The General Hydrography of the Mozambique Channel

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Submitted in fulfilment of the requirements of
the Master of Science degree

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2003

ABSTRACT

The greater Agulhas Current system is believed to form a key link in the global ocean circulation since it is the inter-ocean conduit for warm Indian Ocean water to the Atlantic Ocean. This system has been thought to derive its water from the South Equatorial Current via two sources: the Mozambique Current, and secondly, the East Madagascar Current. In spite of their global significance surprisingly few observations have been made in these source regions.

In March 2000 a multidisciplinary cruise, the first one in 25 years, the Agulhas Current Sources Experiment (ACSEX-1) was carried out in the Mozambique Channel. The main aim of the ACSEX-1 cruise was to establish the existence, trajectory and hydrographic structure of the Mozambique Current. The use of satellite altimetry and numerical modeling revealed high mesoscale activity in the Mozambique Channel. Thus guided by real-time altimetric data, the cruise sections intersected the main regions of high mesoscale activity in the centre of the Channel. From this dataset we are now able to determine whether the Mozambique Current is a continuous current or whether it exists merely of a train of eddies, as the altimetric data suggest.

The results strongly indicate that no intense, coherent, western boundary current exist in the Mozambique Channel. Instead, hydrographic observations have shown that the flow is dominated by a train of large anticyclonic eddies (diameters of 300 km) that reach to the channel bottom. Smaller cyclonic eddies were also identified from the hydrographic data. Several drifters launched during the cruise clearly show the rotating path of water inside the eddies. With the absence of a Mozambique Current, we find that the Mozambique eddies carry heat and salt down the Mozambique coastline into the Agulhas system. Thus, we now believe that these poleward propagating, warm Mozambique Channel eddies provides a significant link in the global ocean circulation system.

ACKNOWLEDGEMENTS

I would like to thank Professor Geoff Brundrit and Isabelle Jane Ansorge for their guidance and support. I would also like to extend a special thank you to my supervisor, Professor Johann Lutjeharms for his time and effort in helping me with this data set, as well as his invaluable advice, suggestions and guidance during this research and the writing of this thesis.

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Chapter 1
INTRODUCTION

Circulation in the southwest Indian Ocean is largely dominated by the anticyclonic sweep of the Agulhas System (Michaelis, 1923; Lutjeharms, 1976). The Agulhas Current itself is a western boundary current flowing close to the South African coast. It has been thought that the surface origins of this current are in the waters of the South Equatorial Current from which a seasonally varying flow branches south to eventually become the Agulhas Current (Lutjeharms, 1976). The southwest Indian Ocean circulation consists of the South Equatorial Current in the north, the Agulhas Current system to the west and the Agulhas Return Current to the south (fig. 1).

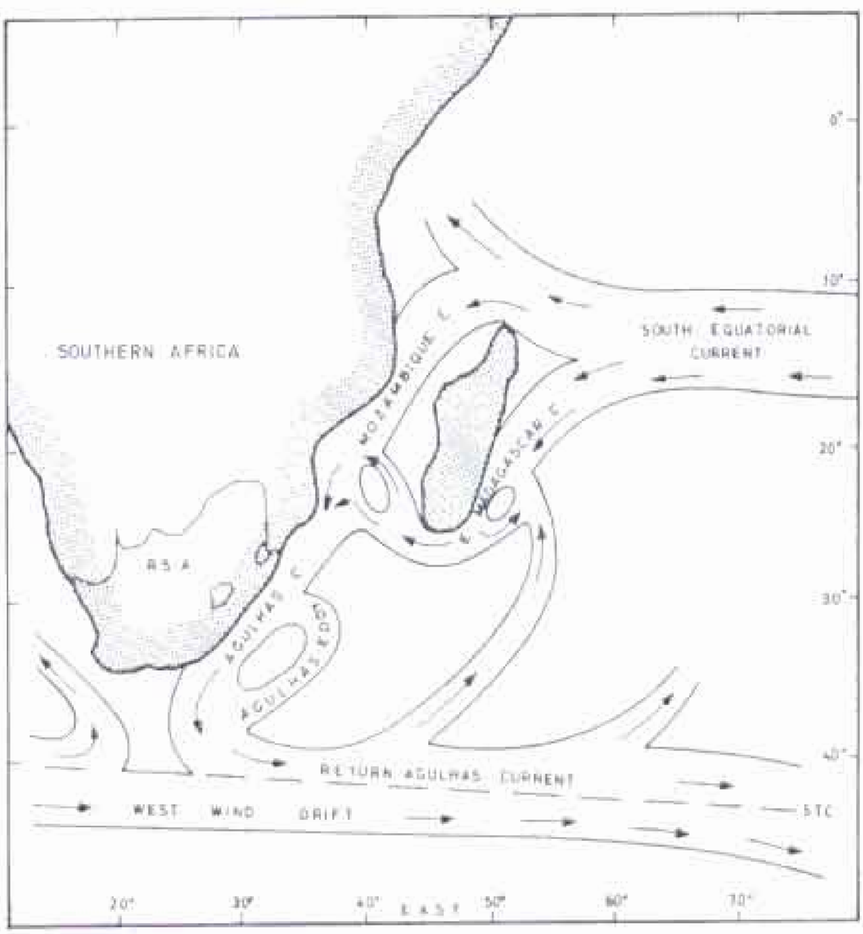


Fig 1.1: The classical concept of the circulation in the southwest Indian Ocean, modified from Duncan (1970).

The southwest Indian Ocean is defined as the region situated between 20° and 40°S and between the African continent and 50°E. This area contains significant bottom features such as the Mozambique, Madagascar and Southwest Indian Ridges separated by adjacent basins (fig 1.2). It is also fringed in part by the African continent and the island of Madagascar.

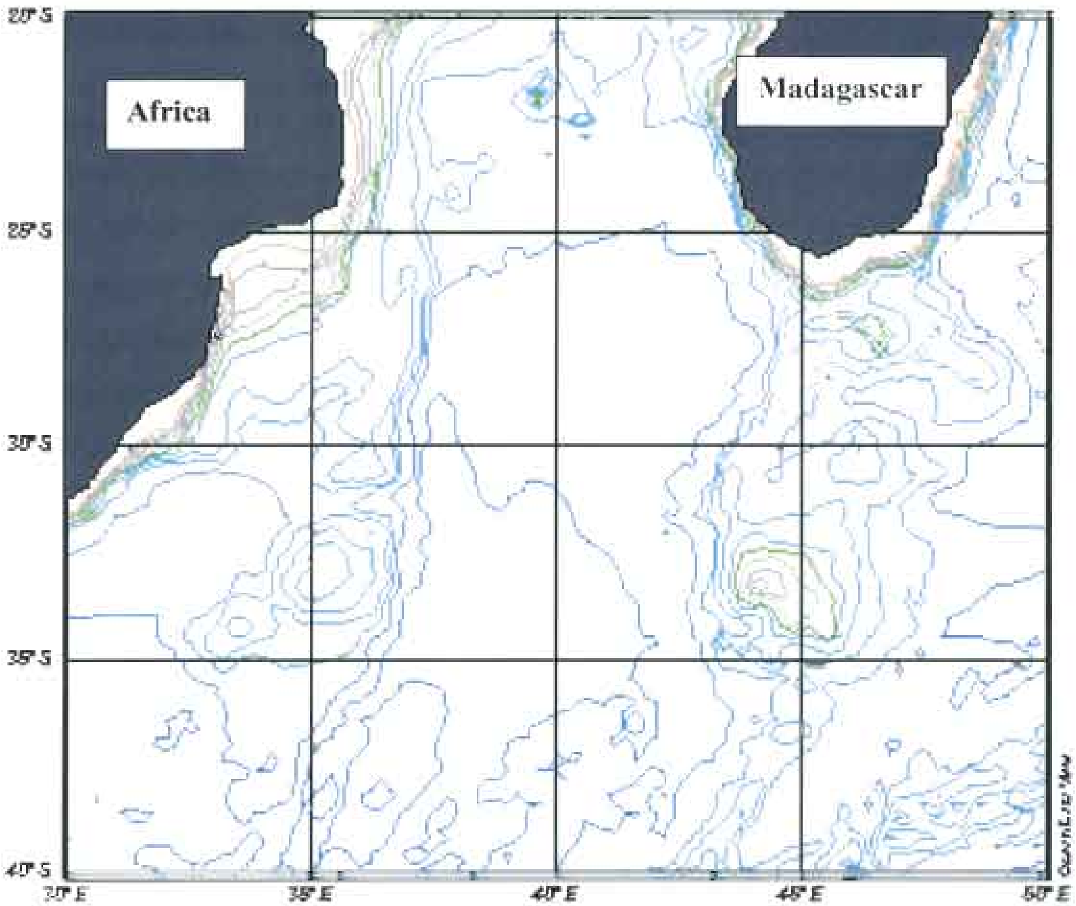


Figure 1.2: The bottom topography of the southwest Indian Ocean

Although geographically only a relatively small fraction of the Indian Ocean, the southwestern part is the most dynamic region and therefore of considerable interest to scientists (fig. 1.3). In the higher-energy regions of the western boundary, where the Agulhas and East Madagascar Currents transport heat and mass southward, the constrained flow, irregular coastline and bottom topography present fertile generating mechanisms for eddies and other mesoscale turbulence (Gründlingh et al., 1991). These circulation features may consist of water masses with quite different characteristics.

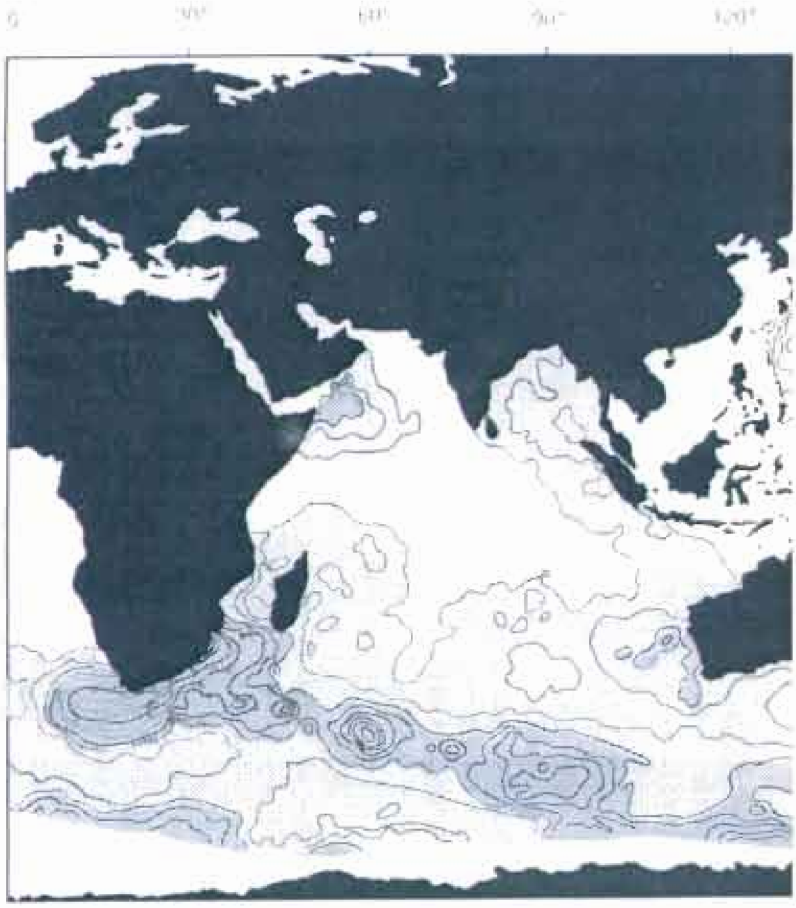


Figure 1.3: Sea height variability as measured by the SEASAT altimeter from 15 September to 10 October 1978. (Modified by Lutjeharms (1996) from Cheney et al., 1983).

The surface layer of the southwest Indian Ocean is dominated by the higher salinity (>35.5) Subtropical Surface Water (fig. 1.4) (STSW; Duncan, 1970). This water mass originates in the subtropical Indian Ocean east of 58°E and between 15 and 35°S. It reaches the southwest Indian Ocean from south of Madagascar, where it comes into contact with low-salinity Tropical Surface Water (TSW, S<35) that propagates southward in the Mozambique Channel (Gründlingh et al., 1991).

