INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION
(of UNESCO)

SEA LEVEL MEASUREMENT AND ANALYSIS IN THE WESTERN INDIAN OCEAN

NATIONAL REPORTS

MADAGASCAR

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Abstract

The global warming has now become an international scientific concern of huge dimension. Sea level is a fundamental element of the climate system, it is an important indicator of the climate change. Sea level observing system will support the monitoring and predicting of climate variability and change in different time-scales. This report outlines the contribution of Madagascar to Global Sea Level Observing System (GLOSS). A tide gauge network was established in the middle of the eighties. It consists actually of three tide gauges float type. The network is maintained by the „ Centre National de Recherches Océanographiques“ (CNRO) of Madagascar with the support of other national and international institutions. The „Département d'Océanographie Physique et chimique“ of the CNRO was designated as the Cell for Monitoring and Analysis of Sea level data for Madagascar. Activities are mainly focused towards tidal prediction and mean sea level variability. Observed hourly height and Mean Sea Level are sent to the International data banks: University of Hawaii Sea Level Center, Permanent Service of Mean Sea Level. Meteorological and oceanographic data are actually collected in the vicinity of the gauge in order to understand the variability of the Mean Sea Level. A seasonal variability appears clearly during 1992 in the North-West coast. A minimum of the Mean Sea Level coincides with the minimum of rainfall, maximum of salinity, maximum of air pressure during the South East trade wind in July and August. Some results are summarized in a serie of graphics. Within the IOC-UNEP-WMO-Pilot Activity on Sea Level Changes and Associated Coastal Impacts in the Indian Ocean, Sea level activities in Madagascar are focused towards coastal erosion. As many parts of the West and East coast of Madagascar are more sensitive to coastal erosion two additional tide gauges to enhance the network are proposed to be installed since a hypothesis of movement of the coast in connection with the presence of a fault S-N along Madagascar and a witness of crust expansion E-W has been expressed.

EXECUTIVE SUMMARY

In response to the recommendation of the IOCINCWIO-IV a Western Indian Ocean Sea Level Project is established within the framework of the IOC-Sida-Flanders Marine Science Programme in the region. Through this project a comprehensive report on sea level data analysis in the region will be prepared.

In preparation of this report, the coordination of this project engaged me to prepare a draft national report on sea level measurement and data analysis for Madagascar. This draft report provides a substantial information on the tide gauge network, capacity available, availability of data and preliminary results. The final result of the analysis of the data will be available through a scientific paper in the near future.

Additional activities in relation with the coastal impacts of sea level change is proposed. These activities are both of national and international importance since the results can give an idea of the continental drift.

Part I: STATUS OF SEA LEVEL OBSERVATION AND RELATED ACTIVITIES

1.- INTRODUCTION

During french domination of Madagascar, the French Hydrographic Service was conducted monitoring of sea level in different area of Madagascar. It was especially aimed to establish a tide table for some of the big harbour. Many years of monitoring was done untill the end of the sixties. Therefore, a tide table for the major harbour is published every year by the Service Hydrographique et Océanographique de la Marine (SHOM). Actually it is the only document providing informations on tide for all Madagascar.

For some reasons, monitoring was stopped for a decade. Madagascar started again to monitor the sea level by joining the GLOSS program in the middle of the eighties. A tide gauge network was established. The Centre National de Recherches Océanographiques (CNRO) of the Ministry of Scientific Research and the Foibe Taosarintanin'i Madagasikara[1] (FTM) conduct a coordinate activities on sea level measurement.

The tide gauge network consists of three gauges situated in Nosy-Be in the North-West, in Toliara in the South-West and in Taolanaro in South-East coast of Madagascar (Positions in Table 1, Annexe I). All gauges are an OTT R16 float gauge. They are provided by the FTM. Installation of the network was a collaboration of the two institutions. The CNRO maintains Nosy-Be and Taolanaro gauges. The Toliara gauge is maintained by the FTM. Two local operators are engaged for the daily maintenance of gauges in Taolanaro and Toliara.

The Département d'Océanographie Physique et Chimique (DOPC) of the CNRO was designated as the Cell for Monitoring and Analysis of Sea level. The DOPC received the software package for tide analysis from the University of Hawaii and started to collect all sea level data. Data were stored in the TOGA Sea Level Center Format for further analysis.

