SEASONAL VARIATION OF TIDES, CURRENTS, SALINITY AND TEMPERATURE ALONG THE COAST OF MOZAMBIQUE

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January, 2002
ACKNOWLEDGEMENTS

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The team members would like to express their gratitude to:

- Eng. Albano Gove – Director of INAHINA
- Dr. António Mubango Hoguane Chair of UNESCO Marine Science at Eduardo Mondlane University - UEM
- Dr. Rui Silva from the Fisheries Research Institute - IIP
- Mr. António Olívio Sitoe from INAHINA – CENADO

For their contribution and support for this report.

This report was made possible through the support provided by the UNESCO - IOC.
<table>
<thead>
<tr>
<th>Contents</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>2</td>
</tr>
<tr>
<td>1. General socio-economic situation of Mozambique</td>
<td>4</td>
</tr>
<tr>
<td>1.1. Geography</td>
<td>4</td>
</tr>
<tr>
<td>1.2. Economic driving forces</td>
<td>4</td>
</tr>
<tr>
<td>1.3. General</td>
<td>4</td>
</tr>
<tr>
<td>1.4. Objective of the study</td>
<td>4</td>
</tr>
<tr>
<td>1.5. Methodology of the study</td>
<td>5</td>
</tr>
<tr>
<td>2. Physical environment</td>
<td>5</td>
</tr>
<tr>
<td>2. 1. Climate</td>
<td>5</td>
</tr>
<tr>
<td>2.2. Wind conditions</td>
<td>5</td>
</tr>
<tr>
<td>2.3. Precipitation</td>
<td>9</td>
</tr>
<tr>
<td>2.4. Rivers</td>
<td>9</td>
</tr>
<tr>
<td>3. Sea Level variations in the coast of Mozambique</td>
<td>10</td>
</tr>
<tr>
<td>4. Temperature and salinity variation along the Mozambique coast</td>
<td>22</td>
</tr>
<tr>
<td>5. Current patterns along Mozambique coast</td>
<td>45</td>
</tr>
<tr>
<td>6. Overall conclusions</td>
<td>51</td>
</tr>
<tr>
<td>7. References</td>
<td>53</td>
</tr>
<tr>
<td>8. Appendix</td>
<td>59</td>
</tr>
</tbody>
</table>
1. GENERAL SOCIO-ECONOMIC SITUATION OF MOZAMBIQUE

1.1. Geography

Mozambique is situated on the eastern coast of Southern Africa, between 10° 27´ S and 26° 52´ S latitudes and 30° 12´ E and 40° 51´ E longitudes. It is bordered by the Republic of Tanzania in the north, by Malawi, Zambia and Zimbabwe in the west, by South Africa and Swaziland in the south and by the Indian Ocean, which makes up to 2700 km of coastline.

1.2. Economic driving forces

Agriculture is the most productive and important sector in the national economy accounting for about 24.6% of gross domestic product (GDP), almost 40% of exports and employing 77.6% of the labour force. Services account for over half of GDP, although the sector employs less than 10% of the working population. Industry contributes with almost the same proportion to the country’s employment as services, but its contribution to GDP is much more modest, of about 8.6% in 1997.

1.3. General

Mozambique has the third largest coastline in Africa characterised by wide diversity of habitats including sandy beaches, sand dunes, coral reefs, estuarine systems, bays, mangroves and sea grass beds.

Coastal resources such as fisheries, agriculture and forestry contribute significantly to the national income and provide social and economic benefits to about two thirds of the population living in the coastal areas.

Different research cruises have been carried out in the Mozambique coastal waters, although they are not undertaken in a regular basis. They are carried out in research and commercial vessels belonging mainly to foreign institutions or companies.

The objectives vary from oceanographic research to evaluation and assessment of fisheries along the coast. Because the research cruises were occasional and directed to specific areas depending on their objectives, the existing oceanographic information is little and does not cover satisfactory the coast.

1.4. The Objective of the Study

The main objective of the study is to describe as concisely as possible the oceanographic conditions of the Mozambique coastal waters. This could be of value for further hydrodynamic studies of coastal areas with particular emphasis on physical processes that most influence the coastal and marine resources, contributing for its sustainable management.

Due to the lack of data, it was not possible to extend this study to analyse the variation of other parameters as suggested in the terms of reference.
The possible beneficiaries of this study include, among others, port services, coastal engineering, coastal management, scientific research and students.

1.5. Methodology of the study

The approach in the methodology used for this report consisted of:

- Data collection,
- Collection of information from existing reports and other documents,
- Desk study.

The data collected will be evaluated with respect to:

- Geography
- Seasonal variation of sea level, salinity, temperature and currents.

The following steps were undertaken:

- Data collection from existing reports and studies,
- Information from existing reports and hydrographic maps with regard to tides, temperature and salinity variations, currents, winds, etc.

2. PHYSICAL ENVIRONMENT

2.1. Climate

The climate in the region north of the Zambezi River is under the influence of the equatorial low-pressure zone with the NE monsoon in the warm season.

The climate south of the Zambezi River is influenced by subtropical anti-cyclonic zone. North of Sofala along the Zambezi River lay a transitional zone, Intertropical Convergence Zone, ICZ, with high rainfall figures (Saetre and Paula e Silva, 1979).