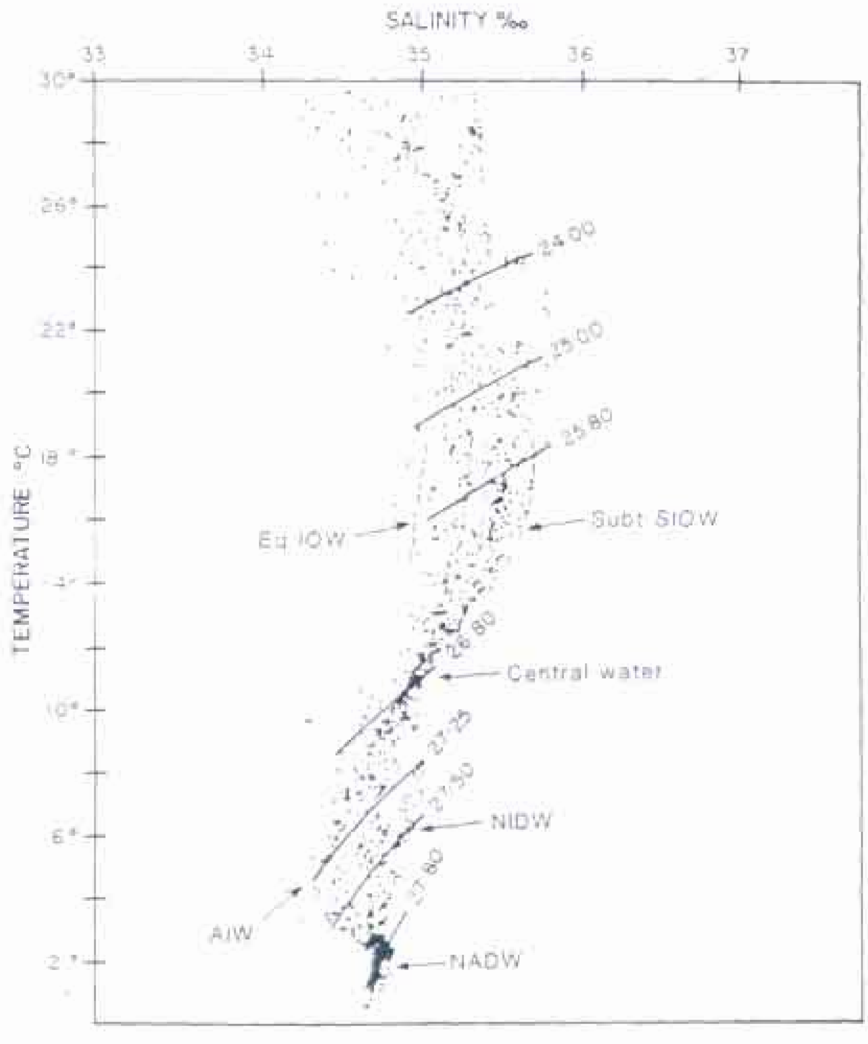


Figure 1.4: A representative temperature - salinity curve for the southwest Indian Ocean (Lutjeharms, 1991).

At about 1000 m, we find a salinity minimum, which signifies the presence of Antarctic Intermediate Water (AAIW, S<34.6). This tongue of low salinity water moves northwards into the south Indian Ocean and returns southwards in an anticlockwise fashion by depth-penetrating flow such as that of the Agulhas Current (Gründlingh et al., 1991). In the north, the southward flowing North Indian Intermediate Water (NIIW, also referred to as Red Sea Water; Gründlingh, 1985; Beal et al., 1999) spreads horizontally through the Mozambique Channel. South of the channel its interaction with AAIW results in a variety of mixing and interleaving processes (Gründlingh, 1985). Sandwiched between STW and AAIW and created from a mixture of these two masses at the Subtropical Convergence, Southern Indian Central Water (fig. 1.4) is recognised by its more-or-less linear TS relationship (Gründlingh et al., 1991).

The leakage of water from the South Indian Ocean into the South Atlantic, via the Agulhas Current, has attracted considerable interest, particularly in the past decade. The reason for this focused research is that this transfer of water between the two oceans is critical in the global heat and salt balance. In addition, the coupled ocean-atmosphere circulation also controls the global climate and climate change. Since the circulation system of the southwest Indian Ocean does seem to play a significant role in the global thermohaline cell, any shortcomings to the argument or gaps in the data in this region may well be important (Lutjeharms, 1996). Such deficiencies do exist. Gordon (1985) has shown that a sufficient flow is maintained through the Mozambique Channel to maintain this component of the global cell. The Mozambique Channel, which separates the African continent from Madagascar, represents an important conduit from the western tropical Indian Ocean to the southwestern Indian Ocean. However, since the continuity of the Mozambique Current is now seriously being called into question (Saetre and Jorge da Silva, 1984; Lutjeharms, 1996), the mechanism by which this transport could take place is unclear. In addition, the sparse hydrographic observations in this area do not give a consistent picture of the feeding of the Agulhas Current.

Furthermore, it has now become abundantly clear that what happens at the Agulhas retroflection is influenced and controlled by what happens much further upstream (Lutjeharms et al., 2000). Therefore, a key aspect in describing and understanding the transport and circulation of the southwest Indian Ocean is to understand the dynamics of the flow passing through the Mozambique Channel. It may come as somewhat as a surprise that the flow patterns of the Mozambique Channel as a whole have last been investigated hydrographically, with antiquated instrumentation and inappropriate station spacing, in the 1950s and 1960s (Menache, 1963). Despite the extensive research undertaken by the World Ocean Circulation Experiment (WOCE) and the International

Indian Ocean Expedition (IIOE) in the Indian Ocean sector, this region (fig. 1.5) is still one of the most poorly investigated ocean regions of the world and this has been the case for more than 25 years (Lutjeharms et al., 2000).

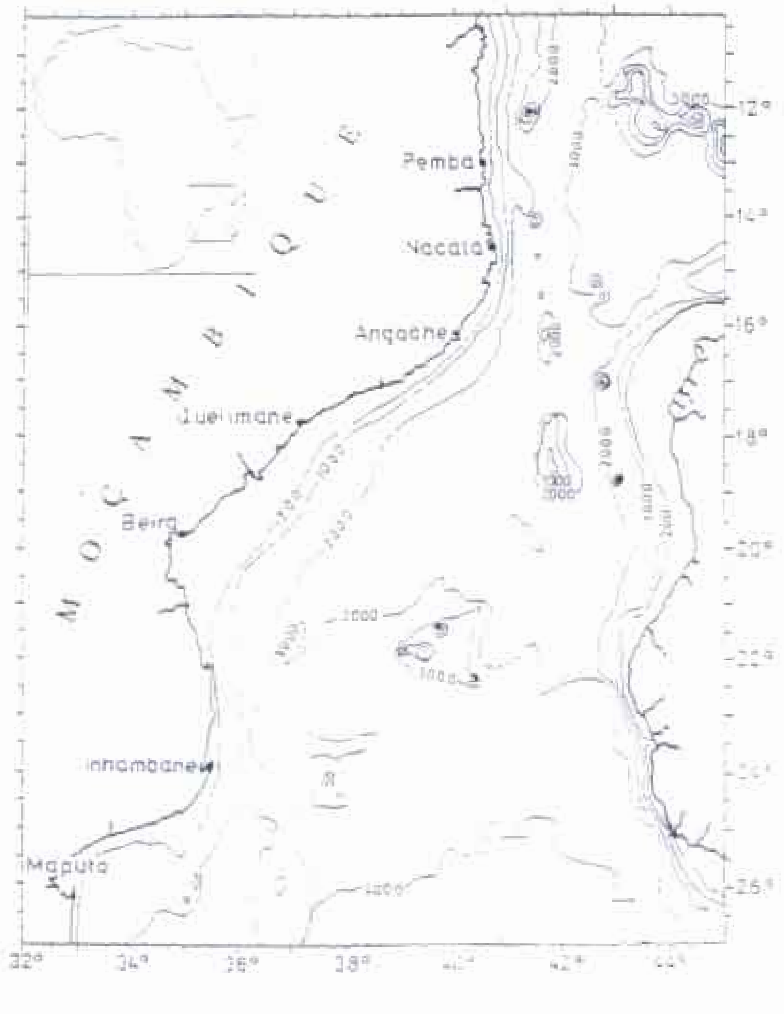


Fig. 1.5: Bathymetric map of the Mozambique Channel (Nehring et al., 1987).

The Mozambique Current is usually considered to be the western limit of the anticyclonic sub-tropical gyre consisting of the South Equatorial Current, the Agulhas Current system and the Agulhas Return Current (Saetre and Jorge da Silva, 1984) (fig. 1.6). The classical concept of a well-defined, continuous western boundary current, the

Mozambique Current, feeding the Agulhas Current, is becoming increasingly unclear. Many questions have now been asked if in fact a continuous flow exists. The concept of a Mozambique Current has been largely based on averages of surface drift (Saetre, 1985) and on sea surface temperatures (Harris et al., 1978). Good hydrographic observations for the Mozambique Channel are exceedingly sparse and are usually confined to coastal regions (Nehring et al., 1987) or to single line of stations (DiMarco et al., 2001).

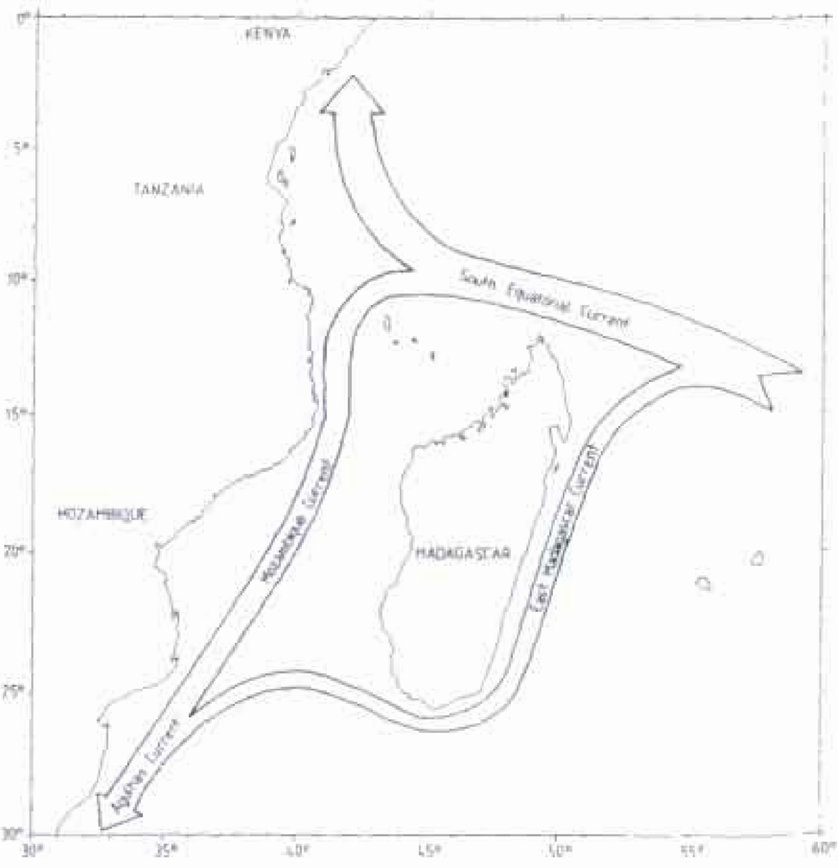


Figure 1.6: The presumed major current system in the area around Madagascar (Saetre, 1985)

A number of hydrographic sections perpendicular to the Mozambican coast have demonstrated the existence of a jet-like current (Schemainda and Hagen, 1983), however, in contrast other surveys have also shown no evidence of such a flow (Soares, 1975; Lutjeharms, 1976). Recent analysis of all existing cruise data yielded no firm conclusions regarding the characteristics of the transport of the Mozambique Current through the Channel (Saetre and Jorge da Silva, 1984).

The northern part of the Mozambique Channel as well as its main source, the South Equatorial Current, is directly influenced by the monsoon (Saetre and Jorge da Silva, 1984). Considerable seasonal variations in velocity and volume transport are therefore to be expected. However, there are conflicting opinions in the available information regarding the seasonal variations of the Mozambique Current (Soares, 1975; Lutjeharms, 1976; Saetre and Jorge da Silva, 1984; Biastoch et al., 1999).

