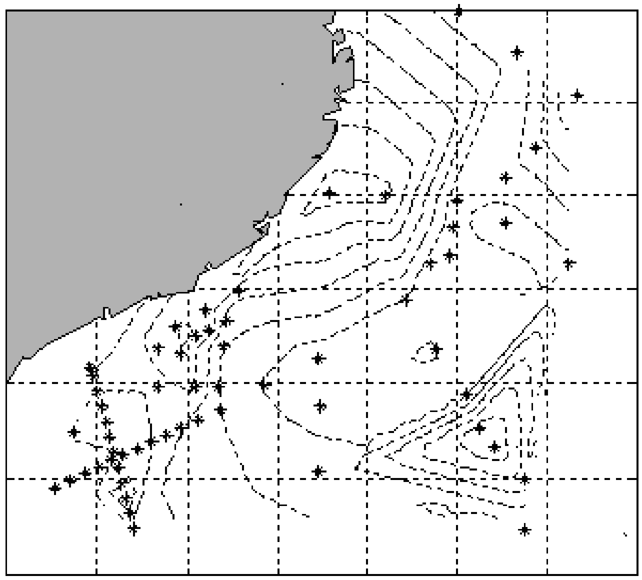
Master Thesis in Physical Oceanography

EDDY STRUCTURE AND DYNAMICS IN THE MOZAMBIQUE CHANNEL



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June, 2010

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Acknowledgements

First of all, I wish to thank my supervisor Tor Gammelsrod, for his unflagging support and valuable contributions throughout this period and to Professor António Hoguane for his encouraging and continued support.

I am also grateful to Eva Falck for her helpful contributions.

My special thanks to the NOMA project, the Bergen University and the Geophysical Institute, which gave me the opportunity to be part of the *Universitas Bergensis* community.

I am pleased to have shared this time with all the other master students at the Geophysical Institute, specially Naftal, Mocuba, Candida, Salma, Waleed, Elfatih and Ahmed.

To Ana Cristina and Bastienne for their availability and kindness in helping with the "last details", thank you.

Lastly but not least, to my family for their unfailing support and care, a huge thanks and to many others that have helped in many ways.

Abstract

The Mozambique Channel circulation is dominated by a sequence of southward migrating cyclonic and anticyclonic eddies and previous studies have been done to investigate the flow, the variability and nature of the currents in the Mozambique Channel and the generation of the Mozambique Channel eddies. This master thesis studies the eddies structure and dynamics, based on data obtained from the 2008 ASCLME-Nansen cruise which includes salinity, temperature, currents, density and oxygen measurements. However, this study is restricted to the northern Mozambique Channel where study areas covering three cyclones and one anti-cyclone were considered. The results indicate the existence of upwelling and downwelling zones placing the thermocline near and far-off the surface, respectively. In addition, the eddies have wavelengths of 500 km, amplitudes of more than 100m and a frequency of occurrence of 4 eddies per year.

Previous studies suggested that the frequency with which these eddies are formed may in turn be controlled by Rossby waves travelling zonally across the South Indian Ocean. The Rossby number found in this research, indicates that the flow in the Mozambique Channel can be considered geostrophic. Furthermore, the Rossby deformation radius is nearly 20km m for the cyclone and 25km for the anti-cyclones so that the eddies scale seems to be controlled by the Channel size.

Contents

1. Introduction

The Mozambique Channel is part of the Indian Ocean that separates Madagascar from the rest of the African Continent, being the Mozambican coast its western boundary. The Mozambique Channel circulation is dominated by a sequence of cyclonic and anticyclonic eddies. De Ruijter et al., (2002) observed that the flow in the Channel is dominated by a train of large anti-cyclonic eddies (diameters > 300km) that propagate southward. At a frequency of 4 per year they cause a net poleward transport of about of 15 Sv.

Previous studies suggested that the frequency with which these eddies are formed may in turn be controlled by Rossby waves travelling zonally across the South Indian Ocean (Schouten et al., 2002c). Harlander et al., (2009), stated that Mozambique Channel Rossby normal modes with periods of sixty to eighty days might destabilize the flow after an anticyclone has passed, triggering the development of a new anticyclone. This in turn could induce eddies with a dominant frequency of four to five per year. A recent study states that the formation of mesoscale eddies in the Mozambique Channel is connected to variability in the transport of South Equatorial Current (Backeberg and Reason, 2010).

The knowledge of the dynamics of circulation in the Mozambique Channel may contribute to understanding of the circulation pattern and support maritime engineering applications. In recent decades, several multinational oil companies have done hydrocarbon surveys off the coast of Mozambique, specifically in the Rovuma basin that is part of the study area. In addition to seismic surveys and geological studies, it is also necessary to have knowledge of the oceanographic patterns of the area to be exploited, such as the circulation and magnitude of the currents. Thus, the study of eddies and circulation pattern in the Mozambique Channel would be a useful addition to the geological studies and surveys that have already been made in the Rovuma Basin trough the knowledge of the strength and amplitude of the currents, especially in the operational locations, where the installation platform and material has to be loaded.

This master thesis is about describing the eddies in the Mozambique Channel. The specific objective is to investigate their structure, frequency, magnitude and current direction along the Channel. This study may contribute to the understanding of water circulation along the Mozambican coast and the Mozambique Channel in general, which does not only affect the Mozambican and Madagascar waters, but also to some extent, the global circulation.

This master thesis is organized as follows:

(1) The Introduction has presented a brief description of the Mozambique Channel, a review of previous studies and a general theory about Mozambique Channel eddies; as well as the motivation and objectives of the study;

(2) The Background gives a more detailed description of the Mozambique Channel, describes the water masses, the currents and the eddies in the Channel;

(3) Data, Instruments and Methods mention the used instruments for collection of data, and describe the methods used in order to monitor the circulation pattern in the Channel. In addition, the ROMS model is introduced in this section;

(4) The Results are given in section 4;

(5) In section 5 the given results are discussed and;

(6) Finally section 6 gives the conclusion of this research work

2. Background

The Mozambique Channel

The Mozambique Channel is a portion of the Indian Ocean which is located between Madagascar Island and southeast Africa. The channel is approximately 460 kilometers wide at its narrowest point between Mozambique and Madagascar. The Mozambique Channel is a pass way for poleward moving tropical and subtropical waters (Schouten et al., 2005).

Figure 1 illustrates the study area and its bathymetry. Nearby the coasts of Mozambique and Madagascar the values vary from 0m to 1500m and increases as the middle of the Channel is approached. The deepest zones are located at the northern entrance of the Channel, where the depth reaches 3000m.

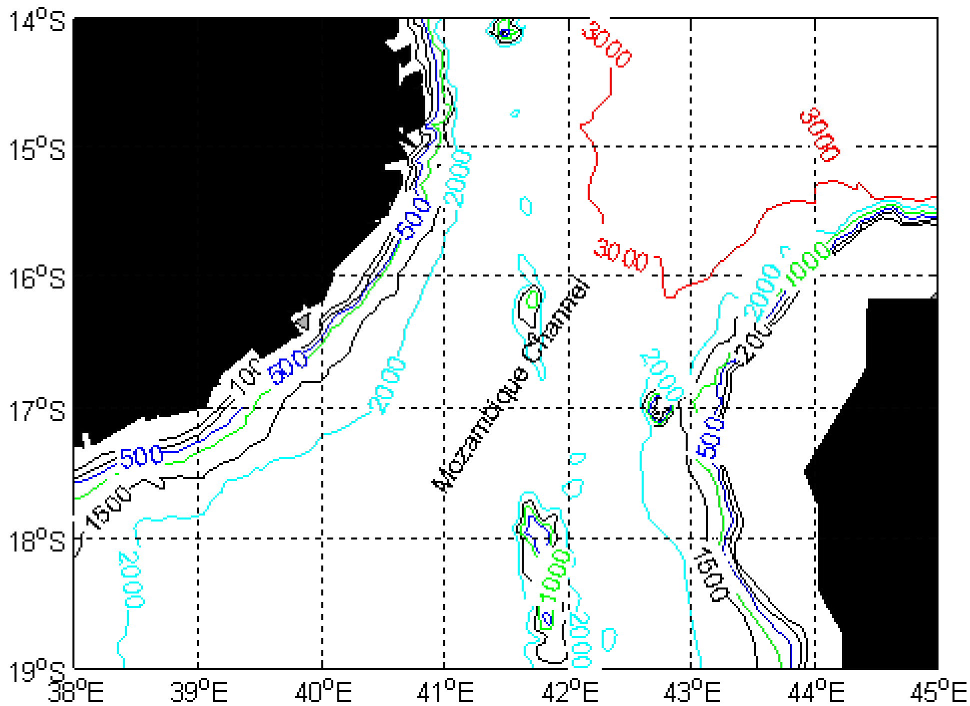


Figure1: The Mozambique Channel bathymetry

Off the east coast of Madagascar, the Madagascar Basin reaches depths of over 5000m. The continental shelves and slopes in the entire region are generally narrow and steep, while the coastlines tend to be straight. (Schumann, from Robinson and Brink, 1998).
The shelf is narrow in the western side of the channel at about 16^{o}S, but wide on the eastern side. The shelves around the islands, particularly Comores in the northern mount of the channel are narrow. These shapes of the shelf edge have implications for the coastal water movement (Lutjeharms, 2000).

2.1 Water Masses

The waters in the Mozambique Channel consist of the predominant water masses of the Southern Indian Ocean. The highest temperatures in this region are found in the north, although within the core of the Agulhas Current, waters with temperatures in excess of 25^{o}C can be transported as far as 35^{o}S in summer, with a drop of about 4^{o}C in winter. There is a spread in the salinities of these high-temperature waters, with low values of around 34.2 x 10^{-3} possibly associated with inputs of fresh water from the large rivers (Schumann, from Robinson and Brink, 1998)

Saetre and Da Silva (1984), identified five different water masses in the Mozambique Channel which are: Equatorial Surface Water (ESW), Sub-tropical Water (SW), Central Water (CW), Antarctic Intermediate Water (AIW) and North Indian Intermediate Water (NIIW); while, according to Kaehler at al., (2008), the water masses in the northern Mozambique Channel are: Subtropical South Indian Ocean Water (Subt. SIOW), Equatorial Indian Ocean Water (Eq. IOW), Antarctic Intermediate Water (AIW), North Indian Deep Water (NIDW) and North Atlantic Deep Water (NADW).

2.2 Currents and Eddies in the Mozambique Channel

The main currents in the Mozambique Channel and the circulation pattern are represented in Figure 2. The south-westward flow in the central part of the Mozambique Channel, the Mozambique Current (MC), starts near the East African coast. At 20^{o}-22^{o}S, the Mozambique Current joins up with the East Madagascar Current (EMC) from the western side of Madagascar. The East Madagascar Current is a narrow but well defined western boundary current derived from the South Equatorial Current (SEC) which splits at the Northeast Coast of Madagascar as the Northeast Madagascar Current (NEMC), about 40% turning southwards as the Southeast Madagascar Current (SEMC) (Rao and Griffiths, 1998).