2.2. Wind conditions

The winds in the northern part of Mozambique are influenced by the monsoon system with NE winds during the southern summer and SW winds during the southern winter. Central and Southern Mozambique are dominated by the SE trade winds.

The bathymetric conditions of Mozambique Channel are shown in figure 1.1.

The Figure 1.2 shows some meteorological stations along the coast, that could be taken as representative for the situation at sea. This figure shows appreciable agreement with wind direction at sea while the force tended to be higher in the sea (Saetre e Silva, 1982).
According to Tinley (1971) northern Mozambique is affected by the extension of the East African monsoon system with winds blowing North to Northeast during the southern summer and South to Southwest during the southern winter. Central and southern Mozambique is affected by the Southeast Trade Wind System and receives easterly prevailing winds throughout the year.

The figure 1.3 shows, on a monthly basis, 10 years average distributions of wind frequencies and forces per directions for the selected meteorological station (Saetre and Silva, 1982).

Figure 1.1. Bathymetric map of the Mozambique Channel.
Figure 1.2. Location of the main rivers and the meteorological and runoff gauge stations. The numbers are the total runoff in the indicated subareas.
Figure 1.3. Mean monthly distribution of wind direction (%) and force (m/s) at four selected coastal Mozambique stations for mean year 1968-1977 (Saetre and Silva, 1982).
2.3. Precipitation

The average annual precipitation is about 1200 mm. The rainfall is mainly restricted to the warm season November to April. According to the classification of Köppen, the northern Mozambique (Cabo Delgado, Niassa, Nampula and Zambezia Provinces) and coastal region have a tropical rain savannah climate, whereas the upland areas of the interior have a humid temperate climate. Ocean currents, particularly the Mozambique warm current, may influence the rainfall.

2.4. Rivers

The rivers shown in Figure 1.3 drain about 141 km$^3$ of water rich in nutrients into the coastal waters. About 80% of this water enters the ocean from Sofala Bank, central Mozambique. Zambezi River, the largest river in eastern Africa, alone, contributes with 67% of the total river discharge in the whole country (Seatre and Jorge da Silva, 1982).

Table 2.1. Seasonal characteristics of Mozambican rivers

<table>
<thead>
<tr>
<th>River</th>
<th>Flood season</th>
<th>Flood peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Period</td>
<td>% of total runoff</td>
</tr>
<tr>
<td>Lurio</td>
<td>Jan-April</td>
<td>67-82</td>
</tr>
<tr>
<td>Meluli</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ligonha</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moloucute</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melela</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nipioide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Licungo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incomati</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umbeluzi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maputo</td>
<td>Dec-Mar</td>
<td>60-64</td>
</tr>
<tr>
<td>Zambezi(1960-1974)</td>
<td>Jan-Apr</td>
<td>56</td>
</tr>
<tr>
<td>Pungoe</td>
<td>Dec-April</td>
<td>74-84</td>
</tr>
<tr>
<td>Buzi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Save</td>
<td>Dec-April</td>
<td>99</td>
</tr>
<tr>
<td>Limpopo</td>
<td>January-April</td>
<td>81</td>
</tr>
</tbody>
</table>
3. SEA LEVEL VARIATION IN THE COAST OF MOZAMBIQUE

Figure 3. Tidal station network in the coast of Mozambique.
Four sea level observation stations are presently operating in permanent basis in the Mozambique coast, and have provided an important contribution supplying data for operational and research applications. Apart from the actual observation network, tidal data have been obtained for different locations from the past and have been used to generate different products and inputs to different studies. Two of the tidal stations (Inhambane and Pemba) are also part of the GLOSS network.

For the purpose of this study, the main tidal characteristics along the coast of Mozambique will be summarised and the seasonal variation of tides will be presented in this report.

Tides in the coast of Mozambique, are of semi-diurnal type (two low waters and two high waters a day) with a daily inequality of about 10-20 centimeters in Maputo, Inhambane, Chinde, Quelimane and Ancoche, to about 30-40 centimetres in Beira, Pembe, Ilha de Moçambique, Nacala, Pemba and Mocimboa da Praia.

3.1. Tidal Amplitudes

The tidal range varies quite considerably between extreme neap tides and extreme spring tides. Tidal amplitudes vary over the year and along the coast.

a) Maputo Port region.

The tidal range varies from less than 30 centimetres and about 380 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 80 centimetres during neap tides and about 300 centimetres during spring tides (see figure below).

![Seasonal variation of tides at Maputo harbour (1974 data)](image)

**Figure 3.1 a)** The variation of tides at Maputo harbour. *Time (day x 2), because of the semidiurnal type of the tides (two high waters and two low waters per day), each scale number should be divided by two to obtain the exact number of days.*
b) **Inhambane Port region.**

The tidal range varies between less than 45 centimetres and about 350 centimetres (reference to chart datum) during extreme spring tides.

Tidal amplitudes vary over the year between 90 centimetres during neap tides and about 280 centimetres during spring tides (see figure below).

![Seasonal variation of tides at Inhambane harbour (1995 data)](image_url)

**Figure 3.1 b)** The variation of tides at Inhambane harbour from the little data available.

c) **Beira Port region**

The tidal range in Beira is large. It varies between less than 60 centimetres and about 730 centimetres (reference to chart datum) during extreme spring tides.

Tidal amplitudes vary over the year between 150 centimetres during neap tides and about 640 centimetres during spring tides (see figure below).

