WESTERN INDIAN OCEAN MARINE SCIENCE ASSOCIATION (WIOMSA)

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (of UNESCO)

TIDAL ANALYSIS AND PREDICTION IN THE WESTERN INDIAN OCEAN

REGIONAL REPORT

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April 2009

PREFACE

The Intergovernmental Oceanographic Commission (IOC) of UNESCO developed a Global Sea Level Observing System (GLOSS) program in 1985 to address the growing concern about the rise in mean sea level around the globe. The objective of GLOSS was to provide high quality standardized data from which valuable sea level products can be produced for international oceanographic programmes and data centres such as World Ocean Circulation Experiment (WOCE), Tropical Oceans Global Atmosphere (TOGA), Univeristy of Hawaii Sea Level Centre (UHSLC) and Permanent Service for Mean Sea Level (PSMSL), and regional research programmes as well as for practical application on a national and regional level.

Through GLOSS, a network of about 300 tide gauges have been installed throughout the globe. The regional component of GLOSS in the Western Indian Ocean (WIO) Region is through IOC's Regional Committee for the Co-operative Investigations in the North and Central Western Indian Ocean (IOCINCWIO), which was established in 1979 by resolution XI-9 of the eleventh session of the IOC Assembly. IOCINCWIO coordinates development and implementation of regional oceanographic research activities in the member states in the region (Comoros, French Indian Ocean islands, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, South Africa and Tanzania).

The development of GLOSS in Africa has been discussed at a number of recent meetings and workshops. For example, at the only GLOSS training course held so far in Africa, at the University of Cape Town (UCT) in 1998, recommendations were made by the many young scientists present for the formation of an African GLOSS Network to coordinate future sea level activities in Africa (including elements involving GPS, altimetry, data analysis, training etc.), with the suggestion that there be 3 overlapping regional groups (west, south and east). The UCT meeting also pointed to the fact that GLOSS in Africa requires a major programme of tide gauge upgrades and, in addition, suggested that maximum use should be made of Regional Oceanographic Data Centre developments. All of these recommendations were consistent with those of the Pan-African Conference on Sustainable Integrated Coastal Management (PACSICOM) also held in 1998.

Sea level observations, analysis and interpretation of data has been one of the areas of concern to IOCINCWIO. Several sessions of IOCINCWIO have been held in the region and recommended the following:

- The establishment of a regional tide gauge network. It was however noted that technical assistance and related training in the installation and operation of gauges and data reduction was required.
- Adoption of the proposal for the implementation of the regional component of the Global Sea Level Observing System (GLOSS) and urging its member states to participate fully in GLOSS.
- Establishment of the regional sea level programme. The programme would address: repair of and maintenance of tide gauge; installation of new tide gauges;

data management; initiation of research activities; capacity building; and seeking for funds to support these activities.

- A training course on sea level data analysis be organised in the region to stimulate the preparation of sea level products for scientific and practical uses.
- Creation of Cells for Monitoring and Analysis of Sea level (CMAS) as one approach to address the above mentioned issues. CMAS was proposed in the IOC-UNEP-WMO Pilot Activity on Monitoring of Sea Level Changes and Associated Coastal Impacts in the Indian Ocean.
- CMAS works closely with the regional GLOSS activities.

The above recommendations have been implemented fairly well within the framework of IOCINWIO. There is an existing regional tide gauge network that was established through the support of IOC. Most of the stations in the region are GLOSS stations and data is available. Recently, ODINAFRICA installed a number of gauges in the region to supplement the GLOSS stations. However, there is still need to strengthen the existing tide gauge network and human capacity at the national and regional levels.

Although there is plenty of sea level data available in the WIO region, it has not been subjected to thorough analysis despite the fact that there is sufficient scientific capacity for analysis and interpretation of data. Tide predictions in particular are only generated in a few countries in the region by local scientists while other countries rely on services from outside to produce tide tables.

In a deliberate effort to encourage the use of sea level data in the region, a project was proposed for tidal analysis and prediction in the WIO region with the support of IOC of UNESCO through its Division of Ocean Data and Information Network for Africa (ODINAFRICA) and the Western Indian Ocean Marine Science Association (WIOMSA).

The main objectives of the project are:

- Collect and analyze sea level data from selected tide gauge stations in the WIO region and prepare tidal predictions for those stations for the period 1 January 2008 – 31 December 2009,
- Compare predictions and actual observations for the period January - June 2008 and submit graphs of the tidal residuals for this period.
- Avail the tidal predictions in an appropriate format on the ODINAFRICA and WIOMSA websites
- Prepare comprehensive national reports which should include: (a) the listing of high and low waters (height against local time and GMT) as well as hourly heights for January 2008 – December 2009, (b) graphs of the tidal variations, as well as tidal residuals for the period for the period January – June 2008.
- Preparation of a comprehensive report on the status of tide gauges in the region and available data.
- Inventory of scientific and technical capacity available for installation, levelling and maintenance of gauges, as well as analysis and interpretation of sea level data

- Provide an insight on the status of sea level monitoring and related activities in some selected locations in the WIO region.

Experts from Kenya, Tanzania, Mauritius, Mozambique and Seychelles were identified to prepare National Reports on Tidal Analysis and Prediction for their respective countries (Annex I). These have been edited and compiled together to form the regional report.

The project kicked-off with a regional workshop for the experts that was held in Mombasa on 1-5 April 2008 to harmonise the methods to be applied in the analysis of available sea level data and identification of suitable softwares to be used for carrying out tide predictions. The experts also drafted the guidelines to be used in preparing the national reports.

The first part of this report covers the physical description of the WIO region, current status of the sea level network, availability of data from stations, and scientific and technical capacity available. The second part is a presentation of the results of harmonic analysis of sea level time series data and tide predictions for selected stations in the region. The report also gives recommendations on how to strengthen the regional network and enhance capacity for tide gauge installation and maintenance as well as data analysis and interpretation.

CONTENTS

1.0 INTRODUCTION

The sea level is defined as the height difference between the level of the ocean's surface (especially the level halfway between mean high and low tide) and the level of a fixed point on the adjacent land. Sea levels are used as a standard in reckoning land elevation or sea depths.

Sea levels are measured by tide gauges. Sea level observations from tide gauges determine the relative position of land and sea at the coastline.

The mean sea level is the average level of the sea calculated from long series of hourly observations. It is a convenient datum from which all terrestrial elevations and submarine depths can be referred. Any instantaneous measurement of sea level in a series may be considered as the sum of three components parts:

Observed sea level = mean sea level + tides + meteorological residuals

Tides are the alternate rise and fall of the sea caused by periodic astronomic factors (relative motions of earth, moon, sun and other stellar bodies). These tide generating factors can be predicted with reasonable accuracy. The sea level data from tide gauge records also contain meteorological and oceanographic signals as well as vertical movements of the earth associated with glacial and other tectonic processes.

The oceanographic signals that can be deduced from tide gauge data include:

- Static inverted barometer effects
- Geostrophic currents
- Coastal upwelling
- Coastal trapped waves
- Seasonal variability
- Low frequency atmospheric forcing
- El- Nino effects
- Secular variability.

1.1 Historical Evolution of Sea Level

The history of the earth can be divided into three broad eras:

- ♦ Paleozoic (ancient age of animals)- 225-570 million years before present
- ♦ Mesozoic (middle age of animals) 65-225 million years before present
- ♦ Cenozoic (new age of animals) 65 million years before present to today

These periods have been marked by alternating rise and fall in the level of the sea surface. The present climatic and continental positions were however established in the Cenozoic era.

About 35000 years ago, the level of the sea surface was same as it is now. This level then reduced, reaching a minimum of about 130metres below the current levels about 15000 years ago. From that point there was a relatively rapid rise in the sea level, gradually slowing down 8000 years ago when the levels were about 15metres below the present levels. The present levels were reached more gradually some 4000 years ago. Since then the changes in the level of the sea surface have not been as dramatic.

In recent years there has been increasing concern about the projected rise in the level of the sea surface, due to global climate change. Industrialization has lead to increased emission of green house gases (carbon dioxide, methane, etc) which leading to a rise in the global temperatures. Global sea level has risen by the order of 15cm over the past 100years. Current models predict an increase in atmospheric temperatures of between 1.5-4.5°C in the next 50 years, accompanied by a consequent rise in the levels of the sea surface in the region of 35-60cm.

However many other factors (e.g. precipitation, evaporation, river run-off, changes in land elevation, deformation of ocean basins, changing wind systems, changes of ocean circulation etc) also contribute to the relative sea level change. In fact in some areas of the world the sea level is actually falling due to some of these factors.

1.2 Measurement of Sea Level

Sea level and tides can be measured by several types of instruments that are available. The choice of equipment will depend on the requirements of the user and resources. The simplest method of measuring the level of the sea surface is using a graduated pole or string immersed in the water. The stilling well float gauge is the most common type of gauge used worldwide. This type of gauge consists of stilling well and a float counterbalanced by some weight. The well filters out high frequency variability. The sea level is determined from the length of the float wire relative to a level fixed to the benchmark. Other methods of measuring sea level include acoustic tide gauges which measure the travel time of acoustic pulses reflected vertically from the air-sea interface, and pressure sensors which measure the hydrostatic pressure of the water column at a fixed point and converts this to sea level. The sea level can also be determined using satellite altimetry.

1.3 Practical Applications of Sea Level

Sea level data and information have a wide range of scientific, research and practical applications that include coastal engineering, in which sea level data are needed as instantaneous levels, as well as statistics of extreme levels over long periods. Short-term measurements, often with real-time data transmission, are needed for ship movements in harbors and ports, for issuing storm surge, tropical cyclone and tsunami warnings, and for the operation of sluices and barrages.

Over a longer period, sea level data are needed for tidal analysis and prediction, for control of siltation and erosion, for the protection of coral reefs, for inputs to models to estimate the paths of pollutants and to forecast water quality, and for the design of reclamation schemes and the construction of disposal sites. In addition, they have application to studies of upwelling (e.g. Somalia current) and fisheries throughout tropical areas.

Historically, many national datum levels for land surveys are based on measurements of mean sea level over some defined period. These levels are often used to define state and national boundaries, for example as specified in the United Nations Convention on the Law of the Sea. Low water levels are used as the datum for tidal predictions and for the datum level in hydrographic charts.

Scientific and practical applications interact in many ways. For example, knowledge of long term sea level rise will need to be input into the engineering design of coastal structures, many of which will have a lifetime of many decades or a century. Insight into the rate of sea level rise may also help in the understanding of complex coastal processes, such as sedimentation and erosion, which may result in high costs. A second example concerns sea level data assimilation into numerical models (e.g. storm surge, water quality, etc).

Sea level data is also used for studies on ocean circulation, long-term sea level changes as well as calibration and validation of satellite altimeter data.

1.4 Generation of Tides and Tidal Predictions

Tides are generated by the effect on the Earth's oceans by gravitational forces between the earth, the moon and the sun, by centrifugal force due to the Earth's rotation, and by centrifugal force due to the Earth's solar orbit. Because of the Earth's period of rotation, there are generally two high and two low tides per day at any given place, (semidiurnal tides), but they occur at times that change from day to day. The average interval between consecutive high tides is 12 hours 25 minutes. Tides occurring once daily are called diurnal. The gravitational effect of the Sun is similar and additive to that of the Moon.

The tides of largest range or amplitude are called spring tides, and occur at New Moon, when the Moon and the Sun are in the same direction relative to Earth, (in conjunction), and at Full Moon, when they are in opposite directions, (in opposition). The tides of smallest range are called neap tides, and occur at intermediate phases of the Moon, at seven and a quarter days after new or full moon, in the first and last quarters, when the moon and sun are separated at 90 degrees, (in quadrature), and the gravitational effect of the sun diminishes that of the moon.

Tides are most easily observed, and of greatest practical importance, along coastlines, where the amplitudes are exaggerated. When tidal motions run into the shallow waters of the continental shelf, their rate of advance is reduced, energy accumulates in a smaller volume, and the rise and fall is amplified. The details of tidal motions in coastal waters, particularly in channels, gulfs, and estuaries, depend on the details of coastal geometry and water-depth variation.

The methods for the prediction of the tides may be classified as harmonic and non-harmonic. By the harmonic method the elementary constituent tides, represented by harmonic constants, are combined in to a composite tide. By the non-harmonic method the predictions are made by applying to the times of the moon's transits and to the mean height of the tide systems of differences to take account of average conditions and various inequalities due to changes in the phase of the moon and in the declination and parallax of the moon and sun.

