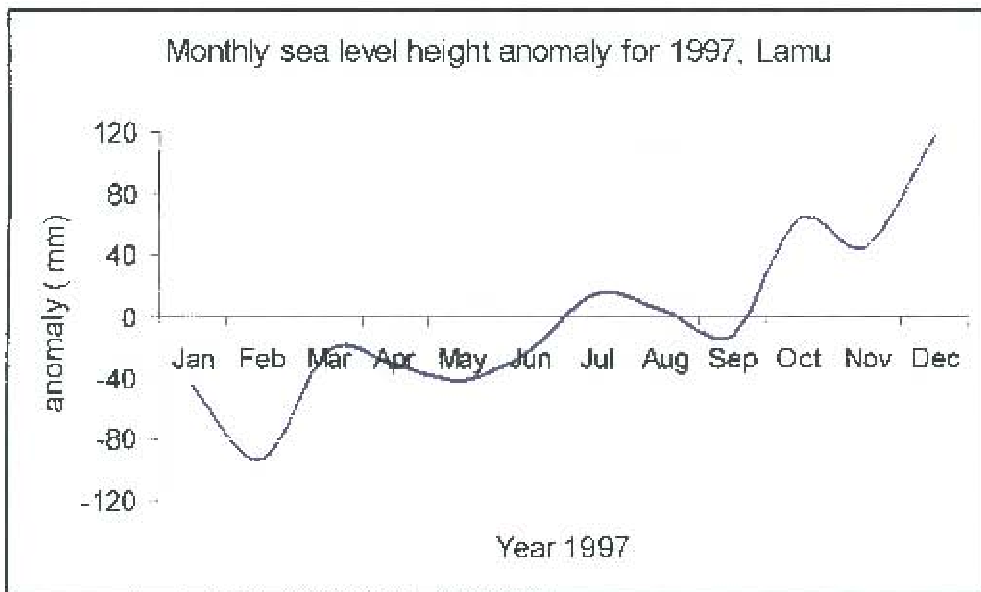


Figure 4.18a Monthly Sea level height anomaly (mm) 1997, Lamu Kenya

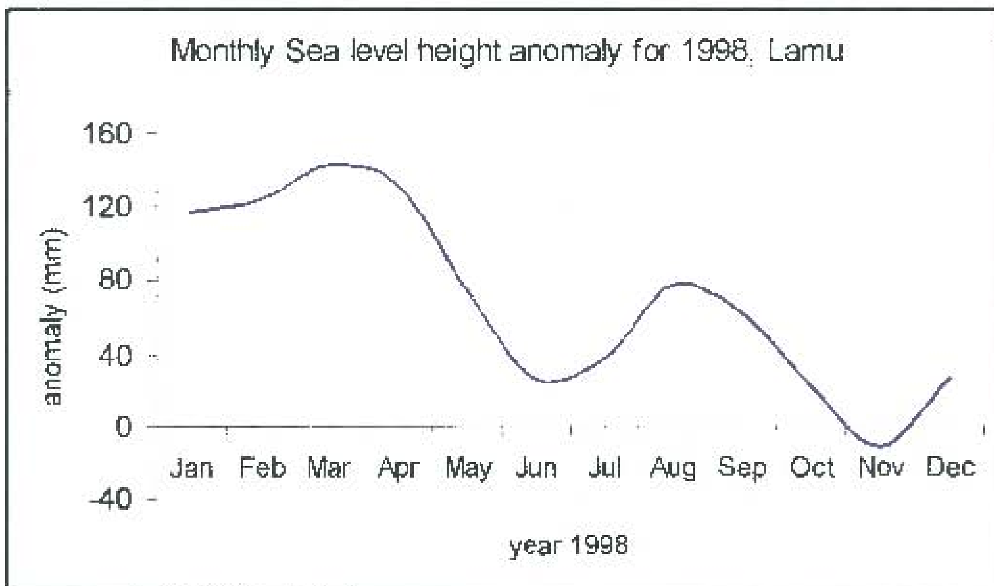


Figure 4.18b Monthly Sea level height anomaly (mm) 1998, Lamu Kenya

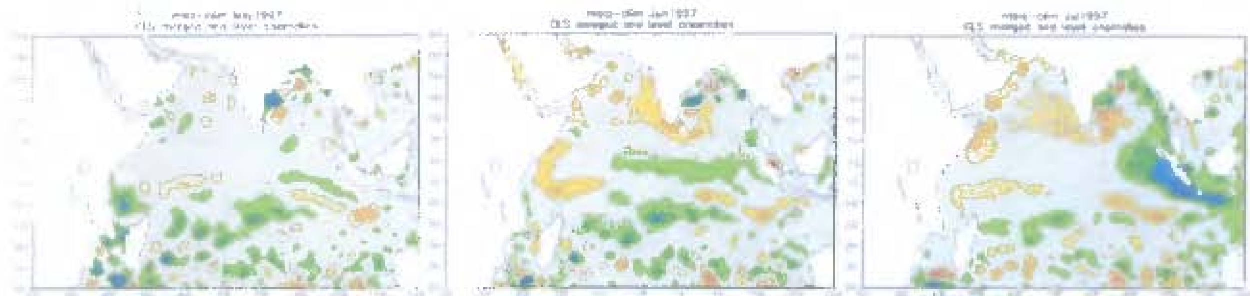
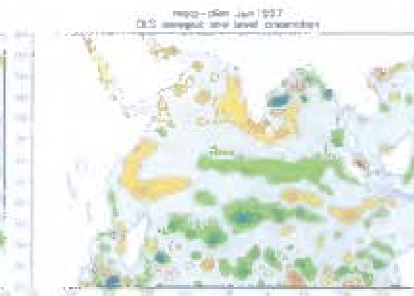
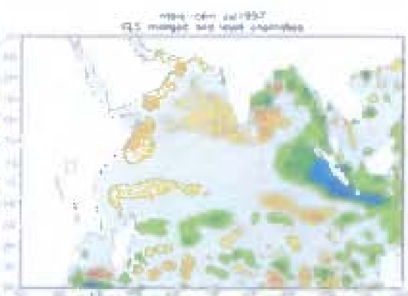




Figure 4.19a May 97 Figures 4.19b Jun 97 Figures 4.19c Jul 97

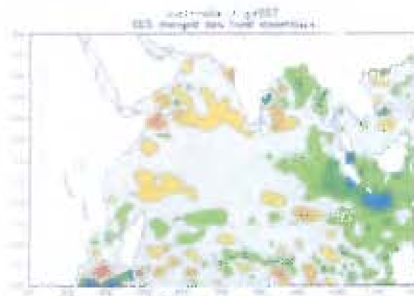


Figure 4.19d Aug 97

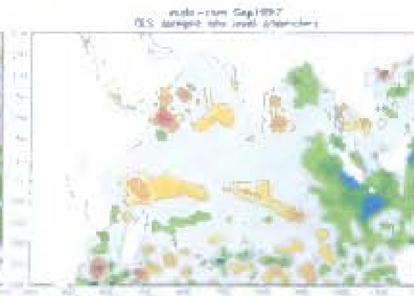


Figure 4.19e Sep 97

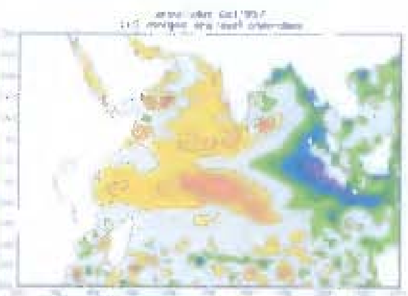


Figure 4.19f Oct 97

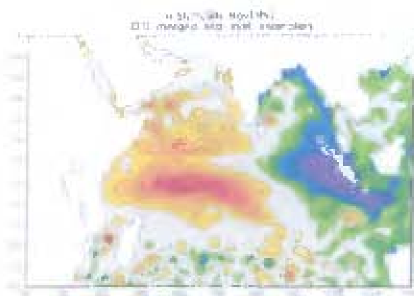


Figure 4.19g Nov 97

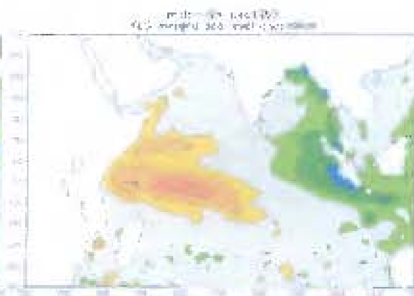


Figure 4.19h Dec 97

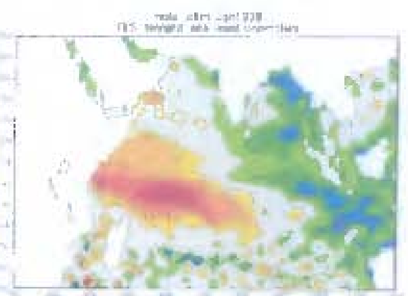


Figure 4.19i Jan 98

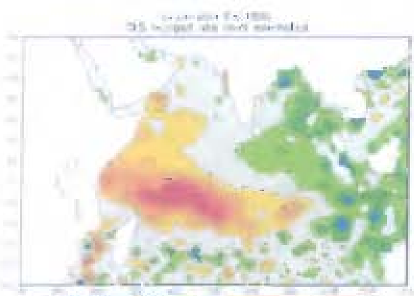


Figure 4.19j Feb 98

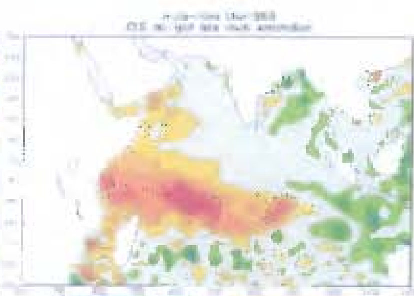


Figure 4.19k Mar 98

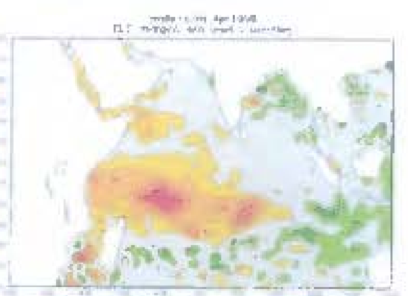


Figure 4.19l Apr 98

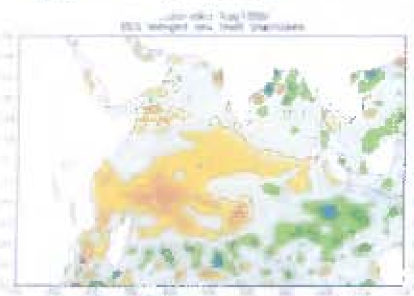


Figure 4.19m May 98

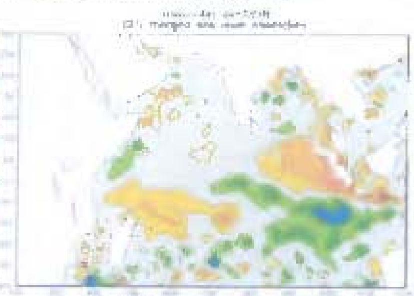


Figure 4.19n Jun 98

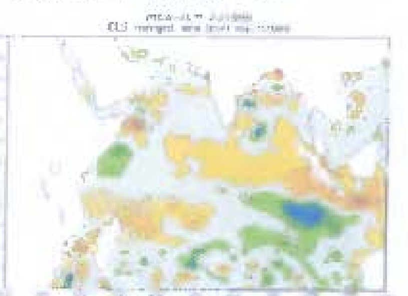


Figure 4.19o Jul 98

Figures 4.19 Monthly sea surface height anomalies from May 1997 to July 1998

The rapid increase in sea surface temperature caused thermal expansion of the upper ocean in the tropical western Indian Ocean, resulting in an increase of sea level height along the East African coast (see Figures 4.17a & 4.17b and Figure 4.18a & 4.18b above).The sea level at Zanzibar began to rise from October 1997 onwards when sea surface temperature there increased. The monthly sea level height anomalies were positive from October 1997 to October 1998. The highest positive sea level height anomaly at Zanzibar was April 1998 at the time of warmest sea surface temperature, when the sea level increased by 117mm as shown in (see Figures 4.17a and 4.17b above and refer to appendix 1 and 4 in page 71 and 74). The highest positive sea level height anomaly at Lamu of 143mm was reached in March and April1998 (near the time of warmest sea surface temperature), as shown in figure 4.18a and 4.18b above (also refer to appendix 2 and 5 in page 72 and 75).