The large tidal range is a dominant factor in the area responsible for the high tidal currents and the huge sediment transports. The tide penetrates deeply into the Beira estuary.
Figure 3.1 c) The variation of tides at Beira harbour. Relatively high tidal amplitudes can be noted.

d) Chinde Port region

The tidal range varies between less than 10 centimetres and about 430 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 100 centimetres during neap tides and about 370 centimetres during spring tides.

e) Quelimane Port region

The tidal range varies between less than 35 centimetres and about 500 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 100 centimetres during neap tides and about 380 centimetres during spring tides (see figure below).
Figure 3.1 d) The variation of tides at Quelimane harbour. Change of reference level can be noted from April

f) Pebane Port region

The tidal range varies between less than 40 centimetres and about 450 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 110 centimetres during neap tides and about 370 centimetres during spring tides.

g) Angoche Port region

The tidal range varies between less than 30 centimetres and about 450 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 110 centimetres during neap tides and about 380 centimetres during spring tides.

h) Ilha de Moçambique Port region

The tidal range varies between less than 25 centimetres and about 430 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 110 centimetres during neap tides and about 350 centimetres during spring tides.

i) Nacala Port region

The tidal range varies between less than 40 centimetres and about 420 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 100 centimetres during neap tides and about 330 centimetres during spring tides (see figure below).
Figure 3.1 i) The variation of tides at Nacala harbour.

j) Pemba Port region

The tidal range varies between less than 25 centimetres and about 440 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 110 centimetres during neap tides and about 350 centimetres during spring tides (see figure below).

Figure 3.1 l) The variation of tides at Pemba harbour for two different years.
k) Mocimboa da Praia Port region

The tidal range varies between less than 50 centimetres and about 480 centimetres (reference to chart datum) during extreme spring tides. Tidal amplitudes vary over the year between 130 centimetres during neap tides and about 370 centimetres during spring tides.

3.2. Mean Sea levels

The determination of the mean sea level is of high interest, particularly for geodesy. Mean sea level is obtained by means of filtering the oscillations due to astronomical tide. It means that the mean sea level is also influenced by meteorological (or oceanographic) conditions.

For the estuaries in particular, the mean sea level varies with the river flows. For example, during floods the mean sea level at Chinde in the Zambezi River mouth increases by some 50 centimetres.

Long period mean sea-level variation can be caused by isostatic movements of the land, ice melting, sea water density variation, pressure and wind regime variation, etc.

In order to obtain a mean sea-level value that can be used with satisfactory severity as geodetic vertical reference, long time series of mean sea-level values are required to resolve (by averaging) the oscillations observed during a large number of years.

Fixed benchmarks were implemented in the main port locations along the coast of Mozambique. The objective was to help monitoring the relative changes of the mean sea level as function of balance between the sea level rise due to the global warming of the planet, and the vertical displacements of the coast due to geological movements.

Daily mean sea-level values are filtered from the hourly-observed data. Monthly and yearly mean values are calculated and used to monitor the mean sea level along the coast.

Consistent results as to the investigation of sea level trends in the coast of Mozambique do not show up with clear evidence as yet, relying in the need for longer and uninterrupted time series, and subject to the application of improved quality control techniques.

Pre-processing techniques were developed and have been used at the Institute of Hydrography and Navigation of Mozambique, envisaging exceeding observed diversions in heights (use of cubic and lagragian polynomials), and diversions in phase (use of the Spline function). The effectiveness of these techniques can be read from the inherent residuals.

Processed mean sea level values were used to plot and analyse its variation against different factors as follows:
a) Maputo Tidal Station (Lat. = 25° 58.5′ S, Lon. = 32° 34.2′E)

Figure 3.2.1 Characteristic mean sea level at Maputo all over the year obtained from about 21 years of data.

Figure 3.2.2 Annual mean sea level plots for Maputo harbour observed data from 1958 to 1999. Adopted mean sea level at Maputo area is 200 cm above Chart Datum.

Mean sea level in Maputo may be influenced by the total rainfall/runoff pattern of the catchments areas of the Incomati, Maputo and Matola river basins, as the tidal station lies in the delta of these rivers. It is otherwise, quite clear from the Figure 3.2.1 the influence of the rain regime of these
rivers. The monthly mean sea-level variation curve indicates a minimum during May to October and a maximum during November to April, which corresponds exactly to the dry and wet seasons of the above-mentioned rivers, respectively.

b) Beira Tidal Station (Lat. = 19º 49.4'S, Lon. = 34º 50.0'E)

**Figure 3.2.3** Characteristic mean sea level at Beira all over the year obtained from about 4 years of data

**Figure 3.2.4** Annual mean sea level plots for Beira harbour. Data observed from 1996 to 1999. Adopted mean sea level at Beira is 356 m above Chart Datum.
Mean sea level in this case may be influenced by the total rainfall/runoff pattern of the catchments areas of the Púngoe and Buzi river basins, as Beira tidal observation station lies in the delta of these rivers.

It become also clears from the Figure 3.2.3 the influence of the rain regime of these rivers.

The monthly mean sea-level variation curve indicates a minimal period from May to middle November and a maximum period from November to April, which corresponds exactly to the dry and wet seasons of the above-mentioned rivers respectively.