Up to and including the year 1884, all tide predictions for the tide tables were computed by means of auxiliary tables and curves constructed from the results of tide observations at the different ports. From 1885 to 1911, inclusively, the predictions were generally made by means of the Ferrel Tide-Predicting machine. From 1912 to 1965, inclusively, they were made by means of the Coast and Geodetic Survey Tide-Predicting Machine. Without the use of a tide- predicting machine the harmonic method would involve too much labor to be of practical service, but with such a machine the harmonic method has many advantages over the non-harmonic systems.

Predicting machines were superseded in 1966 by the advent of digital electronic computers, and this greatly simplified the task of producing tide predictions.

Several tidal analysis and prediction softwares are available some for free and others on commercial basis. The software package developed by University of Hawaii Sea Level Centre (UHSLC) been used in the region. Others are TASK-2000 Developed by the Permanent Service for Mean Sea Level (PSMSL) and T_TIDE developed by Prof. Pawlowitz of University of British Columbia.

2.0 THE WESTERN INDIAN OCEAN REGION

The Western Indian Ocean (WIO) region extends from latitude 12°N to 30° S and longitude 30° to 80° E (Figure 2). The mainland coastal plains lies less than 100m above sea level and is very variable in width. It is narrowest (less than 10km wide) along the Mozambique-Tanzania and Tanzania-Kenya borders and nothern Somalia. It is widest (about 20km) from central Somalia southwards to the north of Mombasa (Kenya), central Tanzania, central and southern Mozambique.

The coastal plain is negligible to almost absent on the granitic islands of the Seychelles, the volcanic-origin islands of Comores and the Mascarenes, and almost the entire eastern coast of Madagascar. Mauritius is less rugged with fairly flat areas along the northern coasts. Western Madagascar's extensive plains are especially associated with the major rivers and are probably the result of deposition of soil from the upland plateaux.

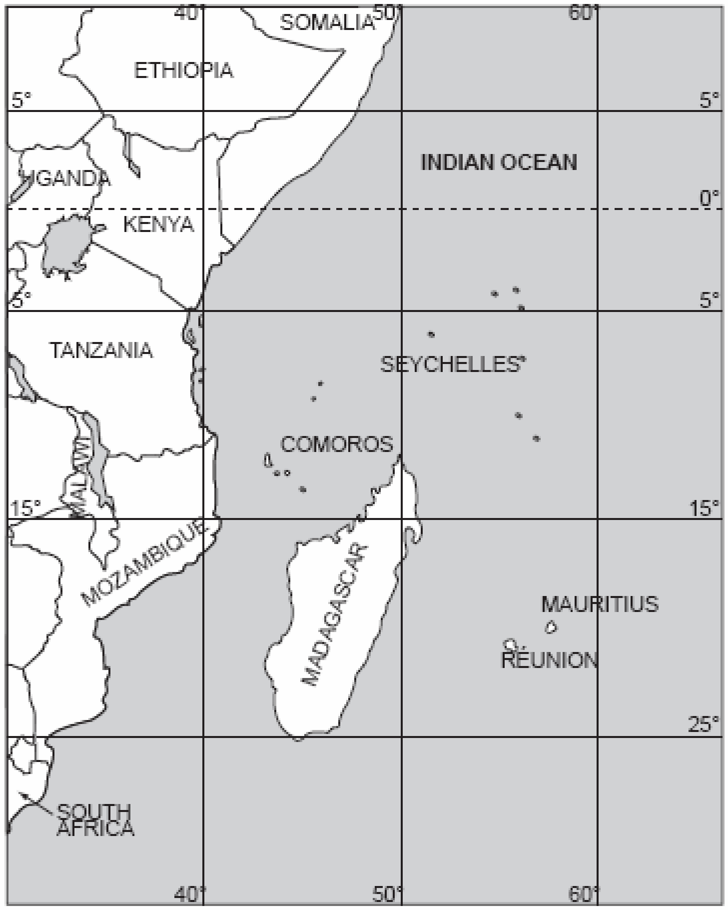

Figure 1: Countries of the Western Indian Ocean

In terms of its geological structure, the coastline of Eastern Africa represents a passive continental margin, from which through geological time continental fragments, large and small, have separated and migrated across the adjoining oceanic crust. Some of these detached continental fragments remain within the region, notably the Seychelles Bank and Madagascar. This structural history has left the mainland states with generally narrow continental shelves. Exceptions include the coasts of southern Mozambique and central Tanzania in the vicinity of Unguja and Mafia islands. In the island states wider shelves feature in western Madagascar and the Seychelles. Pleistocene coral limestone overlap older rocks along much of the mainland coastline and on some of the islands (Arthurton, 1992).

Deep waters surround Comoros and Mauritius from a few hundred meters to several kilometres offshore. There are shallow banks around Rodriguez and other Mauritius dependencies. The main islands of the Seychelles can be characterised as steep granitic outcrops with the absence of extensive; however the Amirantes Archipelago is basically a shelf areas. There is an extensive shelf-platform on the axis between the Seychelles and Mauritius.

2.2 Winds and Ocean Currents in the Western Indian Ocean

The northern part of the Western Indian Ocean region is dominated by the monsoons, which gives rise to reversal of wind and current directions during different seasons.

North East Monsoons: From *December to March*, the north easterly monsoons blow over the northern part of the region. The ITCZ and winds doldrums are located south of the equator around 5°S. The pressure gradient over the ocean are small, barely exceeding 6hPa between Arabia and Madagascar, hence winds are of moderate strength.

During the North East monsoon the flow in the northern part of the region is dominated by the monsoon winds. Above 10°N the North East monsoon current flows westward towards the coast joining the southward flowing Somali current. The Somali current meets the northward flowing East African Coastal current off the Somali coast forming a swift flowing Equatorial counter current flowing eastward off the coast.

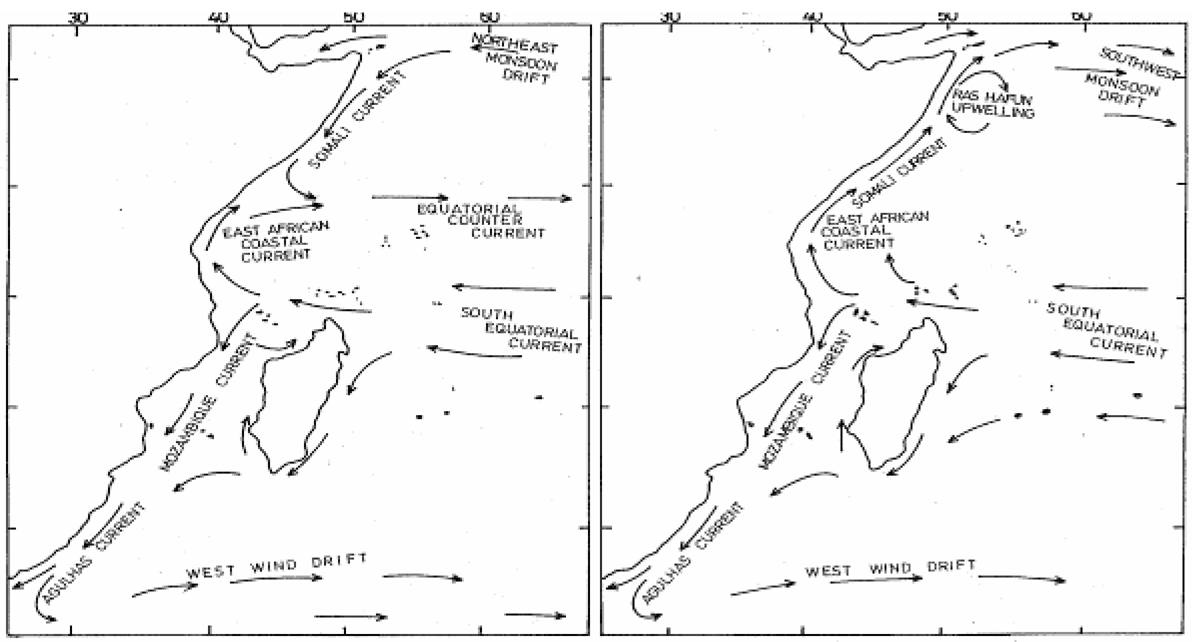

Figure 2: Current patterns in the Western Indian Ocean during the: a) North East Monsoon (right), and b) South West Monsoons (left)

South West monsoon: From *June to September* a very low pressure belt develops over northern Arabia and Pakistan. The pressure gradient between Arabia and Madagascar is now 22hPa acting in the opposite direction, leading to a completely reversal in the direction of the winds. The wind strength is much higher over the entire Western Indian Ocean north of the equator in this period. On the north west shelf the winds blow directly off-shore with moderate strength. The South West monsoon winds is a continuation of the southern hemisphere trade winds which between 10-20°S are stronger during this time of the year than anywhere else in the world.

The Somali current reverses direction and flows northward during the South West monsoon. The flow is enhanced by the East African Coastal Current making it reach speeds of upto 3.5m/s. The Ras Hafun up-welling forms off the northern tip of the Somali coast where the Somali current flows into the eastward flowing South West monsoon current.

The South Equatorial Current dominates the flow from about 8-20°S throughout the year. It strengthens as it flows westward from the Australian coastline, though the velocities rarely exceed 0.3m/s. Part of the current branches off north-east of Madagascar to form the southward Madagascar Current which flows along the eastern coast of Madagascar. The main stream splits after the northern tip of Madagascar into a southward current which flows through the Mozambique forming the perennial Mozambique Current, and a northward component which forms the East African Coastal Current already discussed above. South of Madagascar, the East Madagascar Current and the Mozambique Current join at about 26°S to form the Agulhas Current. The South Equatorial Current and the East African Coastal Current are strongest during the South-west monsoon; the East Madagascar and the Mozambique current systems are strongest during the North-east Monsoon.

The flow further south, in the region bordering the Southern Ocean is dependent on the Trade winds.
Most of the Western Indian Ocean tides are semidiurnal or mixed, mainly semidiurnal. Tidal ranges very greatly within the region (Odido and Francis, 1999). Based on the spring tidal range, the tides are characterised as follows:

- Micro-tidal (0.3-1m) found mainly in the Mauritius and the Reunion;
- Mesotidal (1-2m) found mainly in the Seychelles, the eastern coast of Madagascar and the Rodriguez
- Macrotidal (above 3m) found mainly in the mainland coast, the Comoros and the western coast of Madagascar.

3.0 STATUS OF THE WESTERN INDIAN OCEAN SEA LEVEL NETWORK

Sea level monitoring in the Western Indian Ocean coasts and islands dates back as early as 1926 in Durban, 1932 in Mombasa and 1942 in Port Louis. In subsequent years, several gauges have been installed at all the major ports in the region. These gauges however seem to have operated well for rather short spans of time.

In this report however, we shall focus on the current status of sea level monitoring in five countries in the WIO region that participated in this project namely: Kenya, Tanzania, Mozambique, Seychelles and Mauritius.

The mid 1980's saw a marked increase in the number of stations submitting data to international centres. This was through the Tropical Oceans Global Atmosphere (TOGA) experiment that was launched at around the same time with the Global Sea Level Observing System (GLOSS). Since then, there has been a consistent improvement in the quality of data generated by the various established centres, and also an increase in the number of operational gauges in the WIO region.

There are currently 28 stations in the 5 countries. 11 are operational stations while 17 are historical and/or non-operational. Most of the stations are GLOSS stations. Detailed profiles of the existing stations are presented in the table 1 below:

Table 1: Status of tide gauges in some selected countries in the WIO region.

Country	Operational Stations	Historical / Non-Operational Stations	Remarks
Kenya	-Mombasa -Lamu A & B -Shimoni -Watamu	- Kilindini (EARHC) -Kipevu pilot jetty - Mombasa (Pugh) -Lamu	-Mombasa and Lamu A managed by KMFRI -Shimoni, Lamu B, and Watamu managed by KMD.
Tanzania	-Zanzibar	-Dar es Salaam -Mtwara -Latham Island -Pemba Island	Zanzibar gauge managed by Commission for Land & Environment
Mozambique	-Maputo -Inhambane -Beira -Nacala -Pemba	- Chinde -Quelimane -Pebane -Moma -Angoche -Iiha de Macambique -Mocimboa da Praia	Stations managed by Instituto Nacional de Hidrografia e Navegacao (INAHINA)
Seychelles	-Pointe la Rue	-Port Victoria (Hodoul) -Aldabra -Port Victoria A & B -Praslin	Station managed by Seychelles Meteorological Services
Mauritius	-Port Louis -Rodrigues	-Port Louis -Rodrigues	Both stations managed by Mauritius Meteorological Services

4.0 SEA LEVEL DATA AVAILABILITY

Data from stations in the region is mostly available from mid 1980’s when the GLOSS programme was initiated. Records of sea level data collected in the region before 1960 are sparse.