Most of the data from Taolanaro and Toliara are very bad on quality and many gaps occur due to some technical problems. Only data from Nosy-Be gauge are processed. Prediction from 1998 to year 2000 are actually available.

[1] Institut Géographique et Hydrographique National

The plot of the mean sea level in 1992 shows a seasonal cycle which could be in relation with the seasonal variability of the temperature, salinity or rainfall and the atmospheric pressure.

The Centre National de Recherches Océanographiques plans to install two new tide gauges within a project proposal in the middle West and middle East coast of Madagascar.

MAP 1 : LOCATION MAP OF THE TIDE GAUGES

2.- PHYSICAL ENVIRONMENT

2.1 Geographical setting

Madagascar is the fourth largest island of the world. It is located between 12°S - 26°S and 43°E - 52°E. 400 km from East african coast it is oriented NNE-SSW. It has a land area about 590000 km2 with a maximum extension of 1600 km from North to South and 570 km from East to West. The two third of the land area are crystalline. The west part of Madagascar consists mainly of sedimentary rock. The transversal profil shows a dissymetry between East and West: the west slope is lower than the east slope.

2.2 The coastal zone

The coastline is about 6597 km. The coastal zone is mainly made up of sedimentary rock. The west coast has a wide continental shelf with maximum wide arround 90 km. It is caracterised by the presence of estuaries and fringing coral reef attenuating wave energy. About 300000 ha are occupied by mangroves and the total length of coral reef is arround 1000 km. Whereas the east coast is very straight and has a narrow continental shelf with few estuaries. Coral reef is absent and waves break directly on the coastline.

2.3 Environmental parameters

Climate:

According to the position of Madagascar, it is under the influence of the South East trade wind from April to October while the atmospheric pressure is between 1020mb and 1026mb. The period from November to March is caracterised by a moderate North West wind one part of the North East moonson while the atmospheric pressure ranges from 1008mb to 1012mb. During this period, the south-eastern region of Madagascar is still influenced by the trade wind from the South East. These winds provide the most waves action on the coast. The West coast is more protected due to the presence of the reef. The frequent passage of tropical cyclone enhances the effects of waves leading to coastal erosion in some area.

Hydrological parameters:

From May to October the salinity range is 35% - 35.2% whereas it varies between 31.8% - 34.8% during the rainy period from November to April. The sea surface temperature obtained from a long period of observations is found to be lowest (26.5°c) in August and highest (29.8°c) in March. The sea surface temperature decreases perceptibly from the North to the South. The sea surface temperature of the Mozambic channel and the Indian Ocean differs 1°c in the same latitude.

Data from tide gauges show a semi-diurnal tide for West and East coast. The average tide range for the West coast is arround 3.2m while for the East coast is about 0.30m.

Only a few investigations are done concerning the coastal currents. However, the results of current measurments carried out on the North West coast show the influences of the tide and the wind on coastal current pattern.

3.- STATUS OF SEA LEVEL NETWORK

3.1 Installed and operational stations

<u>Nosy-Be Tide gauge</u>:

The tide gauge is situated at 13° 24S, 48° 18E inside a small bay where the maximum depth is arround 25m. It was installed at the end of the wharf of the Centre National de Recherches Océanographiques in 1985. The gauge is an OTT R16 float gauge with a stilling well. It is owned by the Foibe Taosarintanin'i Madagasikara (FTM) and maintained by the Département d'Océanographie Physique et Chimique (DOPC) of the CNRO.

The tide gauge was installed using the Service Hydrographique (SH)'s benchmark. It is a disk marked with **„SH“**and situated in the wall of the main entrance of the CNRO wharf. It is 7.74m above Hydrographic zero. The tide gauge zero (TGZ) is the Hydrographic zero. The tide gauge benchmark (TGBM) is 3.02m below the SH, 4.72m above Hydrographic zero. It is a flushed bracket on the quay in the front of the tide gauge entrance.