**h) Nacala Tidal Station (Lat. 14º 27.8’S, Lon. 40º 40.8’E)**

![Seasonal variation of Mean Sea-level (MSL) at Nacala](image)

**Figure 3.2.5** Characteristic mean sea level at Nacala all over the year obtained from about 3 years of data
Figure 3.2.6 Annual mean sea level plots for Nacala harbour. Data observed from 1996 to 1998.

Adopted mean sea level at Nacala is 225 cm above Chart Datum.

i) **Pemba Tidal Station** (Lat. 12° 58.0'S, Lon. 40° 29.3'E)

Figure 3.2.7 Characteristic mean sea level at Pemba all over the year obtained from about 5 years of data
**Figure 3.2.8** Annual mean sea level plots for Pemba harbour. Data observed from 1983 to 1998.

Adopted mean sea level at Pemba is 225 cm above Chart Datum.
4. Temperature and salinity variation along Mozambique coast

During the oceanographic research cruises carried out in the Mozambique coastal waters biological, chemical and physical parameters of water have been recorded. For the temperature and salinity profiling some of the instruments used were thermometers, CTD (conductivity-temperature – depth profilers), current meters.

The station network for each survey is not constant although there may be some “traditional” sections. Here, we will only focus on the results recorded in the areas along the coast without specifying for all the cruises the location of the undertaken stations.

For the purpose of this section only temperature and salinity will be presented. The information and data used is compiled from different sources that are referenced.

The approach will be to present, along this section, the characteristics of temperature and salinity profiles of different research cruises along:

1. The whole Mozambique coastal waters (10°27’S to 26°52’S), up to 1000 meters
2. The Sofala Bank (16°S to 21°S), up to about 200 meters

4.1. Temperature and salinity in Mozambique coast (10°27’S to 26°52’S)

The classification and the source of the water masses along the Mozambique coast are described in R. Saetre and Jorge Silva (1982). In the Mozambique coast up to 1000 meters depth the following water masses can be found:

**Surface water**
The waters in the upper 100-150 meters depth consisting of two distinct water masses, the northernmost warm low-salinity surface waters brought by the South Equatorial Current and the southernmost water mass that is originated from the water formed in the centre of the sub-tropical anti-cyclonic gyre of the Indian Ocean.

**Sub-surface water**
The water is characterised by salinity maximum between 150 and 300 meters depth.

**Central Water**
The water lying in the layer between 300 and 600 meters depth.

**Intermediate waters**
They are two different waters masses, the low salinity water from Antarctic origin and the high salinity water from the northern Indian Ocean.

During the period 1977 to 1980 several research cruises were carried out in Mozambican coastal waters and oceanographic data were collected.
Figure 4.1 shows the map of the performed stations from 1977 to 1980. The coast was divided into sub-areas A, B, C, D and E.

Figure 4.1. Hydrographic stations and sub-areas for the cruises carried out from 1977-1980

The names of the research vessels and the number of stations, per area, season and year, are presented in ANNEX A.1
The parameters that characterised the surface waters (surface temperature, surface salinity, surface oxygen and depth of homogeneous layer are presented in Table 4.2 These parameters are grouped in periods of three months.

Table 4.1. Parameters that characterised the surface waters in periods of three months for the cruises held from 1977 to 1980.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Period</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Surface Temperature (°C)</td>
<td>Jan-Feb-Mar</td>
<td>28-31</td>
</tr>
<tr>
<td></td>
<td>Jul-Aug-Sep</td>
<td>26-27</td>
</tr>
<tr>
<td>Surface Salinity (‰/oo)</td>
<td>Jan-Feb-Mar</td>
<td>34.3-35.2</td>
</tr>
<tr>
<td></td>
<td>Apr-May-Jun</td>
<td>34.7-35.1</td>
</tr>
<tr>
<td></td>
<td>Jul-Aug-Sep</td>
<td>35.0-35.3</td>
</tr>
<tr>
<td></td>
<td>Oct-Nov-Dec</td>
<td>34.8-35.2</td>
</tr>
<tr>
<td>Surface oxygen (O₂ ml/l)</td>
<td>Jan-Feb-Mar</td>
<td>4.4-4.8</td>
</tr>
<tr>
<td></td>
<td>Apr-May-Jun</td>
<td>4.5-5.2</td>
</tr>
<tr>
<td></td>
<td>Jul-Aug-Sep</td>
<td>4.5-5.1</td>
</tr>
<tr>
<td></td>
<td>Oct-Nov-Dec</td>
<td>4.4-4.8</td>
</tr>
<tr>
<td>Depth of homogeneous layer (m)</td>
<td>Jan-Feb-Mar</td>
<td>20-80</td>
</tr>
<tr>
<td></td>
<td>Apr-May-Jun</td>
<td>20-120</td>
</tr>
<tr>
<td></td>
<td>Jul-Aug-Sep</td>
<td>60-120</td>
</tr>
<tr>
<td></td>
<td>Oct-Nov-Dec</td>
<td>30-100</td>
</tr>
</tbody>
</table>

According to the available information from the cruises held between 1977 and 1980, the maximum surface temperatures were observed between February and April and the minimum between August and September.

The annual range of temperatures was 2-5 degrees Celsius, in any of the considered sub-areas.

For each quarter of the year the temperatures were higher in the area A, northern Mozambique that in the area E, southern Mozambique.