Sea level data for most stations in the region are available in Joint Archive Sea Level (JASL) format. Table 1 provides information of national institutions holding sea level data from selected stations in the WIO region. Because of close collaboration, the University of Hawaii Sea Level Centre (UHSLC) holds the largest amount of data from the region. This is in form of hourly heights, daily means and monthly means.

The data can be accessed on the internet via the following link:

- http://www.soest.hawaii.edu/UHSLC

However, it should be noted that data available at the UHSLC database does not reflect the complete status of data availability in the region since the information from other stations that were not installed by UHSLC are not included on the website.

Monthly means from several stations can be accessed from the Permanent Service for Mean Sea Level (PSMSL). This centre is particularly noted for data from the older stations that operated in the region before 1970's. The data can be accessed on the Internet at:

- http://www.pol.ac.uk/psmsl/gloss.info.html

Real-time data from most stations in the WIO refion can be accessed via the World Meteorological Organization (WMO) Global Telecommunication System (GTS) on the UHSLC and ODINAFRICA websites using the liks below:

- http://ilikai.soest.hawaii.edu/RSL

- http://www.vliz.be/vmdcdata/iode

Information from the national reports indicate that the volumes of data collected in the region has improved considerably from around 1986 when UHSLC installed several gauges in the region The number of stations delivering data to UHSLC is now a large fraction of the stations operational in the region.

In recent years, the consistency and reliability of data delivery in the region has improved significantly due to upgrading of stations from analogue gauges to digital encoders with multiple sensors. This has also substantially reduced data loss/gaps.

5.0 CAPACITY AVAILABILITY

5.1 Technical Capacity

Through the efforts initiated by different institutions like IOC, PSMSL and programmes such as GLOSS and ODINAFRICA, a number of regional and international training courses and workshops on different subjects relevant to the sea level have been organised and attended by a number of individuals from the WIO region. The level of trained manpower in technical aspects relevant to the sea level activities in the region has improved over the years. The training courses have covered a number of topics such as installation and maintenance of gauges and processing and quality control of data. However, in spite of the training initiatives, currently few technicians in the region have the qualification in the field of installation and maintenance of tide gauges.

Information from the national reports indicates that there is limited capacity in the region for the servicing and maintenance of tide gauges. This capacity has been trained through different initiatives including training courses organised by GLOSS and on-job training locally. No information provided indicated any of the individuals trained has been involved in the installation of the tide gauges in the region.

The capacity building efforts in the region (particularly on technical aspects) should be integrated with the recently launched Indian Ocean Tsunami Warning System (IOTWS) fellowship programmes on Sea Level Science and Applications. Within the framework of establishing an early warning system in the Indian Ocean, IOTWS could provide:

- Tide gauges and spare parts
- Assistance in site selection, installation of gauges and in training of technicians to maintain them
- Facilitation on practical training of tide gauges installation and operation with emphasis on the existing models; levelling; servicing and maintenance checks and quality control of data.
- Training on the use and applications of new sea level-related technologies such as GPS and altimetry and relevant training materials.
- Financial assistance for attendance at international workshops and training courses

5.2 Scientific Capacity

A considerable amount of sea level data is archived in different data centres within and outside the region. In spite of the scientific capacity available, limited use of the data has been made for scientific and practical applications. Even on those few occasions, it has been experts mostly from outside the region who have been leading in making use of the data for different applications.

Factors that were limiting individuals in the region from carrying out tidal analysis and prediction in the past included lack of expertise, computers and tidal analysis software in the institutions in the region and awareness of their importance. In addition, there were very few tide gauges with long-term data. The situation is different now.

There is sufficient capacity in the region now for sea level data analysis and interpretation as compared to installation and maintenance of tide gauges. A considerable number of individuals in the region have received post graduate training in Physical Oceanography and are therefore able to perform analysis and interpretation of sea level data.

Hardware and software required to analyse data is available in institutions participating in sea level monitoring in the region. Most of the institutions have computers and relevant software for tidal analysis and prediction. National institutions have been provided with free tidal analysis and predictions software. These can also be downloaded for free on the internet:

- SLPR2 by University of Hawaii Sea Level Centre (UHSLC)
- TASK-2000 by Permanent Service for Mean Sea Level (PSMSL)
- T_TIDE by University of British Columbia

In spite of the large quantity of data covering the region from tide gauges, and a number of experts have been trained on data analysis, researchers in the region have not made optimal use of the data for their research activities. To encourage usage of available data, refresher courses are required to cover the following areas:

- Data analysis and prediction
- Analysis of satellite altimetry data
- Use of sea level data in numerical models

6.0 TIDAL CHARACTERISTICS IN THE WIO REGION

6.1 Introduction

The study on tidal characteristics and associated aspects in the Western Indian Ocean region are not only challenging but also interesting for several reasons.

(i) As compared to other major oceans, few studies on characterisation of tides and related aspects have been conducted in the region.

(ii) The WIO region lies within the area influenced by both the monsoons and the trade winds. Coastal currents like the Mozambique Current, the Agulhas Current, and the East African Current (EACC), and Somali current are taking place in the region. These phenomenon offer an opportunity to study the influence of coastal currents on the tidal dynamics of the region.

(iii) The region is important for navigation. Major shipping lanes (for cargo and cruise ships) to and from the Middle East to the Atlantic Ocean pass through it. In addition, major ports such as Mombasa, Dar es Salaam, Beira, and Maputo are gateways to several countries in the central, eastern, and southern Africa.

(iv) The region is among the major areas for tuna fisheries in the Indian Ocean and the distribution of the catches.

With that in mind, the information generated through this project will contribute to a better understanding of physical processes taking place in the western Indian Ocean and thus benefit fishery, shipping and tourism sectors in the region.

6.2 Sea Level Dataset Used in the Study

The raw hourly sea level data used for the analysis were obtained online from the University of Hawaii Sea Level Centre (UHSLC), which provides “Research Quality” and "Fast Delivery” data. The Research Quality Database archive provides hourly, as well as daily and monthly mean sea level series. The Fast Delivery database focuses on processing sea level data from a globally distributed set of stations and making it available on a near real time basis. The Fast Delivery Data can also be obtained from the ODINAFRICA website. At least one year of hourly sea level records were used in the harmonic analysis so as to obtain the maximum number of tidal constituents. The choice of the period for harmonic analysis was based on the continuity of the records, i.e. minimal or no gaps.

Techniques employed to ensure the validity of data used have been described in the Caldwell, (1998). The stations whose data has been utilised in the analyses are shown in Table 2.

Table 2: Stations used harmonic analysis and tide predictions

Station	**Latitude (S)**	**Longitude (E)**	**Data Used in the Analysis**
Mombasa	4 ^{o} 04’	39 ^{o} 39’	1999
Lamu	2^{o} 17’	40 ^{o} 54’	2002
Zanzibar	6 ^{o} 09’	39 ^{o} 11’	2003
Dar es Salaam	6 ^{o}49’	39 ^{o} 17’	1988
Inhambane	23^{o} 52’	32^{o} 22’	2007
Pemba	12 ^{o} 58’	40 ^{o} 30’	2007
Pt. Larue	4 ^{o} 40’	55 ^{o} 32’	2006
Port Louis	20 ^{o} 09’	57 ^{o} 30’	1992
Rodrigues	19 ^{o} 40’	63 ^{o} 25’	1992

6.3 Methodology

6.3.1 Analysis and Interpretation

The selected datasets were subjected to the data management procedures. This involved checking for gaps and spikes, and converting data into appropriate formats. Data formatting of the inputs and outputs was done using a combination of platforms such as Texpad, Excel and utility subprograms in SLPR2. Extraction of tidal constituents was performed by subjecting hourly data to Harmonic analysis and finally the prediction of high and lows and hourly values for the specified period (1 January 2008 to 31 December 2009). The residuals were computed from a year data outside the period used in the Harmonic analysis phase. Validation based on the output and known variation that may affect the results.

Three tidal analysis softwares were used in the study namely:

i. SLPR2 by University of Hawaii Sea Level Centre (UHSLC)
ii. TASK-2000 by Permanent Service for Mean Sea Level (PSMSL)
iii. T_TIDE by University of British Columbia

SLPR2

This software used the Fortran programming language under DOS environment and have various steps after proper data management. UHSLC 2006 processing data format was used to extract the Harmonic constituents, predict the 2007 hourly and also the High and Low sea level for validating the software performance. Plots of hourly data and quality checks was carried out before the 2008/2009 tide was predicted. The software includes the M.C.G Foreman’s tidal analysis and prediction routines. For further details please refer to Caldwell, 1998.

T-Tide

This software uses the Matlab programming language and have various steps after proper data management. UHSLC generic 2006 data format was used to extract the Harmonic constituents, predict the 2007 hourly and also the High and Low sea level for validating the software performance. Plots of hourly data and quality checks was carried out before the 2008/2009 tide was predicted. A translation of the Foreman Tide analysis mark the theory and further details of the theory can be found in Classical Tidal "Harmonic Analysis Including Error Estimates in MATLAB using T_TIDE, (Pawlowicz *et. al*., 2002).

Task-2000

This software uses the Microsoft Excel environment and Fortran language, it have various steps in importing data after proper data management. UHSLC generic 2006 data format was used to extract the Harmonic constituents, predict the 2007 hourly and also the High and Low sea level for validating the software performance. Plots of hourly data and quality checks was carried out before the 2008/2009 tide was predicted. The software package is derived from the TIRA tidal analysis programs (Murray, M.T., 1964). For further details please refer to Bell et. al., 1998.

6.3.2 Harmonic Analysis

Harmonic analysis is a mathematical method of extracting sinusoidal components of specific frequencies from e.g. a water level record. In this case, it is based on the "method of least squares". Instead of fitting a straight line to the data by varying its slope and intercept, a set of cosine (or sine) curves with given frequencies ω are fitted by varying *amplitudes* and *phases*, minimizing the sum of deviations from the original curve.

Given a time series $Z(t)$ of data points, its tidal part can be expressed as a combination of sine and cosine functions (*cf*. Shureman, 1941; Dronkers, 1964).

$$Z(t) = \sum_k a_k \sin(\omega_k t) + \sum_k b_k \cos(\omega_k t) \qquad (1)$$

The value of a_k and b_k can be calculated for the given frequencies, ω_k by minimizing the sum of squares of the differences between the assumed function and the given time series Z_n.

Least square fit requires that the following function is minimized

$$f(a_k, b_k) = \sum_{n=1}^{N} \left(z_n - \sum_k a_k \sin(\omega_k t_n) + \sum_k b_k \cos(\omega_k t_n) \right)^2 \tag{2}$$

This requirement is satisfied by

$$\frac{\partial f}{\partial a_i} = 0 \qquad i = 1,\ldots,k \tag{3}$$

and

$$\frac{\partial f}{\partial b_i} = 0 \qquad i = 1,\ldots,k \tag{4}$$

Where

$$\frac{\partial f}{\partial a_i} = -2\sum_{n=1}^{N} \cos(\omega_i t_n) \left(z_n - \sum_k a_k \sin(\omega_k t_n) - \sum_k b_k \cos(\omega_k t_n) \right) = 0 \tag{5}$$

and

$$\frac{\partial f}{\partial b_i} = -2\sum_{n=1}^{N} \sin(\omega_i t_n) \left(z_n - \sum_k a_k \sin(\omega_k t_n) - \sum_k b_k \cos(\omega_k t_n) \right) = 0 \tag{6}$$

The above equations can be rewritten as

$$\sum_k a_k \sum_{n=1}^{N} \sin(\omega_k t_n) \cos(\omega_k t_n) + \sum_k b_k \sum_{n=1}^{N} \sin(\omega_i t_n) \sin(\omega_k t_n) = \sum_{n=1}^{N} Z_n \sin(\omega_i t_n) \tag{7}$$

$$\sum_k a_k \sum_{n=1}^{N} \cos(\omega_k t_n) \cos(\omega_k t_n) + \sum_k b_k \sum_{n=1}^{N} \cos(\omega_i t_n) \sin(\omega_k t_n) = \sum_{n=1}^{N} Z_n \cos(\omega_i t_n) \tag{8}$$

This can be simplified by introducing the notation

$$C_{in} = \cos(\omega_i t_n)\,, \; S_{kn} = \sin(\omega_k t_n) \tag{9}$$

$$\sum_k a_k S_{kn} C_{kn} + \sum_k b_k S_{in} S_{kn} = \sum_n Z_n S_{in} \qquad (10)$$

$$\sum_k a_k C_{kn} C_{kn} + \sum_k b_k C_{in} S_{kn} = \sum_n Z_n S_{in} \qquad (11)$$

Which gives a system of 2*k* equations with 2*k* unknowns; a_i through a_k and b_i through b_k.