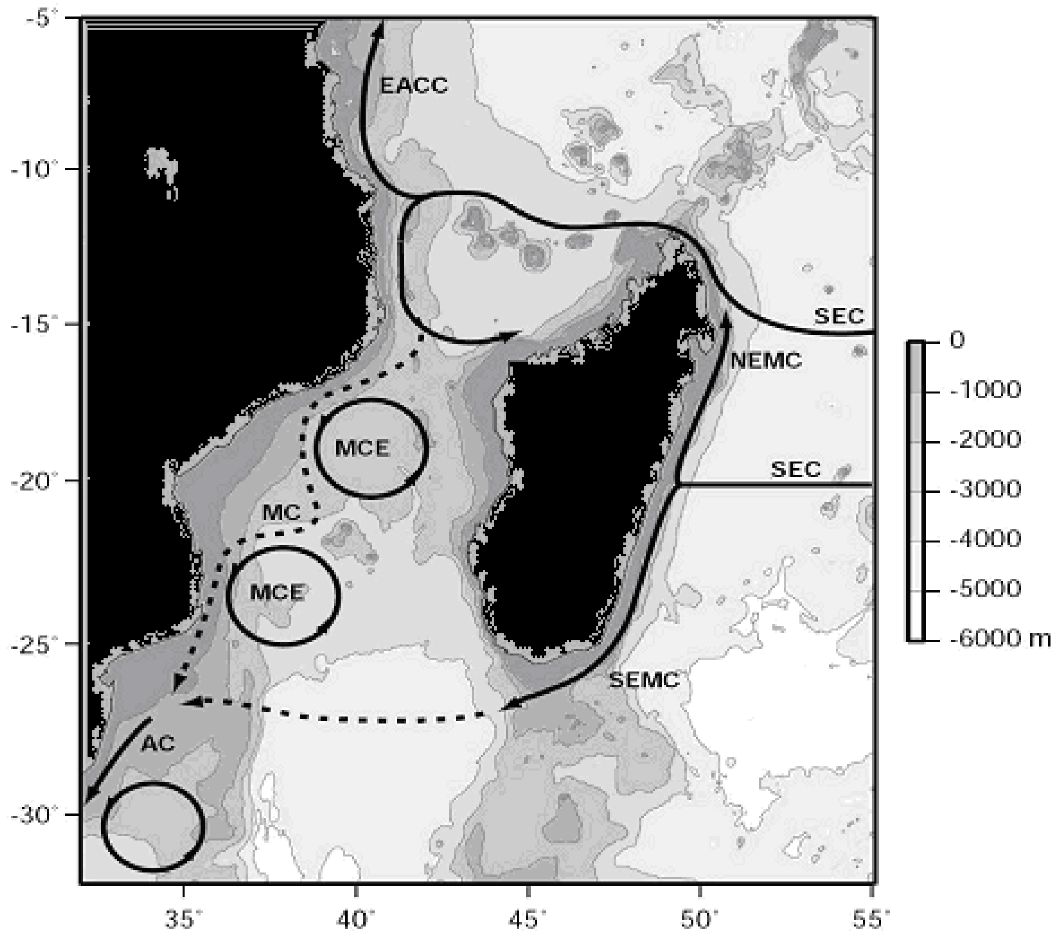


Figure 2: The main currents and Circulation pattern in the Mozambique Channel: South Equatorial Current (SEC), Southeast Madagascar Current (SEMC), Northeast Madagascar Current (NEMC), Mozambique Current (MC), the Agulhas Current (AC); and the Mozambique Channel eddies (MCE). Source: Schouten et al., 2003.

Donguy and Piton (1991) had previously investigated the circulation along the Mozambique Channel and stated that the most prevailing characteristics were an anti-cyclonic eddy in the northern part of the channel and a well established current flowing south-eastward in the central part of the Mozambique Channel. This finding was reconfirmed in later studies, for example, De Ruijter et al., (2002), Ridderinkhof and De Ruijter (2003); and Schouten et al., (2003) who found that the flow was dominated by anti-cyclonic southward migrating eddies. According to Harlander et al., (2009), a significant part of the flow variability might also be the result of a westward-propagation pattern; hence, the Mozambique Channel throughflow is governed by channel-size eddies migrating southward.

The word eddy, in the Mozambique Channel, is generally used to describe features with length scales (inverse wavenumbers) falling in the range of tens and hundreds of kilometres in diameter, and with time scales (inverse frequency) of 10-30 days. Their amplitude in terms of vertical displacement of isopycnals can be 100m or more, and the associated current velocities can be $1ms^{-1}$ or more; although magnitudes of order of $10cms^{-1}$ are more typical (Gill, 1982). Eddies can be generated due to instabilities, wind forcing and flow over topography. Instabilities may take a variety of forms, and the mechanisms are often difficult to identify observationally.

3. Data, Instruments and Methods

In order to investigate the eddies, data from the ASCLME-Nansen cruise along the Mozambique Channel in 2008 will be used. The structure, frequency, magnitude and current direction of eddies in the Mozambique channel will be provided by data from CTD (conductivity temperature and depth measurement instrument), ADCP (Underway Acoustic Doppler Current Profiler). The data includes salinity, temperature, currents, density and oxygen measurements. The eddy tracking was obtained from altimetry data downloaded onboard the ship, and to get additional information on frequency and velocity of the eddies the ROMS model (Regional Ocean Modeling System) will be presented.

Some of the principal tasks of the cruise were to carry out a station grid that would investigate the physical characteristics of cyclonic and anti-cyclonic eddies. Before the cruise commenced, the area of study was restricted to the northern Mozambique Channel, as a number of promising positive and negative anomalies had been identified in this region. Several transects and grids were then planned to dissect areas of interest. Directed to cross the eddies trough the centre, the cruise then commenced to focus on five main study areas (see Fig. 3.1): (1) a north-south transect through two cyclones (**A**, **C**) and one anti-cyclone (**B**), (2) a frontal zone across the Mozambique Channel between eddies A and B, (3) a coastal convergence zone south of Angoche (**D**), (4) the central anti-cyclone (**B**) and (5) the south-western cyclone (**E**).

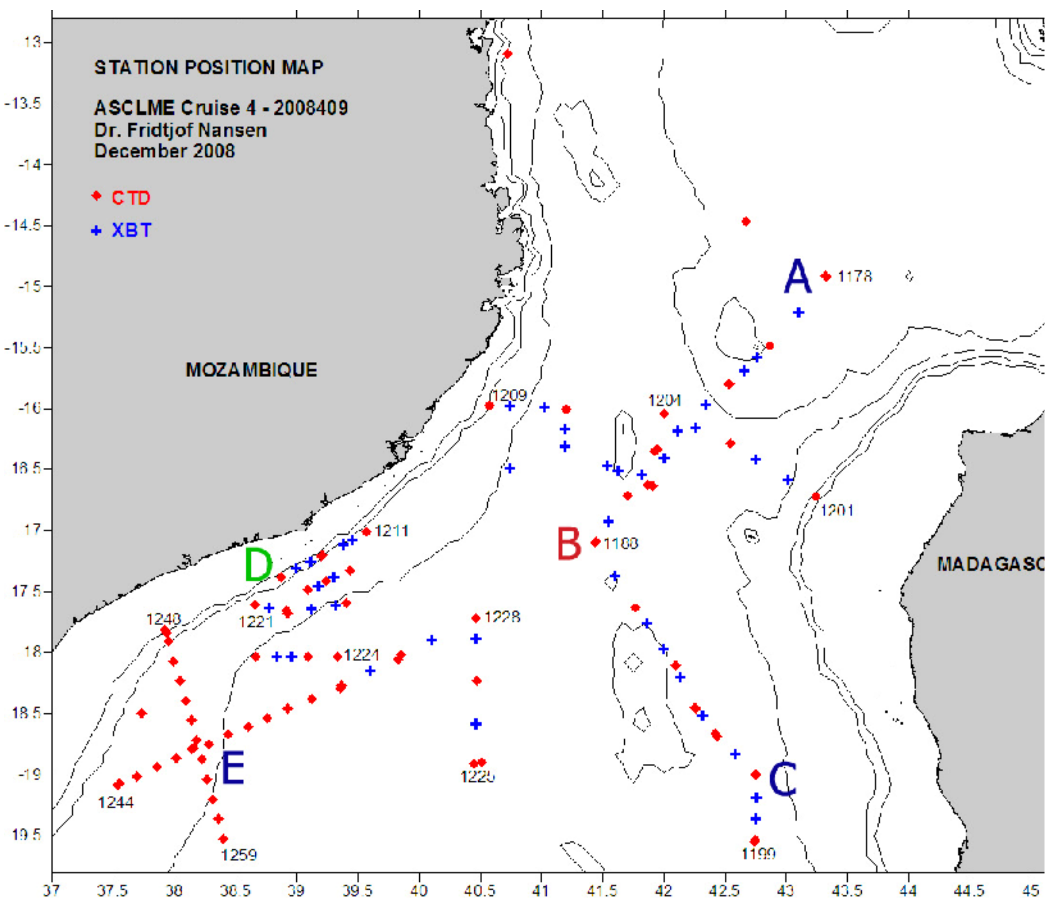


Figure 3.1: CTD and XBT sampling stations in the Mozambique Channel. Areas A, C and E are approximate positions of cyclones, B-anticyclone and D-coastal convergence zone (ASCLME report 2008).

3.1 Instruments description

Seabird 911 plus CTD: Conductivity, Temperature and Depth measuring Instrument.

A Seabird 911 plus CTD was used to obtain vertical profiles of temperature, salinity, pressure and oxygen. Real time plotting and logging was carried out using the Seabird Seasave software installed on a PC.

Sea Guard Current Meter

A mooring was installed and deployed in Pemba, in the northern Mozambique Channel, in order to measure the currents. The instrument used, the Seaguard is a current meter based on modern computer technology combined with advanced digital signal processing; accurate optional parameters are available through a new range of smart sensors that include measurements of temperature, pressure, conductivity, oxygen, wave and tide.

Underway Acoustic Doppler Current Profiler (ADCP)

This instrument transmits high frequency acoustic signals which are backscattered from plankton, suspended sediment, and bubbles, all of which are assumed to be travelling with the mean speed of the water. The ADCP estimates horizontal and vertical velocity as a function of depth by using the Doppler effect to measure the radial relative velocity between the instrument and scatterers in the ocean.

Expendable Bathythermographs (XBT)

A total of 46 XBT's were deployed for this survey. They were placed in between CTD stations to enhance the resolution of the CTD data, and in particular, the temperature data. The model of XBT used was a Lockheed Martin Sippican Deep Blue, rated to 760m.

3.2 Eddy Tracking

The eddy tracking was done using altimetry data, downloaded onboard the ship, by downloading data from the AVISO Web Site (CNES, France) that delivers near real time (NRT) files of sea level anomaly and geostrophic current. Data is available after 7 days, which was suitable for our purpose as the dynamics of the eddies in the area are generally slow to change. Data distributed by CCAR (Colorado Center for Astrodynamics Research) are available on a daily basis, without any delay. It was shown, however, that CCAR data was not accurate in terms of location, at least in closed areas such as the Mozambique Channel. The main reason could be linked to the poor satellite coverage available for a real time delivery.