The monthly sea level height anomalies obtained from satellite data also indicates that sea level around the East African Coast started rise to from October 1997 and the highest anomaly was observed during November 1997 to May 1998 (see Figures 4.19g – 4.19l above). Comparing figures 4.14, 4.15a & 4.15b, 4.16a &4.16b with Figures 4.17a & 4.17b, 4.18a &4.18b and 4.19 above, it can be concluded that there was a relationship between variation of sea surface temperature and sea level height during 1997/98 in the Indian Ocean. Sea surface temperature variability is proportional to sea level although there is a lag of a number of weeks for the maximum influence of sea surface temperature on the sea level. The positive sea level height anomalies coincide with warm anomalies in the western tropical Indian Ocean, as earlier described by Chambers et al (1999) and Singh et al (2001).

Figures 4.20a and 4.20b below show how the Monthly sea level pressure anomalies varied at Zanzibar during the 1997/98 warming period over the tropical Indian Ocean. When the sea level height increased (from October 1997), the sea level pressure anomaly at Zanzibar was negative, but from December 1997 to March 1998 there was a slight increase of sea level pressure instead of the expected decrease.

However, in coastal regions, seasonal winds (monsoon winds) may be more important than sea level pressure in affecting sea level (Eugenie 1974). The strongest negative sea level pressure anomaly over East Africa was observed in November 1997 and August 1998 and positive observed in September 1997 and November 1998. During November 1997, the sea level pressure anomaly was - 0.5 hpa and, in August 1998, it was -0.9 hpa. In September 1997 and November 1998, sea level pressure was 0.8 hpa and 1.0 hpa above average respectively (as seen in Figures 4.20a and 4.20b below and refer to appendix 3, 8, 10 and in pages 73, 78 and 80).

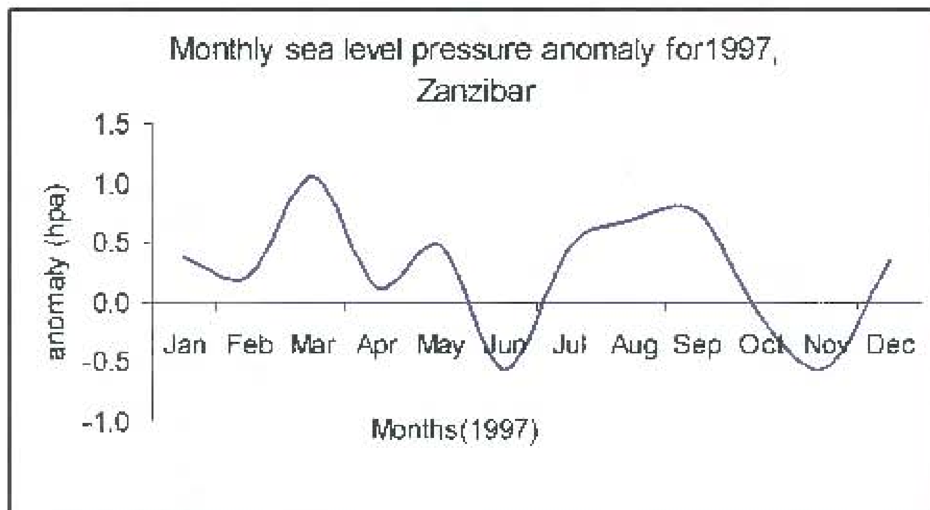


Figure 4.20a Monthly Sea level pressure anomalies at Zanzibar for year 1997

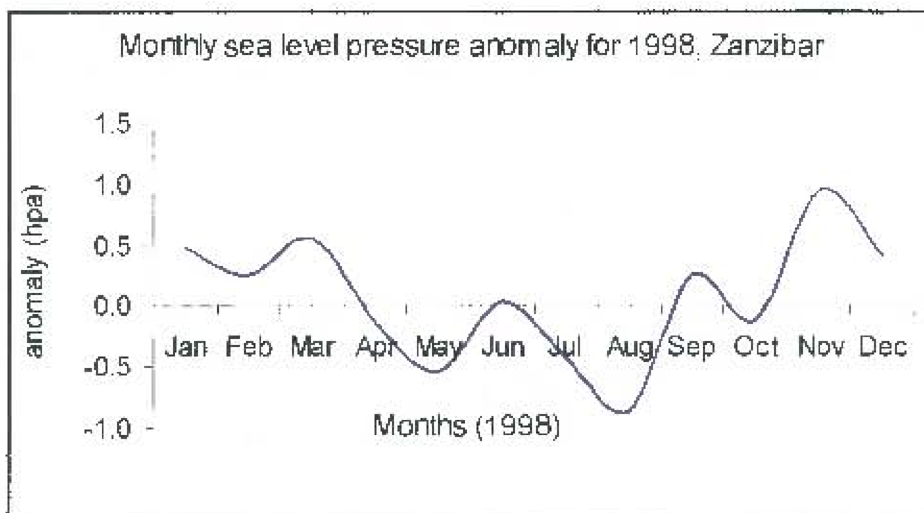


Figure 4.20b Monthly Sea level pressure anomalies at Zanzibar for year 1998

During the anomalous warming in 1997 to 1998, surface zonal wind anomalies (see Figure 4.21a to 4.21f below) portrayed different features. Those figures show that in the middle of 1997, surface zonal winds were close to average over East Africa and the tropical western Indian Ocean, and show considerably stronger easterly anomalies on the eastern side of the basin.

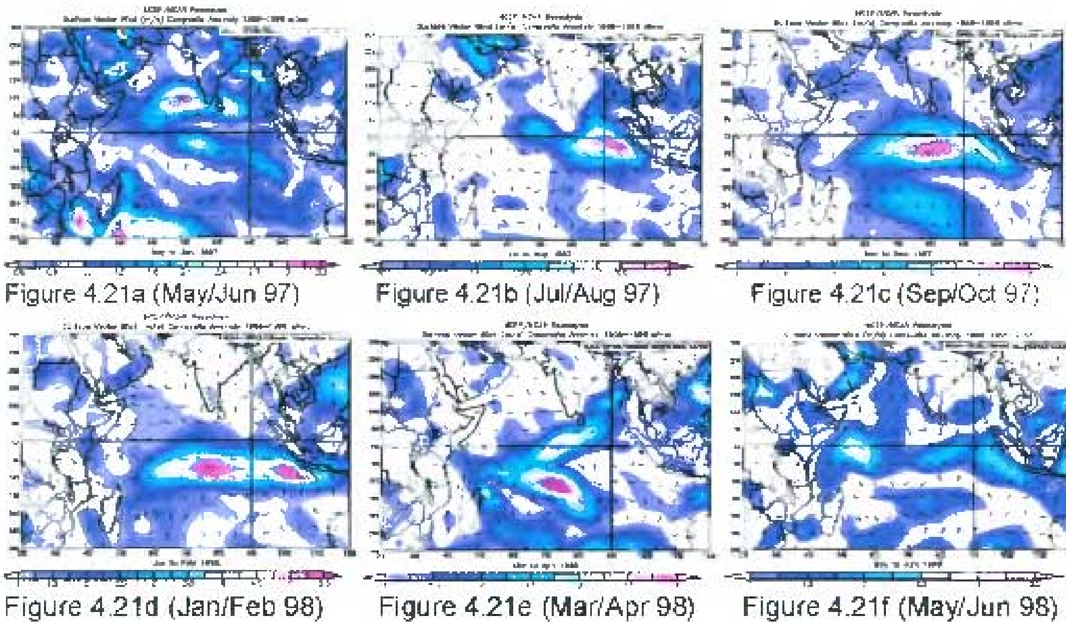


Figure 4.21a (May/Jun 97) Figure 4.21b (Jul/Aug 97) Figure 4.21c (Sep/Oct 97)

Figure 4.21d (Jan/Feb 98) Figure 4.21e (Mar/Apr 98) Figure 4.21f (May/Jun 98)

Figures 4.21a - 4.21f, surface zonal winds anomalies 1997/98

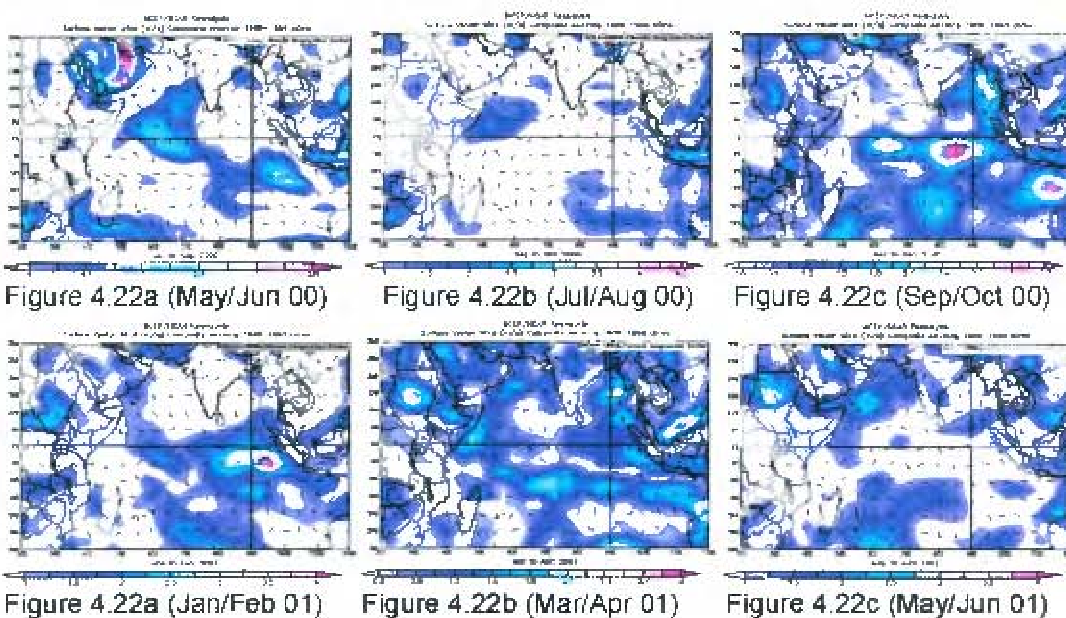


Figure 4.22a (May/Jun 00) Figure 4.22b (Jul/Aug 00) Figure 4.22c (Sep/Oct 00)

Figure 4.22a (Jan/Feb 01) Figure 4.22b (Mar/Apr 01) Figure 4.22c (May/Jun 01)

Figures 4.22a - 4.22f, surface zonal winds anomalies 2000/2001

However, from November 1997 to April 1998, surface zonal wind anomalies were slightly positive over the northeastern East African coast and strong negative surface wind anomalies were observed over the eastern Indian Ocean. The surface wind increased from May 1998 in many areas of the tropical Indian Ocean.