6.4 Classification of Tides

A form number, F, has been defined as the ratio of the sum of amplitudes of diurnal tidal species over semi diurnal species. According to Defant (1958), a simplified definition for F, F = (k1+O1)/(M2+S2), can be used to characterize tidal types. If F is less than 0.25, the tide is referred to as semi-diurnal, and if F is greater than 3.0, the tide is diurnal. Value of F between 0.25 and 3.0 are considered as mixed tides (see Table 3).

Table 3: The classification of the tides based on F-ratio scale

Form number **F = $(K_1+O_1)/(M_2+S_2)$**	**Type of tide**
0 < F < 0.25	Purely semi-diurnal
0.25 < F < 1.5	Mixed, mainly semi-diurnal
1.5 < F < 3.0	Mixed, mainly diurnal
F > 3.0	Purely diurnal

Based on this classification, Inhambane, Pemba, Pointe Larue and Port Louis, are classified as mixed, but mainly semi-diurnal while the rest of the stations classified as purely semi-diurnal (Table 4).

Table 4: Classification of Tides in the Western Indian Ocean Region

No.	**Station**	**Form Ratio**	**Classification**
1	Mombasa	0.20	Semi-diurnal
2	Lamu	0.23	Semi-diurnal
3	Zanzibar	0.16	Semi-diurnal
4	Dar es Salaam	0.18	Semi-diurnal
5	Inhambane	0.61	Mixed mainly semi-diurnal
6	Pemba	0.31	Mixed mainly semi-diurnal
7	Pt. La Rue	0.49	Mixed mainly semi-diurnal
8	Port Louis	0.41	Mixed mainly semi-diurnal
9	Rodrigues	0.14	Semi-diurnal

Table 5: Tidal statistics based on harmonic analysis results

Station	Spring Range (m)	Neap Range (m)	Mean Range (m)
Mombasa	3.12	1.07	2.08
Lamu	2.93	0.99	1.96
Zanzibar	3.63	1.19	1.81
Dar es Salaam	3.19	1.06	1.59
Inhambane	3.44	1.07	1.93
Pemba	2.87	0.74	2.25
Pt. La Rue	1.15	0.45	0.88
Port Louis	1.33	0.10	0.91
Rodrigues	0.51	0.32	0.33

6.5 Significant Constituents and Tidal Range

For all the 9 stations, the most significant tidal amplitudes are those of the principal lunar (M_2) and principal solar (S_2). Diurnal constituents (O_1 and K_1) also dominate the amplitudes. (see to Annex iv).

Tidal ranges at the stations in the WIO region are presented in Table 5. They could broadly be classified into three main categories as follows:

- Micro-tidal (spring tidal range of 0.3-1m) – Rodrigues
- Meso-tidal (spring tidal range of 1-2m) – Port Louis and Pointe Larue
- Macro-tidal (spring tidal range of more 3 m) – Mombasa, Zanzibar, Dar es Salaam, and Inhambane.

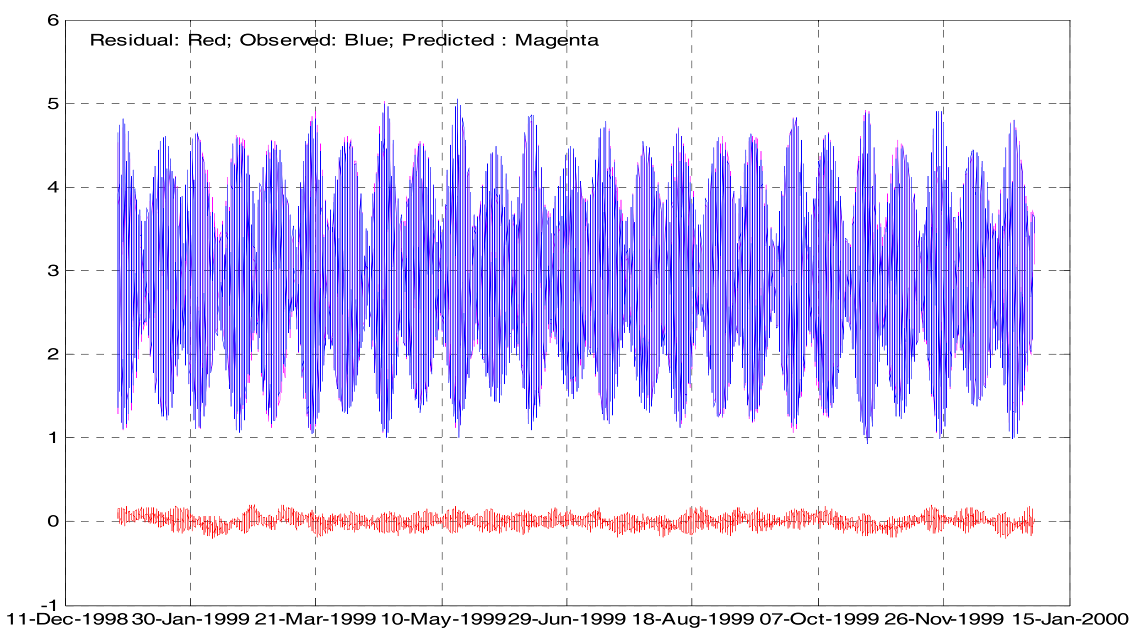

Figure 3: Graphs of observed (blue), predicted (Magenta) and residual (red) using 1999 hourly sea level data for Mombasa by T_TIDE.

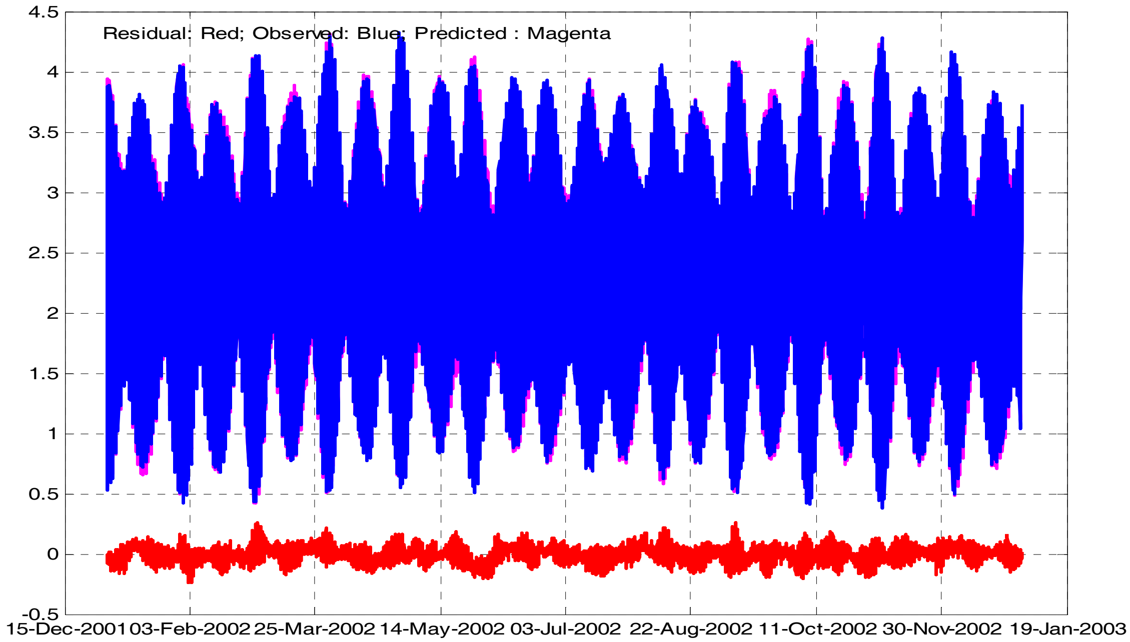

Figure 4: Graphs of observed (blue), predicted (magenta) and residual (red) using 2002 hourly sea level data for Lamu by T_TIDE.

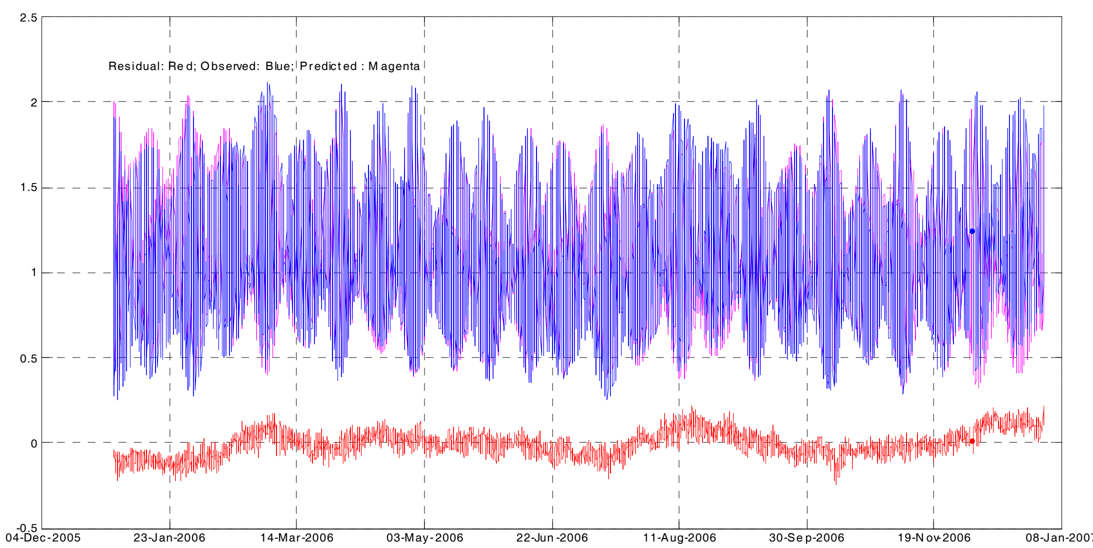

Figure 5: Graphs of observed (blue), predicted (mangeta) and residual (red) using 2003 hourly sea level data for Pointe Larue station by T_TIDE.

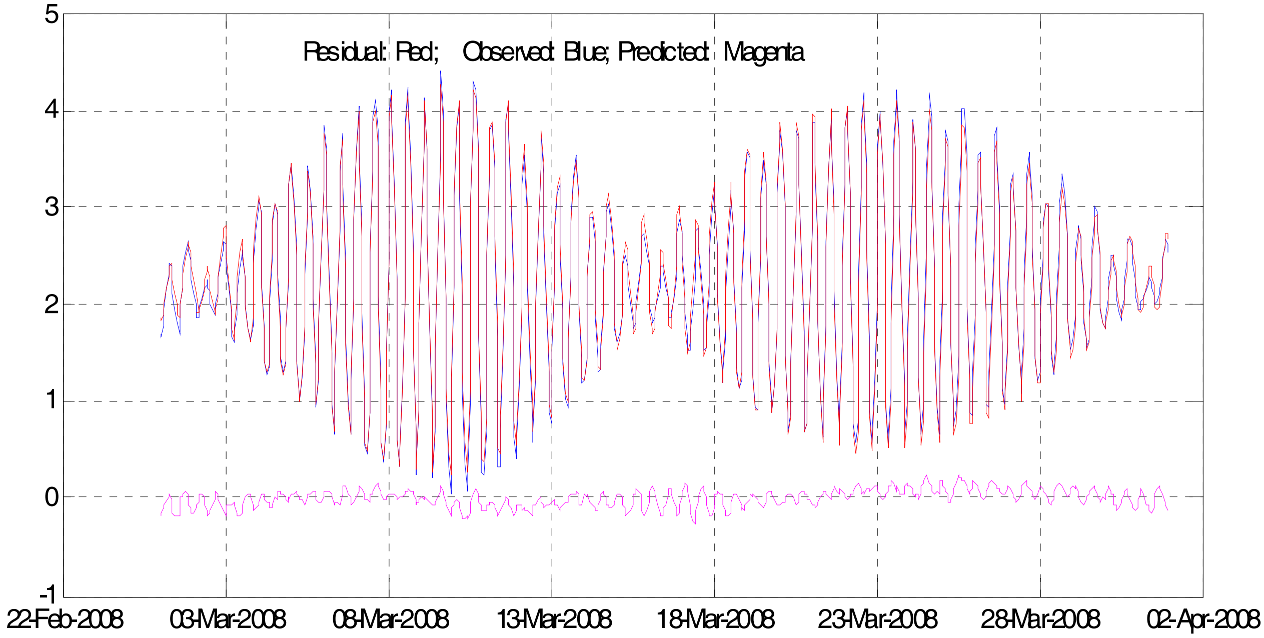

Figure 6: Graphs of observed (blue), predicted (red) and residual (mangeta) using 2008 hourly sea level data for Pemba station by T_TIDE.