In any of the sub-areas A and B the maximum salinity values were recorded during the period September-October, when the divergence of the South Equatorial current was in its northernmost position.

The minimum values were recorded in the period March-April when the influence of the water of Equatorial origin has its maximum influence.

In the sub-area C, the salinity variations follow the seasonality of the average trend of the river runoff, ANNEX A.2. This sub-area is the most influenced by Zambezi River.
The highest salinity values were recorded in the sub-area D during the period July-August and the minimum were recorded in March, when the influence of the modified Equatorial Surface waters was greatest. This area showed values of salinity below 35 ppm, which may have been caused by the southward transport of water from the Sofala Bank area.

Less variation, throughout the year, was observed in sub-area E, apart from the period January-March.

At the sub-surface level (according Wyrtki (1971); Lutjeharms (1972) quoted by Saetre and Jorge da Silva (1982) two core layers of salinity maximum and oxygen minimum can be identified at the same depth range.

For the observations during 1977-1980 cruises, there was an increase of salinity oxygen in the core layer from North to South of the oxygen and salinity values. There were no relevant seasonal variations of salinity maximum layer.

In the first quarter, there was a variation of the maximum salinity in the northernmost area while in the southernmost area (sub-areas, E and D) the influence of the Sub-tropical water was strong, so exerting its influence to the surface waters.

In the central water layer, comparing the T-S (temperature-salinity) and the T-O2 (temperature-oxygen) diagrams it was concluded that the core of the intermediate oxygen maximum was within the central water with the centre at the temperature of 11º C and salinity of 35 ppm.

In the intermediate water layer the results from the cruises showed a oxygen maximum at the layer between 400 and 500 meters depth.

The Oxygen decreases towards the north from values higher that 5.0 m/l to lower than 4.5 m/l. Only the sub-area E showed a seasonal variation.
The next figure shows the typical profile of the horizontal distribution of the surface temperature waters along Mozambique coast recorded during the cruise on-board of R/V Nikolay Reshetnyak.

Figure 4.2. Typical horizontal distribution of surface temperature during May- June of 1979.
The next figure shows the typical profile of the horizontal distribution of the surface salinity waters along Mozambique coast, recorded during the cruise on-board of R/V Nikolay Reshetnyak.

Figure 4.3: Typical horizontal distribution of surface salinity along the coast, May-June of 1979.
The next figure shows the horizontal distribution of the temperature at 150 meters depth along Mozambique coast recorded during the cruise on-board of R/V Nikolay Reshetnyak.

Figure 4.4. Horizontal distribution of temperature at 150 meters, May-June, 1979.
Figure 4.5. Shows the horizontal distribution of salinity at 100 meters in the south and central Mozambique on board of Kometa Galeya during 4 April to 6 May 1989.

Figure 4.5. Horizontal distribution of temperature at 100 meters in southern and central Mozambique, April - May 1989.
The Figure 4.6 shows the horizontal distribution of salinity at 150 meters depth on-board of R/V Dr. Fridjof Nansen, in April - May 1990 in south and central Mozambique.

**Figure 4.6.** Horizontal distribution of salinity at 150 meters depth on-board of R/V Dr. Fridjof Nansen, April - May 1990
The next figure shows the horizontal distribution of temperature at 150 meters depth recorded in the southern and central Mozambique during the cruise on-board of R/V Dr. Fridjof Nansen.

**Figure 4.7.** Horizontal distribution of temperature at 150 meters, April-May 1990, on-board of R/V Dr. Fridjof Nansen.
4.2. Sofala Bank (16° 00'S to 21° 00' S)

4.2.1. General characteristics

- Location

Sofala Bank is the largest shelf in the Eastern African Coast located in the central Mozambique between the latitudes 16° S and 21° S, Figure 4.8.

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Figure 4.8. Sofala Bank, bathymetry and main rivers in the area
• Climate

The climate of the region is subtropical humid with two seasons, the summer or rainy season, from October to March and the winter or dry season, from April to September. The average annual rainfall is about 1140 mm. In the southern Sofala Bank the evaporation, about 1650 mm per year, prevails over the precipitation by about 500 mm per year.

• Tides

The tidal range near the coast in Sofala Bank is relatively bigger compared to the tides in the rest of the coast. The mean tidal range near Beira Harbour during the spring is about 6.4 m (Brinca et al., 1982), whereas in the Southern Mozambique and at the shelf break in Sofala Bank the tidal range is about 3 m (Hoguane, 1996, Gammelsrød and Hoguane, 1995)

• Morphology

The morphology of the coastal zone in Sofala Bank is characterised by flat land with an almost continuous fringe of mangrove swamps. These swamps are associated with main rivers and with tidal creeks.

The bottom in the central and northern Sofala Bank is flat and mostly muddy. The southern Sofala Bank is characterised by sand waves caused by strong tidal currents (Sætre and Paula e Silva, 1979 and Brinca et al., 1982).

• Coastal waters

The coastal waters in Sofala Bank are characterised by estuarine environment, because of the rivers draining into the shelf, including the Zambezi River, one of the largest in Africa.

The southern part of Sofala Bay, though, is characterised by high saline water, particularly during the dry season, because the evapotranspiration exceeds the precipitation.