ADCP data from a depth of approximately 16m deep was plotted together with the geostrophic currents from altimetry on Figure3.2. The north-south section was surveyed over a period of 3 days (29 November – 2 December), while the comparative geostrophic velocities were averaged for all available satellite measurements leading up to 1 December. In the figure, the magnitude of the geostrophic currents are differentiated by colors, where red represents the maximum (80cm/s) and dark blue, the minimum. The vectors (magenta) represent the onboard ADCP data collected.

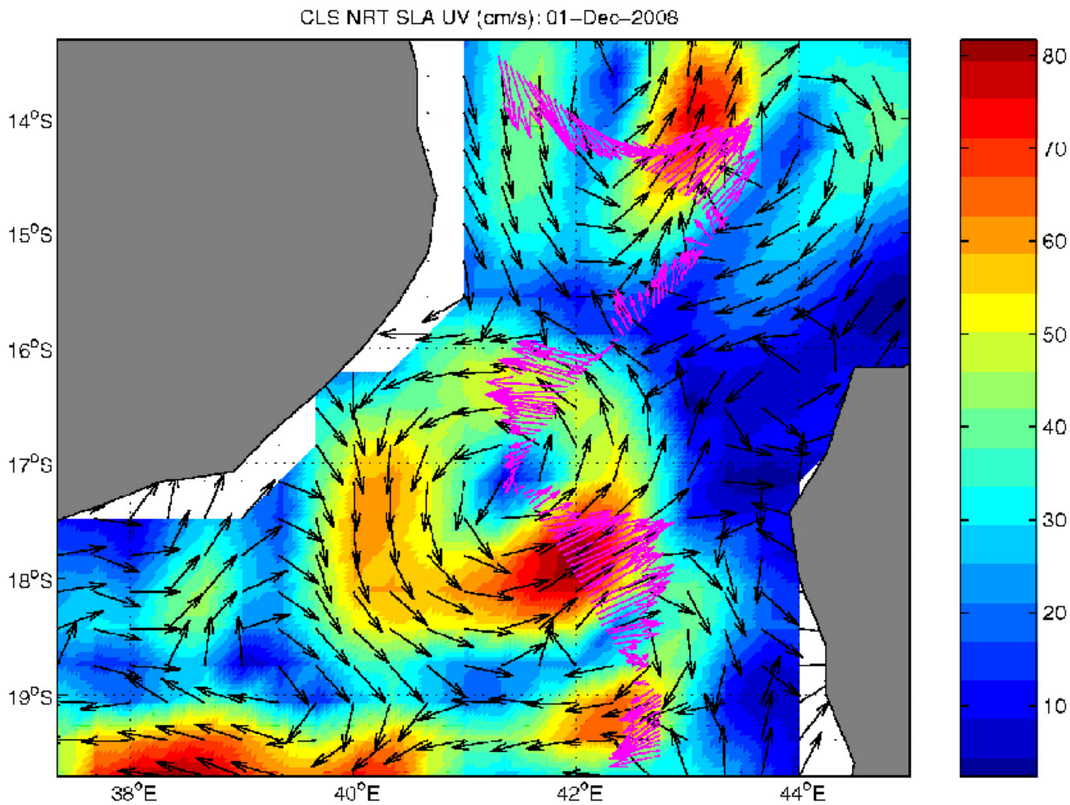


Figure3.2: Geostrophic currents derived from satellite altimeter sea level measurements on December 1st 2008 and the ADCP current vectors (magenta) from 16 m depth (From Kaehler et al., 2008).

SHM Satellite

Altimetry satellites measure the distance from the satellite to the ocean surface by recording the time a radar pulse takes to travel from the satellite to the target surface and back again. (source: www.aviso.oceanobs.com).

Sea level data from multiple altimeter missions are merged to provide a gridded map. These data were obtained from the SSALTO/DUACS near-real time mode multimission altimeter data processing system at Centre National d'Etudes Spatiales (CNES; www.aviso.oceanobs.com). The gridded data has a horizontal resolution of 1/3º on a Mercator grid, which therefore provides grid-resolution of 24km to 37km in the greater Agulhas region, including the Mozambique Channel.

Model

To achieve the proposed objectives the model ROMS (Regional Ocean Modeling System) was as well used. The Regional Ocean Model System (ROMS) is a free-surface, hydrostatic, primitive equation ocean model that uses stretched, terrain-following coordinates, in the vertical and orthogonal curvilinear coordinates, in the horizontal. Initially, it was based on the S-coordinate Rutgers University Model (SCRUM) described by Song and Haidvogel (1994). ROMS was completely rewritten to improve both its numeric and efficiency in single and multi-threaded computer architectures. It was also expanded to include a variety of new features including high-order advection schemes; accurate pressure gradient algorithms; several subgrid-scale parameterizations; atmospheric, oceanic, and benthic boundary layers; biological modules; radiation boundary conditions; and data assimilation.

(http://www.oceanmodeling.org/index.php?page=models&model=ROMS, from Kaehler et al., 2008)

4. Results

CTD measurements

Water Masses

A T-S diagram of the water masses of the northern Mozambique Channel is shown in Figure 4.1.The T-S diagram shows water masses with high salinities and temperatures at the surface and intermediate depths. Below that, follows a layer with maximum salinity and temperatures around 17,5^{o}C. Further down, the temperature and salinities decrease with the increasing depth and afterwards, the salinity increases slightly up to 34,9ppt while temperature continues decreasing.

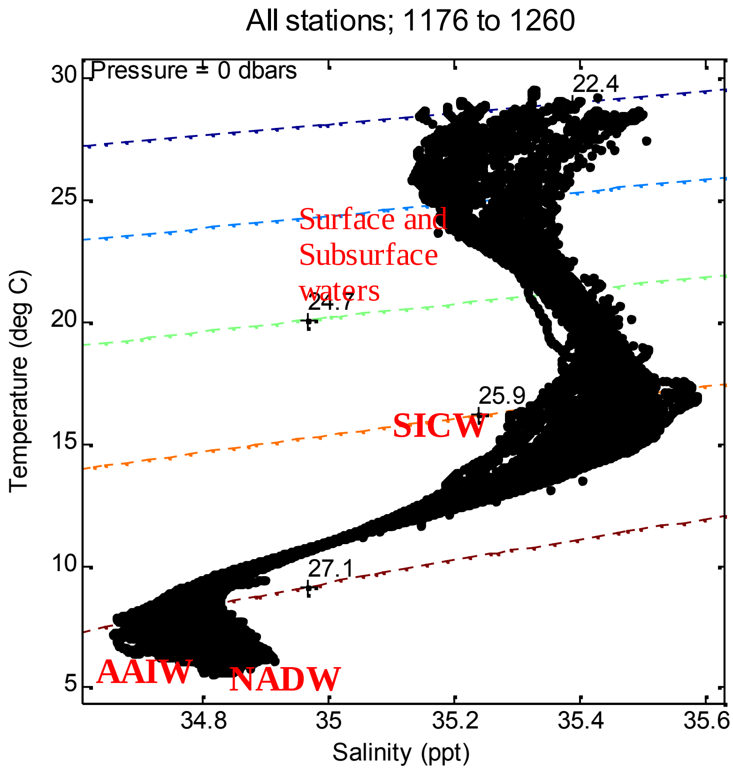


Figure 4.1: Temperature-salinity diagram of the water masses in the Northern Mozambique Channel

Acoording to the results, the water masses in the northern Mozambique Channel are: North Atlantic Deep Water (NADW), Antarctic Intermediate Water (AAIW), South Indian Central Water (SICW) and the upper surface and subsurface waters.

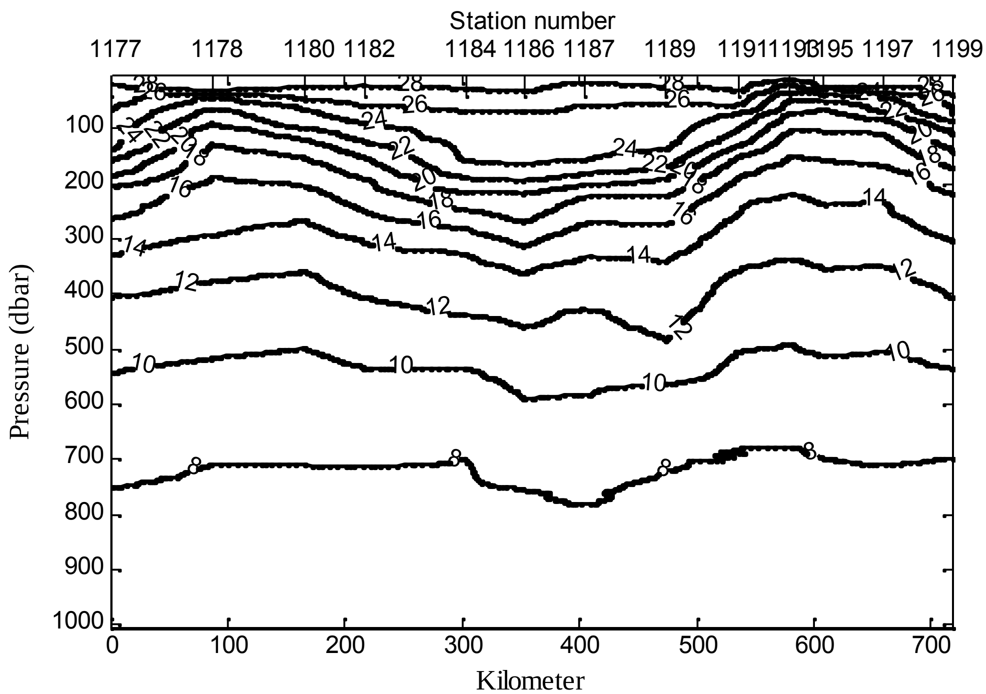
North Atlantic Deep Water (NADW) is the cold, salty water originated near Greenland.

Antarctic Intermediate Water (AAIW) is the low-salinity water of Antarctic origin, with temperatures ranging from 2,2-5^{o}C and salinity from 33,8-34,6ppt.

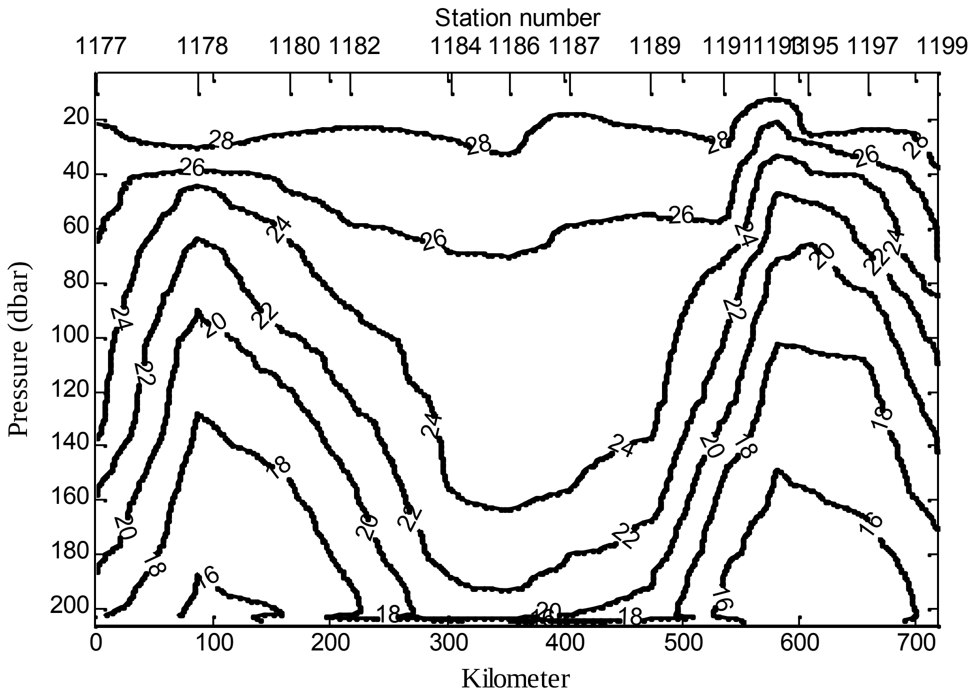
South Indian Central Water (SICW) is the central water with temperatures ranging form 6-16^{o}C and salinity from 34,5-35,6ppt.