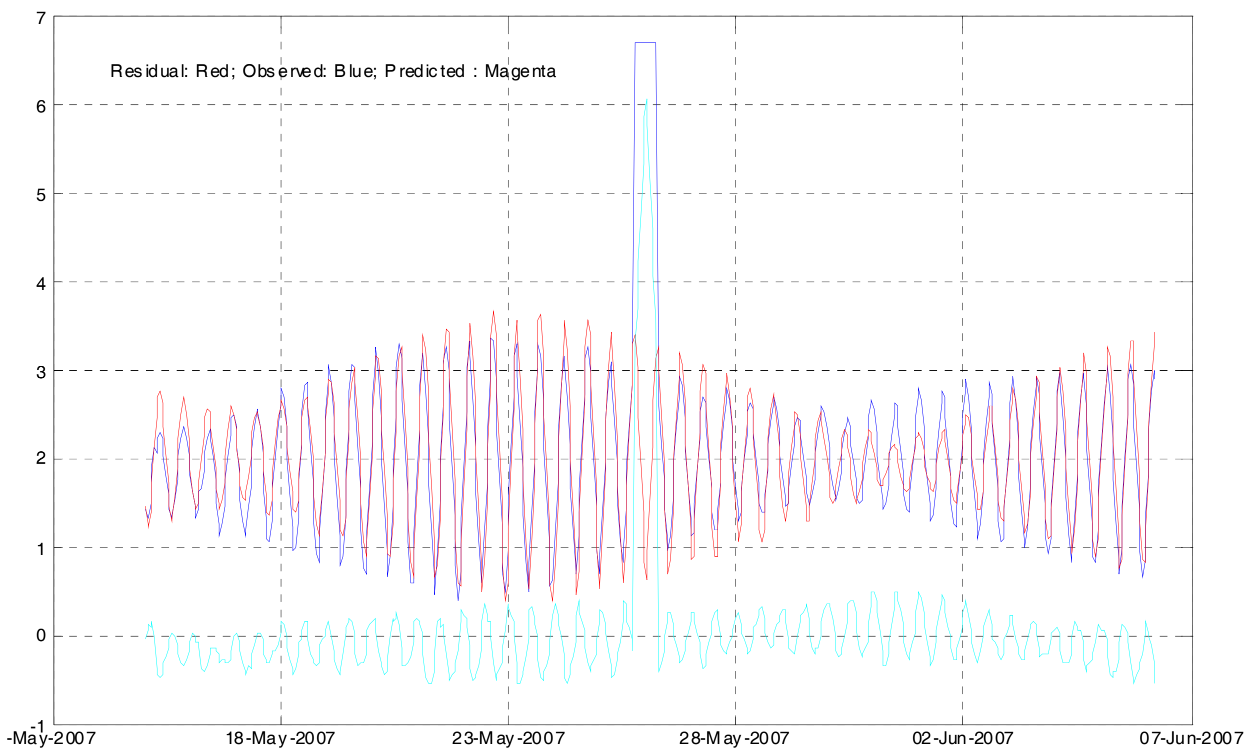

Figure 7: Graphs of observed (blue), predicted (red) and residual (green) using 2007 hourly sea level data for Inhambane station by T_TIDE.

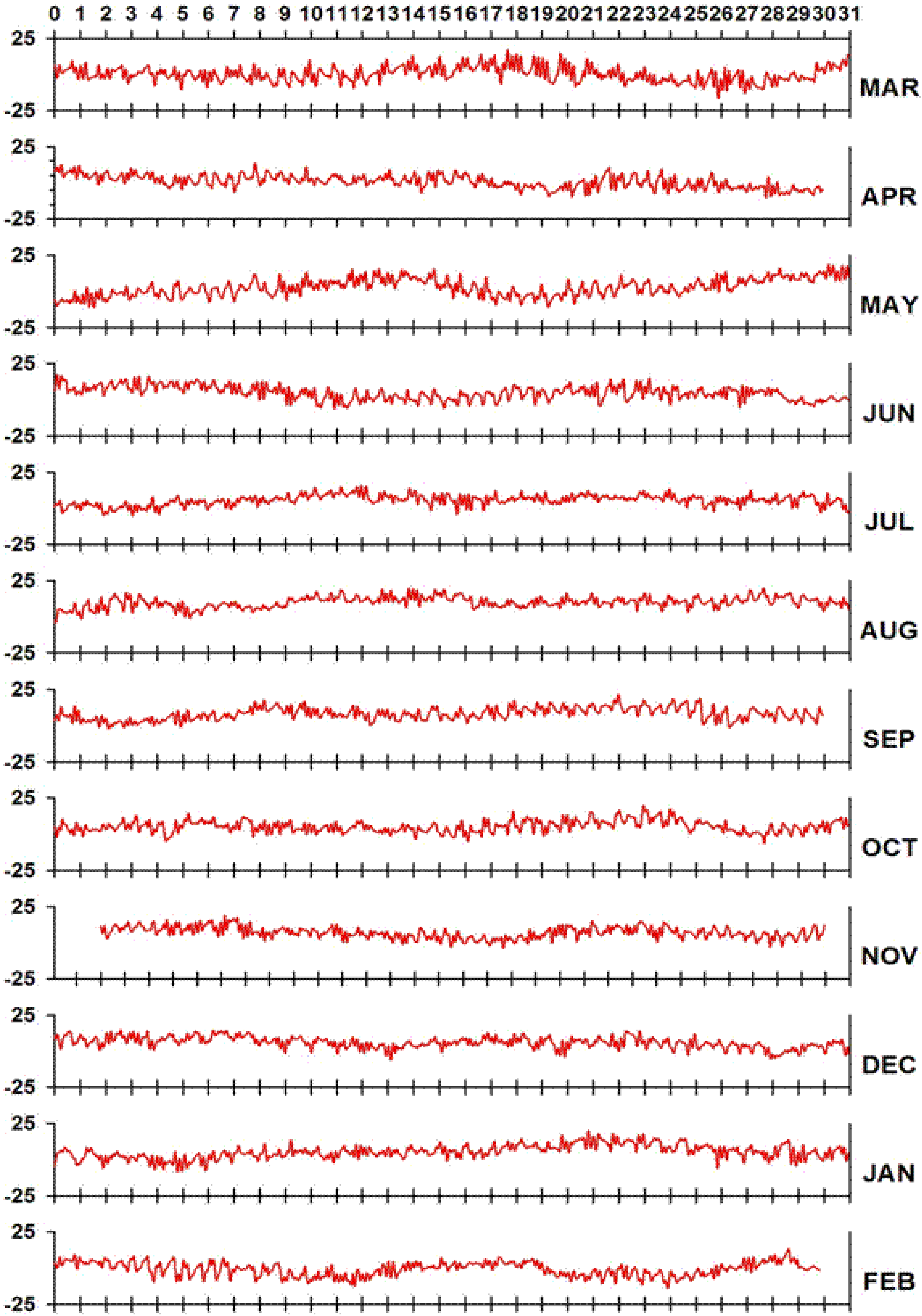

Fig. 8: Plot of Residual Sea Levels (mm) in Zanzibar for March 2007 to February 2008 by SLPR2

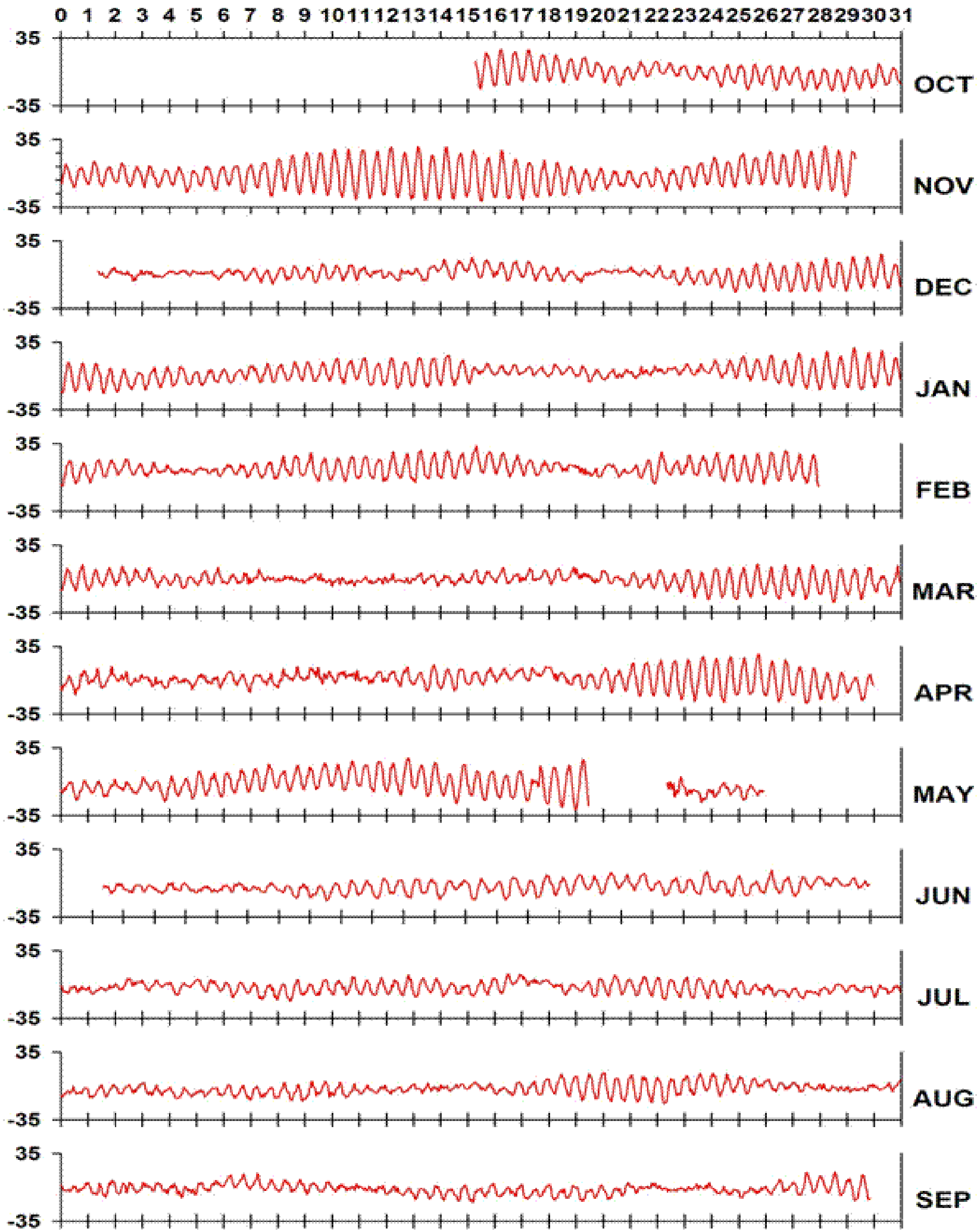

Figure 9: Plot of Residual Sea Levels in Dar es Salaam for October 1989 to September 1990 by SLPR2