Three other benchmarks can be used for levelling. The first is 2.52 km from the entrance of the quay of the CNRO in the wall of the SOBANO[2]. The second is 2.11km from the first at the main entrance of the cemetery of the city. The third is 1.01km from the second at the retaining wall near the first bridge on the way to the airport. These benchmarks are installed and controlled by the FTM. Relationships between all of the benchmarks are available at the FTM. Benchmarks are from three known geodetic points obtained by triangulation from the base point situated in Toamasina in the East coast.

The data are continuously recorded in a paper fixed on a drum.The analog data on sea level are filtered into hourly height by hand. They are stored in the data bank of the Centre National de Recherches Océanographiques (CNRO) in TOGA Sea Level Center format for quality control, tidal prediction and for further analysis.

Analysis and prediction of the tide are performed by the DOPC. Observed and predicted hourly data are available in TSLC format. Tide tables untill year 2000 are also available.

Daily Mean sea level (MSL) is defined at noon by using the Doodson X0 filter.

The tide gauge does not have any data transmission facilities. Therefore, data are sent by mail to the other data banks: PSMSL, TOGA project and University of Hawaii Sea Level Center.

The tide gauge is operational since 1985. Hourly data are available from 1987 up to now. But there are some gaps due to technical problems. The DOPC gets support on spare parts and paper chart from the University of Hawaii.

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[2] Société de Batelage de Nosy-Be

Additional informations on surface temperature, salinity in the vicinity of the gauge are available for some period. Meteorological informations series on air pressure, wind and rainfall are avalaible for a long period at the Meteorological station of the airport of Nosy-Be, about 10 km from the tide gauge.

MAP 2 : LOCATION MAP OF NOSY-BE TIDE GAUGE

Taolagnaro Tide gauge:

The tide gauge is situated at 25°01S, 47°00E in a very closed area. It was installed in the quay of the harbour Taolanaro in 1989 with the cooperation of the CNRO and the FTM. The gauge is owned by the FTM and operated by the CNRO. It is an OTT R16 float tide gauge with a stilling well.

The tide gauge is installed with respect to a rivet set on the beacon in front of the gauge. It is 3.81m above the hydrographic zero. The tide gauge benchmark is 1.03m below the rivet. The tide gauge zero is the hydrographic zero.

Two other benchmarks can also be used for leveling: one fixed on wall of the main entrance of the harbour, the second is on the base of the beacon in the corner of the national road n°12 and the regional road to Irondro. These benchmarks are installed by the FTM and controlled at least once a year. Relationships between benchmarks are available at the FTM.

Data are continuously recorded with a chart fixed on a drum.

The tide gauge is installed in a very closed area where many traffics of boats occur. Therefore, records are influenced by short period fluctuations. The amplitude range of the tide is 0.30m to 0.60m then waves from either boats or from the open sea mask the tide record. The clock system of the gauge fails sometimes, many gaps occur or delay few hours of the records appears. The records in analog charts are available but they are very poor on timing and considered not to be accurate.

Additional informations on surface temperature, salinity in the vicinity of the gauge are not available. However, some data on waves can be obtained upon request from one project for mining in the region. Meteorological informations series on air pressure, wind and rainfall are avalaible for a long period at the Meteorological station of the airport of Taolanaro, about 3km from the tide gauge.

3.2 Installed but not operational

Toliara Tide gauge:

The tide gauge in Toliara is an OTT R16 float tide gauge with a stilling well. It is not yet committed to the GLOSS project. It was installed in 1991 in the quay of the harbour of the city in a shallow lagoon. It is maintained by the FTM. It is not operational for some period due to the cyclone event. The quay was destroyed. Only analog data on charts from 1991 till 1993 are available.

Meteorological informations on air pressure, wind and rainfall are avalaible for a long period at the Meteorological station of the airport of Toliara, about 5km from the tide gauge.

3.3 Planned stations

Two additional tide gauges are planned to be installed within a project proposal (Annexe II). The geographical positions of the planned stations are given in the Table 2, Annexe I.

Map 3: LOCATION MAP OF TAOLANARO TIDE GAUGE

Morondava Tide gauge:

Morondava is a big city situated in the middle West coast of Madagascar. It is known with the accelerated erosion of the coastline. Big part of the avenue was eroded. The erosion process seems to be enhanced by the frequent cyclone tropical. Waves and water flows during the cyclone in 1994 eroded a big part of the beach near the mouth of the harbour.