Over the past few years, the argument that the Mozambique Current contributes very little to the Agulhas Current further south has been gaining considerable support (Stramma and Lutjeharms, 1997). It has also been claimed that very little, if any, of the water entering the northern Mozambique Channel actually leaves the Channel at the southern end (Soares, 1975), but instead recirculates through an assembly of eddies (Harris, 1972; Gründlingh et al., 1991). However, in a more recent investigation the southward passage of water through the Channel has again been proposed (Nehring et al., 1987).

Past numerical models have simulated a very small, undeveloped western boundary current, with very little variability, in the Mozambique Channel. In contrast, Biastoch et al. (1999), using the Modular Ocean Model (MOM: Pacanowski, 1996), has shown the generation of anticyclonic eddies at the northern mouth of the Mozambique Channel and their poleward progression down the east coast of the Channel. In addition, analyses of satellite altimetry have also revealed the considerable variability in the Mozambique Channel, indicative of varying current patterns and eddies (Wakker et al., 1990). However, satellite altimetry shows that the variability only starts halfway down the channel, which is in conflict with all numerical models to date (Lutjeharms et al., 2000). Unfortunately, due to the lack of appropriate hydrographic data within the Channel none of the numerical models or even the altimetric observations from satellites can be unambiguously verified, until now.

In March 2000 a multidisciplinary cruise, the Agulhas Current Sources Experiment (ACSEX) was carried out in the Mozambique Channel, the first one in 25 years. The ACSEX sections have been carefully design to intercept the purported trajectory of the Mozambique Current. The cruise sections also intersected the main regions of high mesoscale activity in the centre of the Channel. In this way we are able to verify whether the Mozambique Current is a continuous current or whether it exists merely of a train of eddies, as altimetric data suggests. Secondly, the hydrographic data collected during the ACSEX cruise will also allow us to study the characteristic water properties of the Mozambique Channel.

In order to place these results into proper perspective, it would be essential to establish what has been known about this region and its water circulation up till now.

Chapter 2

South West Indian Ocean: Review of Early Work

Research on this region can be traced back to the 18th Century when Rennel (1778) gained knowledge of the surface currents in this region from analyses of ship's drift. In 1832, he demonstrated that the Mozambique Current and the South Equatorial Current form the sources of the Agulhas Current and the Agulhas Return Flow is given as the dominant continuity flow south of the Agulhas Bank. This work was later confirmed by Kerhallets (1851) chart, which showed the southerly current in the Mozambique Channel and the South Equatorial Current passing the southern tip of Madagascar (fig 2.1). These two streams, the Mozambique and South Equatorial Current, merge near Port Elizabeth to form the Agulhas Current, which then subdivides into a branch entering the Atlantic Ocean and an easterly return current merging with the West Wind Drift at 20°E (Pearce, 1980).

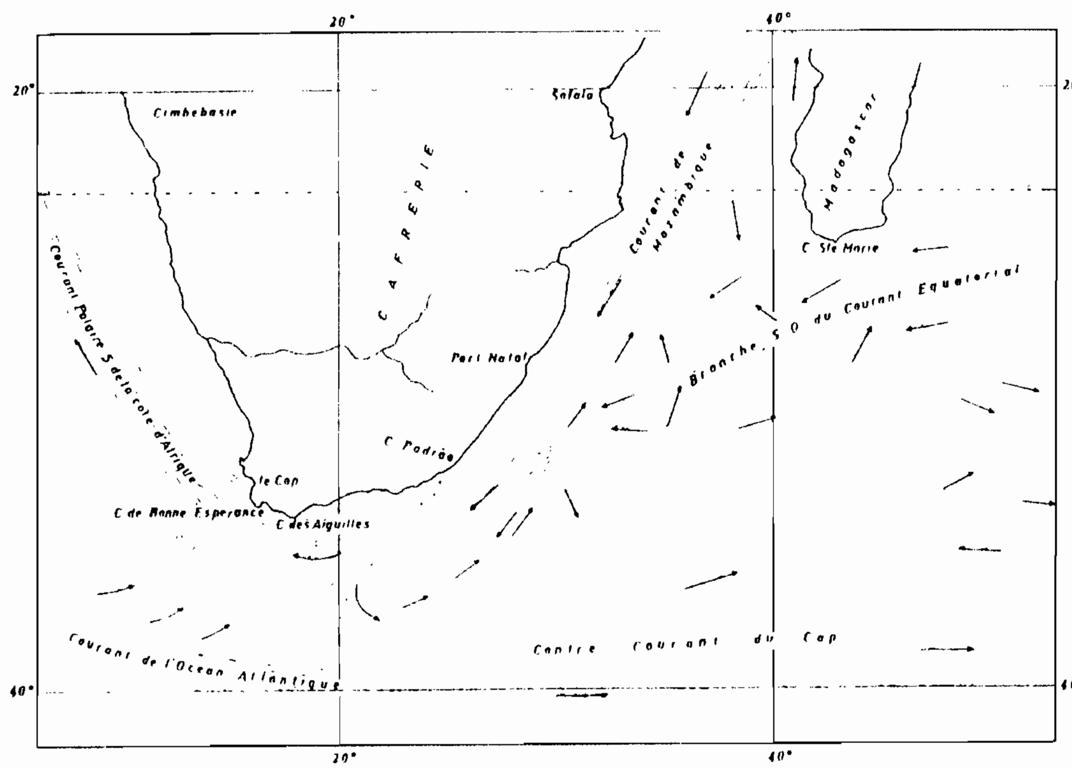


Fig 2.1: Kerhallet's 1851 chart, in which the major circulation elements are depicted (Pearce, 1980)

Petermann's Chart (fig. 2.2) gave further suggestions that the Mozambique and South Equatorial currents merged off the South African coast to form the Agulhas Current. However, unlike Kerhallet's chart where only a single retroflection formed, Petermann's chart showed a series of retroflections between 15°E and 45°. In the southern Atlantic Ocean, the cool northerly flow off the Cape west coast is shown as part of a completely separate current system. The interaction between these two major current systems on the Agulhas Bank results in a confused system of eddies (Described as 'Wirbelungen by Mühry 1864). Despite the limitation of the data, which consisted largely of ship's drift, these 19th century charts were reasonably accurate in depicting the general circulation of the Agulhas Current System.

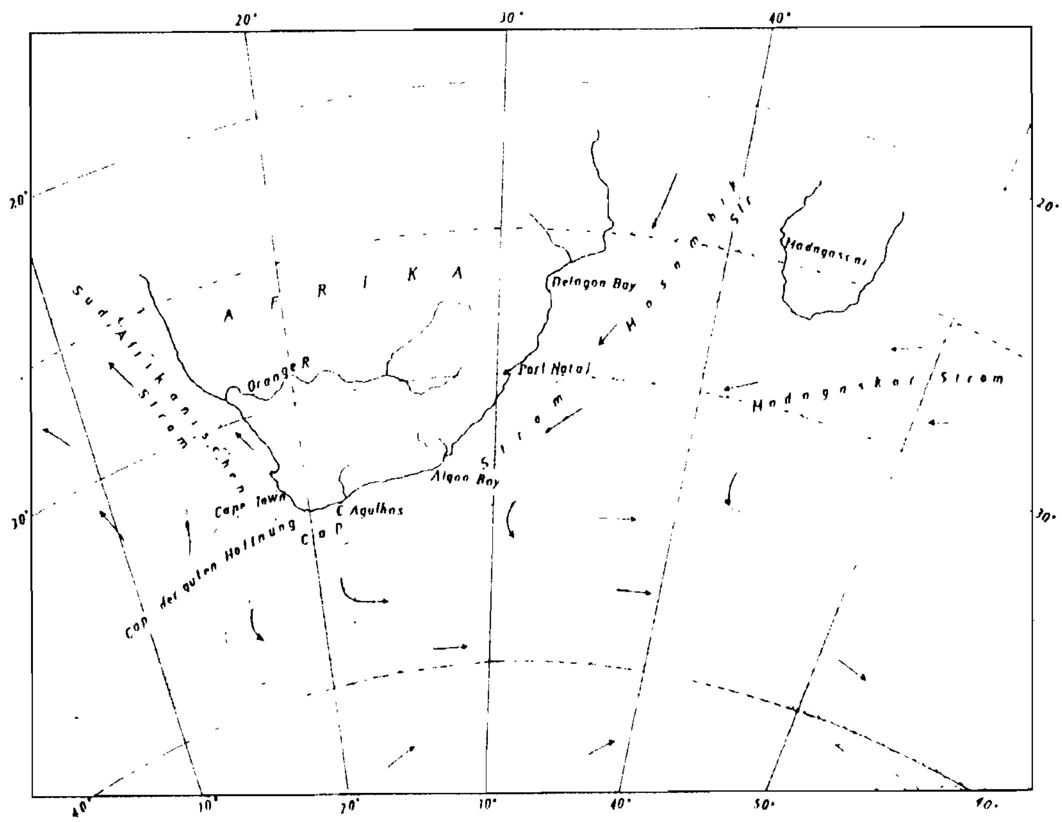


Fig. 2.2: Petermann's (1865) chart of the Agulhas Current System, with a series of easterly return flows and little Agulhas water entering the Atlantic Ocean (Pearce, 1980).

Brennecke (1915), making use of the data collected during the Planet cruise of 1906 and the Möwe cruise of 1913, described temperature and salinity measurements made across the Mozambique Channel, for the first time, taken at depths greater than a 1000 m. He showed that a temperature differential existed across the Mozambique Channel with warmer water next to the African coast and colder water on the east side of the Channel. He related this to the Mozambique Current and a current entraining colder water as it proceeds northwards. For the first time enough data of a scientific nature was now available to make possible some conclusions about the nature of the large scale ocean regime relying on more than ship's drift and extending deeper than just the surface (Lutjeharms, 1972).

Following on this discovery Michaelis (1923) made a study on the variation in current directions and speeds during the two Monsoon seasons. He also tried to relate these to the surface isotherms and winds (Lutjeharms, 1972). This fundamental, but important work of Michaelis (1923) provided information on the Agulhas Current water. He also presented a general picture of how the various currents fitted together in the southwest Indian Ocean. He showed that the South Equatorial Current divided into approximately equal branches in the vicinity of Mauritius, one branch leading southward and the other toward the northern tip of Madagascar, the latter causing a narrow and intense current to pass the island. Passing Cape d'Ambre, the northern branch continues straight on towards the African Coast where it again divides; some going north to meet head on the south going Somali-current and to flow east as the return flow, the rest, hugging the coast, flowing south as the Mozambique Current (Lutjeharms, 1972). However, in an attempt to relate the surface isotherms with his current analysis, he found that no correlation existed in the Mozambique Channel. This he assumed was due to the lack of data. In 1926, Peach succeeded in extending the findings of Michaelis (1923) by plotting surface isotherms to show the variation in surface currents over a year in the vicinity of 0°S-30°E and 30°S-62°E.

Recently, the flow in the Mozambique Channel and especially its continuity and input to the Agulhas Current have been addressed. In contrast to previous opinions that the

Mozambique Current continues more-or-less coherently in the Agulhas Current (Duncan, 1970), it has lately been claimed that very little, if any, flow passes southward through the channel (Soares, 1975). Instead, many scientists now believe that the Mozambique Current consist of a train of intense anticyclonic eddies (Lutjeharms, 1976; Saetre and Jorge da Silva, 1984). Modelling studies and altimeter observations from satellites have shown no evidence of a Mozambique Current. Instead, we observe considerable variability in the channel, indicative of varying current patterns and eddies. Unfortunately, the lack of data prevents an accurate validation of both datasets.

Mozambique Channel

Surface Currents and Surface Water Masses

Menache's (1961, 1963) important contributions on the currents in the Mozambique Channel followed on the cruises of the *Robert Giraud* in 1957 and the ORSOM I campaign in 1958 (Lutjeharms, 1972). In contrast to previous studies Menache showed, from dynamic topography, that the Mozambique and Agulhas Current are not continuous. He claimed that during October and November 1957 the water transported by the Mozambique Current turned back at the southern mouth of the Mozambique Channel and flowed north along the western side of Madagascar.