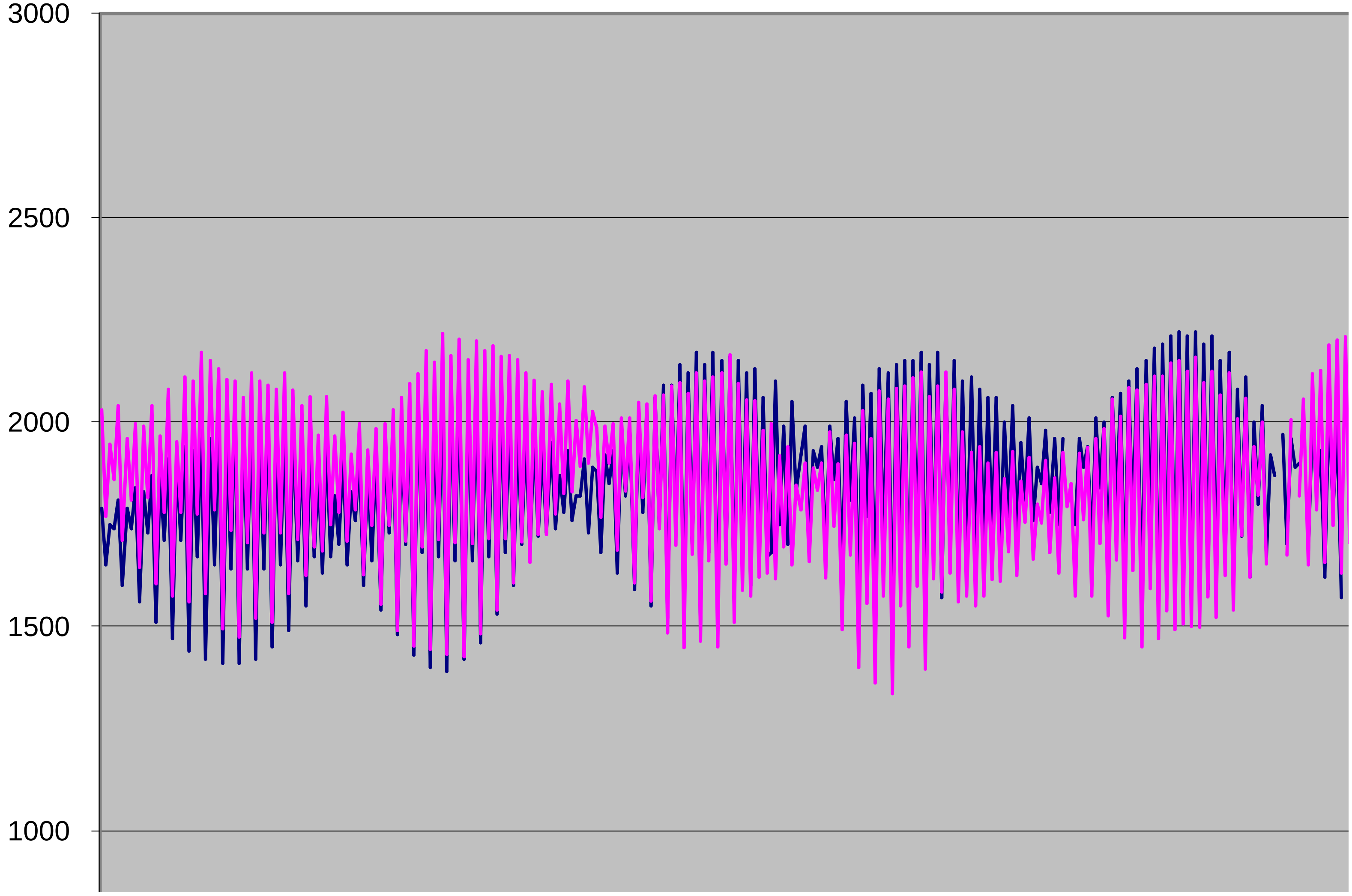

Figure 10: Graph showing Observed v/s Predicted (mm) for Port Louis tide data from 01 January to April 2008 (by SLPR2)

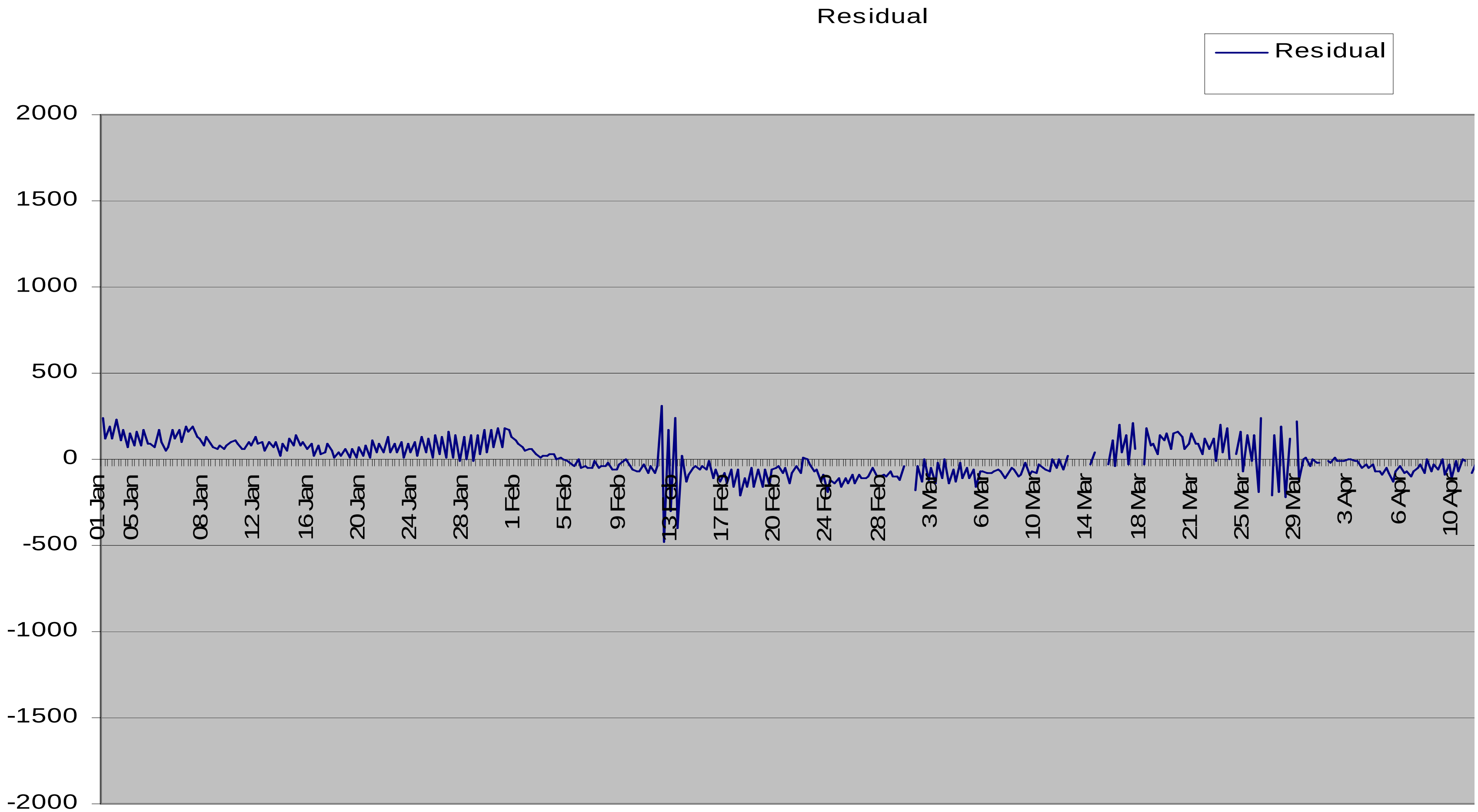

Figure 11: Graph showing residual plot (mm) for Port Louis station from January to April 2008 (by SLPR2).

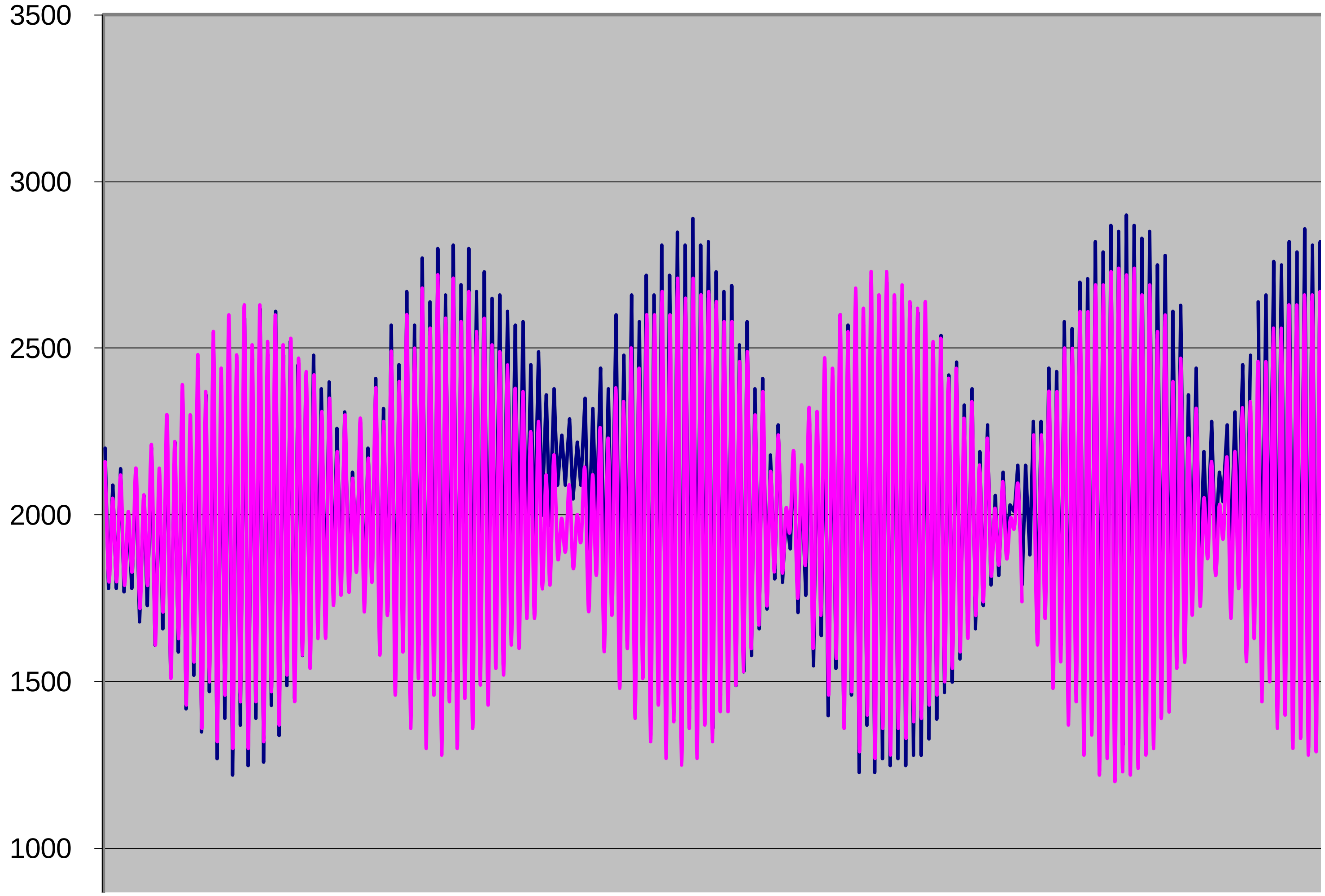

Figure 12: Graph showing Observed v/s Predicted (mm) for Rodriues tide data from 01 January to April 2008 (by SLPR2)