Vertical distribution of temperature, salinity, density and oxygen

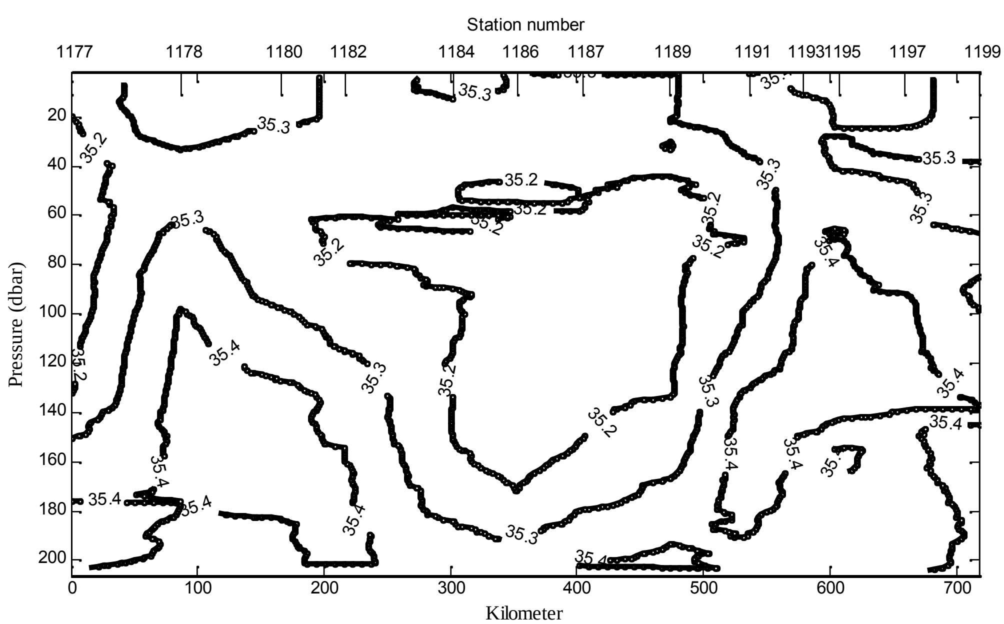
From the CTD measurements shown in Figures 4.2, the results in general shows that the parameters (temperature, salinity, density and oxygen), have greater variability from the surface to a depth of 200m. These results correspond to Section 1, the northeast part of the channel, transect A-B-C in Fig. 3.1.



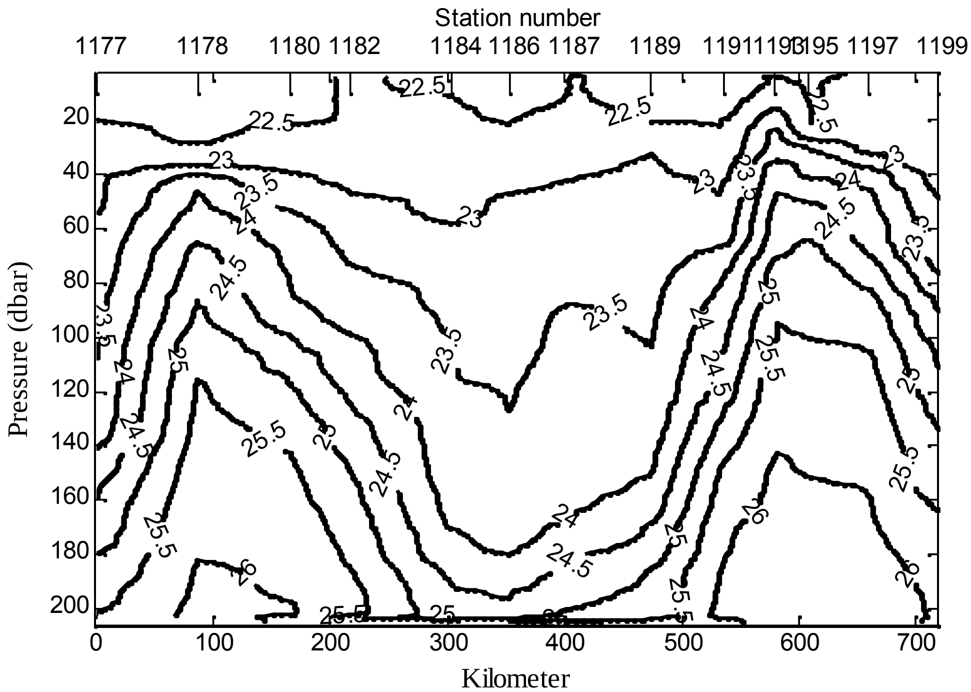
a) Temperature distribution at Section1 (ABC) to a depth of 1000m



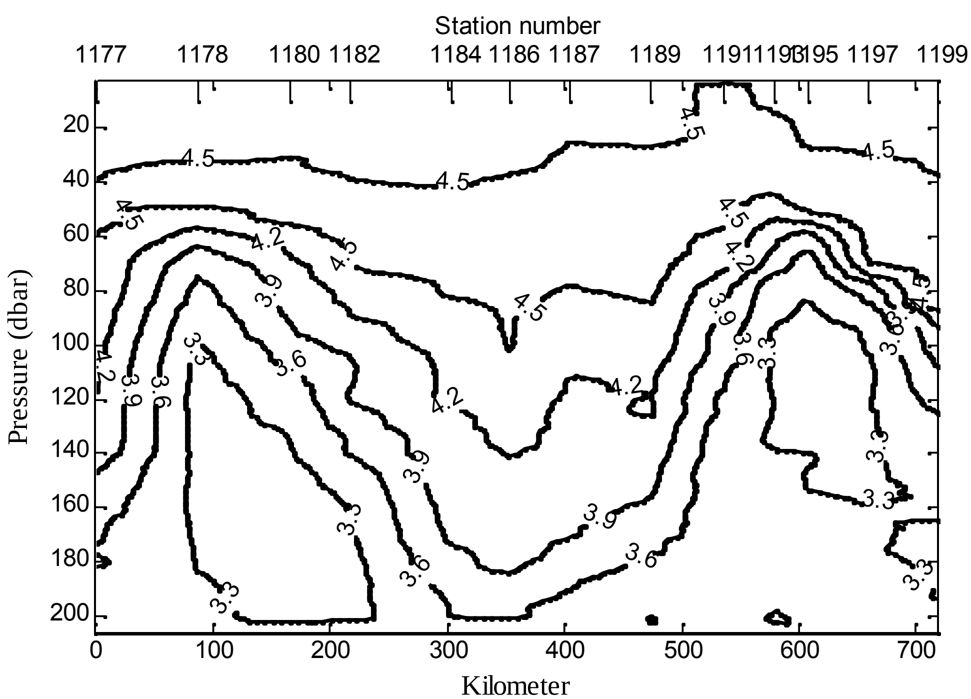
b) Temperature distribution at Section1 (ABC) to a depth of 200m



c) Salinity distribution at Section 1 (ABC) to a depth of 200m



d) Density distribution at Section1 (ABC) to a depth of 200m



e) Oxygen distribution at Section 1 (ABC) to a depth of 200m

Figures 4.2: a, b, c, d and e): Vertical temperature, salinity, density and oxygen distributions along Section 1 (ABC) in the Mozambique Channel.

Figure 4.2a shows the overview of the temperature distribution to a depth of 1000m. It is seen that there is greater temperature variability in the upper layer, from 0m to 200m approximately. For this reason in the next figures the distribution is shown for the parameters above mentioned, to a depth of 200m.

In figure 4.2b the wavy structure of the isotherms have wavelengths of 500km and amplitudes of more than 100m. There are two evident upwelling zones, at 100km and 600km respectively, and a downwelling zone at 350km.

For the salinity variation along Section1 (Figure 4.2c),the amplitude of the isolines is nearly 80m and the wavelength 500km.; The salinity has slightly fluctuating values, the maximum salinity being 35,4 and the minimum 35,2ppt.

The density shows a similar pattern as the temperature. From a depth of 50m to 200m the wavy structures are almost regularly spaced, with 600km of wavelength and 100m amplitude and the density increases with the increasing in depth, from 22,5 to 26 g/cm^3 (Figure 4.2d).

The oxygen section in Figure 4.2e shows a wavy structure, with the oxygen distribution almost constant from 0m to 60m with the maximum oxygen values of 4,5ml/l at this surface zone and minimum of 3,3ml/l. The wavelength of the undulations is 500km and 100m of amplitude.

Temperature Profiles

The Figure 4.3 shows the temperature variation with depth at the stations crossed by the cyclones (upwelling zones) and anticyclone (downwelling zone) in Figures 4.2 also represented in Figure 3.1.

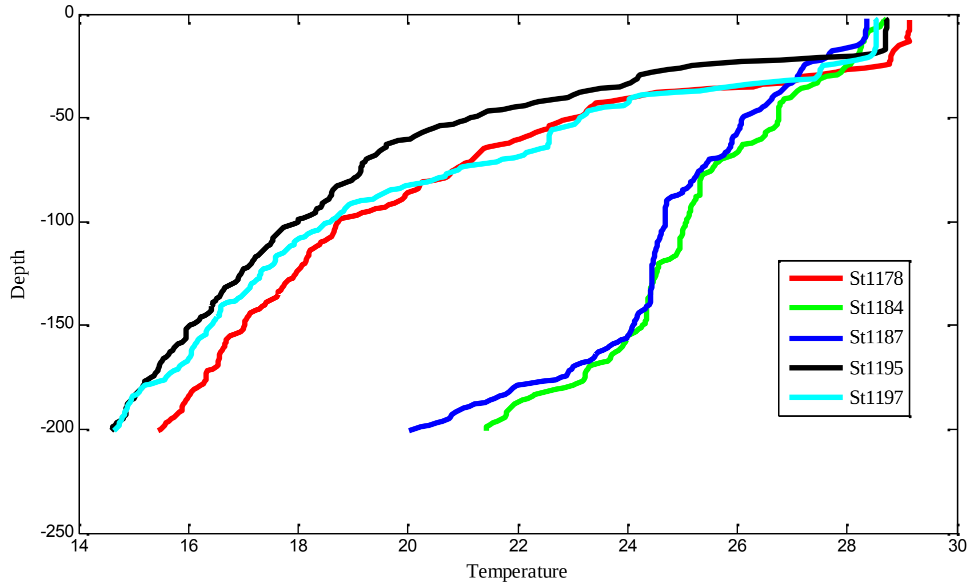


Figure 4.3: Temperature profiles at stations 1178, 1184, 1187, 1197 and 1180, region crossed by the cyclones A and C and anti-cyclonic eddy B in figure 3.1

In figures 4.3, stations 1178, 1195 and 1197 are located at positions where the thermoclines are near the surface. Stations 1184 and 1187 are located at positions with thick mixed layers and the thermoclines are situated at depths greater than 150m.