4.2.2.Background

Along the Mozambique coast, about 80% of the total water that is drained into the coastal waters enter the Indian Ocean from Sofala Bank. The Zambezi River, alone, contributes with 67% of the total river discharge in the whole country (Saetre and Jorge da Silva, 1982).

Because of the terrigenous input of nutrients from the rivers in the area, Sofala Bank it is highly productive. It hosts an important fishery, the shallow water shrimp. The most abundant species in this area are the *pneaeus indicus* and the *metapneaeus monoceros* representing about 48% and 42% of the total shrimp catch, respectively (Silva, 1989).

Shallow water shrimp is the most valued fishery in Mozambique and it is a source of foreign currency. It is exported to European and South African markets.
Mainly foreign companies that owe vessels and operate in the area exploit the fishery at the industrial scale. Because of the importance of the shallow water shrimp, Sofala Bank is one of the areas along the Mozambique coast that has been surveyed quite often.

Hydrographic surveys in Sofala Bank started in 1977, on-board different commercial and research vessels. For the oceanographic point of view some of the primary objectives of the surveys have been, mainly, to determine:

- The distribution and influence of the fresh water from the rivers in the availability of the fishery resources, particularly in the availability of shallow water shrimp Jorge da Silva (1986), Gammelsrød (1988) and Hoguane (2001).

- The causes of the seasonal occurrence of high salinity that is observed in Sofala Bay, southern Sofala Bank, and its influence in the distribution of the fishery resources (Jorge da Silva, 1984).

4.2.3. Temperature and salinity structures in Sofala Bank

We will present some horizontal and vertical profiles of the temperature and salinity observed in Sofala Bank, during different cruises. Annex A.4 shows the station network for the cruise carried out on April 1998, on-board R/V Fengur.
Next figure shows the horizontal distribution of surface salinity in the southern and central Mozambique. The variation was recorded during the period April-May 1990, on-board R/V Dr. Fridjof Nansen.

![Diagram of Sofala Bank temperature distribution](image-url)

**Figure 4.8.** Horizontal distribution of surface temperature n Sofala Bank, recorded on-board of R/V Dr. Fridjof Nansen, April-May 1990.
The next figure shows the horizontal distribution of surface salinity in the southern and central Mozambique. The variation was recorded during a cruise held on-board of the vessel S. Rybak during the period 18 November to 4 December 1982.

**Figure 4.9.** Horizontal distribution of surface salinity, observed in 18 Nov - 4 December 1982, on-board S. Rybak
Figure 4.10. Shows the horizontal distribution of surface salinity, observed in Sofala Bank onboard of Kometa Galeya in the period 18-25 April 1989.
Figure 4.11. Shows the horizontal distribution of surface temperature, observed in Sofala Bank on-board of Kometa Galeya in the period 18-25 April 1989.
The figures show the vertical profiles of salinity and temperature observed in April 1998 along the section F and H in Sofala Bank on-board R/V Fengur.

Figure 4.12. Vertical profile of salinity in section F and temperature in section H, Sofala Bank, taken on April 1998.
4.3. Maputo Bay (25º 55’ S and 26º 10’ S)

4.3.1. General characteristics

• Location

Maputo Bay is located in the southern part of Mozambique between the Latitudes 25º 55’ S and 26º 10’ S and the Longitudes 32º 40’ E and 32º 55’ E, ANNEX A.5. It is about 40 km long and 30 km wide, thus with an area of about 1200 km².

• Rivers

There are five rivers draining into the bay. Incomati River in the northwest, Umbeluzi River, Tembe River and Matola River that form the Estuary of Espírito Santo in the west and Maputo River in the southwest side of the bay. The main rivers are Incomati, Maputo and Umbeluzi.

The mean monthly discharge of these rivers varied from 10 m³s⁻¹ to 800 m³s⁻¹. All these rivers are located in the western side of the bay.

Table 4.3. Averages of maximum and minimum runoff from the main rivers, observed during 25 years, 1960-1985 (Anon., 1998).

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<th>River</th>
<th>River runoff (m³ s⁻¹)</th>
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<td>Maputo</td>
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4.3.2. Background

Activities related to Maputo Bay

• One of the major ports in South Eastern Africa, Maputo Harbour is located in the bay, so there are risks of the oils spills as it happened in 1992 with the Tanker Katina P.
• Some of the above-mentioned rivers draining into the bay are international. They are used for agriculture purposes in the upper riparian thus there are inflow pollutants and river flow reduction in the lower riparian, Mozambique.

• The existence of mangroves and high level of nutrients from the rivers favours the development of commercially valued fisheries such as shallow water shrimp and small pelagic species.

• The capital of the country, Maputo City is connected to the bay. It is overpopulated, with about 2 million people, with no adequate treatment of domestic waste.

• The main industries in the country are located in Maputo and Matola City and they drain their waste in the bay.

All these factors contribute for the possible pollution of the bay through domestic, industrial and agricultural waste what in turn may affect the water quality and thus the productivity of the ecosystems, corals, fisheries, etc.

Different oceanographic surveys have been carried out in the bay with the aim of determining the characteristics of the water masses, the pattern of the currents, the tides, temperature and salinity structures among others.

There are also studies along the Incomati Estuary for the determination of the extension of the salinity intrusion and its effect on the agriculture.

Different institutions with different national and overseas partnership have been involved in the research in the bay and its surroundings. Some of them are the Fisheries Research Institute - IIP and the Eduardo Mondlane University.