Due to the high rate of the erosion process, about 5km in 30 years (personal communication), the topography of the bottom is a subject of change in a very short time. Therefore, navigation is difficult in some area of the region.

Some structures were built in the sixties to stop the erosion but they are not very effective. Some of them are already broken.

Hypothesis on change of sediment budget due to the construction of dam, about 150km from the coast and land movement are emitted.

Focuses are now toward the erosion process. The Centre National de Recherches Océanographiques prepares one project for studying the dynamic of the beach and trying to give some advice for coastal protection and engineering (Annexe II). Within this project we plan to install a new tide gauge in the harbour of the city in a channel with mangroves on the border. But one problem for the installation is that there is not enough water during the low water. In this case a pressure tide gauge might be suitable. In case we use float tide gauge we do install a plateform in the open sea.

Manakara Tide gauge:

The whole East coast of Madagascar are more sensible to the frequent big waves from East. Some cases of coastal erosion appear in different cities. In some there are also case of sedimentation.

Manakara is one city of East coast. It is choosen for implementation of a project for studying the coastal erosion process of the East coast of Madagascar where effects of waves and flows from rivers are more dominating factors leading to erosion.

The Centre National de Recherches Océanographiques prepares actually one proposal for dealing with the coastal erosion of the East coast (Annexe II). Installation of a new tide gauge is planned within this project. It will be installed in the harbour of the city in channel with brackish water.

4.- AVAILABILITY OF DATA FROM THE STATIONS

4.1 Nosy-Be Tide gauge

Observed and predicted data are available from the Centre National de Recherches Océanographiques.

Analog data from charts are available from 1987 up to now. However, there are some gaps due to some technical problems.

Raw hourly observed data is available in TOGA Sea Level Center (TSLC) format from 1992 to 1996.

Quality controled data are available from 1992 to 1994 in TSLC format.

Hourly predicted data are available from 1996 to 2000 in TSLC format. Predicted high and low tide are also available from 1996 to 2000.

4.2 Taolagnaro Tide gauge

Only raw analog data on charts are available at the Centre National de Recherches Océanographiques up to 1989 with many gaps which are due to some technical problems.

4.3 Toliara Tide gauge

Raw analog data on charts are available at the Foibe Taosarintanin'i Madagasikara from 1991 to 1993.

5.- CAPACITY AVAILABLE

5.1 Installation and maintenance of gauges

The Centre National de Recherches Océanographiques (CNRO) and the Foibe Taosarintanin'i Madagasikara (FTM) are the institutions responsible for sea level measurement in Madagascar. Two technicians are avalaible for installation and maintenance of gauges from both institutions. Two local operators are trained localy for the daily maintenance of the gauge in Toliara and Taolanaro.

One scientist[3] from the CNRO received training on installation and maintenance of gauge in 1987 in Bidston Observatory United Kingdom and in 1990 in Service Hydrographique et Océanographique de la Marine in Brest France.

5.2 Analysis and Interpretation of data

The Centre National de Recherches Océanographiques has actually a software package for tidal data analysis from the University of Hawaii. One scientist[4] has been trained on the software in India in 1995. Quality control of the data and prediction can actually be done at the CNRO.

6.- SEA LEVEL PRODUCTS

Due to the quality of the data from the two other stations, only data from Nosy-Be gauge are processed. Therefore, quality controlled of hourly data from 1992 to 1994 for Nosy-Be gauge are actually available at the CNRO. Predicted hourly height from 1998 to 2000 are also available. A tide tables for Nosy-Be from 1998 to 2000 are also produced by the CNRO (chart. 1, 2, and 3).

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[3] Roger Lalao RANAIVOSON, MRS/CNRO, P.O. Box 68 (207) Nosy-Be Madagascar
(not involved anymore on sea level measurement)
[4] Noasy Tovonirina RAZAKAFONIAINA
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These products remain as an internal reports of the CNRO. Diffusion of the products are now envisaged.