The weakening of surface zonal wind and the increase of sea surface temperature and sea level height from 1997 to 1998 were related to changes in oceanic and atmospheric circulation over the tropical western Indian Ocean, induced by El Niño, and amplified by the positive phase of the Indian Ocean Zonal Dipole Mode event.

During 2000 to 2001, cool anomalies occurred over the tropical western Indian Ocean and East African coast at the end of the protracted La Nina events (Allan et al 2003). During this two year period. sea surface temperature in the region was almost always below average. According to Reynolds monthly sea surface temperature anomalies, the lowest negative monthly sea surface temperature anomalies over tropical western Indian Ocean were observed around October 2000 and July 2001 (See Figures 4.23a to 4.23o below). At Zanzibar the lowest negative anomaly was observed from July to September in both 2000 and 2001. In August (2000 and 2001) the sea surface temperature was less than -3.0^{0} C below average (see Figures 4.24a and 4.24b). At Lamu, lowest sea surface temperature was observed in January and August 2001. Sea surface temperature anomalies here were below -1.2^{0}C and $- 0.3^{0}$ C on these months (see Figure 4.25a and 4.25b above).

Cooling of the tropical western Indian Ocean in 2000/2001 caused a decrease in sea level height over the East African coast. The corresponding data obtained from the Zanzibar and Lamu tide gauge stations show that sea level height was below average for the whole period of cooling from January 2000 to December 2001 (see Figure 4.26a, 4.26b, 4.27a and 4.27b below and refer to appendix 1, 2, 6 and 7 in pages 71, 72, 76 and 77).

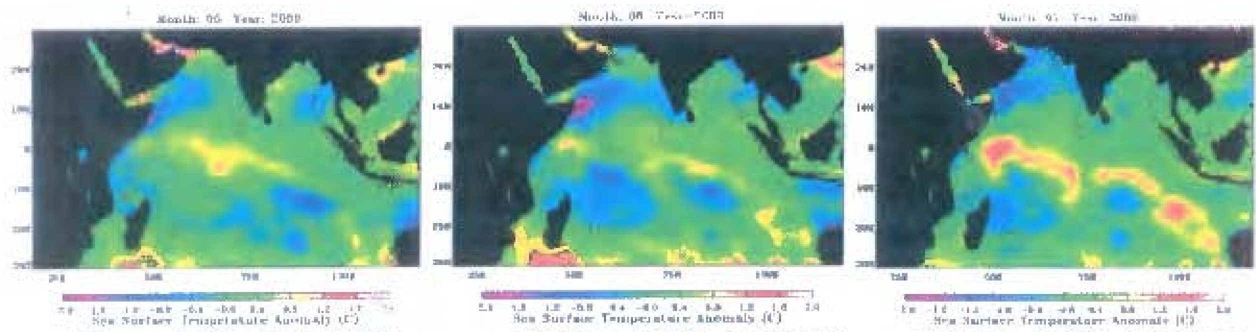
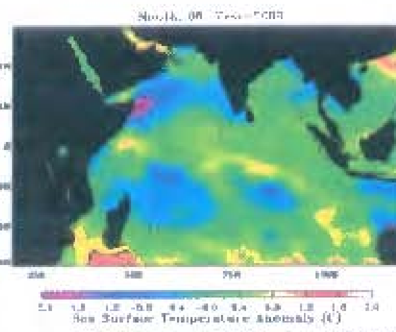
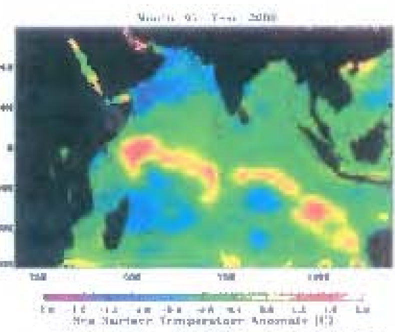


Figure 4.23a May 2000



Figures 4.23b Jun 2000



Figures 4.23c Jul 2000

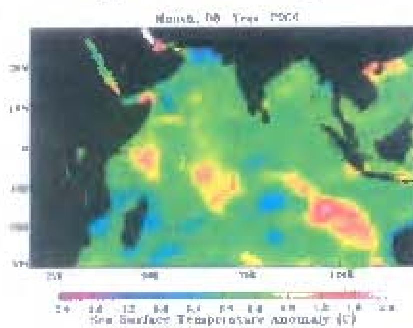


Figure 4.23d Aug 2000

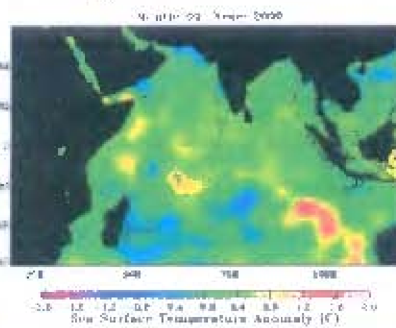
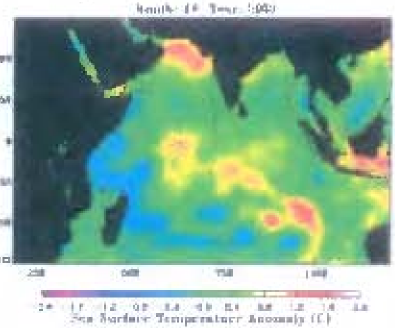


Figure 4.23e Sep 2000



Figures 4.23f Oct 2000

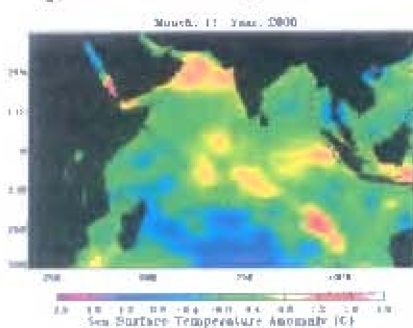


Figure 4.23g Nov 2000

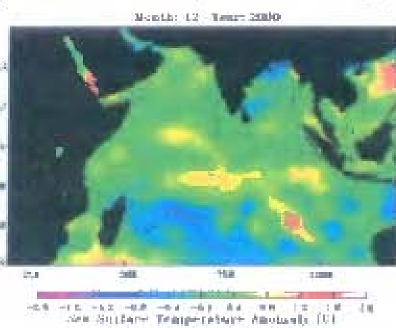
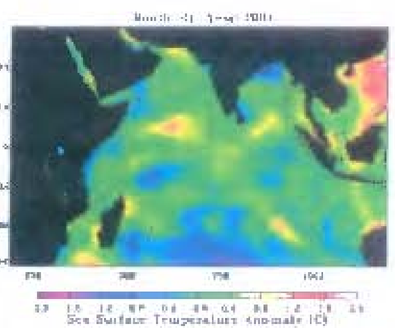


Figure 4.23h Dec 2000



Figures 4.23i Jan 2001

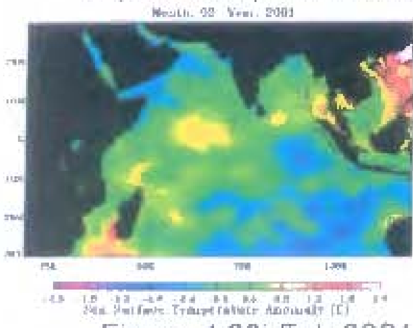


Figure 4.23j Feb 2001

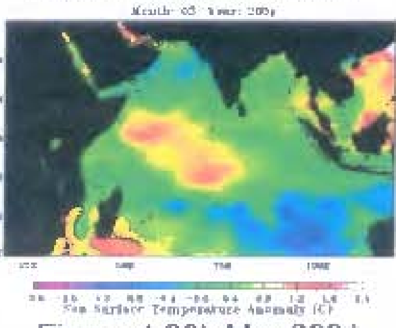
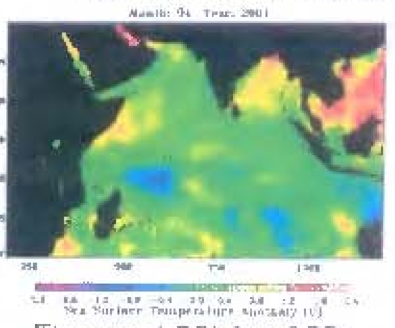


Figure 4.23k Mar 2001



Figures 4.23l Apr 2001

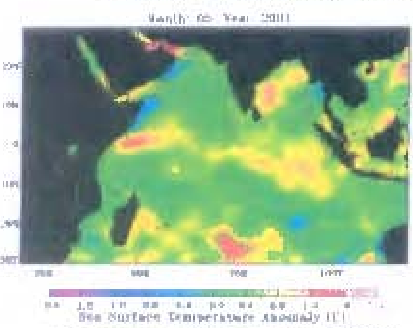


Figure 4.23m May 2001

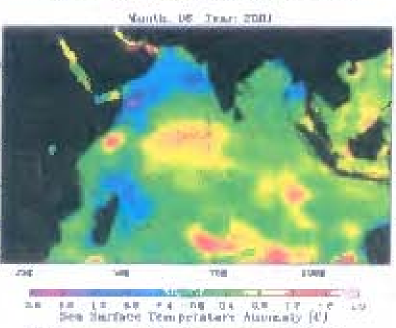
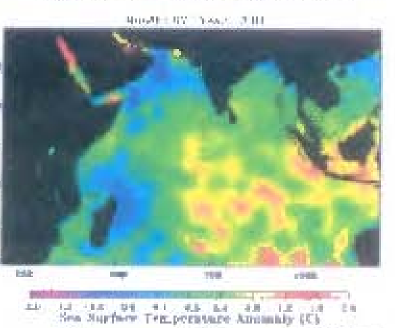