Although Menache (1963) has found no evidence of a continuous, consistent Mozambique Current, there are other authors that have demonstrated the existence of a jet-like current. In April 1964, the *Almirante Lacerda* carried out a cruise in the Mozambique Channel. This data was used by Lutjeharms (1968) to construct maps of the dynamic topography and isentropic surfaces at various depths. In contrast to Menache, he showed that the Mozambique Current flows southwards past Maputo. Additional evidence that the Mozambique Current existed was provided by Crepon (1964), who published the only extensive results of Geomagnetic Electro Kinetograph (GEK) measurements in the Indian Ocean. He showed that the Mozambique Current was quite clearly identified in the Mozambique Channel. However, at the northern mouth of the Channel he found no sign of the Mozambique Current although measurements continued to 30 miles offshore.

Nehring et al. (1987) and Schemainda and Hagen (1983) calculated geostrophic surface velocities within the Mozambique Current. They found that the highest surface velocity (257 cm/s) within the Mozambique Current was observed in the region between 14°S and 16°S. According to Nehring et al. (1987), the Mozambique Current represents an oceanic jet stream in this region. However, south of 16°S, in the area of SE trade winds, the geostrophic surface velocities generally decrease with increasing latitude.

However, the more recent work of Saetre and Jorge da Silva (1984), who examined all existing hydrographic data, could find no evidence of a continuous Mozambique Current nor do they support the classical concept of the Agulhas Current as an extension of the Mozambique Current. Soares (1975) reached a similar conclusion for the southwest monsoon season. He stated that the Mozambique Current, already poorly defined at the surface, lacks continuity below 250 m. A similar conclusion was also reached by Lutjeharms (1971) for the sub-surface circulation during the northeast monsoon season. Duncan and Schladow (1981) and Saetre (1985) gave further support for this interpretation. By using ships drift observations, Duncan and Schladow (1981) found two discrete regions of high current speeds; one between 10 and 20°S and another south of 30°S. Saetre (1985) identified three separate areas of high average current speed and directional stability may even be taken as support for the concept of a non-continuous Mozambique Current.

Water Masses and Deep Water Movement

In 1929, T/S plots were used for the first time to identify water masses in the Mozambique Channel. Möller (1929) made use of data gathered from all previous exploratory cruises and discussed the water masses present according to temperature and salinity parameters. For the first time Antarctic Intermediate Water and Red Sea Water were observed lying between 500 and 1000 m depth in the Mozambique Channel. Her work was, however, severely hampered by the non-uniform distribution of stations. After World War I, newly developed techniques considerably increased the accuracy of temperature and salinity measurements enabling the full water column to be studied. Using these techniques, Thomsen (1933) argued that Möller`s (1929) identification of a thick layer of North Indian Deep Water, continuing at a depth of 200 m to 3000 m to the southern Subtropics, could not be supported by the new temperature and salinity methods. Möller (1933), however, disagreed with Thomsen's (1933) findings and defended her conception of the flow of the North Indian Subtropical Water below the Antarctic Intermediate Water reaching to nearly 20°S. It was not until 1935 when the observations of Clowes and Deacon (1935) threw some new light on this question. They decided that the flow as represented from their data is a compromise between the portrayals by Möller and Thomsen. The high salinity water found below 2000 m, south of 25 °S, is due to Atlantic Deep Water circling eastwards around Cape Agulhas and not due to North Indian Deep Water (Lutjeharms, 1971). By using the oxygen distribution they clearly point out that the influence of the North Indian Deep Water does not terminate at 20°S but is clearly shown to reach latitudes of 35 °S, where it is sandwiched between Antarctic Intermediate and Atlantic Deep Water. They also observed that due to changes in conditions at its origin, the volume and salinity of the North Indian Deep Current are subject to large variation.

Nonetheless, in 1935 Thomsen carried his research even further and discussed at length the origins and movements of some of the major characteristic water masses of the Indian Ocean (Lutjeharms, 1972). He showed that Red Sea Water originates in the Red Sea where it has a salinity of 40 and a temperature of 23 °C and flows into the Indian Ocean at about 800 m. It mixes with the surrounding water and very soon forms only about 10% of the water mass that continues as the salinity maximum (35,35) and oxygen minimum (0,62 ml/l) at 9,8 °C (Lutjeharms, 1972). The influence of this water is restricted to the western side of the ocean and does not extend further south than the northern part of the Mozambique Channel. Antarctic Intermediate Water (34,2 and 5 °C), on the other hand, forms in the antarctic and subantarctic zones and constitutes a salinity minimum at about 1000 m. Tracing this water in its northern movement across the ocean, he found that it is being diluted rapidly as it passes through the Mozambique Channel. According to Thomsen (1935), the depth of the salinity minimum decreases swiftly after it passes Madagascar showing its rising up over the Red Sea Water.

In the 1960's more work was done on the deeper layers and their movement as more deep station data become available. Zaklinskii (1963) investigated the deep circulation of water making use of Mamayev's theory and determination of the level of no motion in the Indian Ocean (Lutjeharms, 1971). Using these methods he found, at 1500 m, a general west-east flow away from Madagascar, a large anticyclonic eddy northeast of Madagascar and a cyclonic eddy in the northern mouth of the Mozambique Channel. At 2000 m he found that the east-west flow remains, but the two eddies are reversed in direction. He believed that the bottom topography has a considerable effect on this circulation.

Taft (1963) carried out an analysis of the Southern Ocean, including the Indian Ocean, using the isentropic method on the 26,81, the 27,07, the 27,28 and the 27,49 sigma-t surfaces. He found that low-oxygen highly saline water penetrates southward through the Mozambique Channel. In 1976, Lutjeharms carried out a similar isentropic investigation, but restricted his research area to the South West Indian Ocean and limited the time interval for his investigation to the Northeast Monsoon Season. His analysis showed that at sigma-t 26,80 there is no continuous flow through the Mozambique Channel (fig. 2.3).

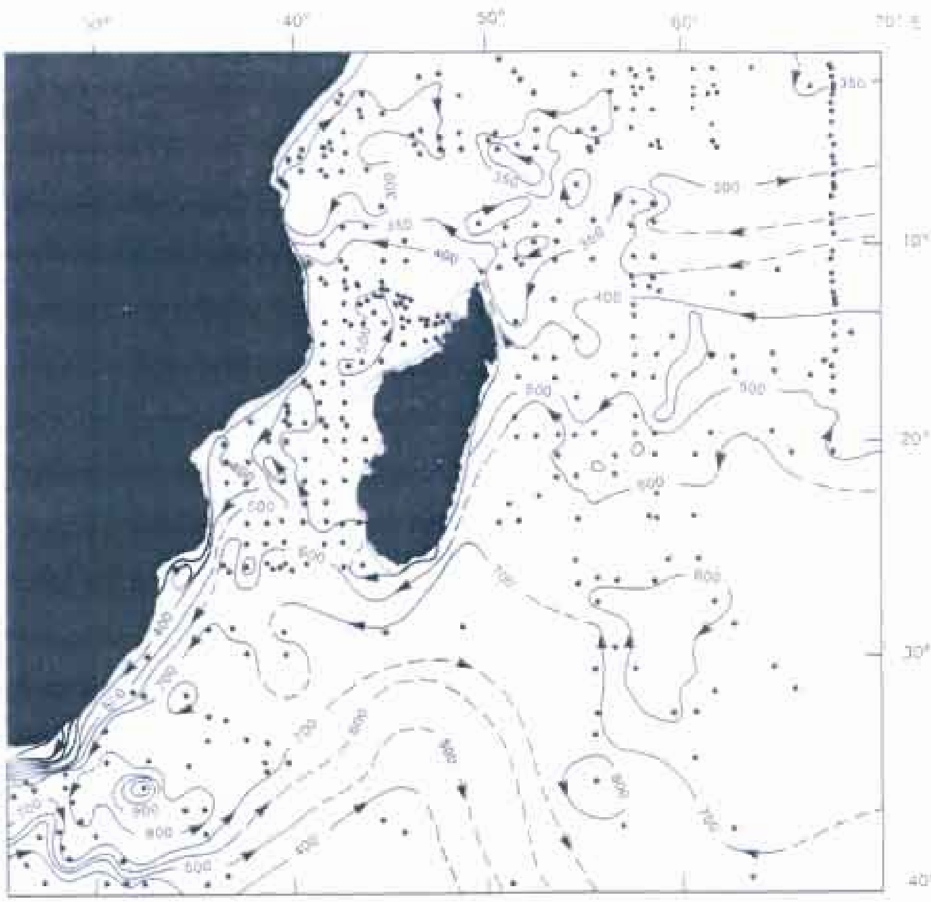


Figure 2.3: Circulation in the southwest Indian Ocean during the Northeast Monsoon season as expressed by the depth of the 26.80 sigma-t surface. Contouring intervals are at every 100 m, except for one 350 m contour to clarify some features. Hydrographic stations on which the analysis is based are shown as dots. (Modified after Lutjeharms 1976).

The Mozambique Current then derives all its water from the East Madagascar Current that flows past Cape St. Marie recurving back into the channel and feeding the Mozambique Current at about 18 °S. At greater depths his analysis shows that the East African Coastal Current has disappeared and the circulation north of the South Equatorial Current, as also in the Mozambique Current, is indistinct, existing of numbers of disjointed eddies (Lutjeharms, 1976).

Circulation Patterns in the Mozambique Channel

Recent analysis in the Mozambique Channel found that the transport through the Channel may have a seasonal cycle (Biastoch et al., 1991). Donguy and Piton (1969) described the surface circulation in the northern mouth of the Mozambique Channel and showed a variation in circulation from season to season. They found that during summer an anti-clockwise circulation around the Comore Islands was noticeable, while during winter months the water of the upper layers seemed to come from more southerly parts of the Mozambique Channel. Soares (1975) analyzed data from the southwest monsoon season in 1960 and 1962 and concluded that only a small part of the water entering the northern Mozambique Channel actually left the channel at the southern end. Lutjeharms (1976), using all the available data from the northeast monsoon season, concluded that the major source of inflow into the Agulhas Current is the Mozambique Current during this season.

In 1984, using all existing cruise data to date (historical and recent data), Saetre and Jorge da Silva (1984) presented a circulation pattern for the upper layer of the Mozambique Channel for two seasons (fig. 2.4).

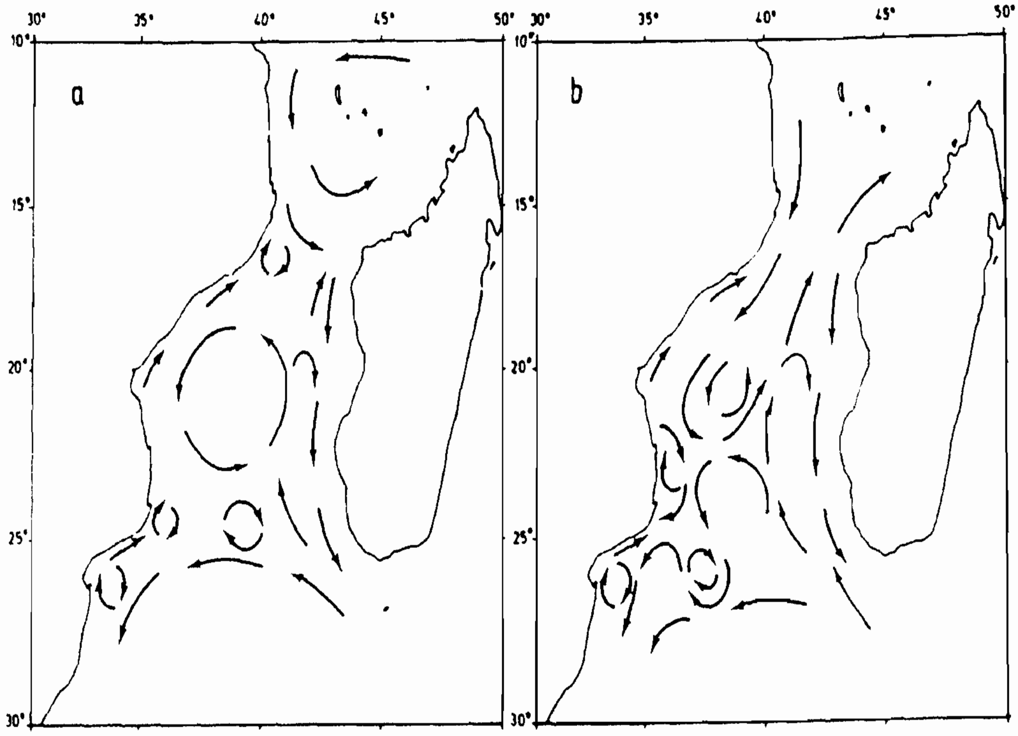


Fig. 2.4: Tentative circulation patterns in the upper layers of the Mozambique Channel. (a) November to April, (b) May to October (Saetre and Jorge da Silva, 1984)

Saetre and Jorge da Silva (1984) suggested that the constriction of the Channel at 16 °S causes much of the initially southward flow to be returned northwards in the form of an anticyclonic gyre, especially in summer. In winter (fig. 2.4b), this gyre moves southwards to protrude into the centre part of the Channel where it interacts with mesoscale flow patterns into the region.