During French domination up to1960, some sea level measurements were made for some harbours: Nosy-Be, Antsiranana in the North and Toamasina in the East of Madagascar. The mean sea level was defined for each harbour as well as the major component of the tide (Table 3, Annexe I). Therefore, a tide table is produced every year by the Service Hydrographique et Océanographique de la Marine (SHOM) in Brest for Nosy-Be, Antsiranana, Toamasina and some other harbours.

7.- BIBILIOGRAPHY OF SEA LEVEL LITERATURE

N.T. RAZAKAFONIAINA, 1998 - Le niveau de la mer à Nosy-Be, une prédiction de 1997 à l'an 2000, Rapp. tech. CNRO.

Service Hydrographique et Océanographique de la Marine, Paris - Annuaire des Marées tome 2, Ports d'Outre Mer.

7.- RECOMMENDATIONS

Madagascar still suffers from lack of manpower working on physical oceanography and related subjects. Training of one scientist working on this field would be usefull for the processing and analysis of the sea level data.

Collection of data from gauges for processing and distribution to the other data banks remain a big problem for the Centre National de Recherches Océanographiques. Therefore, in order to enhance the national network and the contribution of Madagascar to the global monitoring of sea level change, assistance on data transmission and computer facilities will be usefull and appreciated.

Within the planned activities in the future mentionned in Annexe II, regional cooperation would be usefull since the monitoring of land movement could give some information on the plate drift of the East african region.

Part II : OCEANOGRAPHIC AND METEOROLOGICAL DATA

1.- OCEANOGRAPHIC DATA

Only oceanographic data close to the tide gauge of Nosy-Be are actually available. Series of data from the fifties are available for the Sea Surface Temperature, Salinity, Density. Some gaps occur during the seventies, but the data can give an idea of the evolution of the oceanographical parameters.

Seasonal cycle occurs for the sea surface temperature and salinity. The lowest temperature and highest salinty appear during the SW monsoon in July, August and September; the winter in the southern hemisphere. While the highest temperature and lowest salinity appear during the NE monsoon; the summer in the southern hemisphere. Therefore the seasonal variation of density occur which can explain the seasonal fluctuationof the mean sea level.

2.- METEOROLOGICAL DATA

Meteorological data are managed by the Direction de la Météorologie Nationale. Cooperation for free exchange of the data is actually envisaged.

2.1- West coast of Madagascar: from Nosy-Be to Toliara

The climate of the West coast of Madagascar is dependent on the Inter-Tropical Zone of Convergence (ITZC) movement. Situated arround 20-25°N during the SW monsoon, July - August, while the atmospheric pressure arround Nosy-Be is between 1018-1020 mbars and 1024 mbars in Toliara, it generates an east to south-easterly wind for the whole West coast. During the NE monsoon when the low pressure is situated in the Mozambic channel, 1008-1010 mbars arround Nosy-Be, a West to North-West wind blows in the northern part of the channel while the East to South-East wind continue blowing in the southern part, near Toliara. These situations give some explanations of the seaonal fluctuation of the mean sea level. The wind from East generates drift of the water to the offshore: fall of the mean sea level. While westerly wind accumulates the water near the coast: rise of the mean sea level. Maximum of rainfall and river runoff (Annexe I, Table 4) are observed during the NE monsoon (Dec-March) while minimum are observed during the SW monsoon (Aug-Sept).

2.2- Taolanaro

The climate of the South-East of Madagascar is influenced by the presence of the Mascareignes High Pressure which generates North-Easterly wind and meridional High Pressure in the South of Madagascar responsible of wind from the South. Therefore, the wind blows for the whole year from the East. However, maximum speed (>20 km/h) is observed during the winter, September and October. Maximum perturbation of the climate system is observed during June and July. Cold and wet wind from the South are observed.

The data concerning rainfall during 1954-1984 shows a seasonal fluctuation. Maximum rainfall values are observed on March and minimum on September. This seasonal fluctuation can explain the seasonal cycle of the river runoff in the vicinity of the gauge (Annexe I, Table 4).

ANNEXE I

City	Nosy-Be	Taolanaro	Toliara
Latitude	13° 24' S	25° 01' S	23° 23' S
Longitude	48° 18' E	47° 00' E	43° 40' E

Table 1 : Positions of the operational stations.

City	Morondava	Manakara
Latitude	20° 18' S	22° 08' S
Longitude	44° 16' E	48° 03' E

Table 2: Positions of the proposed stations.