The overall objective of the research is to contribute for the environmental management of the bay.

4.3.3. Temperature and salinity variations

The hydrographic station network in Maputo Bay is showed in Annex B.4. We will only show the temperature and salinity variations along sections A and D.

Section A is transversally orientated from the Espírito Santo Estuary, western side, and the Inhaca Island, in the eastern side of the bay. It is the most representative for the spatial and temporal salinity variation monitoring because of the presence of the rivers in the western side of the bay and the influence of the open sea in the eastern side.

Section D, in the eastern side of the bay is located in the interface between the bay and the open sea.
The following figure shows vertical profiles of temperature and salinity variation, along section A, performed on April 2000.

**Figure 4.13.** Shows vertical profiles of temperature and salinity variation, along section A, performed on April 2000.
The following figure shows vertical profiles of temperature and salinity variation, along section A, performed on November 2000.

**Figure 4.14.** Show vertical profiles of temperature and salinity variation, along section A, in 16 November 2000
The following figure shows vertical profiles of temperature and salinity variation, along section D, performed on 16 November 2000.

**Figure 4.15.** Show vertical profiles of temperature and salinity variation, along section D, in 16 November 2000
5. Current patterns along the coast of Mozambique

The Mozambique current is usually considered as a part of the anti-cyclonic sub-tropical gyre consisting of the South Equatorial Current, the Agulhas Current system and the eastward flow situated to north of the sub-tropical convergence, Figure 5.1.

The northern part of the Mozambique Current as well as its main source, the South Equatorial Current, is directly influenced by the monsoon winds. Considerable seasonal variations in velocity are therefore to be expected. The South Equatorial Current is strengthened during the southwest monsoon in April-October. According to Wyrtki (1973), only one third of the South Equatorial Current water turns south as the East Madagascar and the Mozambique Current. It is likely, however, that this ratio is also subject to seasonal variations. There are significant discrepancies in available information on the seasonal variations of the Mozambique and Agulhas Current (Lutjeharms (1977), Grundlingh, (1980)). In addition to seasonal variations, the inter-annual variability also seems to be significant (Lutjeharms, 1972).

![Figure 5.1: Surface currents of southwest Indian Ocean for February and August (Anon, 1977).](image)

1) Agulhas Current.
2) Mozambique Current
3) Somali Current.
4) South Equatorial Current.
5) East Madagascar Current.
5.1. Currents

At regional level the wind system near the surface seems to be important, so, it is responsible for the major currents upper stratum in sea. Changes in winds system imply changes in the oceanic currents and the wind induces the circulation in the Mozambique coast.

In 26 March – 16 April 2001 there were a recovery and redeployment of an array of current meter moorings in Mozambique Channel, at 17° S by a “RV Pelagia cruise 64PE177”. Hydrographic observations of the South Equatorial Current are made on a section to the north of the Mozambique and Madagascar in Mozambique Channel, see figure 5.2.

The current meter mooring ACS04 to ACS10 had been deployed during the cruise in March - April 2000 at the narrowest part of Mozambique Channel. The position of these moorings in cross-section is shown in figure 5.3.

Figure 5.2: Distribution of hydrographic stations.
The preliminary results of the studies made during the cruise “RV Pelagia cruise 64PE177” in Mozambique channel, showed that the data from current meter moorings confirm that the currents in Mozambique Channel are dominated by the presence of anti-cyclonic eddies.

Figure 5.4 shows the current speed and direction (raw data) as observed at the top of the mooring ACS06. These raw data clearly show that during the period of observations (one year, 4-5 events occur in which the current speed strongly increases for a period of about two months. Data from other moorings look similar and those 4-5 events can be recognised in which the current speed increases while the current direction gradually changes. The current direction at the moorings on the eastern side of the channel changes more or less opposite to the change in current direction on the western side of the channel. This suggests that during the events with a high current speed, anti-cyclonic eddy pass through the mooring section.

In average, this eddies cause a southward flow in the western part of Mozambique. Between these periods when an eddy passes, the current speed decreases and fluctuates strongly. Then, tidal motions seem to dominate currents. Two ADCP’s (Acoustic Doppler Current Profiler) were mounted on the top of the moorings near the Mozambique side of the shelf. ADCP data from mooring ACS04 suggests that close to the self the currents are dominated by tidal motions during
the entire period whereas ADCP data from mooring ACS05, at some 50 Km off the slope, clearly show the dominant influence of the anti-cyclonic eddies on the currents.

Analysis of currents as to this study was also taken from the surface currents fields in the Mozambican coast presented as figures 5.07-5.18, obtained several ship drifts by the American National Oceanographic Data Center (NODC). During summer (figure 5.16, 5.17, 5.18, 5.7, 5.8, 5.9 and 5.10) the current is strong and during winter (figures 5.12, 5.13 and 5.14) the current is weak.

![Figure 5.4](image)

**Figure 5.4** Current speed (top) and direction (bottom) (both raw data) from the current meter at the top of mooring ACS06.