Numerical Models and Altimetric Observations

Due to the lack of appropriate hydrographic data in the Mozambique Channel, many authors have relied on numerical models and altimetric observations from satellites to observe flow patterns in the Mozambique Channel. Numerical models on the whole simulate a very small, undeveloped western boundary current, with very little variability, in the strip of ocean where the Mozambique Current is suppose to lie (Lutjeharms, 2000). There are existing models that cover this region but these are either global (Thompson et al., 1997; McClean et al., 1997) and therefore not practical for running sensitive studies, required for separating single problems, or are not eddy resolving.

In contrast to other models, Biastoch and Krauss (1999), using the high-resolution Modular Ocean Model (MOM: Pacanowski, 1996), showed the generation of anticyclonic eddies at the northern mouth of the Mozambique Channel and their poleward motion down the east coast of the channel (fig. 2.5). In their model, they could track the relatively shallow eddies (estimated to reach only 400 m deep) until 34 °S, where the Agulhas separates from the coast (Schouten et al., 2001). There the eddies disintegrate in the model but still cause an extra interoceanic transport (Biastoch and Krauss, 1999). Such a transport pulse might control the timing of the ring shedding at the Agulhas Retroflection (Schouten et al., 2001). The origin of these modelled eddies was attributed to local barotropic instability of the modelled South Equatorial Current (Biastoch and Krauss, 1999). According to Biastoch and Krauss (1999), these eddies are responsible for drastic enhancement of heat transfer from the Indian Ocean to the South Atlantic.

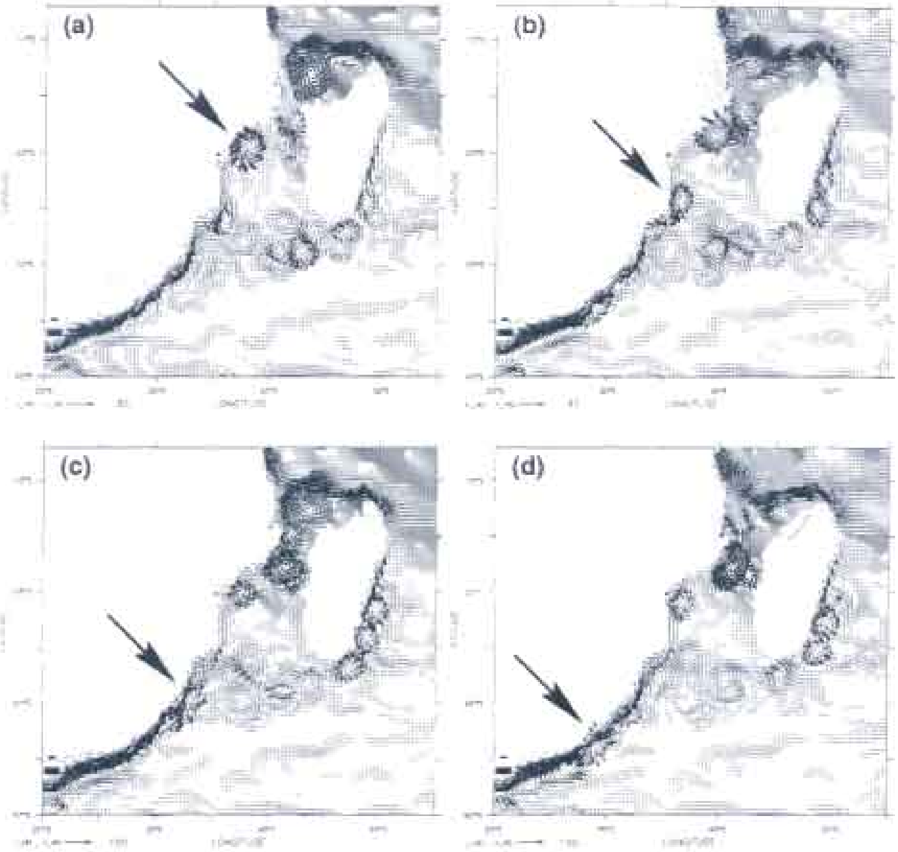


Fig. 2.5: Velocity vectors in 41-m depth for model days 30 Aug 31, 20 Oct 31, 19 Nov 31, and 10 Dec 31. Note the marked eddy (Biastoch and Krauss, 1999).

The development of satellite technology has provided further impetus in the study of the flow patterns in the Mozambique Channel. The use of modern satellite altimeter imagery has revealed considerable variability in the Mozambique Channel (fig. 2.6). Mesoscale eddies and meanders are one of the dominant sources of flow variability in the ocean. Suitable observational coverage of eddies in space and time is severely limited by the difficulty of sampling using conventional ship borne instruments (Snaith and Robinson, 1996). The advent of satellite altimetry and a combination of satellite platforms has facilitated the study of such processes, particularly in parts of the ocean otherwise difficult to reach (Ansorge and Lutjeharms, 2002). This has started with the launching of the European Space Agency (ESA) satellite ERS-1 in 1991, the TOPEX/Poseidon (T/P) mission in 1992 and ERS-2 in 1995. These two missions, which have been flying concurrently since mid-1992, have provided complementary data sets. T/P is a highly precise altimetric mission dedicated to large scale sea level monitoring (fig. 2.6), while the observations from ERS-1 and ERS-2 are less precise, but have denser spatial coverage. As a result, the combination of the two data sets allows the highly accurate mapping of ocean variability with excellent spatial and temporal coverage (Le Traon et al., 1995).

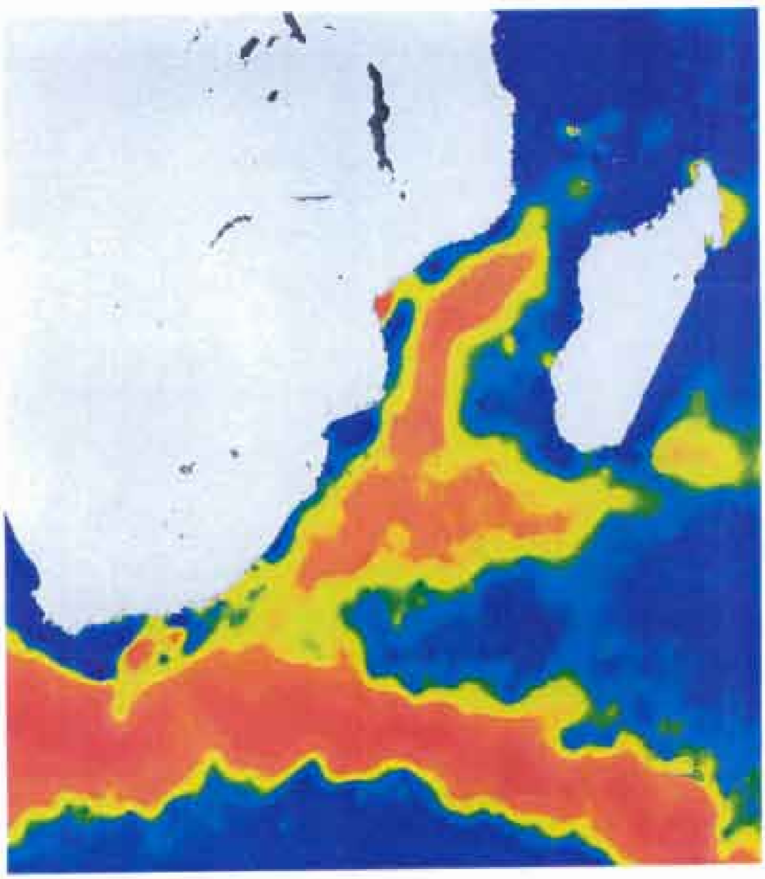


Figure 2.6: Sea Level variability in the Southwest Indian Ocean. This information is from the altimeter onboard the TOPEX/Poseidon satellite for the period 1992 to 1998. Red indicates more intense eddy activity in the ocean (Lutjeharms et al., 2000).

However, the measured variability from satellite altimetry only starts halfway down the channel, which is in conflict with all numerical models to date (Lutjeharms *et al.*, 2000). Unfortunately, the reliability of information received from these models on the Mozambique Current is seriously impaired by the very small number of observations.

Conclusions

Although the Indian Ocean has been extensively studied through the IIOC and WOCE programs, the Mozambique Channel remains surprisingly poorly investigated. Furthermore, due to the sparseness of hydrographic data in this region, an uncertainty exists about the general circulation pattern in the Mozambique Channel. Several authors present theories on a steady circulation in the Mozambique Channel that were inconsistent with one another (Soares, 1975 (fig 2.7a); Saetre and Jorge da Silva, 1984 (fig 2.5); Donguy and Piton, 1991(fig 2.7b).

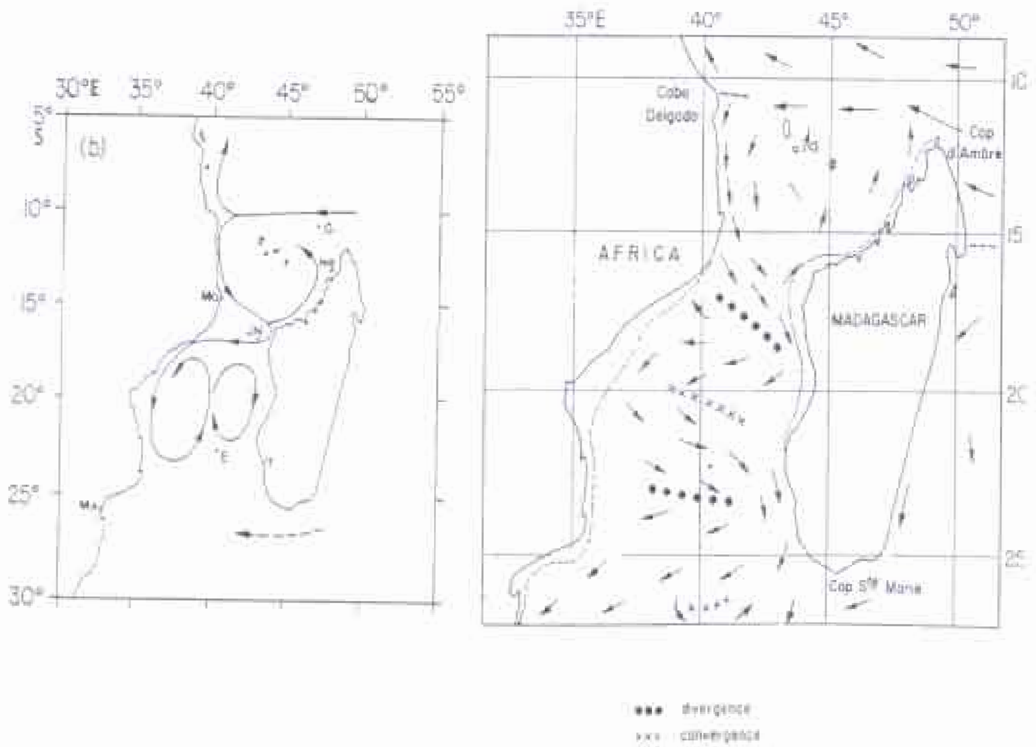


Figure 2.7: Surface circulation in the Mozambique Channel: a) scheme submitted by Soares (1975). Meteorological and tide gauge stations are located on this map: G, Glorieuses Islands; JN, Juan da Nova; E, Europa; MO, Mozambique Island; NB, Nosy-Bé; MA, Maputo; T, Tulear; b) scheme presented by Donguy and Piton (1991).

However, these authors are in agreement that the dominant circulation in the channel is clearly anticyclonic. Some, however, support the theory of a nonpermanent circulation in the channel (Harris, 1972). Biastoch and Krauss (1999), however believe that the discrepancies in the hydrographic data can only be explained by a nonpermanent circulation and the occurrence of eddies in the Mozambique Channel.

In summary, it seems that the overall impression from the historical literature is of a very variable region, with a general southward net flow. However, it is evident from this review of the existing literature that a number of key questions on the circulation in the Mozambique Channel still remain unanswered mainly as a result of sparse hydrographic sampling. In the next chapter, we intend to identify some of these questions and deal with them in more detail.