City	Antsiranana	Nosy-Be	Toliara	Toamasina
Latitude	12° 15' S	13° 24' S	23° 23' S	18° 08' S
Longitude	49° 19' E	48° 18' E	43° 40' E	49° 26' E
Mean Sea Level	143	231	210	67

Table 3: The Mean Sea Level expressed in **cm** above the Zero Hydrogrphic.
Source: Annuaire des marées, tome 2, Ports d'Outre Mer, Service Hydrographique et Océanographique de la Marine, Paris.

River	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	Annual
Sambirano[5]	36.5	120	275	368	336	214	104	56.1	35.8	26.2	20.8	19.4	133
Fiherenana[6]	36.0	63.5	72.2	67.4	54.1	20.3	17.9	15.7	16.0	18.3	23.3	24.8	35.4
Efaho[7]	7.24	9.25	21.3	30.9	22.7	12.8	8.73	5.81	10.2	9.86	3.65	3.25	12.0

[5] near the Nosy-Be gauge
[6] near the Toliara gauge
[7] near the Taolanaro gauge

Table 4 : Monthly and annually mean of the river runoff expressed in $\mathbf{m^3/s}$ in the vicinity of the tide gauges.
Source: Fleuves et Rivières de Madagascar, ORSTOM, CNRE, DMH, Paris 1993.

ANNEXE II

CASE OF STUDY FOR PROTECTION OF THE COASTLINE IN MORONDAVA AND MANAKARA

1.- BACKGROUND

* Some part of the avenue of the city of Morondava are eroded during the five decades.
* Two-thirds of the city of Bosy, an ancient city about 100 km North from Morondava, are totally disappeared. Therefore, most of the population migrate to another place.
* The beach along the city of Manakara are eroded and the protection of the entrance of the harbour is actually slowly damaged by waves.
* The situation seems to be enhanced by the frequent tropical cyclon.
* Many constructions such as hotel, houses, roads are endangered. Therefore, investors do not want to do more investment.
* The construction of some break current along the beach of Morondava in the sixities seems attenuating the problem but does not solve it. Some of them are broken.
* No informations are available concerning the tide, current, waves and the type of the sediment.
* The presence of faults nearby and crust expansion E-W observed in some area give some idea of land movement.

2.- OBJECTIVES

The main objectives are as follows:

* To get hourly heigth of the sea in one year period for defining a tide table for the region.
* To get information on the river runoff in the area in one year basis.
* To identify the trend of the mean sea level in one year basis.
* To identify the flow along the shoreline.
* To get information on frequency and direction of waves.

* To map the bottom sediment and monitor the dynamic of the sea bottom and the shoreline.
* To assess the sediment budget in the area.
* To simulate the dynamic of the sediment through numerical model.
* To design a structure for protecting the shoreline against erosion.
* To get information on land movement of the West and East coast.

3.- ACTIVITIES

The keys activities are structured in target-phases:

3.1.- Target phase 1

* installation of tide gauge at the harbour of Morondava for identification of the trend of the mean sea level,
* installation of a fixed GPS station for monitoring the land movement,
* installation of bouys along the shoreline for monitoring waves,
* installation of mooring current meters along the shorline for identifying the main near shore current,
* box sampling of sediment along the shoreline for mapping the type of the sediment.

3.2.- Target phase 2

* monitoring of the sea level,
* monitoring of the land drift,
* prediction of tide,
* monitoring of waves,
* monitoring of the sediment and the dynamics of the shoreline and the bottom,
* Elaborating a data base.

3.3.- Target phase 3

* identifying the trend of the mean sea level,
* identifying the frequency of waves, storms,
* numerical modelling of the dynamic of the coast.

4.- EXPECTED OUTCOME

This project should provide informations on tide, current, waves and the dynamic of the sediment as well as some informations on the land movement for the development of acceptable solution for protecting the coast from erosion. It should also give technical advise and policy for coastal engineering.

5.- PARTNERSHIP

A cooperation with the „Institut et Observatoire Géophysique d’Antananarivo“ of the University of Antananarivo and the Institut of Geosciences of the University of Kiel, Germany is envisaged.