Figure 4.23n Jun 2001



Figures 4.23o Jul 2001

Figures 4.23 Monthly sea level temperature anomalies from May 2000 to July 2001

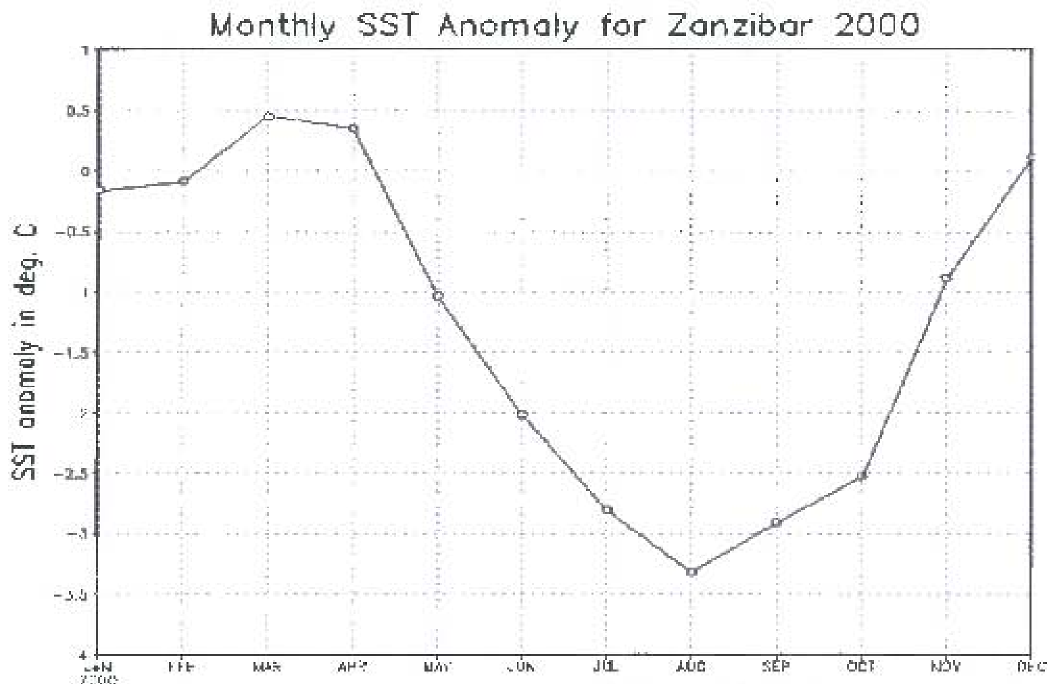


Figure 4.24a Monthly SST anomalies (^{O}C) around Zanzibar for 2000

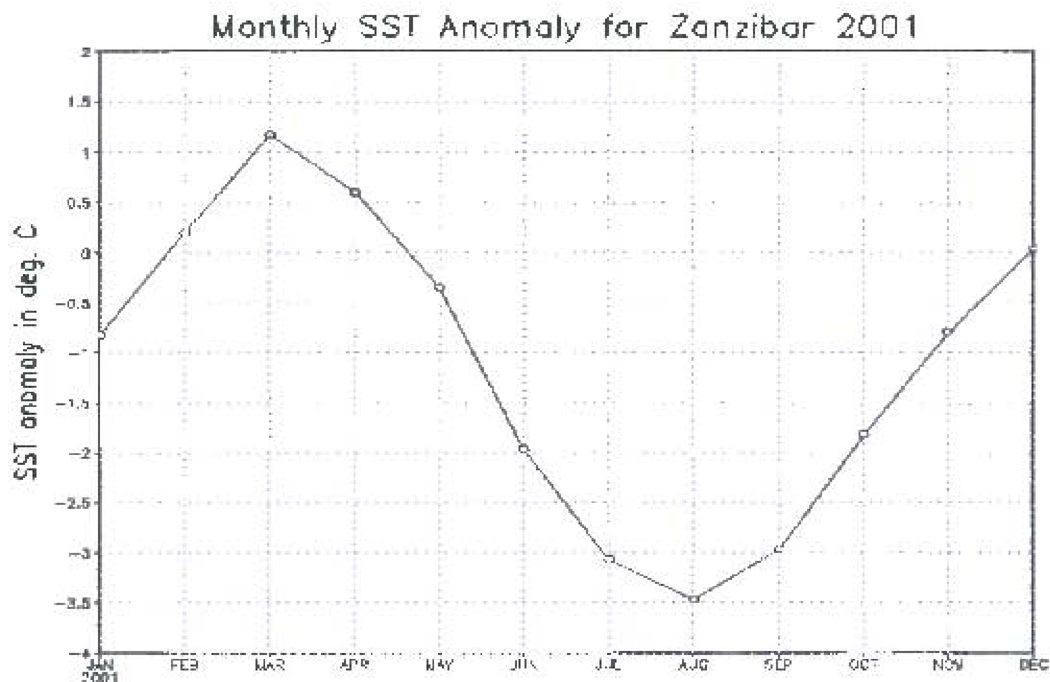


Figure 4.24b Monthly SST anomalies (^{O}C) around Zanzibar for 2001

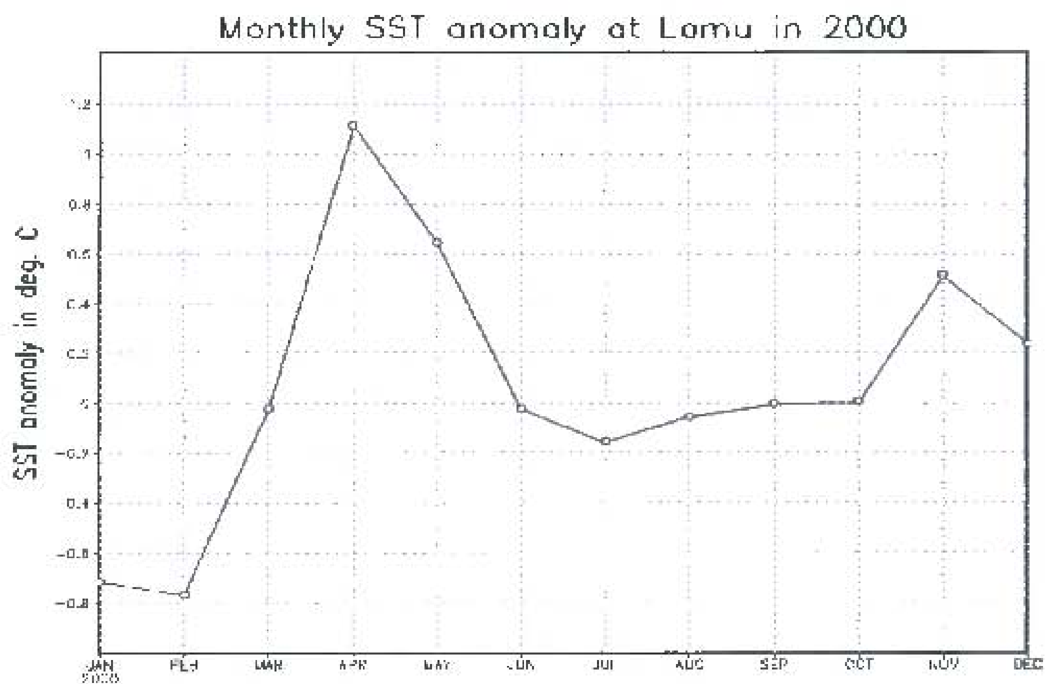


Figure 4.25a Monthly SST anomalies (°C) around Lamu for 2000

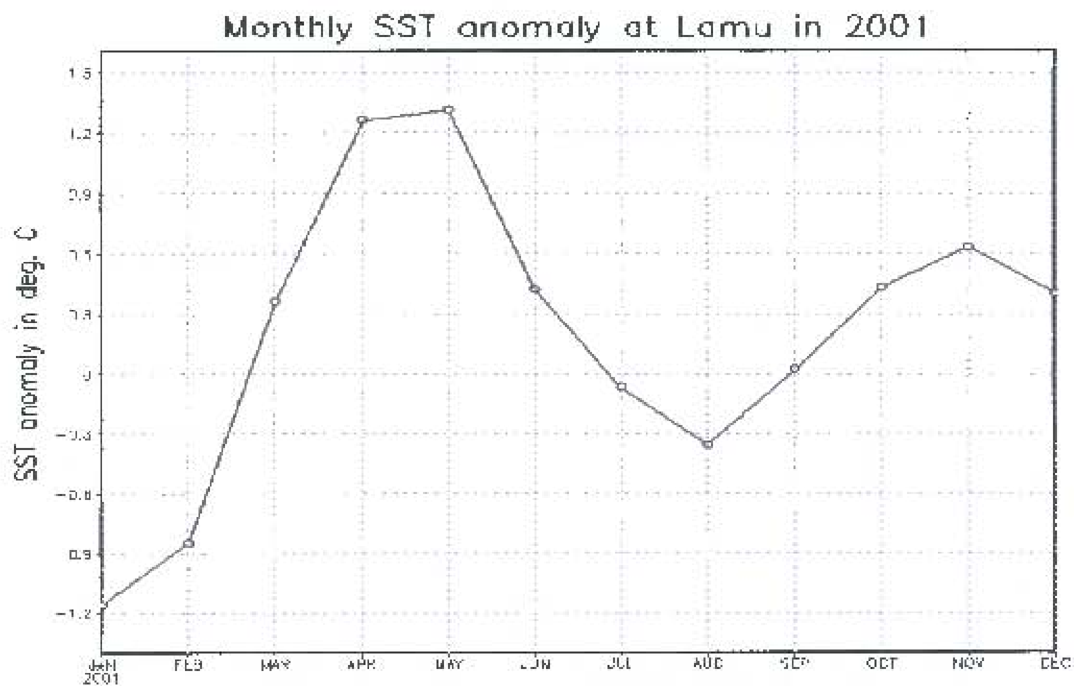


Figure 4.25b Monthly SST anomalies (°C) around Lamu for 2001

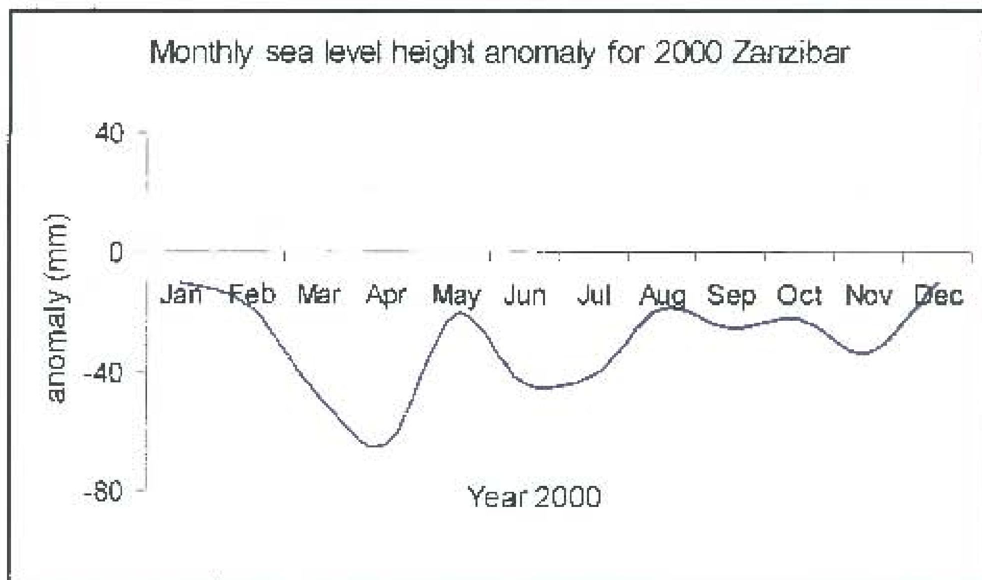


Figure 4.26a Monthly sea surface height anomalies for 2000 Zanzibar

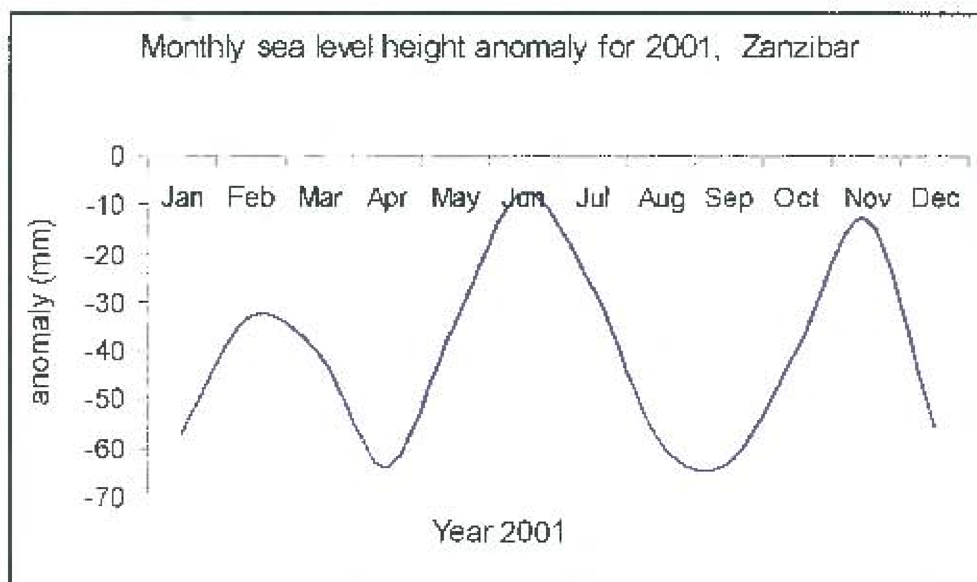


Figure 4.26b Monthly sea surface height anomalies at Zanzibar for 2001

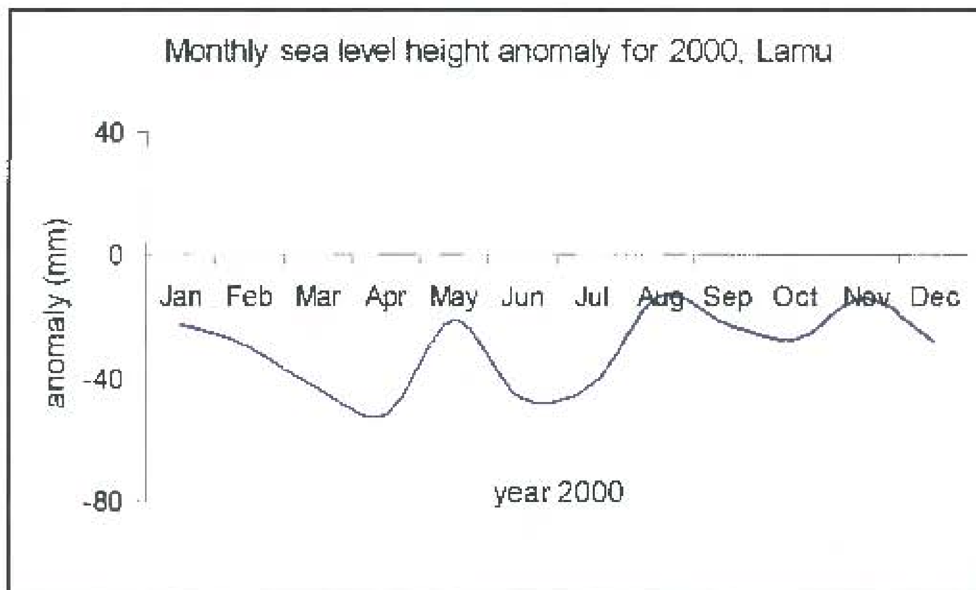


Figure 4.27a Monthly sea surface height anomalies at Lamu for 2000

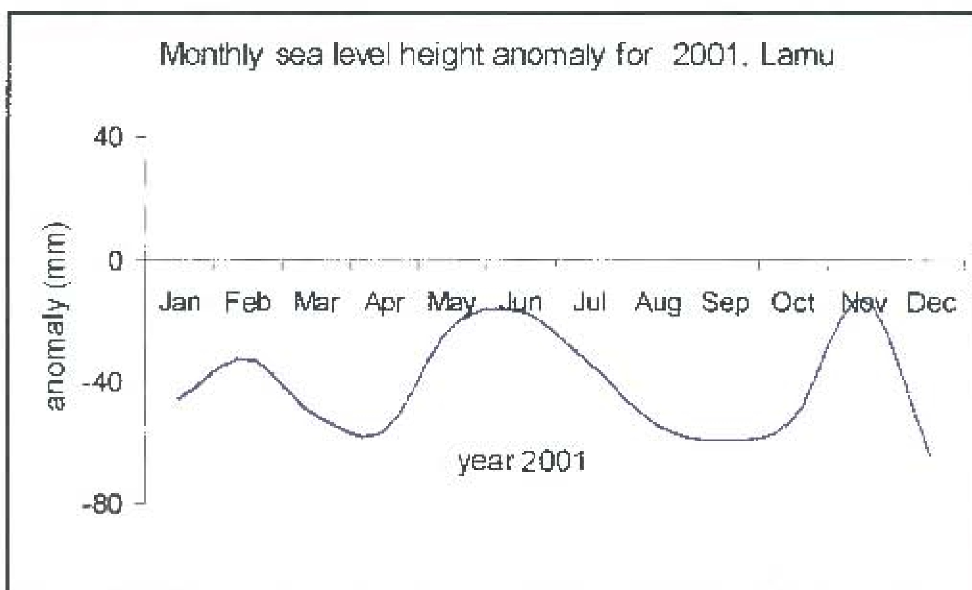
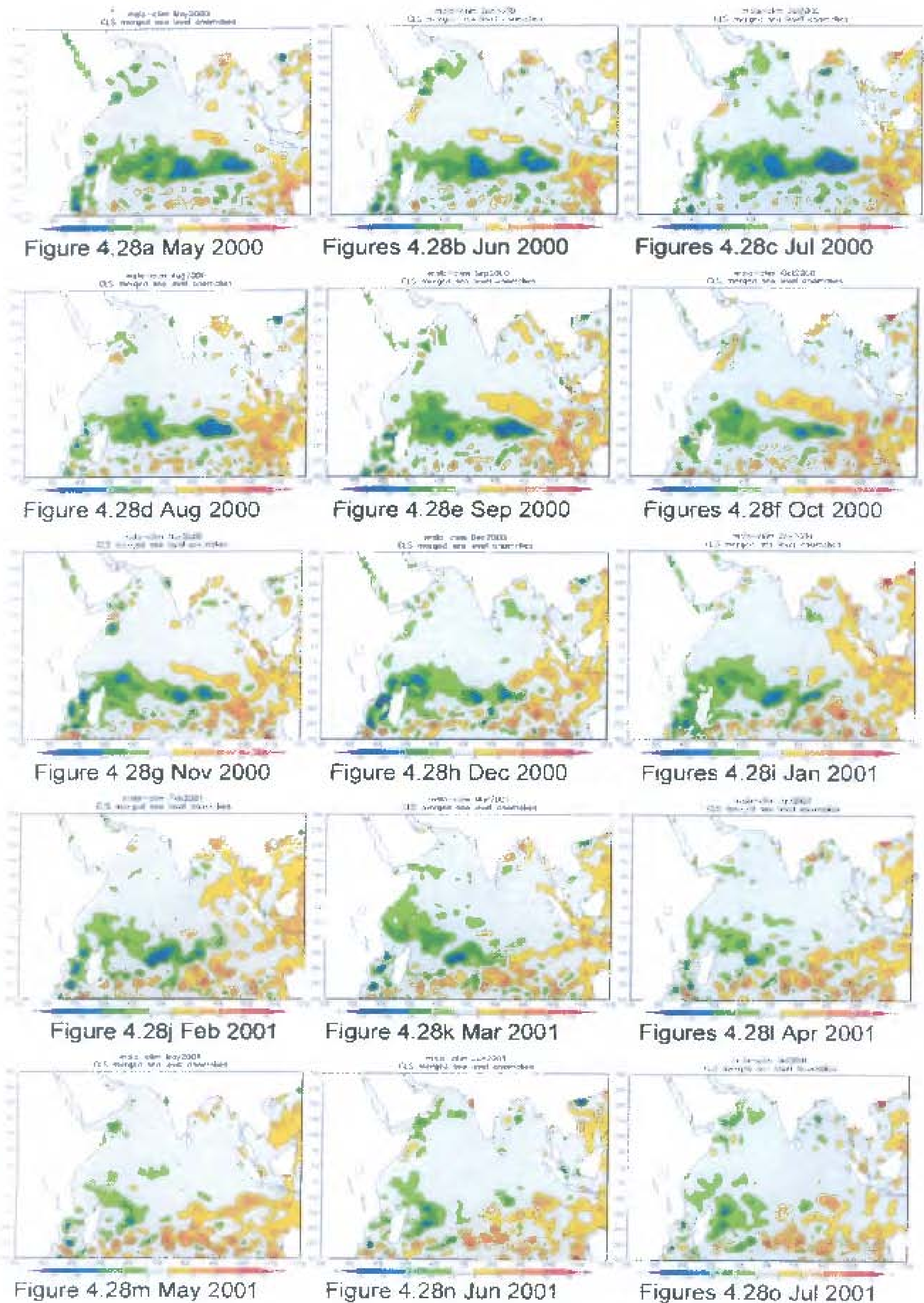


Figure 4.27b Monthly sea surface height anomalies at Lamu for 2001



Figures 4.28 Monthly sea surface level anomalies from May 2000 to July 2001

The lowest sea level height anomalies occurred in 2001, with Zanzibar decreasing by 64mm in April 2001 and Lamu decreasing by 59mm during September.

Monthly sea level height anomalies derived from satellite altimetry data were also negative over the western Indian Ocean during 2000/2001 (see Figures 4.28a – 4.28o above), consistent with the result obtained from Zanzibar and Lamu. Thus, decreased sea level height at Zanzibar and Lamu (East Africa) coincided with the cold phase of ENSO (La Niña) in the tropical western Indian Ocean. The decrease in sea surface temperature and sea level height during 2000/2001 over the tropical western Indian Ocean led to a reduction of moist air transported from the ocean, and stabilized the atmosphere over the East African coast, resulting in reduced rainfall.

Chapter 5

Summary and Conclusion

From this study it can be concluded that the predominant feature of tides around Zanzibar is semidiurnal which indicates an hourly variation of sea level of two high and two low water levels daily as seen in figure 4.1. This is due to the daily gravitational forces of attraction between the sun and the moon on the earth and water. On a monthly scale, there are two spring and two neap tides with different tidal ranges.