Chapter 3

Research Objectives

The greater Agulhas Current system forms a key link in the global thermohaline circulation since it is the inter-ocean conduit for warm Indian Ocean water to the Atlantic Ocean (Lutjeharms et al., 2000). The Agulhas Current was thought to derive its water from the South Equatorial Current via two sources: the Mozambique Current, flowing through the Mozambique Channel along the east coast of Mozambique, and secondly, the southern branch of the South Equatorial Current (the East Madagascar Current). According to Gordon (1985) the Mozambique Channel is considered an important part of the chain.

In the last few decades, however, the exact mechanism of this influx has become a point of contention in this oceanic region. Menache (1963) contended that in the months of October and November 1957, the water transported by the current turned back at the southern mouth of the Mozambique Channel. It then flowed north along the western side of Madagascar. With the help of modern satellite imagery and numerical modelling, scientist now believe that the Mozambique Current may not exist but that it recirculates through an assembly of large anticyclonic eddies (Saetre and Jorge da Silva, 1984; Gründlingh et al., 1991). Unfortunately, the reliability of information received from these models on the Mozambique Channel is seriously impaired by the very small number of hydrographic observations. Great uncertainty therefore remains about the role of the Mozambique Current. Furthermore, it is also now believed that events occurring at the Agulhas retroflection region are influenced and controlled by what happens further upstream (Lutjeharms et al., 2000). In spite of their global significance, surprisingly few hydrographic observations have been carried out in these source regions.

Although a considerable number of hydrographic stations between Africa and Madagascar exist, no firm conclusions regarding the characteristics of the transport of the Mozambique Current through the Channel have been made. One of the main reasons for this is the manner in which data have been gathered over the years. As a result, a number of open key questions arise:

1) Does a continuous, consistent Mozambique Current along the shelf edge of Mozambique exist?

The classical concept of a well-defined, continuous western boundary current, the Mozambique Current, feeding the Agulhas Current, has been in existence for a long while and is shown in all contemporary ocean atlases. It has however been questioned in the past (Menache, 1963) and many questions have now been asked if it in fact does exist? A number of hydrographic sections perpendicular to the Mozambican coast have demonstrated the existence of a jet-like current (Schemainda and Hagen, 1983; Nehring et al., 1987), but in contrast other surveys have also shown no evidence of such a flow (Soares, 1975; Lutjeharms, 1971; Saetre, 1985). Saetre and Jorge da Silva (1984) have examined all existing hydrographic data and could not reach any firm conclusions regarding the characteristics of the transport of the Mozambique Current through the Channel.

2) Does the Mozambique Current consist of a train of eddies?

There are many authors that have shown evidence that a continuous, consistent Mozambique Current does not exist, nor do they support the classical concept of the Agulhas Current as an extension of the Mozambique Current (Lutjeharms, 1971; Soares, 1975; Saetre and Jorge da Silva, 1984). These authors have instead suggested that a range of eddies of various sizes circumscribe the circulation in the channel. However, there are still conflicting opinions about the general circulation pattern in the Mozambique Channel. Several authors present theories on a steady circulation in the Mozambique Channel that were inconsistent with one another (Soares, 1975; Saetre and Jorge da Silva, 1984; Donguy and Piton, 1991). However, these authors are in agreement that the dominant circulation pattern in the channel is clearly anticyclonic.

Analysis of tracks of surface drifters as well as studies using satellite altimetry (Wakker et al., 1990) and numerical modelling (Biastoch and Krauss, 1999) have shown no evidence of a consistent, continuous Mozambique Current. Instead they have revealed considerable variability in the Mozambique Channel, indicative of varying current patterns and intense anticyclonic eddies. Unfortunately, the lack of data prevents an accurate validation of both datasets.

3) What are the characteristic water properties within the Mozambique Current?

The distribution of water masses in the Mozambique Channel have been investigated by Clowes and Deacon (1935), Lutjeharms (1971) and Saetre and Jorge da Silva (1984). At least five various water masses have been identified within the channel in the last decade: Equatorial Surface Water (ESW), Subtropical Water (SW), Central Water (CW), Antarctic Intermediate Water (AAIW) and North Indian Intermediate Water (NIIW).

The ACSEX-1 cruise collected observations, which will seek to answer these three open key questions.

Using modern hydrographic data, surface drifters, satellite altimetry and geostrophic current observations we are now able to verify whether eddies exist in the channel. We will also be able to verify whether TOPEX-ERS and MODAS altimetry represents specifically eddies in this region. The hydrographic data obtained during the ACSEX-1 cruise will also be used to determine, in more detail, the various water masses in the Mozambique Channel and its movement through the channel. In addition, a detailed analysis of the currents water structure will also be looked at by grouping the hydrographic stations according to T/S diagrams.

In order to achieve the correct answers to the key questions proposed above, the correct methodology in the analysis of the data has to be employed.

Chapter 4
Methods

In order to address the above research questions, the hydrographic data collected during the Agulhas Current Sources Experiment (ACSEX) cruise have been analysed (fig. 4.1). Combine, the XBT and CTD datasets, collected during this cruise, provides an extensive coverage of the Mozambique Channel, roughly between 25 °S - 15 °S and 35 °E - 45 °E.

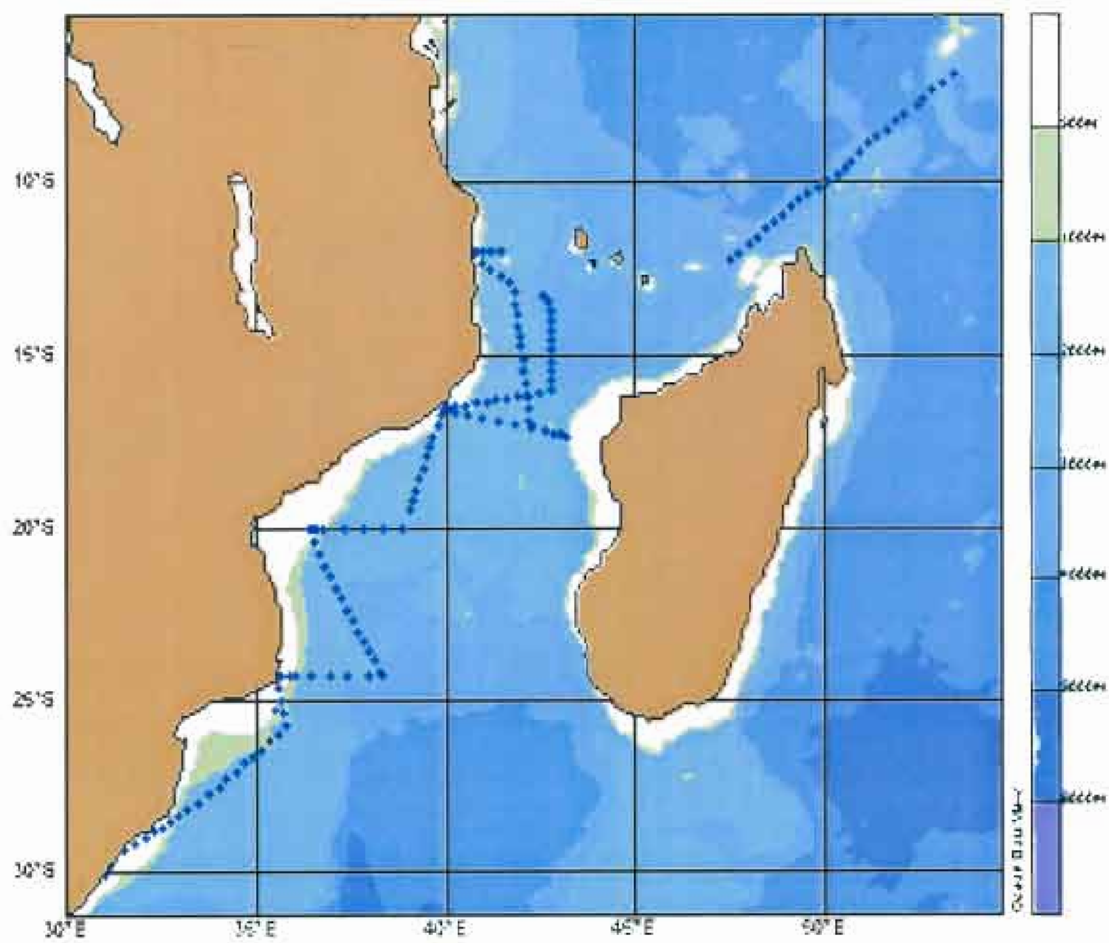


Fig. 4.1: The distribution of all CTD and XBT cruise tracks used during this investigation.

This survey was carried out on board the Dutch research vessel *Pelagia*, between 13 April and 20 May 2000. This cruise formed part of the 'Pelagia around Africa' programme, which is part of the Dutch contribution to the international CLIVAR programme. The cruise was funded by the Institute for Marine and Atmospheric Research of Utrecht University (IMAU) and the Netherlands Institute for Sea Research (NIOZ).

The purpose of the ACSEX cruise was specifically designed to intercept the purported trajectory of the Mozambique Current between Mozambique and Madagascar, roughly between 25 °S - 35 °E and 15 °S - 45 °E. This survey therefore provided the unique opportunity to carry out an investigation aimed in the Mozambique Channel.

The ACSEX cruise consisted of 41 closely spaced CTD (conductivity-temperature-depth) stations that span the Mozambique Channel, thus enabling the geostrophic velocity and volume transport to be accurately calculated. Several XBT (expendable bathythermograph) lines were also undertaken as they fill geographic gaps between the CTD cruise tracks.

Hydrographic sections

CTD - sections I, II and IV run from the African shelf to the center of the Mozambique Channel; the main section III crosses the entire channel at its narrowest width (fig. 4.2). The distance between stations varied from 5 nautical miles on the continental slope to 30 over the central region of the channel. At standard depths of 4000 m, 2500 m, 1500 m, 1000 m, 800 m, 600 m, 400 m, 200 m, 100 m, 50 m and 10 m bottle samples were obtained to determine nutrient and oxygen concentrations.

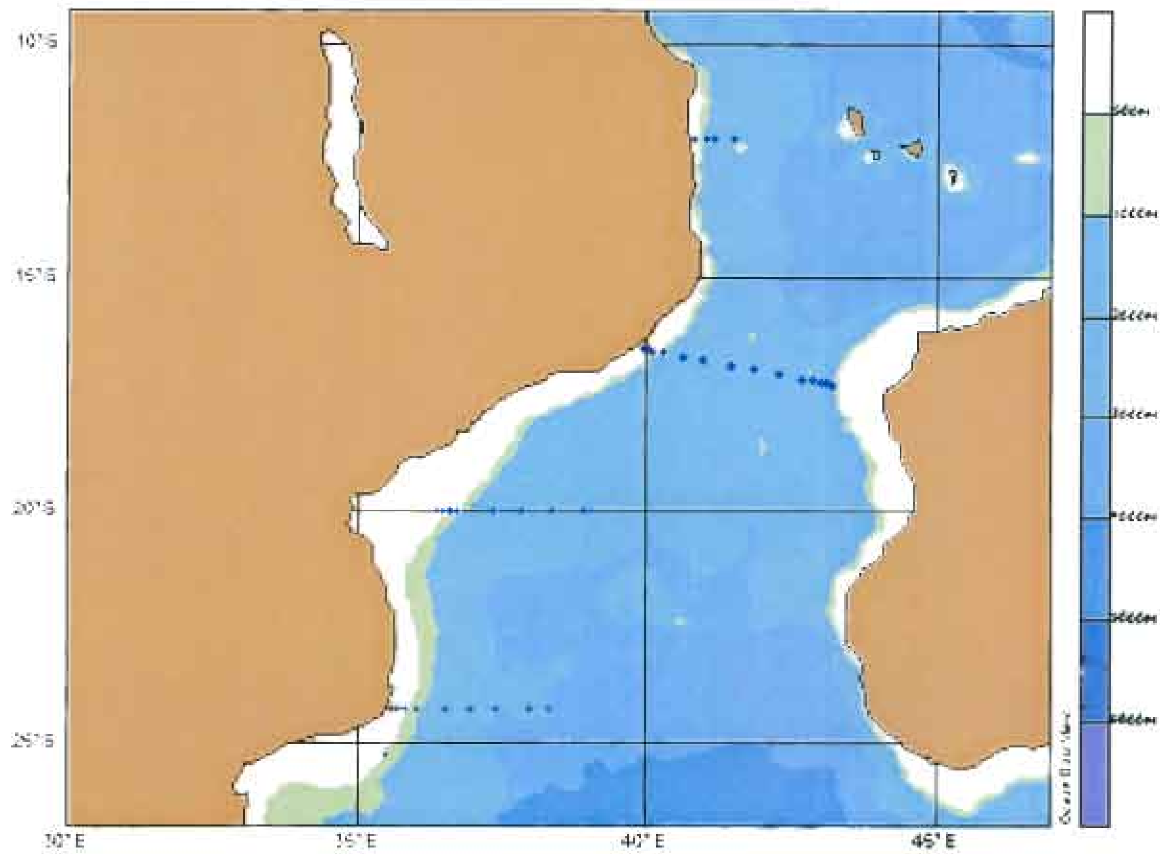


Fig. 4.2: The distribution of the CTD stations occupied during this cruise.