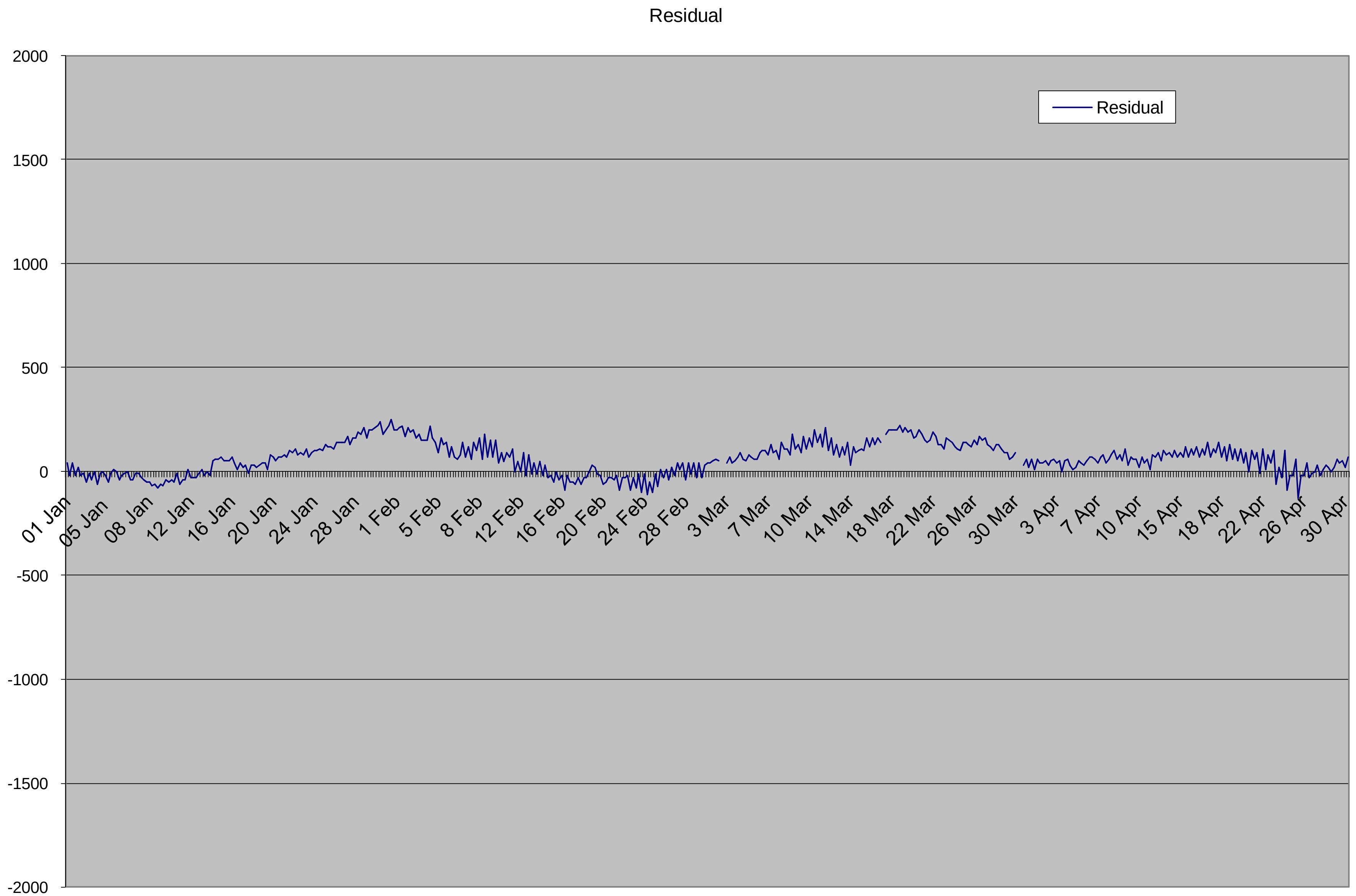

Figure 13: Graph showing residual plot (mm) for Rodrigues station from January to April 2008 (by SLPR2).

7.0 Summary

The tidal characteristics at nine stations are presented in Tables 4 and 5. Based on classification of tides according to Defant (1958), Inhambane, Pemba, Pointe Larue and Port Louis, are classified as mixed, but mainly semi-diurnal while Mombasa, Lamu, Zanzibar, Dar es Salaam and Rodriguez stations are classified as purely semi-diurnal.

The tides in the WIO region could be broadly classified into 3 categories: (i) Micro-tidal (spring tidal range of 0.3-1m – Rodriguez station), (ii) Meso-tidal (spring tidal range of 1-2m – Port Louis and Pointe Larue stations) and (iii) Macro-tidal (spring tidal range of more 3 m – Mombasa, Zanzibar, Dar es Salaam, and Inhambane stations).

This analysis of sea level data from nine stations selected in the Western Indian Ocean region has mainly focused on characterization of tides through harmonic analysis procedure and production of tide tables for major ports in the region. The predictions generated in this project are in form of High Low listings and hourly values for the period of 1st January 2008 to 31 December 2009 (2 years duration).

The tide tables for the nine stations in the Western Indian Ocean region can be accessed online via the WIOMSA and ODINAFRICA websites. The predictions for the selected stations are also contained in the respective national reports.

For most stations, the residuals are small. They could be attributed to local forcing by wind stress and air pressure fluctuations (inverse barometer effect). This indicates that water level variations are exclusively driven by astronomical tides. Is also further indicates that meteorological forcing plays a minor role in the water level variations at the stations for the selected period of data analysis.

There is need to carry out an in-depth mathematical analysis of available tide data in the region as well as analytical and numerical modelling of physical processes. This is necessary to provide further insight on tidal dynamics in the region. In that regard, information such as meteorological parameters (e.g. wind speed and direction, atmospheric pressure, rainfall, SST, etc) and bathymetry data are essential. These are parameters that may affect sea level (especially during periods of extreme oceanic events e.g. tropical cyclones, storm surges, etc) but were not taken into consideration in this analysis. It will also be interesting to examine the seasonal variability and both short-long-term sea level trends in the region.

This study indicates that the three software packages (SLPR2, T_TIDE and TASK-2000) are reliable for producing tide predictions with only about 10% variation owing to other factors such as Meteorological, hydrological etc. T-Tide and SLPR2 uses the same routine but different programming language and have similar output. The two packages generate 68 tidal constituents from harmonic analysis. The slight difference with the third package (Task2000) is mainly in the number of constituents.

For most stations, the data used for harmonic analysis does not display any gaps, possible timing shifts, data spikes or glitches in the hourly residuals. Harmonic analysis was therefore able to resolve most of the higher frequency and tidal constituents with close periods as shown in Fig. 9 and in the appendices. The non-tidal record therefore displays variations of a few days, amplitude of a few centimetres.

The predictions for Dar es Salaam station however are less precise as shown in the plot on residuals in Fig. 12. The residuals clearly show tidal oscillations that were not completely resolved by the harmonic analysis. The quality of the tide predictions is rather poor most probably because of significant gaps in the observations.

8.0 RECOMMENDATIONS

In order to make optimal use of available capacity to generate high quality sea level data for scientific use and practical application, there is an urgent need to develop and strengthen institutional linkages at national and regional levels between organisations with an interest in sea level data observations and analysis such as marine research institutions, meteorological organisations, hydrographic and surveying departments, port and harbour authorities, and universities.

Concerted efforts should be put in place to enhance the sea level network in the WIO region through provision of spare parts and training to tide gauge technicians to enable them perform minor repairs and maintenance checks.

It is important to have GPS stations at key locations in the region. Data from operational GPS stations should be availed and training on GPS/Sea level data linkages be provided to local experts.

Measurements of additional parameters at tide gauge locations are necessary, especially atmospheric pressure, air temperature, wind speed and direction, sea surface temperature (SST) and salinity. This could be carried out by equipping the existing tide gauge stations with additional sensors or automatic weather stations (AWS).

Additional resources for research should be availed particularly in the area of physical sciences. This will encourage the analysis and interpretation of data collected in the region in previous global programmes such as TOGA and WOCE thereby generate useful information for the region.

Although the number of scientists and technicians available to maintain the tide gauges and perform analysis of sea level data and tidal predictions has increased over the years, the capacity is still inadequate. The following areas need particular attention in terms of capacity building:

- Tide gauge installation and maintenance
- GPS benchmark leveling
- The use of satellite altimetry data
- The assimilation of data in numerical models for weather and ocean forecasting.

There is need to provide technicians and scientists with refresher courses, including introduction to emerging technologies and techniques for sea level studies. Regional training workshops and short-term internships to specialised sea level data centres such as UHSLC and PSMSL should be considered. Another approach is on-site training of tide gauge technicians.

Acknowledgement

This project is supported by the Western Indian Ocean Marine Science Association (WIOMSA) UNESCO/IOC through a contract assignment. This regional report for the WIO region is a compilation of information contained in the national reports prepared by Scientists from 5 participating countries namely: Kenya, Tanzania, Mozambique, Seychelles and Mauritius.

The assistance provided by Ocean Data and Information Network for Africa (ODINAFRICA) is highly appreciated. Many thanks to Mr. Sam Ng'ete of Kenya Marine & Fisheries Research Institute (KMFRI) for assisting to post the tide predictions for the region on the WIOMSA and ODINAFRICA websites.

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ANNEX II: Profile of Operational Sea level Stations

Station Name	Lat Long	Responsible Organisation	Collaborating Institution(s)	Type of Sensor/ Manufacturer	Data Span	Mode of Transmission	Data Sources	Others Sensors	Remarks
Kenya Mombasa	*04°4' S 39° 39'E*	*KMFRI*	*UHSLC*	*Fisher & Porter Float gauge on stilling well*	*1986- 2008*	*Near Real-time*	*-UHSLC -ODIN-AFRICA -PSMSL*	*-Radar -Pressure*	*-Significant gaps -digital data*
Lamu	*02°17' S* 040° 54' E	*KMFRI*	*UHSLC*	*-Float gauge on stilling well -UH Ref. level switch*	*1996-2008*	*Near Real-time*	*-UHSLC -ODIN-AFRICA -PSMSL*	*-Radar -Pressure*	*-Few gaps - digital data*
Tanzania Zanzibar	*06.49' S 39.17E*	*Zanzibar Department of Surveys & Urban Planning*	*UHSLC*	*Radar/ Vegapuls Pressure/Druck Float/ Vaisala*	*March 1984- March 2008*	*Real time*	*UHSLC ODINAFRICA*	-	*No significant gaps*
Mozambique Maputo	25° 58'S 35° 34'E	*INAHINA*		*Float type & Radar Gauge*	1940-74;1981-84;1986;1994-2000;2003-2004	Non real time	UHSLC		
Inhambane	23° 52'S 32° 22'E	*INAHINA*	*POL*	*Radar Gauge*	1948-49;1994-95;2005-06	Near Real time	ODINAFRICA	Pressure sensor	Significant gaps
Beira	19° 04'S 34° 50'E	*INAHINA*		*Radar Gauge*	1952-53;1984;1995-99	Non Real time	UHSLC, INAHINA		Significant gaps
Nacala	14° 27'S 40° 40'E	*INAHINA*		*Float Type*	1982-83;1995-99;2000-04	Non Real Time	UHSLC, INAHINA		Significant gaps
Pemba	12° 58'S 40° 29'E	*INAHINA*	*POL*	*Float and Radar Gauge*	1938;1970-71;1973;1983-84;1996-99;2005-2008	Near aReal Time	ODINAFRICA, INAHINA	Pressure sensor	Significant gaps

Seychelles *Pointe Larue*	04.67S 55.53*E*	*Met. Services*	*UHSLC*	*-Radar/* *VEGA* *-Encoder/* *Sutron SDR* *-Switches/* *UHSLC Ref. Level Switch* *-Pressure/* *GE Druck,PTX1830*	*1993- 2008*	*Real time*	*UHSLC ODIN-AFRICA*	*-Water Temp. (WTMP)* *-Battery voltage*	*Non-Significant gaps, started with a* float/well, Handar 436-A, Encoder 436-B
Mauritius Port Louis	*20° 9' S* *57° 30'E*	*Mauritius Meteorological Services (MMS)*	*UHSLC*	*SUTRON- Satlink Logger/transmitter*	*1986*	*Real time*	*MMS*	*Pressure, Radar, Sutron Encoder, 2 Tide Switches*	*Data available as from 1986, the station has been upgraded on March 2008*
Rodrigues	*19°40' S* *63°25' E*	*Mauritius Meteorological Services (MMS)*	*UHSLC*	*SUTRON- Satlink Logger/transmitter (upgraded on March 2008)*	*1986*	*Real time*	*MMS*	*Pressure, Radar, Sutron Encoder, 2 Tide Switches*	*Data available as from 1986, the station has been upgraded on March 2008*

ANNEX III: Profile of Historical/Non Operational Stations

Station Name	Lat Long	Responsible Organisation	Collaborating Institution(s)	Type of Sensor/ Manufacturer	Data Span	Data Sensors	Remarks
Kenya Lamu	*02°17'S* 040° 54' E	*KMFRI*	*KPA*	*Valeport BTH 700 gauge*	*1988-1992*	-	*data in analogue charts*
Kilindini	-	*EARHC*	*KPA*	-	*1933-1956*	-	*-scant info on gauge and data*
Kipevu	-	*KPA*	-	*Munro gauge*	*1960 - 1976*	-	*-scant info on gauge and data*
Kilindini	-	*PSMSL*	*KPA*	-	*1975-1976*	-	*- data available at PSMSL*
Tanzania Dar es Salaam	*06.49S* *39.17E*	*Institute of Marine Sciences (University of Dar es Salaam)*	*UHSLC, Tanzania Ports Authority (TPA)*	*Pressure/Leupold and Stevens, Model A-71*	*6 July 1986 to 30 September 1990*	*Pressure*	*An analogue SEBA float gauge was installed in 1997 but data has not been digitized*
Mtwara	*10.17S* *40.11E*	*Department of Surveys and Urban Planning*	*Not available*	*Munro IH 40; Munro IH 109*	*1956-1957; 1959-1962*	*Pressure*	*Only monthly and annual data is available*
Tanga	*05. 04S* *39.06E*	*Department of Surveys and Urban Planning*	*Not Available*	*Munro IH 40*	*1962-1966*	*Pressure*	*Only monthly and annual data is available*
Latham Island	*05.21S* *39.38E*	*Zanzibar Department of Surveys and*	*Not Available*	*Munro IH 109*	*None*	*Pressure*	*No data is available*