The temperature decreases with the increase in depth at all the above mentioned locations, with relatively high temperature gradients at station 1187, where the value changes from 28^{o}C to nearly 15^{o}C at 200m. The lowest temperature gradient is at station 1195, varying from 28^{o}C to almost 14.5^{o}C at 200m.

ADCP Current Measurements

Figure 4.4 shows the ADCP horizontal measurements along the Mozambique Channel.

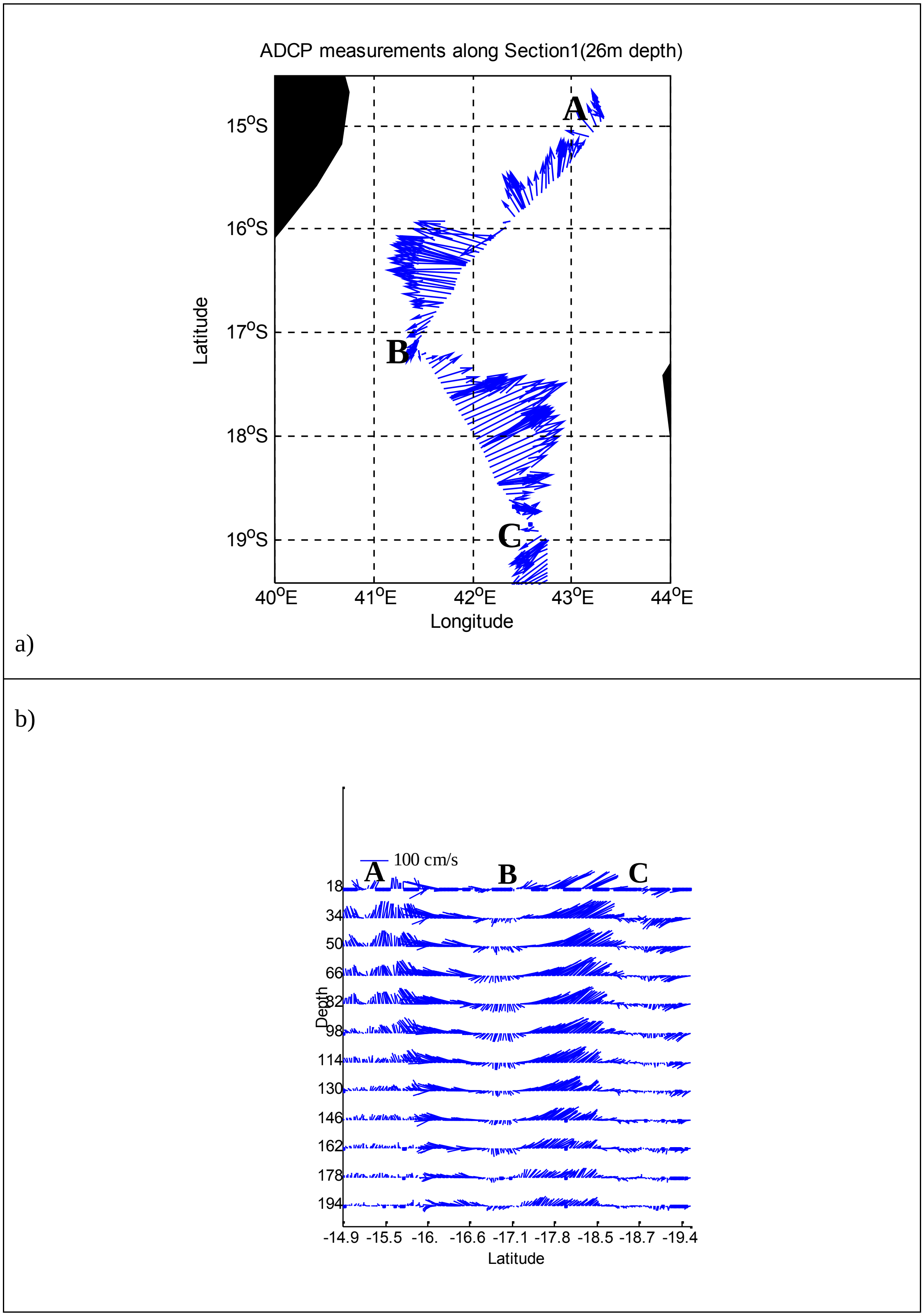


Figure 4.4a and b): ADCP velocity measurements along Section1. a) horizontal distribution at 26m depth and b) horizontal distribution with depth.

Figure 4.4 shows: a) Horizontal velocity distribution at 26m depth along the Channel while the horizontal structure with depth is shown in Fig 4.4b). The current has a meandering trajectory along the Channel. In the northern branch of the section, the currents are directed northweastwards from 14,5 to 17^{o}S, turning to southwestward from around 17 to 17,3^{o}S. From nearly 17^{o}S to 19^{o}S, the currents are directed northeastwards changing afterwards to a southwestward direction. There is a clockwise currents structure in A and C (cyclones) and anti-clockwise in B (anti-cyclone).

The currents are strongest near the surface (Figure 4.4b) and decrease with the increasing depth. The maximum velocities are found in locations with the highest temperature gradients (Figure 4.2) which are the stations between anti-cyclone B and the two cyclones A and C, where the thermocline is located near the surface. Figure 4.4b also illustrates that in the approximate location of the center of anti-cyclone B, the currents are directed southwards and, in the approximate locations of the centers of cyclones A and C, the currents are directed northwestwards and northeastwards, respectively.

Figure 4.5 shows the east and north velocity components, the strongest velocity components along the channel. The east velocity has values of more than 100cm/s and for the north velocity the values are more than 50cm/s.

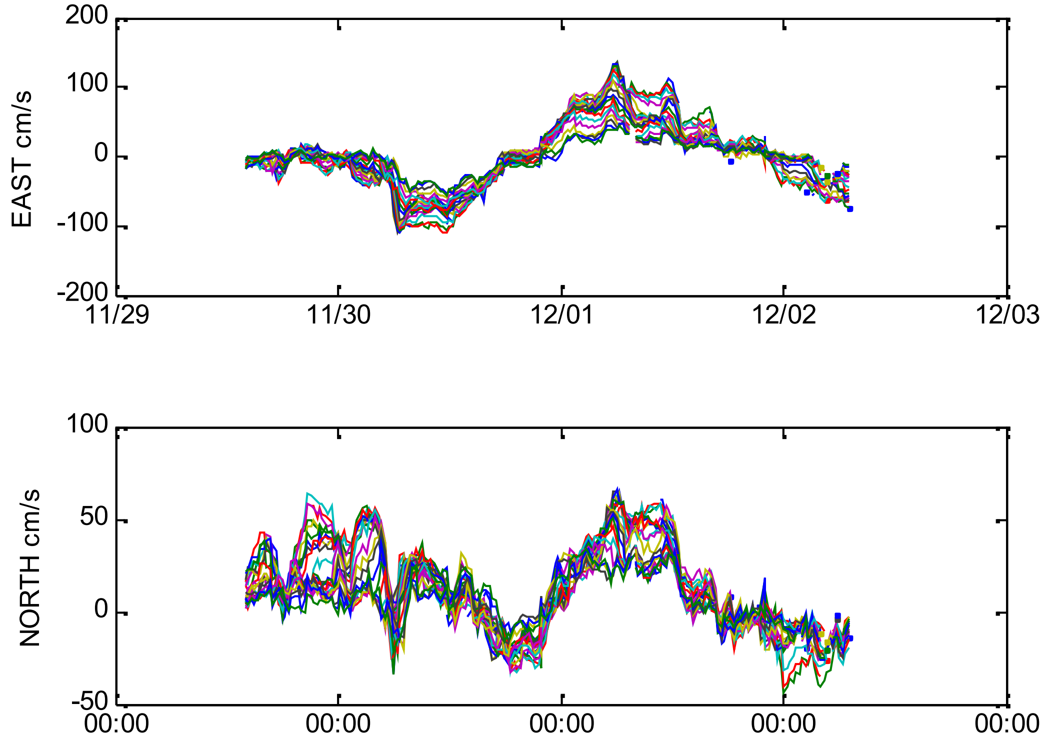


Figure 4.5: East and North velocity components

5. Discussion

5.1 Eddy Structure

The eddy occurrence in the Mozambique Channel can be seen either by the vertical variation of temperature, density and oxygen or by the horizontal variation of these parameters. It can also be seen by the meandering trajectory of the currents along the Mozambique Channel.

Figure 5.1, illustrates the horizontal temperature distribution along the study zone, at a depth of 50m, which is the depth where the eddy wave structure is most developed as seen in Figure 4.2. It also shows the current trajectory along the Channel.