The tidal range of the spring and neap tides depend on the period of the year. It can be commented that the highest spring tide and the lowest neap tides are observed during March while lower spring tides and higher neap tides may be experienced around June, as clearly shown from figures 4.2 and 4.3.

During the year, there are typically two high water and two low water periods (as seen on figure 4.5) which are caused by seasonal changes. The higher water periods were observed from March to May and from October to November. The low water period may be experienced from July to August and January to February. Due to the geographical location, the major factors that cause seasonal variation of sea level in Zanzibar are the seasonal change of direction of the monsoon winds and associated pressure systems over the East African coast, and seasonal change of sea surface temperatures over the East African coastal region and tropical western Indian Ocean. These variations influence the seasonal weather patterns and current systems over the tropical Indian Ocean.

Hourly and daily variations of sea levels are influenced by local weather systems. Hourly and daily data can be used for investigating the impact and time of occurrence of oceanic natural disasters such as tsunamis and tropical cyclone induced storm surges.

to a decrease in sea level height (Figures 4.20a – 4.20o, Figures 4.21a & 21b, Figures 4.22a & 4.22b and Figures 4.23a – 4.23o, in chapter four above).

In general, ENSO is the coupled ocean–atmosphere process that includes El Niño and La Niña. Both El Niño and La Niña have an impact on climate variability over the East African region, where El Niño (warm phase of ENSO) tends to produce the opposite climate variations of La Niña. Considering IOZDM and ENSO events that occurred over the East African region and tropical western Indian Ocean during 1997/1998 and 2000/2001 (El Niño and La Niña years), it may be concluded that interannual variation of sea levels can be used as an important indicator of climate variability.

The study of sea level variation around Zanzibar suggests that further studies on sea level variation over East African coast and the tropical western Indian Ocean region are needed.