Pemba Island		*Urban Planning*					
	06.50S 39.50E	*Not Available*	*Not Available*	*Not Available*	*None*	*Pressure*	*No data is available*
Mozambique Chinde	18^{o} 54.1'S 36^{o} 18.6E				1983		
Quelimane	18^{o} 00'S 36^{o} 58.2'E	*INAHINA*	*ODINAFRICA*	*Float Type*	1951-52; 1963;1986; 1995	Pressure sensor	Significant gaps
Pebane	17^{o} 16'S 38^{o} 08'E	*INAHINA*	*UHSLC*		1963		Significant gaps
Moma	16^{o} 44'S 39^{o} 14.7'E				1972-73; 1982		
Angoche	16^{o} 13.9'S 39^{o} 54.1'E	*INAHINA*	*UHSLC*	*Float Type*	1966-67; 1969		Significant gaps
Iiha de Mocambique	15^{o} 01.7S 40^{o} 44.2'E	*INAHINA*	*ODINAFRICA*	*Float*	1938-39	Pressure sensor	Significant gaps
Mocimboa da Praia	15^{o} 01.7S 40^{o} 44.2'E	*INAHINA*			1939; 1984		
Seychelles Port Victoria (Hodoul)	*04.40 S 55.28 E*	Ministry of National Development	*IOS*	*Munroe; float /stilling well.*	1962-1979	*NA*	*Significant Gaps, Replace by the current station Victoria-A/B*
Aldabra	0930.0 S 46,46.2 E	*British Royal Society*	*IOS*	*pneumatic bubble type*	1975-1977	*NA*	Nobody knows what happen after the British moved out.
Port Victoria A&B	04.62 S 55. 46E	*BHTS Coast Guard*	*PSML, UHSLC*	*QR 16, mechanical. autographic*	1977-1992	*NA*	*Significant gaps, moved location in 1987*
Port Victoria	04.62 S 55.46 E	*BHTS Coast Guard*	*PSML, UHSLC*	*OTTR 16, mechanical*	1987-2006	*NA*	*Non Real time,*

							Digitisation ongoing, Significant gaps
Praslin	04,20.6 S 55,46.0 E	*Met. services*	*UHSLC, PSML, Bidston University*	*Leupold andStevens analogue*	1987-1989	*NA*	1989: Fischer and Porter anal to digital
Mauritius Port Louis	*20^{o} 9' S* *57^{o} 30'E*	*Mauritius Meteorological Services (MMS)*	*UHSLC*	*Steven's Floating A71 Stilling Well*	1986 - 2008	*Tide switch Floats-stilling well*	*Upgraded to Sutron on March 2008*
Rodrigues	*19°40' S* *63°25' E*	*Mauritius Meteorological Services (MMS)*	*UHSLC*	*Steven's Floating A71 Stilling Well*	1986 to date	*Tide switch Floats-stilling well*	*Both Sutron and Steven's A71 operational*

ANNEX IV: Significant Tidal Constituents for Stations in the WIO Region

Major constituents, amplitude and phase for Kenya stations

Symbol	**Constituent name**	**Mombasa**		**Lamu**	
		Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
M_2	Principal lunar semidiurnal	104.57	66.72	97.90	227.36
S_2	Principal solar semidiurnal	51.29	66.59	48.60	72.80
N_2	Larger lunar elliptic semidiurnal	1923	2750	1801	233.28
K_1	Luni-solar declinational diurnal	19.28	156.03	20.79	160.92
K_2	Luni-solar declinational semi diurnal	13.93	203.83	14.09	215.06
O_1	Lunar declinational diurnal	11.45	242.62	12.51	34.64

Major constituents, amplitude and phase for Tanzania stations

Symbol	**Constituent name**	**Zanzibar**		**Dar es Salaam**	
		Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
M_2	Principal lunar semidiurnal	120.42	25.40	106.25	25.47
S_2	Principal solar semidiurnal	60.91	64.59	53.05	65.11
N_2	Larger lunar elliptic semidiurnal	22.61	4.36	20.92	5.58
K_1	Luni-solar declinational diurnal	18.43	355.86	17.63	357.31
K_2	Luni-solar declinational semi diurnal	16.71	61.34	14.19	62.79
O_1	Lunar declinational diurnal	11.22	0 .84	10.59	1.20

Major constituents, amplitude and phase for Mozambique stations

Symbol	Constituent name	Inhambane		Pemba	
		Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
M_2	Principal lunar semidiurnal	112.79	33.55	90.19	82.16
S_2	Principal solar semidiurnal	59.31	73.40	53.29	140.37
N_2	Larger lunar elliptic semidiurnal	20.40	15.69	12.35	76.81
K_1	Luni-solar declinational diurnal	12.61	1.80	1.86	149.52
K_2	Luni-solar declinational semi diurnal	16.53	69.08	1.39	261.43
O_1	Lunar declinational diurnal	8.74	6.57	3.01	1.58

Major constituents, amplitude and phase for Mauritius stations

Symbol	Constituent name	Port Louis		Rodrigues	
		Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
M_2	Principal lunar semidiurnal	15.16	350.49	41.34	335.53
S_2	Principal solar semidiurnal	10.17	38.13	25.19	43.78
N_2	Larger lunar elliptic semidiurnal	4.29	86.51	7.59	59.48
K_1	Luni-solar declinational diurnal	6.35	286.94	5.54	315.04
K_2	Luni-solar declinational semi diurnal	2.23	184.67	6.12	181.61
O_1	Lunar declinational diurnal	4.18	263.33	3.44	296.72
SA		12.14	228.34	13.43	252.07

Major constituents, amplitude and phase for Seychelles station

Symbol	Constituent name	Point Larue	
		Amplitude (cm)	Phase (deg)
M_2	Principal lunar semidiurnal	40.11	13.98
S_2	Principal solar semidiurnal	17.75	52.55
N_2	Larger lunar elliptic semidiurnal	8.22	350.27
K_1	Luni-solar declinational diurnal	18.27	0.01
P_1	Solar diurnal	5.40	357.94
O_1	Lunar declinational diurnal	10.44	4.55

ANNEX V: Maps showing location of tide gauges some selected countries in the WIO region.
(Red dot represents operational stations and blue dot is non-operational stations)

Kenya


N
UGANDA
KENYA
RWANDA
BURUNDI
DEMOCRATIC REPUBLIC OF CONGO
ZAMBIA
MALAWI
MOZAMBIQUE
INDIAN OCEAN
Kagera
Victoria
Mara
Natron
Kilimanjaro 5892m
Mwanza
Shinyanga
Manyara
Arusha
Moshi
Kigoma
Malagarasi
Tanga
Pemba
Tabora
Singida
DODOMA
Dodoma
Zanzibar
Dar Es Salaam
Tanganyika
Kisigo
Rukwa
Morogoro
Pwani
Mafia
Rufiji
Iringa
Mbeya
Ruhaha
Kilombero
Lindi
Mtwara
Ruvuma
Malawi
0
150
300
Kilometres

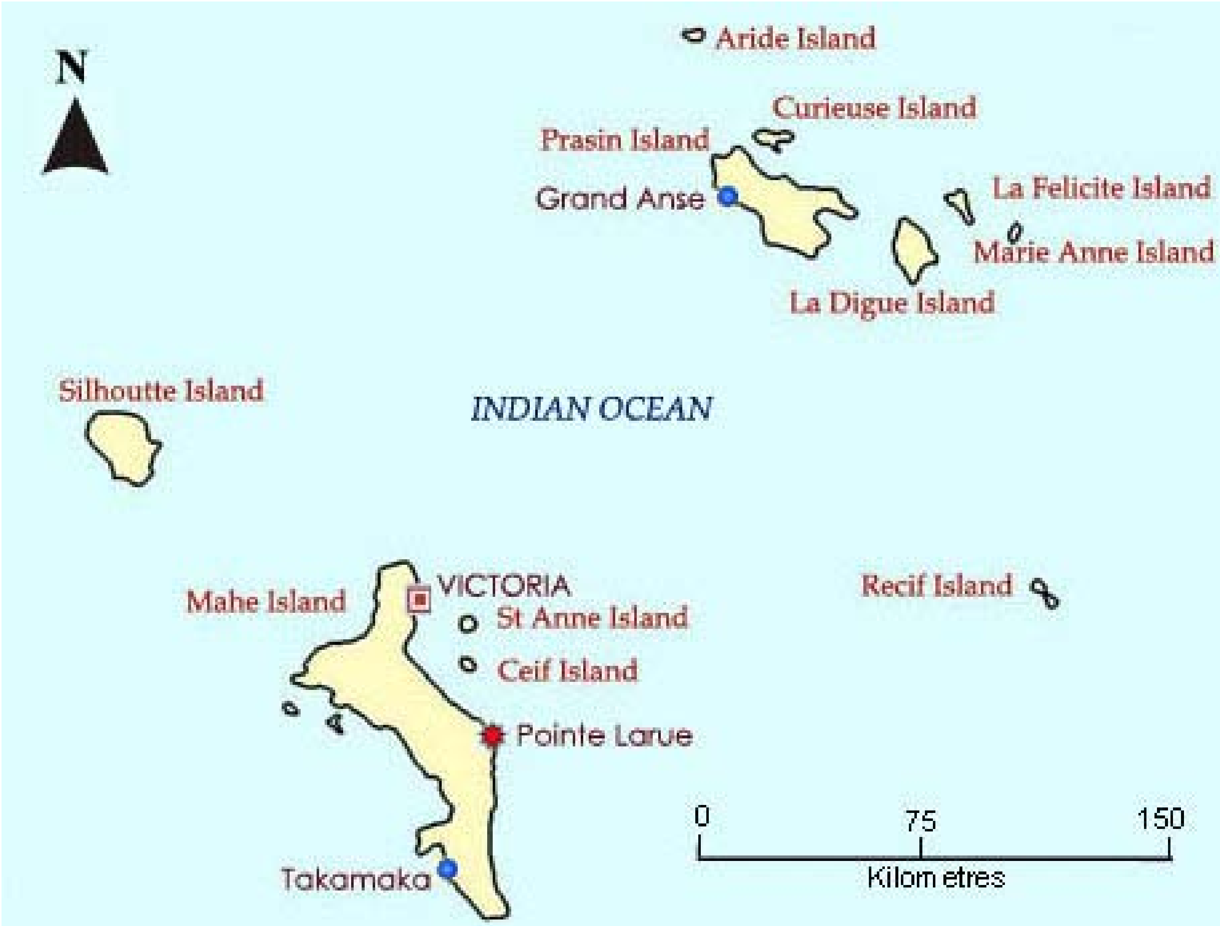
Tanzania


N
TANZANIA
Niassa
Lugenda
Cabo Degaldo
Pemba
ZAMBIA
MALAWI
Lurio
Nicala
Nampula
Tele
Zambezi
Manica
Zambezi
Quelimane
Sofala
ZIMBABWE
Binga
2436m
Beira
INDIAN OCEAN
Save
Gaze
Inhambane
Limpopo
Changane
Inhambane
SOUTH AFRICA
Maputo
MAPUTO
SWAZ-
ILAND
0
150
300
Kilometres

Mozambique


N
Agalega Island
INDIAN OCEAN
Rodrigues Island
Riviere du Rempart
Poudre' Or
Pamplemousses
PORT LOUIS
Moka
Flacq
Black River
Tamarin
Moka
Grand Port
Mahebourg
Savanne
Souillac
0
150
300
Kilom etres

Mauritius


N
Aride Island
Curieuse Island
Prasin Island
Grand Anse
La Felicite Island
Marie Anne Island
La Digue Island
Silhoutte Island
INDIAN OCEAN
Mahe Island
VICTORIA
St Anne Island
Ceif Island
Pointe Larue
Recif Island
Takamaka
0
75
150
Kilom etres
Seychelles

South Africa