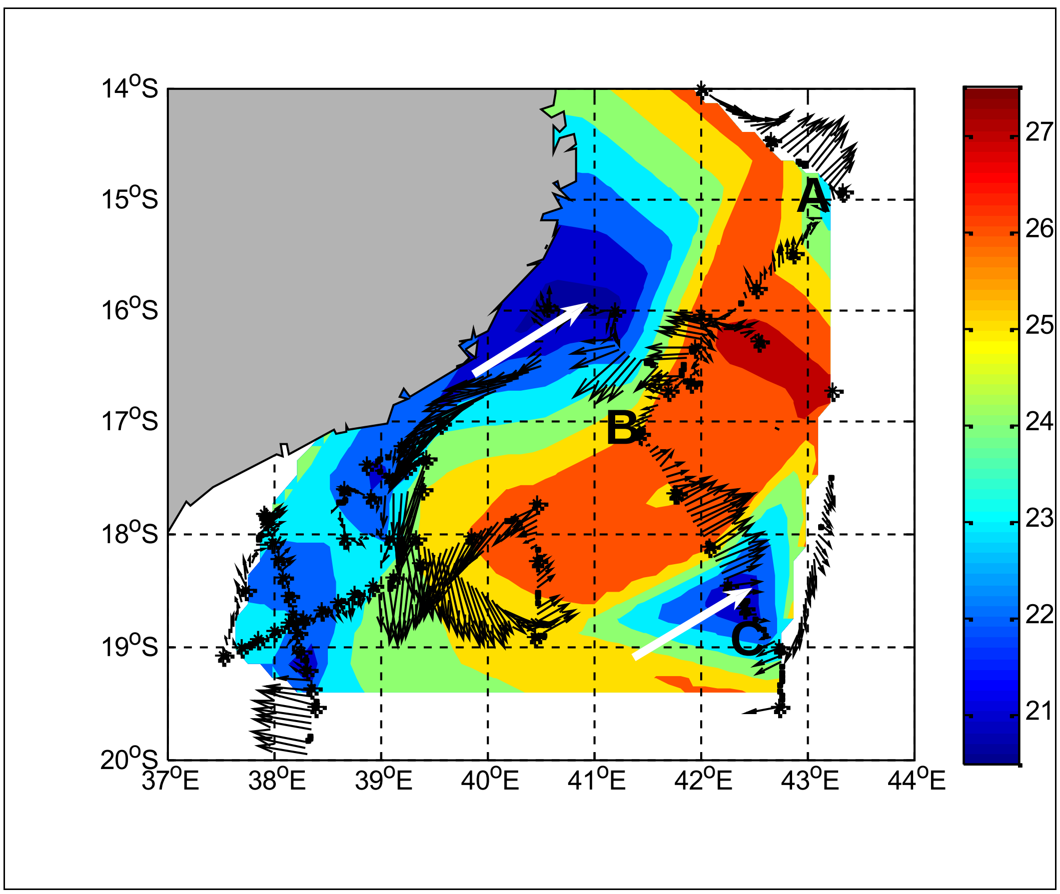


Figure 5.1: Horizontal Temperature distribution at a depth of 50m

In Figure 5.1, 3 cyclones can be identified: A and C, and a cyclone located near the shore, which is centered around 16°S, 41°E. The cyclones have distinct cold waters in the eddy epicenters (white arrows appoints cyclonic eddy centers) and around the eddies. At the cyclone peripheries the temperatures are relatively warm and increase with increasing distance from the eddy centers. The anticyclone B has warm waters in the eddy centre and around the eddy.

In the approximate positions of the cyclonic eddies A and C (stations 1178 and 1195 from Figure 4.2 and 4.3), the thermoclines are located near the surface. In the approximate location of anticyclonic eddy B, the thermocline is displaced from the surface to relatively deep layers. The proximity of the thermoclines to the surface may explain the relatively low temperatures at a depth of 50m in the location areas of the cyclonic eddies.

The current measurements from ADCP along the Mozambique Channel (Fig.4.4a) shows that the flow along the Channel does not have a continuous trajectory, flowing mostly westwards in the northern branch and eastwards in the southern branch.

5.2 Eddy Dynamics

Geostrophic Approximation

An important feature of the response of a rotating fluid to gravity is that it does not adjust to a state of rest, but rather to a geostrophic equilibrium. The oceanic circulation is a result of a balance of forces. If the Coriolis force acting on moving water is balanced by a horizontal pressure gradient force, the current is said to be in geostrophic equilibrium and is described as a geostrophic current (Brown et. al, 1989).

$$fu = -\alpha \frac{\partial p}{\partial y}, \qquad fv = \alpha \frac{\partial p}{\partial x}, \qquad \alpha = \frac{1}{\rho} \tag{1}$$

Derived from the equation of motion:

$$\frac{d\vec{v}}{\partial t} = \frac{\partial \vec{v}}{\partial t} + \vec{v} + \nabla \vec{v} = -\frac{1}{\rho}\nabla p - 2\vec{\Omega} \times \vec{v} + \vec{g} + F \tag{2}$$

And assuming that friction is negligible

Where:

f is the Coriolis parameter

u,v are the velocity components

∂p is the pressure gradient

$\partial x, \partial y$ are the space shift

g gravity

ρ water density

Ω angular velocity of Earth rotation

F friction and other forces

Differentiating equation (1) with respect to z gives:

$$\frac{\partial}{\partial z}(fu) = -\alpha \frac{\partial}{\partial z}\frac{\partial p}{\partial x}, \qquad \frac{\partial}{\partial z}(fv) = \alpha \frac{\partial}{\partial z}\frac{\partial p}{\partial y} \tag{3}$$

Changing the order of differentiation and using the hydrostatic equation $\frac{\partial p}{\partial z} = -\rho g$, gives:

$$\frac{\partial}{\partial z}(fu) = \alpha \frac{\partial}{\partial x}(-\rho g), \qquad \frac{\partial}{\partial z}(fv) = \alpha \frac{\partial}{\partial y}(\rho g) \tag{4}$$

And the thermal wind equations:

$$\frac{\partial}{\partial z}(\rho f u) = -g\frac{\partial \rho}{\partial x}, \qquad \frac{\partial}{\partial z}(\rho f v) = g\frac{\partial \rho}{\partial y} \quad \text{and} \quad \frac{\partial}{\partial z}(\rho f V_H) = -g\frac{\partial \rho}{\partial n_H} \qquad (5)$$

V_H is the total horizontal velocity ($V_H = (u^2 + v^2)^{\frac{1}{2}}$) and η_H is the distance perpendicular to the vector V_H.

Integrating the thermal wind equation from the surface to a 200m depth and assuming that at 200m the current velocity is zero:

$$\int_{-200}^{z}(\rho f u)dz = -g\int_{-200}^{z}\frac{\partial \rho}{\partial x}dz \qquad (6)$$

Assuming u(200)=0 gives the following equation for the geostrophic velocity profile

$$u(z) = -\frac{g}{\rho f}\int_{-200}^{z}\frac{\partial \rho}{\partial x}dz \qquad (7)$$

The next velocity profiles are based on equation 7, assuming that the velocity at 200m depth is zero. Figure 5.2a shows the vertical geostrophic velocity variations from the CTD measurements along the Mozambique Channel and Figure 5.2b and c shows geostrophic velocity variations from ADCP measurements along the northern Mozambique Channel.

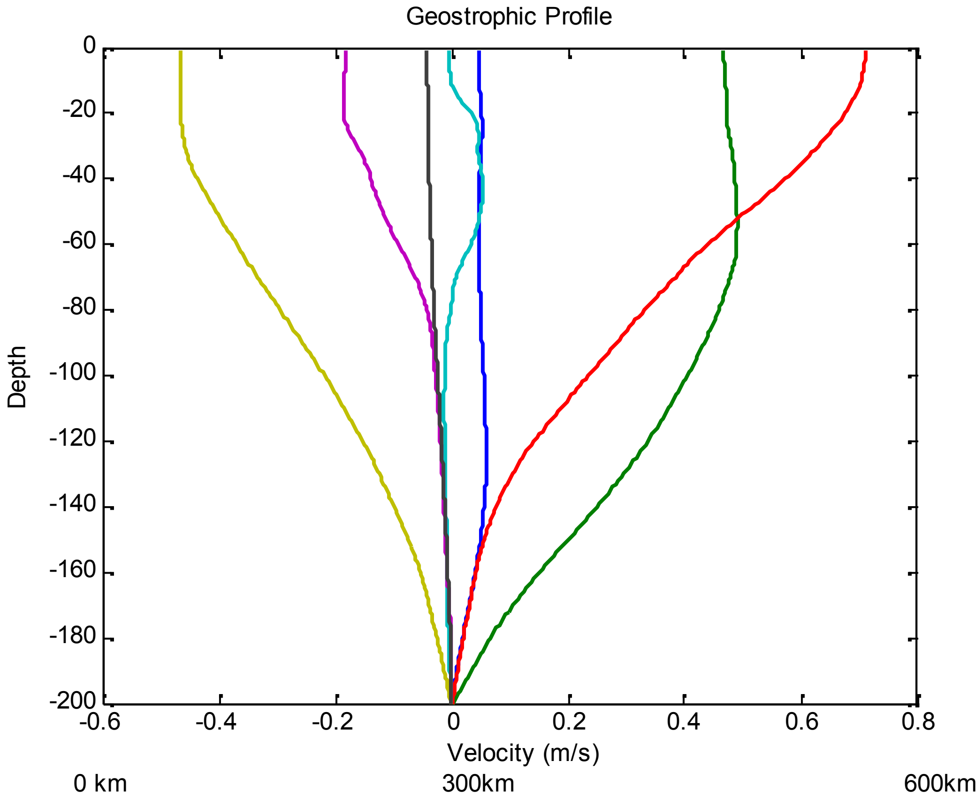
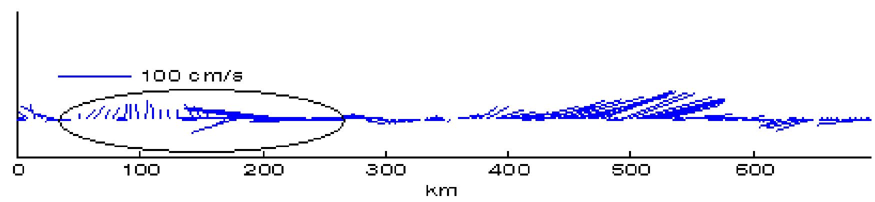


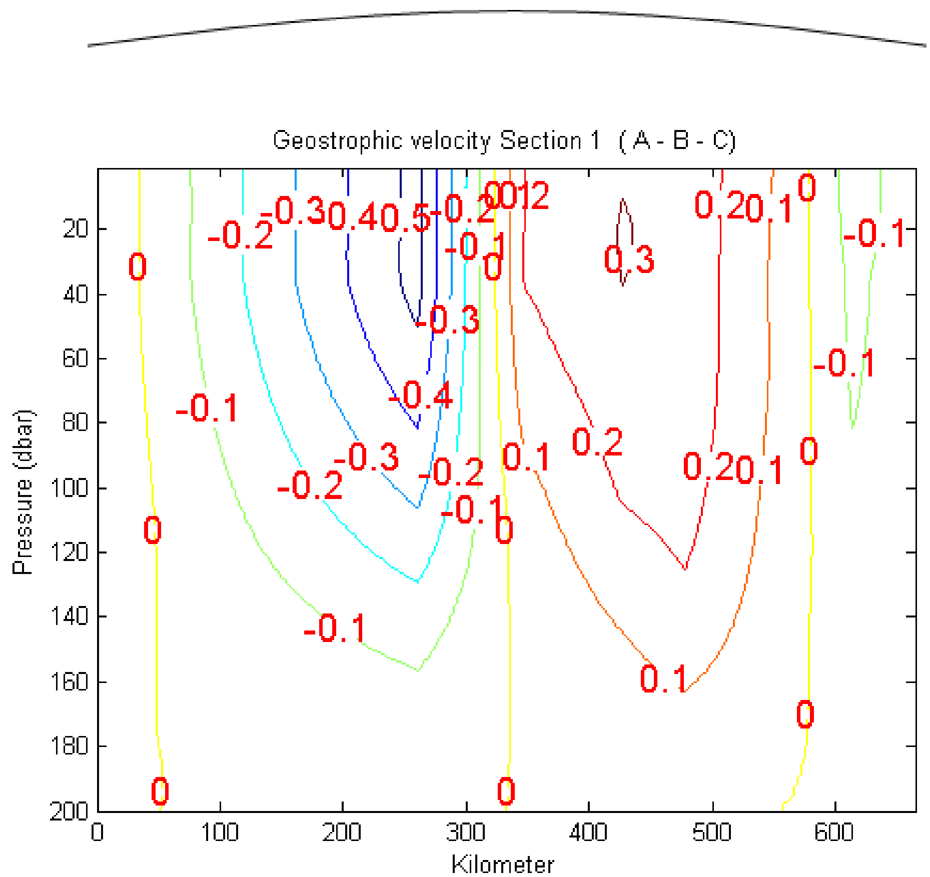
Fig 5.2 : Geostrophic profile with depth from CTD measurements at Section1

In Figure 5.2, the geostrophic velocity profiles are shown. The currents are directed westwards from 0m to 300km, directed eastwards from 300km to 600km, decreasing from 0.7m/s to 0m/s, from the surface to the reference depth of 200m and being null at the eddy centre.