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Permanent Service Mean Sea Level Web page *http://www.pol.ac.uk/psmsl/*

NCEP Web page *http://www.cdc.noaa.gov/*

The Royal Netherlands Meteorological Institute (KNMI) Web page
http://climexp.knmi.nl/

Appendix 1

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	31	44	20	8	10	32	-1	-37	-27	-21	-39	-42
1997	-32	-79	-28	-40	-41	-40	0	-1	-26	35	8	56
1998	47	65	81	117	53	33	48	82	54	24	-14	43
1999	47	-2	11	-17	9	19	27	29	38	5	-10	-35
2000	-10	-18	-48	-63	-20	-43	-41	-19	-25	-22	-33	-10
2001	-57	-33	-41	-64	-34	-7	-27	-59	-63	-40	-13	-56
2002	-40	-27	8	-20	-20	-31	-40	10	5	-22	32	-17
2003	-34	-3	12	41	17	39	10	19	25	21	29	11
2004	48	53	-19	39	30	2	24	-24	21	20	41	47

Monthly Sea Level height anomalies (mm) at Zanzibar for the period of nine years from January 1996 to December 2004

Appendix 2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	19	45	18	3	2	17	-17	-44	-50	-31	-48	-49
1997	-46	-93	-22	-30	-41	-21	15	4	-12	64	45	118
1998	117	124	143	131	74	27	37	77	62	21	-12	26
1999	29	-13	-9	-32	-4	16	34	29	40	-2	-13	-14
2000	-23	-30	-43	-52	-21	-46	-42	-13	-22	-27	-14	-28
2001	-46	-33	-51	-56	-22	-16	-34	-54	-59	-52	-13	-64
2002	-42	-42	15	-23	-22	-21	-50	-3	-12	-14	5	-13
2003	-39	-11	-16	54	15	38	28	14	14	9	12	-4
2004	28	52	-34	5	21	10	27	-9	41	34	37	28

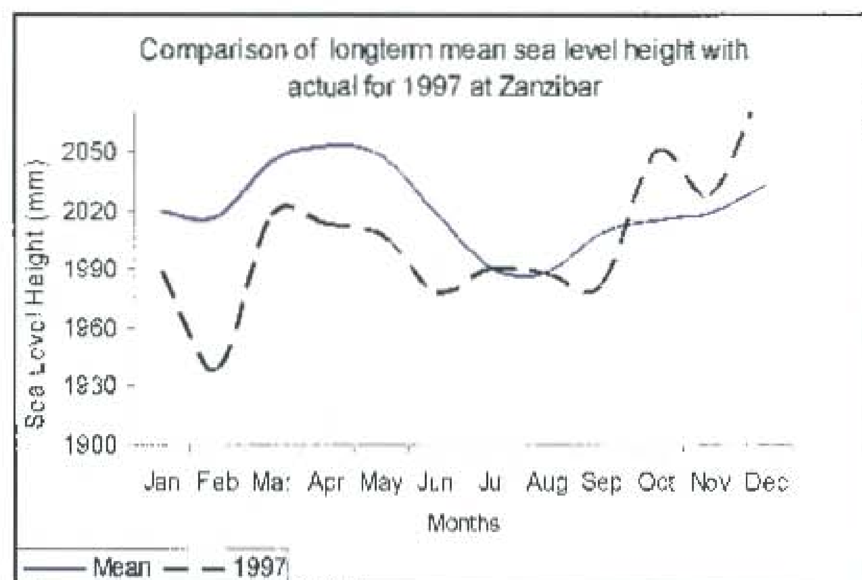
Monthly Sea Level height anomalies (mm) at Lamu for the period of nine years from January 1996 to December 2004

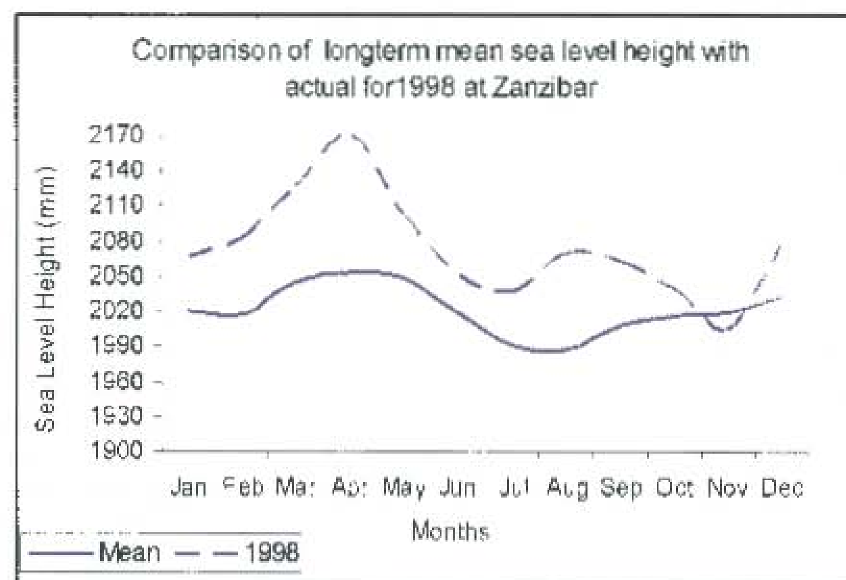
Appendix 3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	-0.7	-1.4	-0.4	0.2	0.0	-0.5	0.3	-0.3	-0.5	0.0	0.0	0.0
1997	0.4	0.2	1.1	0.1	0.5	0.6	0.5	0.7	0.8	-0.1	-0.5	0.3
1998	0.5	0.2	0.6	-0.1	-0.6	0.0	-0.4	-0.9	0.3	-0.1	1.0	0.4
1999	-0.2	0.1	-1.6	0.7	0.3	-0.2	0.3	-0.1	-0.5	-0.3	0.4	0.6
2000	-0.7	-0.3	-0.1	0.2	0.3	0.2	-0.9	-0.4	-0.3	-0.4	-1.3	-0.6
2001	-0.5	-0.2	0.3	0.1	0.0	0.0	0.0	0.3	-0.8	-0.3	0.7	0.1
2002	0.5	1.0	0.1	-0.4	-0.3	0.2	0.4	0.5	0.9	0.9	0.1	0.2
2003	1.0	1.3	-0.2	-0.5	-0.2	0.2	0.4	0.1	1.7	1.2	-0.6	0.0
2004	0.5	0.2	-0.3	-0.1	0.0	0.0	0.0	-0.3	0.8	0.3	-0.7	-0.1

Monthly sea level pressure anomalies (hpa) at Zanzibar for the period of nine years from January 1996 to December 2004

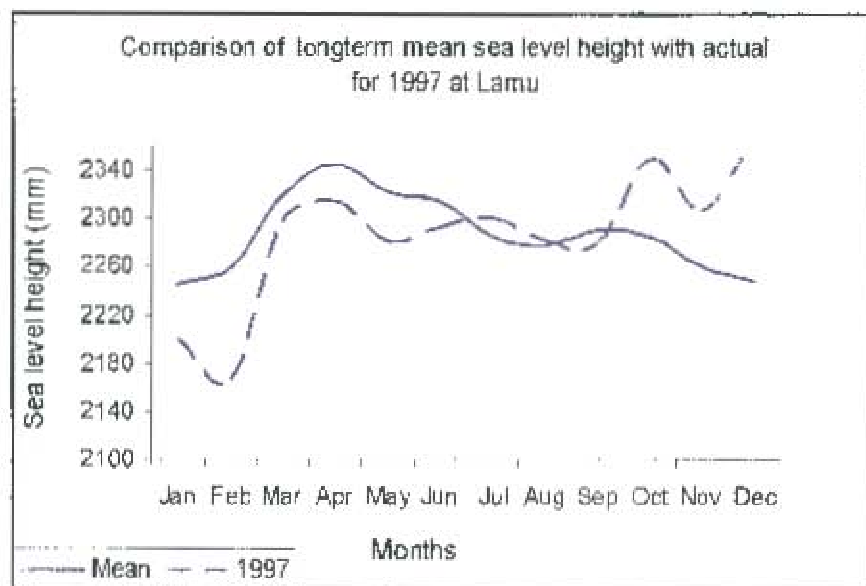
Appendix 4

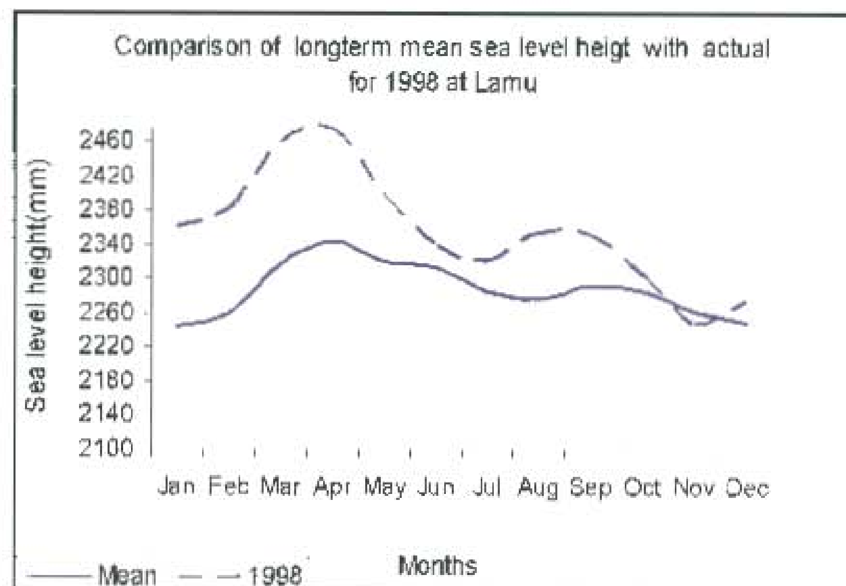




Comparison of long-term mean sea level height with actual of 1997 and 1998 at Zanzibar

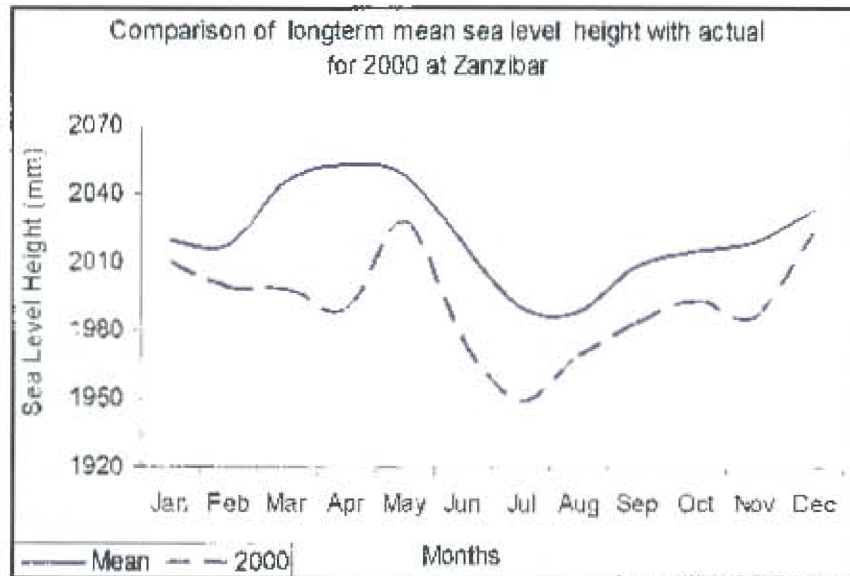
Appendix 5

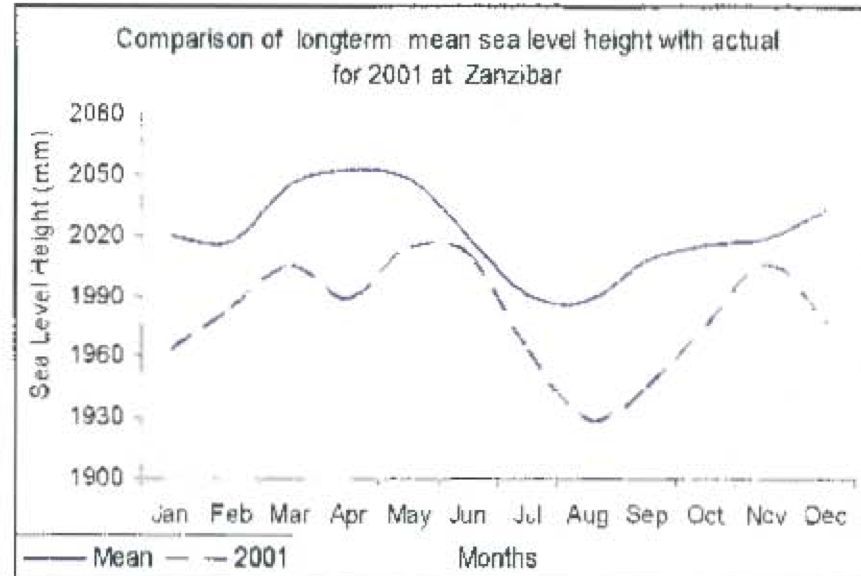




Comparison of long-term mean sea level height with actual of 1997 and 1998 at Lamu