The Pelagia CTD/Rosette contains a Seabird 911 CTD, with additional electronic sensors on fluorescence (Chelsea Instruments Aquatracka MKIII), K-meter (PAR light attenuation), a transmissometer and a Seapoint STM OBS. The CTD samples at a 24 Hz rate. The Rosette holds 22 12 l water bottles. An ADCP is attached to the CTD frame to measure the current profile.

XBT

Approximately 142 XBT's were deployed during 2-hour intervals between each hydrographic section (fig. 4.3). XBT stations were sampled to a maximum depth of 760 m. No acclimatization was required as the difference between the probe's storage temperature and that of the sea surface temperature were minimal.

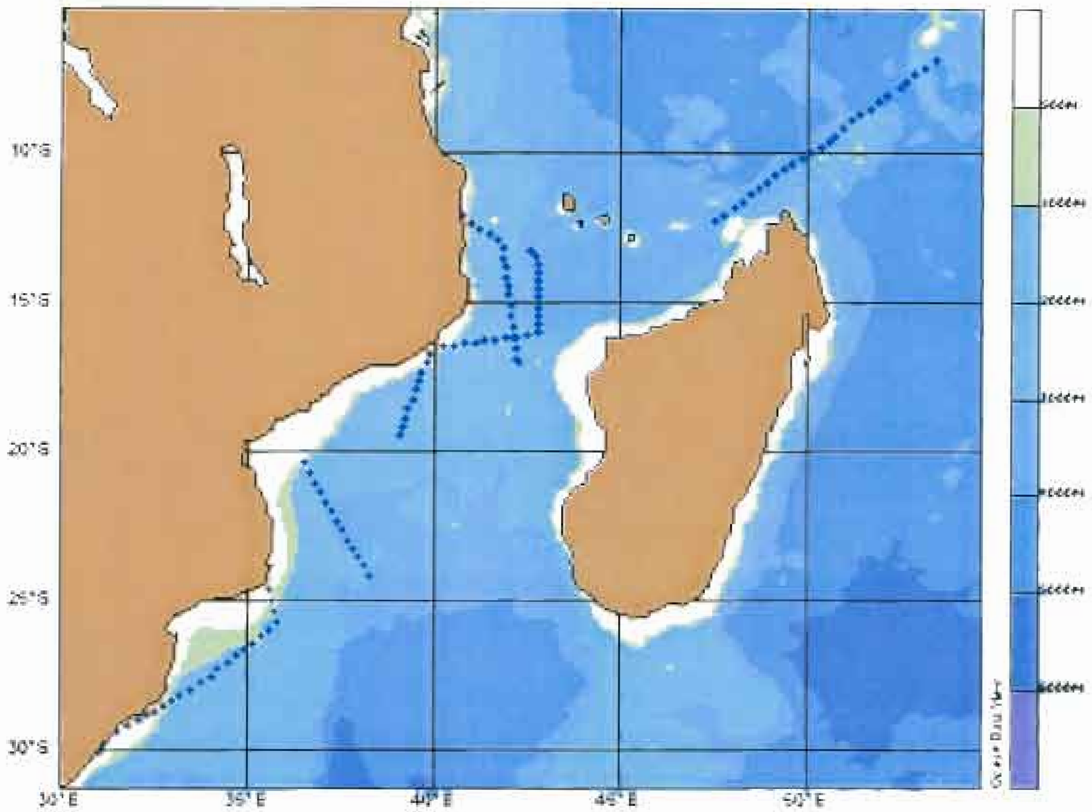


Fig. 4.3: The position of the XBT transects occupied during this cruise.

Surface Drifters

Seven Argos surface drifters were also placed in various parts of the channel were eddies were thought to occur. These drifters were tracked by satellite and their trajectories will give added information of the behavior of features that have been identified from the hydrography. All the drifters had a drogue, centered at a depth of 15 meters, to eliminate wind effects on the drifters and make them better current followers. These drifters can typically transmit for about 1.5 years, although some have lasted 5 years. All drifters transmit data via Argos receivers aboard the National Oceanic and Atmospheric Administration's (NOAA) two operational Polar Orbiting Environmental Satellites (POES). Data is formatted by Argos for global distribution to operational forecast offices and ocean/atmosphere modeling centers by the Global Telecommunications System (GTS). To encourage drifter deployments, oceanographers have added barometers and wind sensors to the drifters. In addition, the data provided by Argos drifters are useful in current measurement, oil spill or floating debris tracking, discharge dispersement calculations and similar studies. These drifters and the location information are generously made available by the NOAA Atlantic Oceanographic and Meteorological Laboratory.

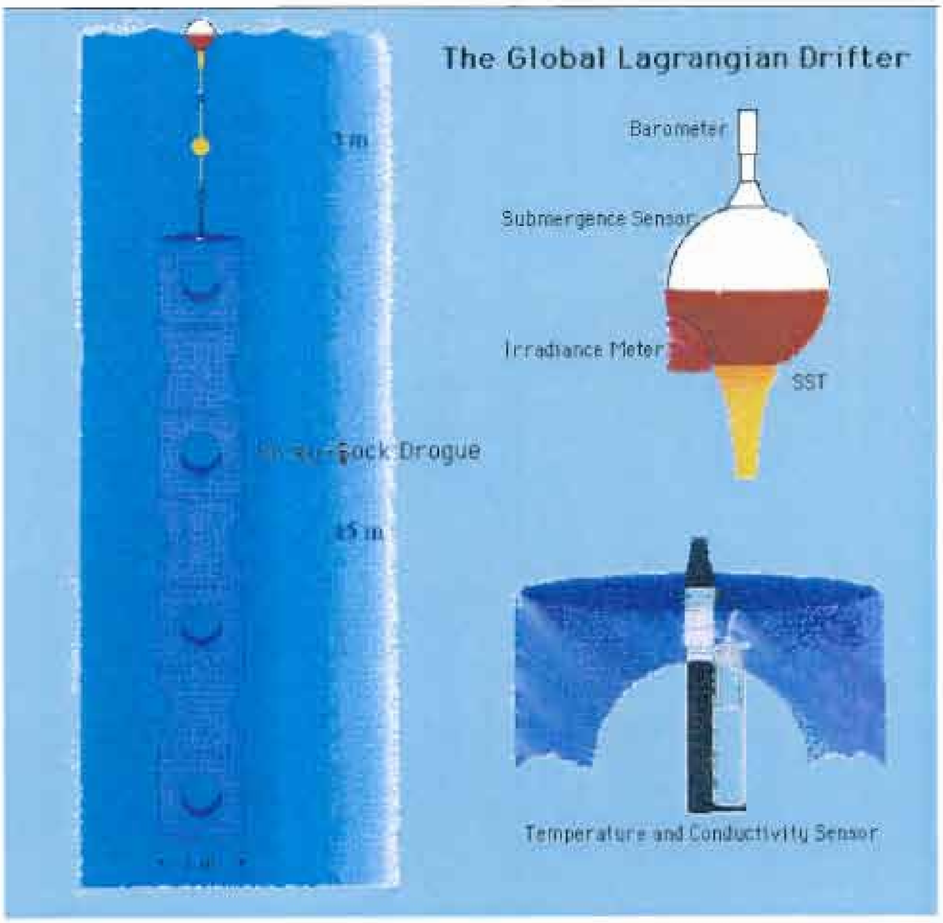


Fig. 4.4: Diagram displaying the Global Lagrangian Drifter on the left hand side and schematics of the sensor attachments (barometer, submerged SST, irradiance and SEACAT) on the right hand side.

Altimetry

Real-time ERS-2 Geophysical Data Records (RGDR), in conjunction with the higher precision TOPEX data, were downloaded from the Colorado Center for Astrodynamic Research. The area extending across the South-West Indian sector of the Indian Ocean from 8°-45°S and 10°-50°E was selected for the period May – September 2000. Also, between May – April 2000, additional images were downloaded for the region 9°-30°S and 30°-48°E, in which the Mozambique Channel lies.

RGDR used in this study have been corrected using the University of Texas 3.0 tide model (Ma et al., 1994). Dynamic height associated with current geostrophic currents were computed using fully corrected sea surface heights referenced to the Ohio State University geoid (Rapp et al., 1991).

Global sea surface height variability from the ERS-2 altimeter collinear differences have shown a large decrease in orbit and media errors following improvements in the ERS-2 processing in the late 1998 (Lillibridge et al., 1997). Sea height variability associated with actual variation in currents and the effect of seasonality yield rms values of 15-20 cm, while values associated with ERS-2 are now only 5-10 cm (Lillibridge et al., 1997). These combined measurements allow the height of the sea surface to be established with an accuracy of less than 13 cm.

For more information regarding the major source of errors determining the dynamic height, refer to Park and Gamberoni (1995).

A 3-month animation of the Mozambique Channel was also created using sea surface height images from the Modular Ocean Data Assimilation System (MODAS) (attached CD-ROM). These images were obtained with special permission from the Naval Research Institute at the Stennis Space Center. For more information on MODAS sea surface height images refer to: http://www7330.nrlssc.navy.mil/modas/

Water Properties

The classification used in the literature to identify the various water masses in the South-West Indian Ocean lacks uniformity. Therefore, we will use the following terminology for the water masses as described by Saetre and Jorge da Silva (1984).

Tropical Surface Water (TSW) – The warm and low salinity water brought into the area by the South Equatorial Current.

Sub-tropical Water (SW) - formed in the southern sub-tropical gyre and occupies the upper 300 m in the water column in the southern channel. It is characterized by a salinity maximum (> 35.5) at 25,8 σt and between 17-18 °C.

Central Water (CW) - this water lies over a depth range between 300-600 m and has a temperature between 9-14 °C. It is characterize by a near linear T/S relationship, from 15-8° C and the presence of an oxygen maximum.

Antarctic Intermediate Water (AIW) - the low-salinity water of Antarctic origin. This water mass is characterized by a salinity minimum 34.4; 27,25 σt at 5 °C.

North Indian Intermediate Water (NIIW) - the high salinity water formed from the Arabian Sea with contribution of water from the Red Sea and Gulf of Oman. During its progression down the East Coast of Africa, the core salinity of NIIW reduces from about 38 at the Red Sea exit, to about 34.7 in the Mozambique Channel. This classification is preferred to *Red Sea Water* (RSW) as it is in accordance with the term AIIW found approximately at the same depth zone.

North Atlantic Deep Water (NADW) - This water mass is characterized by a salinity maximum (>34,8) at 27,8 σt, lying below the AIIW minimum, at depths between 1600 and 3000 m.

Vertical Sections and Profiles

Vertical sections for temperature, salinity, oxygen, phosphate, nitrate and silica have been drawn using a graphical analysis software package called Ocean Data View (ODV). Hydrographic profiles showing the potential temperature-salinity (T-S), temperature-oxygen and temperature-nutrient relationships for individual and groups of stations have also been drawn using ODV. These profiles have been used to identify and characterize the various water masses found in the Mozambique Channel.

ODV is a Windows (9x/2000/NT) program used mainly for the interactive exploration and graphical analysis of oceanographic profile data (bottle, CTD, XBT, etc.). ODV is designed to be flexible and easy-to-use. Users are not required to know the details of the internal data storage format nor are they required to have programming experience. Vertical sections of geostrophic velocity were also calculated and drawn using ODV.

This software can be downloaded from http://www. awi-bremerhaven.de/GPH/ODV.