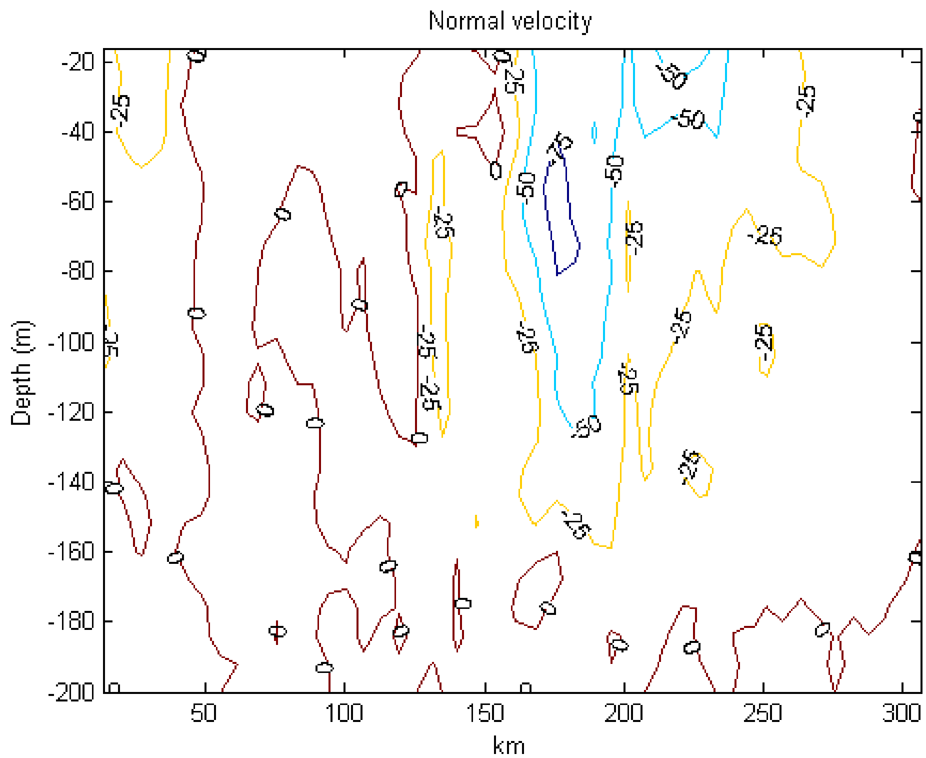
Figure 5.3 compares the CTD geostrohic profile with the ADCP cross-sectional current distribution and current measurements at 18m depth.



a) ADCP current measurements at 18m depth



b) Geostrophic velocities for section 1 (A-B-C)



c) ADCP current component normal to section1N (A-B)

Fig 5.3 : ADCP current measurements along the Channel at 18m (a), Geostrophic velocities for section 1 (A-B-C). Negative velocities are westwards (b) and (c) ADCP current component normal to section1N (A-B).

The ADCP current measurements at 18m (Fig.5.3a) shows strong westward current around 200km. Current velocities are near zero at 350km, which corresponds to position B in Fig.3.1, the centre of the anti-cyclonic gyre. Near 500km the currents are again strong but with a component towards east, compare Fig.4.4a.

Fig.5.3b shows the corresponding geostrophic currents which are normal to the section, and it can be noticed that it corresponds quite well with the ADCP measurements. The normal velocity distribution from the surface to the reference depth of 200m, shows negative currents ,to the west from 0m to 300km and positive currents, to the east from 300 to 600km, interspersed by regions of null currents. The currents decrease from the surface to the bottom and from the periphery to the eddy centers, where the velocity is zero. Above the geostrophic section in Figure 5.3b, the curve shows the surface tilt reconstructed. A negative (westward) maximum is found at about 250km; there is zero velocity in the centre of the eddy and maximum eastward current around 450km.

Figure 5.3c shows the ADCP component normal to the section for the northern branch of the eddy (A-B in Fig.3.1). To make a comparison with geostrophy, the velocity at the reference depth (200m) depth has been subtracted. Again we see that it compares quite well, although the observations show stronger westerly currents (-75cm/s) than the geostrophy (-50cm/s).

The comparison of geostrophic currents from Figure 5.3b and Figure 5.3c and the measurements shows that the vertical shear in the velocity is of the same order of magnitude.

For there to be exact geostrophic equilibrium, the flow should be steady and the pressure gradient and the Coriolis force should be the only forces acting on the water, other than the attraction due to gravity. In the real oceans, other influences may be important; for example, there may be friction with nearby coastal boundaries or adjacent currents, or with the sea-floor. In addition, there may be local accelerations and fluctuations, both vertical and horizontal. Nevertheless, within many ocean currents, including all the major surface current systems, the flow is, to a first approximation, in geostrophic equilibrium (Brown et. al, 1989).

If a water parcel is accelerating in any way, the pressure gradient and Coriolis forces cannot be in balance. If the water parcel is in circular motion around a centre of high or low pressure, the parcel is subject to a centripetal acceleration in order to maintain the circular path:

Centripetal acceleration + pressure gradient force + Coriolis force= 0

$$a_c = \frac{v^2}{r}; \qquad (9)$$

$$\frac{u^2}{r} = \frac{1}{\rho}\frac{\partial p}{\partial r} - fu \qquad (10)$$

One of the parameters describing fluid flow is the Rossby number that is the ratio of inertial to Coriolis force.

$$R_o = \frac{\frac{u^2}{r}}{fu} \quad (11)$$

$$R_o = \frac{u}{rf} \quad (12)$$

The Coriolis force, $f = 2\Omega \sin \Phi$ (13)

$$f = 2\frac{2\pi}{T}\sin \Phi \quad (14)$$

Where Φ is the latitude

The period of rotation T is 24 hours

A small Rossby number (R_o<1), indicates that the geostrophic approximation is valid

For the Mozambique Channel eddies:

r is 250km;

f is approximately $5x10^{-5}$ s^{-1}, and

u varies from 0 to 1m/s

Thus, the Rossby number R_o is in the order of 0,1 and the flow in the Mozambique Channel can be considered geostrophic.

Rossby deformation radius

The Rossby deformation radius can be described as the horizontal length scale of a rotating system measuring the distance over which the gravitational tendency to render a free surface flat is balanced by a tendency of the Coriolis acceleration to deform the surface. Or it can also be described as the horizontal extent over which a rotating stratified fluid is affected when disturbed.

In stratified fluid, the appropriate length scale is called the internal Rossby deformation radius, and is given by:

$$Ro_i = \frac{ND}{f} \qquad (15)$$

in which N is the buoyancy frequency and D is a characteristic vertical length scale.

$$N^2 = -\frac{g}{\rho}\frac{\partial \sigma_\theta}{\partial z} \qquad (16)$$

Using the simplified version assuming a 2 layer system, the formula will read:

$$Ro_i = \frac{\sqrt{g'H}}{f} \qquad (17)$$

where H is the thickness of the upper layer and g' is the reduced gravity

$$g' = g(\rho_2 - \rho_1)/\rho_2 \qquad (18)$$

To calculate the Ro_i, two stations crossed by the eddies will be used. The first will be a station with the thermocline located near the surface (station 1178), and the second, a station with the thermocline displaced from the surface (station 1187).
The Coriolis parameter *f* is in the order of $5x10^{-5}$ and gravity g is $9,8m/s^2$.

Station N°	H(m)	$\rho_1(kg/m^3)$	$\rho_2(kg/m^3)$	*g'*	Ro_i
1178	40	1022.5	1025	0,024	19 600m
1187	160	1023.5	1024.5	0,01	25 300m

Thus, the horizontal length scale of the disturbance is nearly 20km for the cyclone and 25km for the anti-cyclones and this result confirms that the eddies scale may be controlled by the Channel size as suggested by Harlander et al., (2009).

5.3 Eddy associated processes: upwelling

Mesoscale features in the Mozambique Channel play a major role in producing and transporting energy in the pelagic realm and thereby strongly support the Channel's life support system (Kaehler et al., 2008). In 2004 Weimerskirch et al., carried out a study about the foraging strategy at sea of frigatebirds breeding on Europa Island (22.3^{o}S, 40.3^{o}E) in the Mozambique Channel using satellite transmitters and altimeters. According to the study, frigatebirds foraged over extensive distances, up to 612 km from the island, usually during the incubation or post-breeding periods, concentrating their effort in the western oceanic waters of the channel where overall productivity, although low, was still higher than in the eastern part of the channel. This delineation would be due to a persistent field of mesoscale anticyclonic gyres composed by 3 major eddies moving slowly southward. These eddies and the associated cyclonic vortices in the westernmost part of the channel could enhance productivity. However birds tended to avoid the centers of the cyclonic eddies where the production was likely to be lower.

Kaehler et al., (2008) found that cyclonic features were defined by strong central upwelling regions in terms of temperature, salinity and oxygen. The central portion of cyclonic eddies also exhibited elevated chlorophyll concentrations, presumably as a result of increased nutrient inputs and primary production. In contrast, anti-cyclonic features exhibited central downwelling and overall low biological biomass. Intermediate boundary zones between the eddies and areas close to the coast, at times also exhibited high chlorophyll biomass.

Offshore eddies would have far-reaching consequences for the coastal environment, for example for the birds and the top-predator fish species such as tuna and swordfish that (from acoustics) seems to aggregate and forage in areas of high eddy induced production.

The next Figures, Figures 5.6a and b, shows the horizontal temperature distribution along Channel at 2m depth and the difference depth 2m-50m. The temperature difference distribution shown below (Figure 5.6b), gives a tentative projection of the temperature distribution as a result of vertical movement of water driven by density differences.