### 5.2. Circulation pattern along the Mozambique coast

Along the Mozambique coast the circulation pattern seems to be characterized by the influence of three anti-cyclonic cells changing their position along the coast, and some smaller cyclonic eddies. Figure 5. 8 show the approximate position of these features. For convenience, the cells have been numbered I, II and III while the eddies are called a, b, c, d and e. In this figure the circulation features are shown as fully developed. This was found convenient for elucidation purpose although it does not represent any observed situation.
5.3. General features in the Mozambique Channel

The circulation in northern part of the channel seems to be dominated by an anti-cyclonic movement. Several authors (Donguy and Piton 1969, Duncan 1970, Harris 1972, Lutjeharms, 1976, Parfenovich 1980, Piton, Pointeau and Ngoumbi 1981) observed this. Donguy and Piton (1969), however, claim this movement to be present only during the time of north-east monsoon season while during the south-west monsoon season the water of the upper layers seemed to come from more southern parts of the Mozambique Channel.

Figure 5.8 gives tentative circulation patterns in the layers of Mozambique Channel. During the southern summer there seems to exist an anti-cyclonic gyre in northern part of the channel (I), and another one in central part, (II), separated by a cyclonic eddy at 16° - 18° S (Figure 5.7 b). During some parts of the year, most likely southern winter, these two anti-cyclones seem not to be separated. The northern anti-cyclone may then extend as an anti-cyclonic tongue into the central parts of the channel (Figure 5.7 a).
Figure 5.7. Dynamic features of the Mozambican Coast.

Figure 5.8: Tentative circulation patterns in the upper layer of the Mozambique Channel.
6. Overall conclusions

Tides in the coast of Mozambique are of semidiurnal type with a daily inequality, which varies from place to place between 10 and 40 centimetres.

Tidal amplitudes vary along the coast and over the year, from about 280 centimetres at Inhambane to about 570 centimetres at Beira.

No clear evidence has been found with regard to the variation of the mean sea levels particularly as an impact of global climate changes. Long time series of mean sea levels have been lacking and a permanent sea level monitoring is required.

**Coastal water along the Mozambique coast are characterised by the presence of:**

A surface layer of equatorial and subtropical origin partly mixed with coastal waters with low salinity.

A surface layer of water of subtropical water, with a salinity maximum at approximately 150-200 m, resulting from the propagation of subtropical water under the equatorial surface water.

A central water layer, found at 400-500 meters, corresponding to and oxygen maximum, the core, which is approximately coincident with 11 o C, and the salinity of 35.0 ppt isohaline.

A layer of Antarctic Intermediate water the core of which the south rises from about 900 m in the south to 600 in the north.

A layer of North Indian Intermediate water characterised by a salinity maximum and an oxygen minimum in the 800-1000 m north of 18º S.

**Sofala Bank is characterised by water masses with:**

Low Salinity Shelf Water (LSSW), with salinity below 34.8. It is found near the river mouths.

Oceanic Water, with salinity between 34.8 and 35.4. It is found near the shelf break.

High Salinity Shelf Water (HSSW), with salinity above 35.4, found in the southern Sofala Bank.

**In Maputo Bay, there are two main distinct water masses:**

The western side of the Maputo Bay is dominated by low saline water, freshwater from the rivers, with a high spatial and temporal variability and the eastern side is dominated by high saline water, from the ocean, with low variability.
The currents in Mozambique coast

The eastern side is dominated by high saline water, from the ocean, with low variability.

Mozambique Current is subject to seasonal variations caused by monsoons.

Figures 5.7 -5.18 show summer monsoon due to southern wind trade and northern wind.

Mozambique Current is periodic. During summer monsoon, October - April, the current is strong and during winter, June - August is weak.

The strongest winds are associated with the southwest monsoon season. The northern monsoons are strong.

The frequency of the northern winds in Pemba (see Pemba location in Figure 1.2) shown in Figure 1.1.

The northern winds during summer are very strong and during winter are weak. Mozambique Current is bounded the coast.
7. References


RV Pelagia Cruise Report: cruise 64PE177, Agulhas Current Sources Experiment (ACSEX-III), 26 March – 16 April 2001 by H. Ridderinkhof chief Scientist.


Tabelas de Mares.(1995). INAHINA

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ANNEX A.1. Stations performed in the Mozambican waters, per area, season and year, from August 1977 to November 1980 (stations for shelf studies are not included). HS hydrography station, BT bathythermography station.

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Annex A.2. Shows the monthly means of freshwater runoff for some main rivers. \( C(\%) \) is the variability coefficient, \( Q \) the average monthly runoff and \( S \) is the standard deviation.
Annex A.3. T-S (temperature-salinity) and T-O2 (temperature-Oxygen) diagrams, for the cruises in Annex A.1. a) and b) refers to the period April – September while c) and d) refers to October - March cruises.
Annex A.5. Hydrographic station network in Maputo Bay
ANNEX B

Surface currents (ship drift) in the Mozambican coast as referred in section 5.
Figure 5.7: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of January (minimum five observations).
Figure 5.8: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of February (minimum five observations).
Figure 5.9: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of March (minimum five observations).
Figure 5.10: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of April (minimum five observations).
Figure 5.11: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of May (minimum five observations).
Figure 5.12: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of June (minimum five observations).
Figure 5.13: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of July (minimum five observations).
Figure 5.14: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of August (minimum five observations).
Figure 5.15: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of September (minimum five observations).
Figure 5.16: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of October (minimum five observations).
Figure 5.17: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of November (minimum five observations).
Figure 5.18: Surface Current (ship drift) in the Mozambican coasts corresponding to observations of December (minimum five observations).