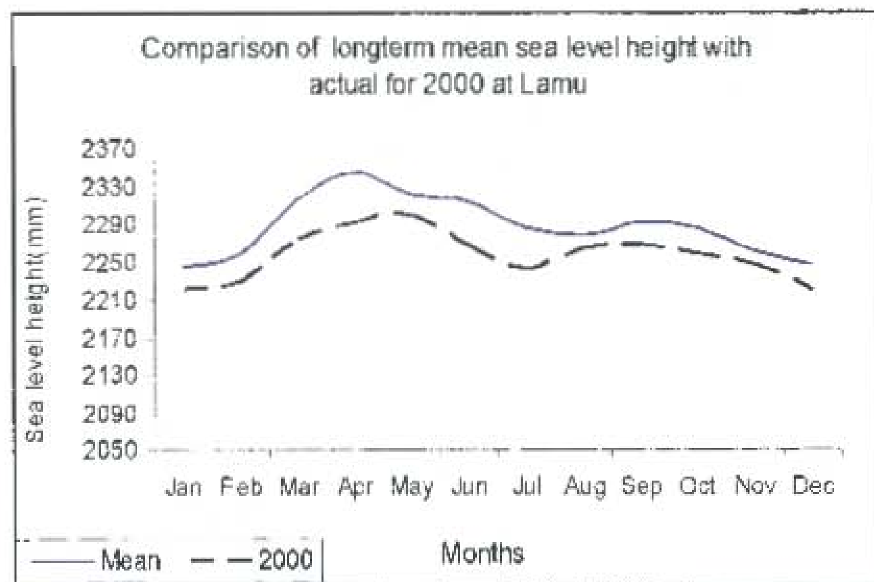
Appendix 6

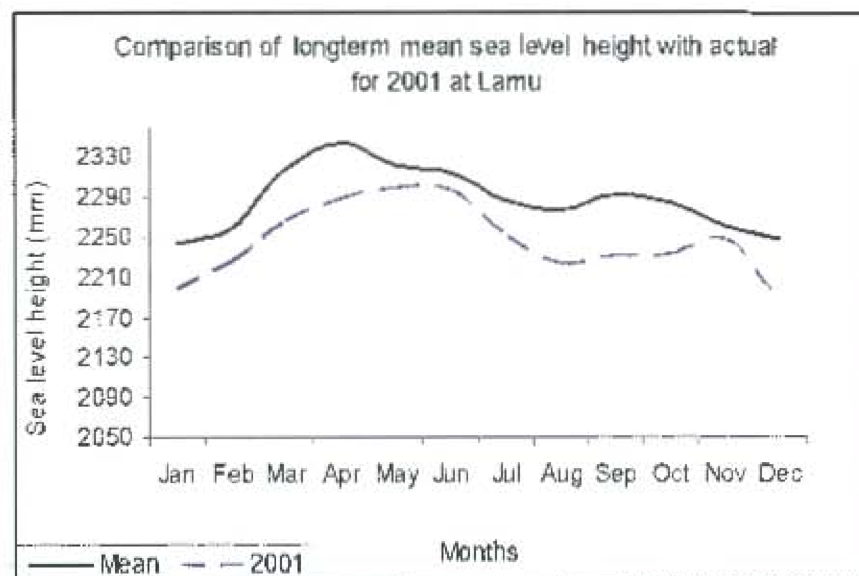




Comparison of long-term mean sea level height with actual of 2000 and 2001 at Zanzibar

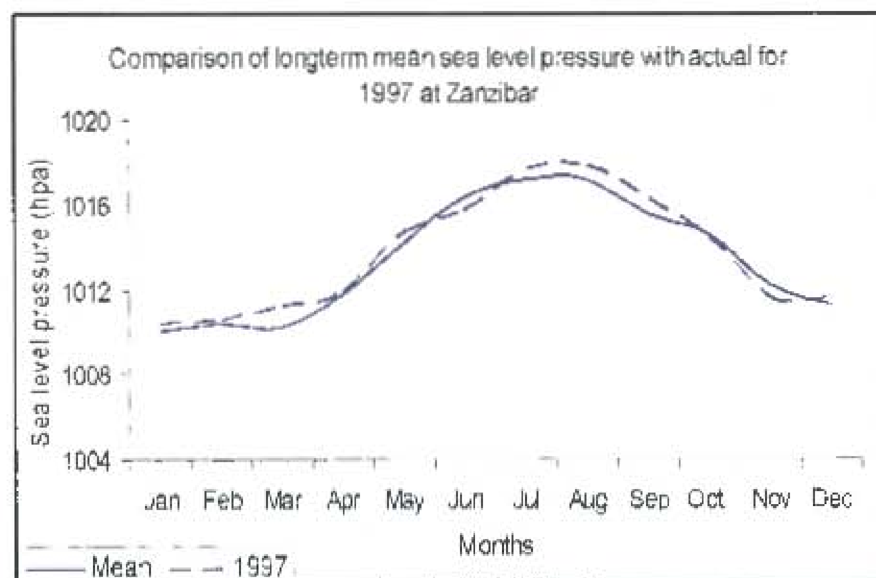
Appendix 7

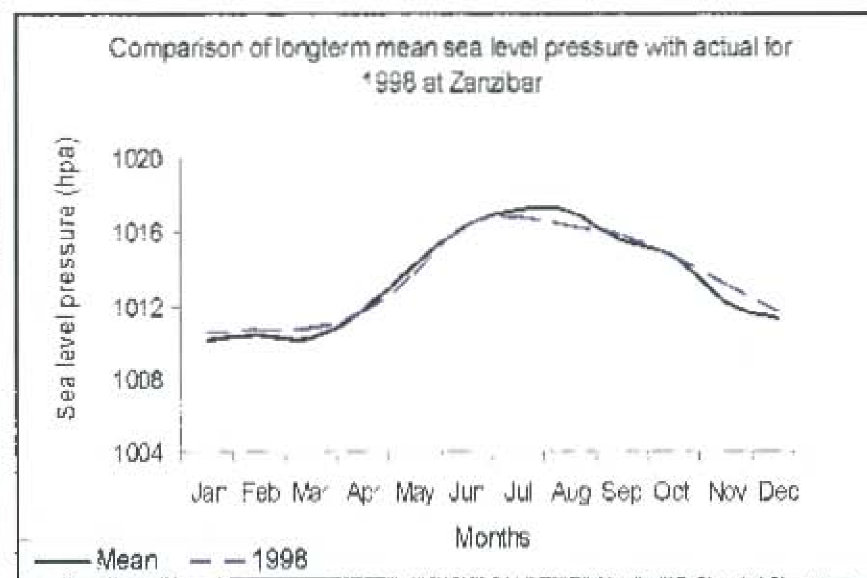




Comparison of long-term mean sea level height with actual of 2000 and 2001 at Lamu

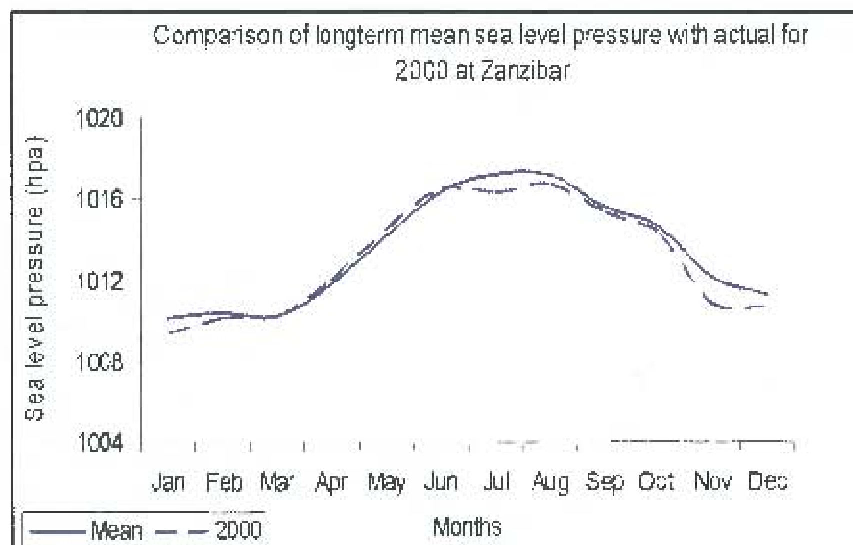
Appendix 8

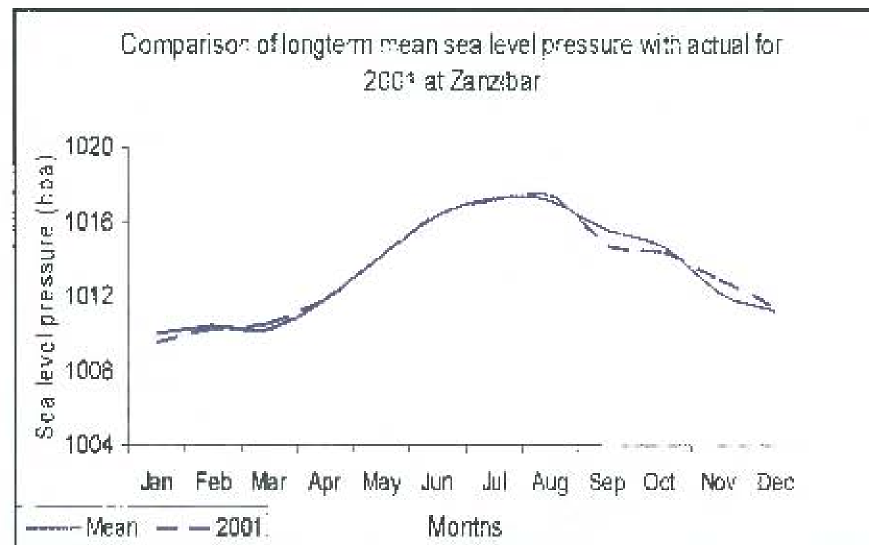




Comparison of long-term mean sea level pressure with actual of 1997 and 1998 at Zanzibar