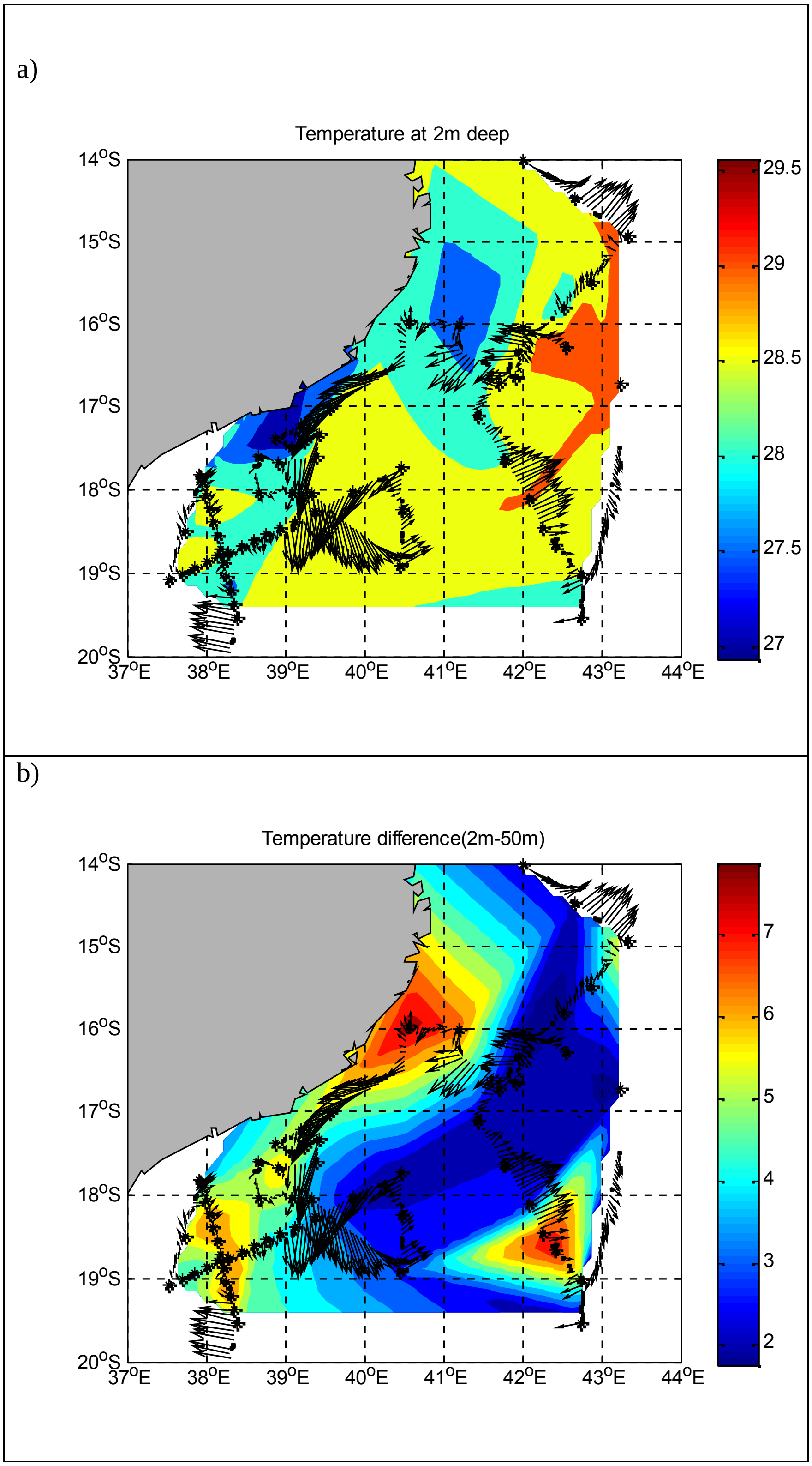


Figure 5.6a and b): Temperature distribution at 2m depth and temperature-difference (2m-50m) distribution along the Mozambique Channel.

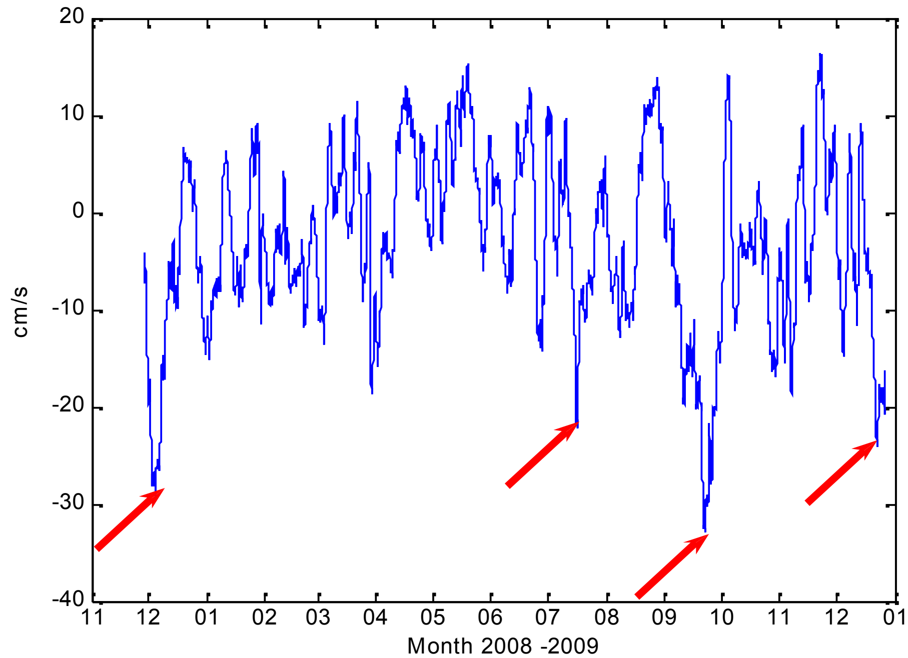
Figures 5.6a shows relatively low temperatures in the location of cyclonic eddy centers and relatively high temperatures for the anticyclone B. Figure 5.6b shows high temperature-differences in the eddy centers and low temperature-differences in the peripheries around the eddy centers. The values observed in the temperature difference based distribution may be evidence of upwelling processes occurring in this region, more specifically in the cyclonic eddy centers and its peripheries where temperature difference values are high.

Weimerskirsch et al., (2004) stated that the cyclonic vortices in the westernmost part of the channel could enhance productivity. This is confirmed by Figure 5.6b, showing that the most expected places for concentration of birds would be the peripheral frontal areas between the cyclonic and anticyclonic eddies, since these are areas of high productivity, induced by the eddies and by the high temperature gradients. On the other hand, in the centers of the cyclonic eddies the production is expected to be lower and anti-cyclonic features exhibit central downwelling.

5.4 Eddy frequency and velocity

Pemba Mooring Measurements

To look for additional evidence of eddies in the Mozambican Channel we present the one year long time series of current measurements obtained at Pemba in Fig.5.7a since the current is mainly oriented along the coast we only show the north-south component. The SeaGuard was situated at 800m depth where the average current was towards the south and the speed occasionally was above 20cm/s, which is rather strong for such depths.



a)

b)

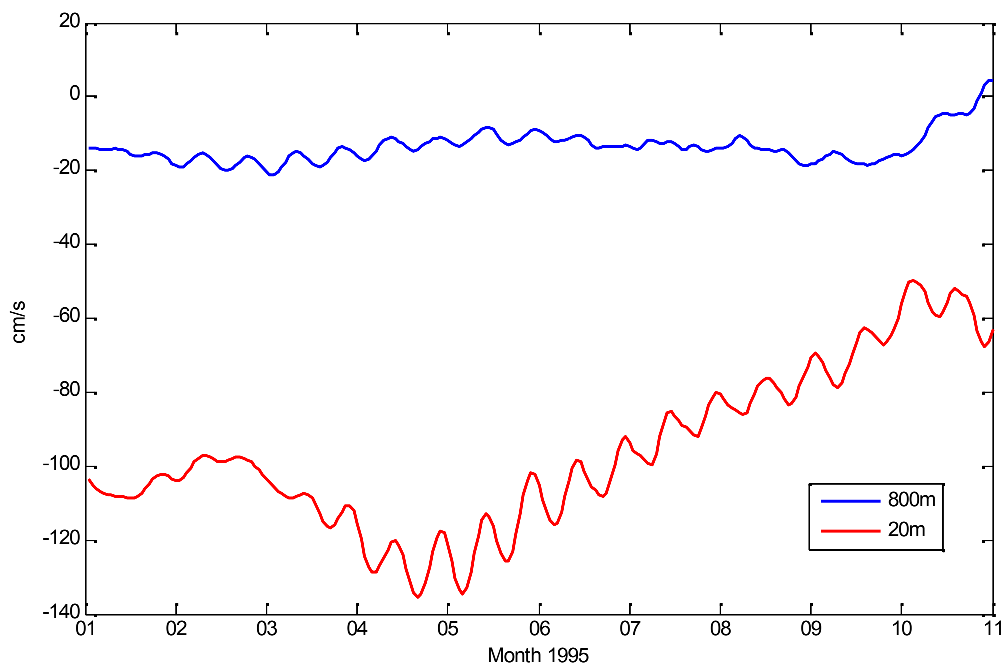


Figure 5.7a and b:Velocity time-series in the northern Mozambique Channel from 2008 to 2009 at a) measurements at 800m and b) modeled at 800m and 20m. The arrows indicate the eddies.

The strong current maxima seen in Figure 5.7a, may be caused by the eddies. Defining that at a depth of 800m a velocity above 20cm/s is caused by an eddy, the velocity time-series show the presence of four eddy events in one year, which compares well with Harlander et al., (2009). The possible eddies are pointed out with arrows.

Using the ROMS model, the available one year velocity data (approximately) from the year 1995 was modeled for 800m and 20m (Fig.5.7b), since ROMS model results were not available for 2008. By using the 1995 data, the model gives a design of the current pattern along the Channel. The upper blue curve shows the modeled current for 800m depth, and as it can be noted, it agrees with the measurements obtained in Fig.5.7a. The current is in average towards the south and seldom above 20cm/s. So this gives some confidence in the model although the model does not reproduce the current maxima defining the eddies.

The red curve in Fig.5.7b represents the modeled currents at 20m depth, and shows that the current at the surface is much stronger, with maximum currents of more than 130 cm/s. So the eddies defined in Fig. 5.7a of more than 20 cm/s may have a surface signal of more than 1 m/s. This concurs with our ADCP measurements which can be seen in Fig.4.4 and Fig.4.5 that show eddy velocities of more than 1m/s.

These magnitudes of currents, in cases of water pollution by oil or any other pollutant can spread the pollutants rapidly to coastal zones, affecting the ecosystem. Also such strong currents may heavily influence navigation and operations at sea, as well as put strong stress on building structures at sea, such as oil rigs.

6. Conclusion

As intended from the objectives, the results of this work aim to describe the eddies, its structure, frequency, magnitude and current direction along the Mozambique Channel.

Considering that a velocity above 20cm/s in a depth of 800m is caused by an eddy, its frequency of occurrence in the Mozambique Channel is four eddy events in one year. These eddies have surface signals of more than 1m/s and the cyclonic and anticyclonic southward migrating eddies that dominate the circulation have wavelengths of 500 to 600 km and 100m of amplitude.

In the cyclonic eddies (divergence centers), the thermoclines are located near the surface while in the anticyclonic eddies (convergence centers), the thermoclines are displaced from the surface to relatively deep layers.

The results show that the horizontal length scale of the disturbance (Rossby deformation radius) is nearly 20km m for the cyclone and 25km for the anti-cyclones; therefore the eddies scale may be controlled by the Channel size as suggested by Harlander et al., (2009).

The currents in the Channel can be considered to be in geostrophic equilibrium, and whereas these geostrophic currents are westward intensified in the northern part of the study area, they are eastward intensified in the southern part, having velocities of more than 1m/s. These magnitudes of currents, in cases of water pollution could spread the pollutant rapidly to coastal zones, affecting the ecosystem. Also such strong currents might heavily influence navigation and operations at sea, as well as put strong stress on building structures at sea, such as oil rigs.

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