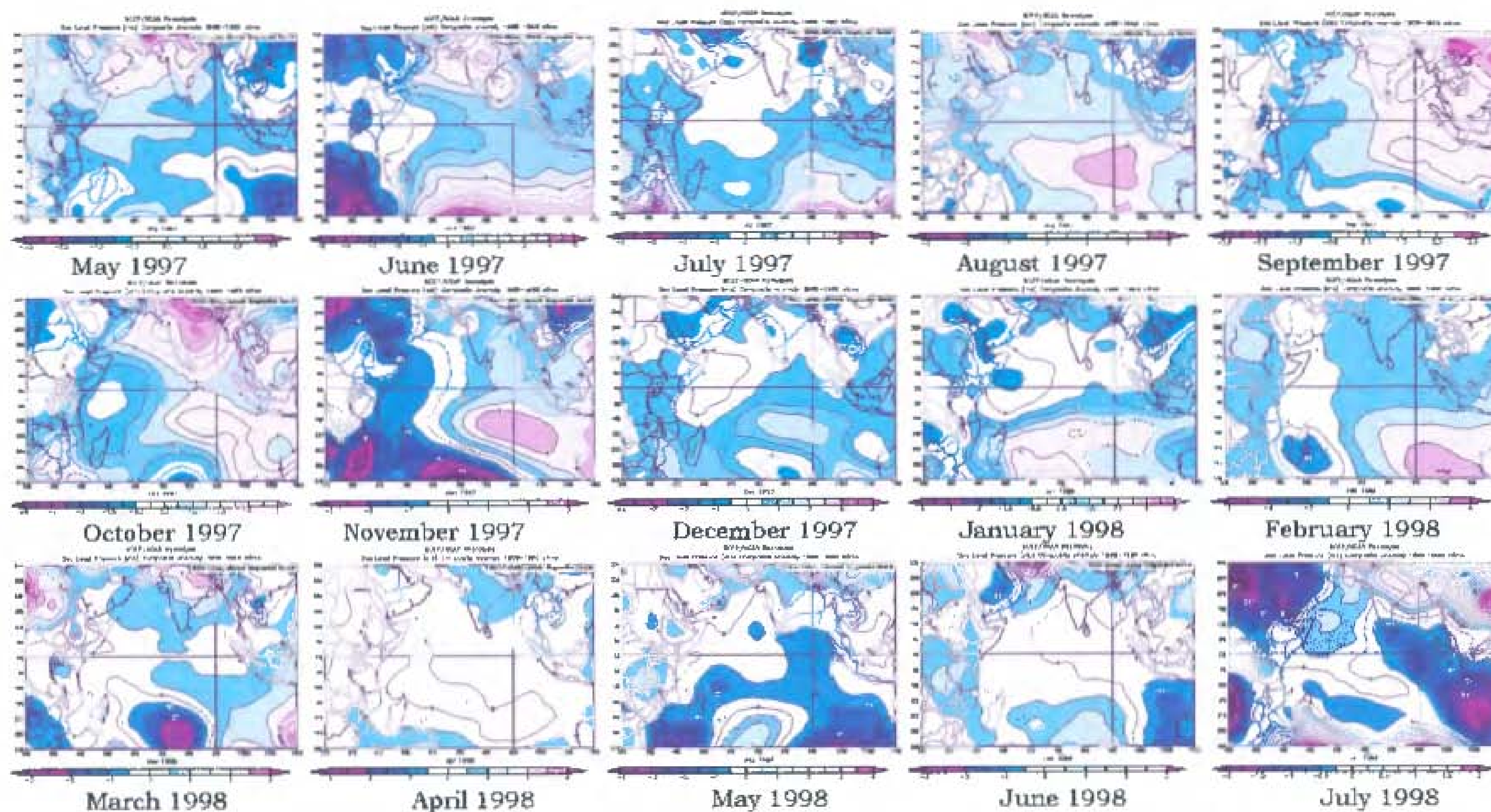
Appendix 9





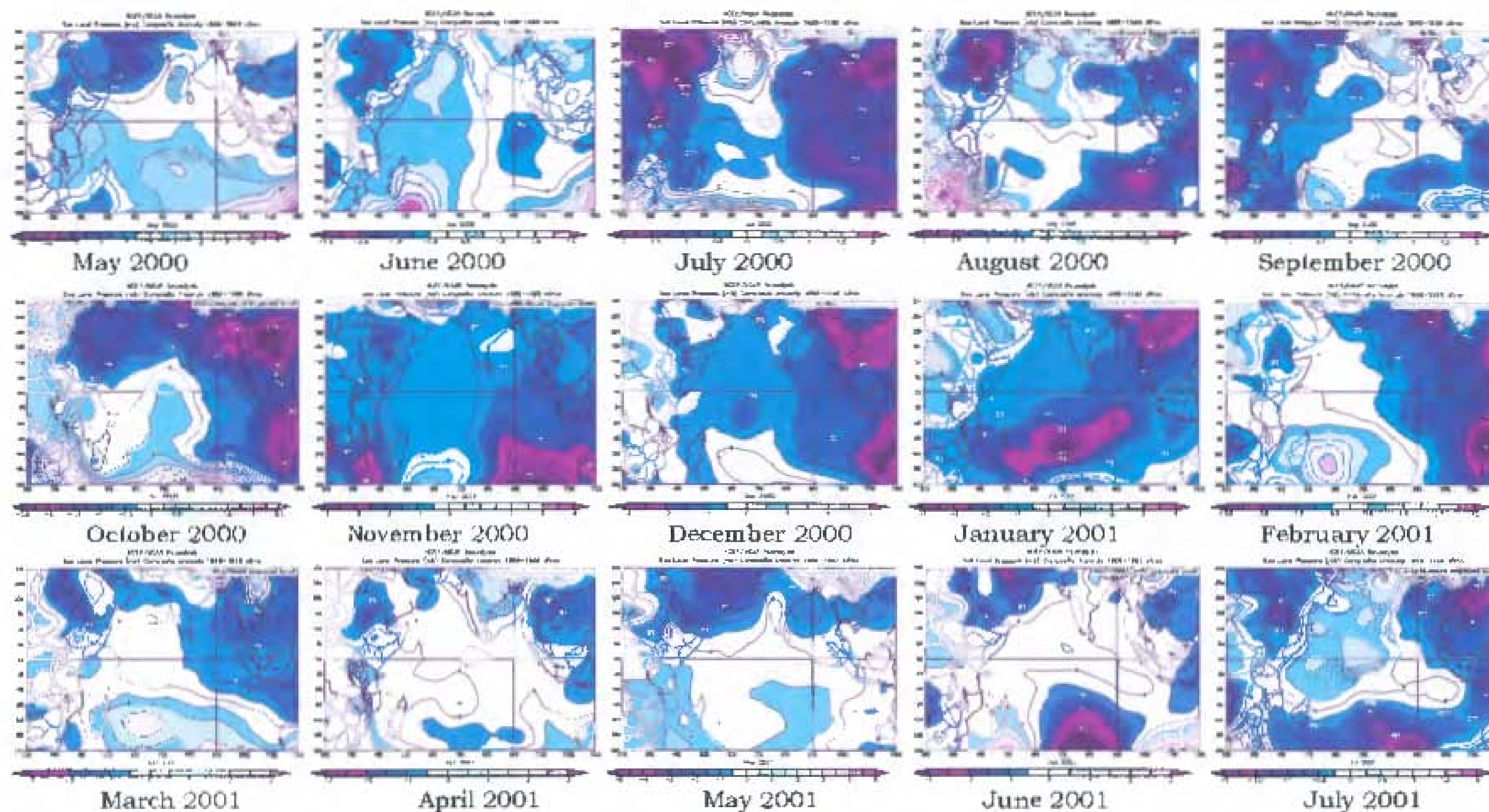
Comparison of long-term mean sea level pressure with actual of 2000 and 2001 at Zanzibar

Appendix 10



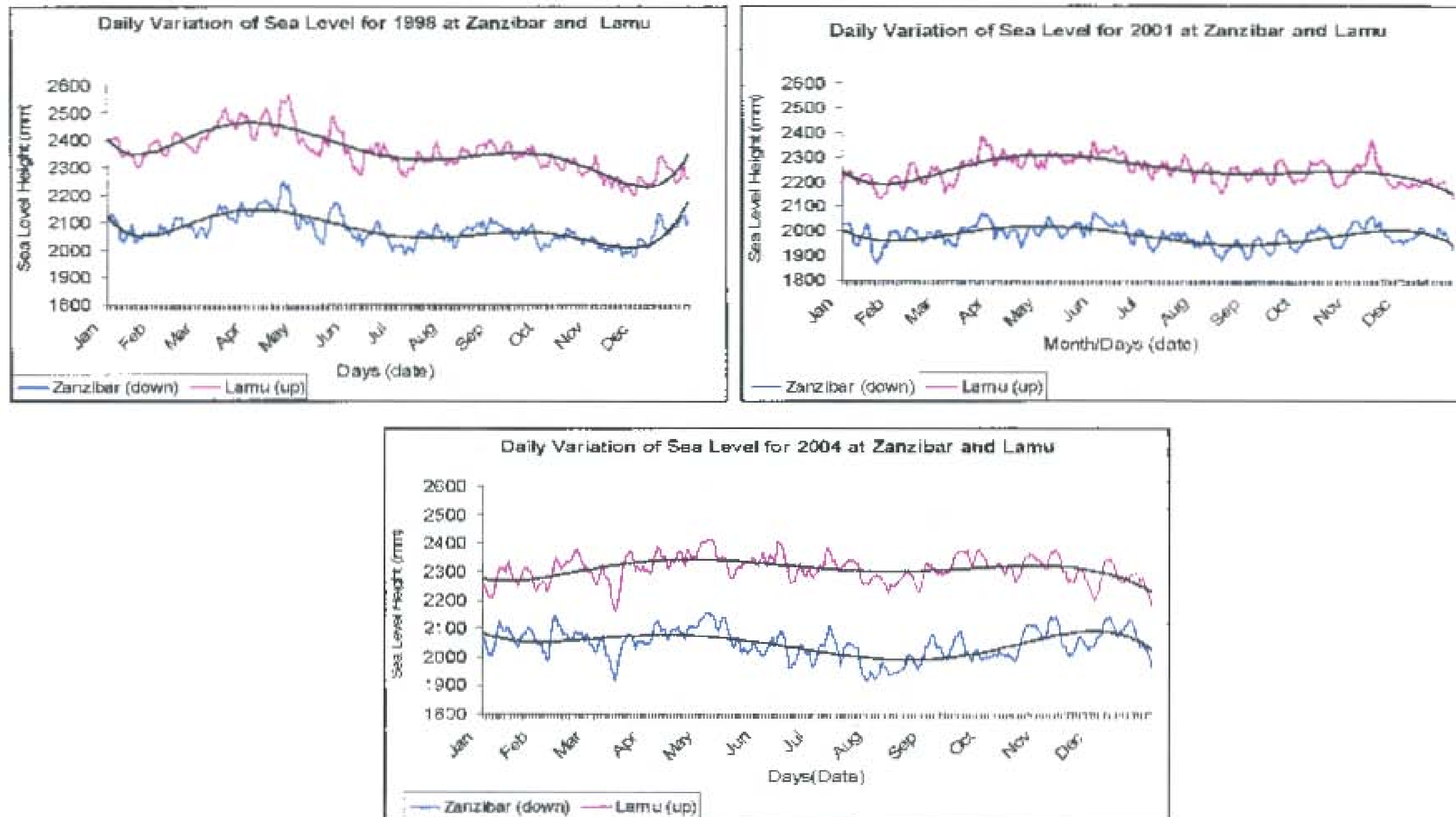
Monthly sea level pressure anomalies from May 1997 to July 1998

Appendix 11



Monthly sea level pressure anomalies from May 2000 to July 2001

Appendix 12



Daily sea level Variations during extreme warm year (1998), extreme cold year (2001) and neutral year (2004)