Chapter 5
Water Masses

The aim of this chapter is to identify the various water masses found in the Mozambique Channel during the ACSEX-1 cruise and to study their movement through the channel. Figures 5.2-5.5 represents T-S diagrams that were derived from 4 selected sections (CTD-sections-I, II, IV and III) in various parts of the Mozambique Channel (fig. 5.1). We will start by firstly identifying from the T-S diagrams, the various water masses found in the Mozambique Channel. Secondly, we will then describe, in more detail, the movement of these water masses as they pass through the channel.

The water structure in figure 5.2 is characteristic of the southern mouth of the Mozambique Channel (Saetre and Jorge da Silva, 1984). At the surface traces of very fresh Tropical Surface Water was observed between stations 5 and 6, its origin unknown. The salinity maximum at 25,80 σt and between 17-18 °C in the surface waters of the channel indicates the presence of Sub-tropical Water. Below the surface waters, the T-S profile shows a nearly linear slope from 15 ° to 8 °C, marking the presence of Central Water. Between the Central Water and Deep Water i.e. between stations 1 and 6, we find the salinity minimum of the Antarctic Intermediate Water 34,4 at 5 °C and at sigma-theta 27,25 σt. The least scatter is shown for water with temperatures of 2 °C and below (Lutjeharms, 1991). The salinity maximum at 27,80 σt is caused by the presence of North Atlantic Deep Water. We also find that between stations 7 and 9, we observe a slight salinity maximum at 5 °C indicating the presence of the North Indian Intermediate Water. It is not unusual to find the presence of North Indian Intermediate Water so far south in the channel. Recent studies (Beal *et al.*, 2000) have shown that remnants of North Indian Intermediate Water have been identified as far south as the Agulhas Current.

Figure 5.3 and 5.4 displays the water characteristics observed in the central part of the Mozambique Channel. The salinity maximum of the Sub-tropical Water occurs at 16 °C and 25,80 σt. The salinity minimum, which is due to the influence of the Antarctic

Intermediate Water, is observed at 7-8 °C. The salinity maximum at 6 °C for both figure's 5.3 and 5.4 indicates the presence of the North Indian Intermediate Water. However, in figure 5.3 we observe another salinity minimum at 27,60 σt and between 3 ° and 4 °C. This can be explained using the salinity (fig. 5.9) and oxygen (fig. 5.8) results, which shows Antarctic Intermediate Water wedged between low-oxygen, high-salinity North Indian Intermediate Water. Another salinity maximum at about 2 °C is caused by the presence of North Atlantic Deep Water. When compared to the other T-S diagrams (fig. 5.6), we notice that figure 5.3 appear to be more convoluted at intermediate depths. This, we believe, is caused as a result of the intense mixing between the NIIW and AAIW in this region. However, we find that mixing at intermediate depths in the center of the channel, between these two water masses is greater than in the northern or southern parts of the channel. Unfortunately, the reason for this is unknown.

Figure 5.5 displays the water characteristics observed in the northern part of the channel. Traces of very fresh low salinity water is observed at station 1. Since this station is very close to the coastline, the low salinity's is probably as a result of a nearby river run-off. A slight salinity maximum indicates the Sub-tropical Water at 25,25 σt between 18-20 °C and between 35,4-35.6. Once again there is a slight salinity maximum at 6 °C; 27,5 σt indicating the presence of the North Indian Intermediate Water. We also observe very low salinity water (34.7) between 7-8 °C, indicating the presence of AAIW.

Now that we have identified the various water masses found in the Mozambique Channel, we now intend to discuss their movement, in more detail, as they pass through the channel.

North Indian Intermediate Water

Observed salinity (fig. 5.7) and oxygen (fig. 5.8) results show that easily detectable masses (high salinity- low oxygen water) of North Indian Intermediate Water enters the Mozambique Channel at the northwest, at depths of 700 to 1500 m. It then propagates southward in the shape of a current with variable width and thickness, at a depth between

800 and 1200 m, covering the entire channel at its narrowest width (fig. 5.9). Oxygen results indicate that the core of the North Indian Intermediate Water lies at 1000 m (fig. 5.8). At 20 °S, our salinity results (fig. 5.10) show the presence of North Indian Intermediate Water separated from the coast by a northward intrusion of low salinity Antarctic Intermediate Water. Results from oxygen concentrations taken during this section (fig. 5.11), show the core of the North Indian Intermediate Water roughly at a 1200 m. Oxygen concentrations taken from the *Almirante Lacerda* cruise in 1964, along 20 °S, also confirm a North Indian Intermediate Water core at 1200 m (Harris, 1972). At 24 °S, our results show that the North Indian Intermediate Water remains offshore, separated from the coast by a northward intrusion of the low-salinity Antarctic Intermediate Water (fig. 5.12). This is confirmed by the oxygen results (fig. 5.11), which show a band of low-oxygenated water off the coast. It also shows that the core of the North Indian Intermediate Water lay roughly at 1500 m. Therefore, as this water mass spreads southwards, we observe that the oxygen minimum erode and deepen (from 1000 m in the north of the channel, to 1200 m in the centre of the channel, to 1500 m in the south of the channel). The observation that the core of the North Indian Intermediate Water descends as it moves southwards through the Mozambique Channel was also observed in the work of Beal *et al.* (2000). We also notice that the salinity maximum observe in figure 5.6, which indicates NIIW, erodes as in flows southwards through the channel from > 34,8 in the north to 34,7 in the south. These distributions can also been seen in the oxygen and salinity results of the *Almirante Lacerda* cruise in 1964 (Harris, 1972). Saetre and Jorge da Silva (1984) have reached similar conclusions for the propagation of the North Indian Intermediate Water through the Mozambique Channel. However, they came to the conclusion that once this water mass reaches depths > 3000 m it leaves the channel along the southwest coast of Madagascar.

Antarctic Intermediate Water

The source region for Antarctic Intermediate Water is located near the surface north of the Antarctic Polar Front, from where it spreads northward into the other oceans. Traces of Antarctic Intermediate Water entering the Mozambique Channel along its western coastline is identified from the salinity (fig. 5.12) and oxygen (fig. 5.11) sections along the 24 °S line. Results show that this water mass entered the channel at a depth between 900 – 1200 m and is represented by salinity minimum of 34.4 – 34.6 at temperatures between 4 and 6 °C (fig. 5.2). Observed oxygen (5.11) and salinity (fig. 5.12) results show that the core of the Antarctic Intermediate Water lay at roughly 1000 m. Similar results were also reported by Tchernia *et al.* (1951) and Orren (1963), who also observed that the core of Antarctic Intermediate Water in the Mozambique Channel lies at depths of 1000 m. As we move northwards through the channel, observations from figure 5.6 show an increase in the salinity and temperature of the Antarctic Intermediate Water from 34.5 to 34.7 and from 4 ° to 7 °C. This increase, we believe, is a direct result of the vigorous interaction with North Indian Intermediate Water. Along the 20 °S line, observations from our temperature and salinity results (fig. 5.10) show traces of AAIW along the western coast of Mozambique at depths between 600 and 1500 m. However, as we move further offshore the width of this water mass decreases dramatically at 37 °E and is now confined to a thin layer between 1200 and 1500 m. Along the coast the core of the Antarctic Intermediate Water remains at 1000 m, but as one moves further offshore the depth of the core increased by 300 m to 1300 m. In the narrows of the Channel, our temperature and salinity results (5.9) show that Antarctic Intermediate Water is confined to a thin layer between 500 and a 1000 m. However, another layer of the Antarctic Intermediate Water, between 1500 and 2000 m was also identified. What we observe is North Indian Intermediate Water wedged between two layers of Antarctic Intermediate Water. Results from the ACSEX-3 cruise in 2001, which occupied the same hydrographic line along the narrows of the Channel, also identified two layers of Antarctic Intermediate Water separated by the low salinity, high oxygen North Indian Intermediate Water (fig. 5.13). However, no one else has observed this before ! Traces of the Antarctic Intermediate Water is also observed in the northern mouth of the channel (fig. 5.5) Antarctic Intermediate Water can therefore be found throughout the Mozambique Channel.

Interestingly, we should also point out that Soares (1975) observed that Antarctic Intermediate Water enters the Mozambique Channel at both ends. Saetre and Jorge da Silva (1984) also showed that Antarctic Intermediate Water might sometimes round the northern tip of Madagascar and intrude into the Mozambique Channel from the north.

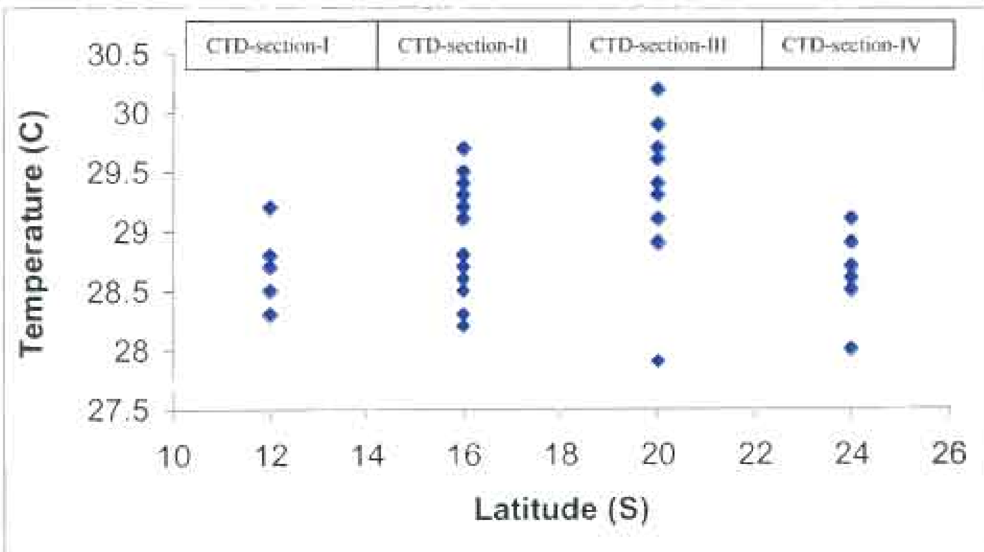
The same observations are evident in the distribution of temperature and salinity at the core layer of the Antarctic Intermediate Water in the atlas of Wyrtki (1971). Unfortunately, we have no hydrographic stations at the northern tip of Madagascar and therefore cannot confirm these observations.

Central Water

The water mass lying approximately in the depth range 200 to 600 m has been called the Central Water Mass (Sverdrup *et al.*, 1942). This water is believed to originate at the Subtropical Convergence and propagates towards the tropics by isopycnal spreading (Sprintall and Tomczak, 1993). This water mass has been characterized by a near-linear T-S relationship and the presence of an oxygen maximum. Traces of this water mass are found throughout the Mozambique Channel. By comparing the t-s diagrams (fig. 5.6), we find that the slope of the Central Water increases as we move northwards through the Channel. We are not sure why this occurs, but there are some possibilities. One possibility is that as this water mass spreads northwards through the channel, it interacts with water masses above and below it, which may change its water properties resulting in the steeper slope. Another possibility was suggested Magnier and Piton (1974). In dealing with data from the northeast monsoon season, they found that Central Water also intrudes from the east of Madagascar into the northern part of the Mozambique Channel. Therefore, its possible that the Central Water we observe in the northern part of the channel is not the same water mass that entered the channel from the south, resulting in the steeper slope we see in the t-s diagrams.

Surface and Subsurface Waters

The surface water in the northern Mozambique Channel is relatively fresh, between 34,7-35,2 characterized by high temperatures > 28 °C. These low salinities are due to the inflow of Pacific water through the Indonesian Archipelago and then westward by the South Equatorial Current, as well as through excess precipitation > 200 cm at these latitudes. As it propagates southward in the Mozambique Channel this water mass comes into contact with the higher-salinity (S > 35.5) Sub-tropical Surface Water. These high values (> 35.5) are due to excess evaporation, between 60-160 cm, occurring at these latitudes. It seems that when these two water masses come into contact with each other, the Tropical Surface Water superposition's itself over the Sub-tropical Surface Water, resulting in a subsurface salinity maximum at depths of 150 - 200 in the surface waters of the Mozambique Channel (fig. 5.6). We also observe a drop in sea surface temperatures, from 28 - 26 °C, as we move southwards through the Channel (table 5.1). However, surface salinity values increases from 34.7 to 35.25 (table 5.1).



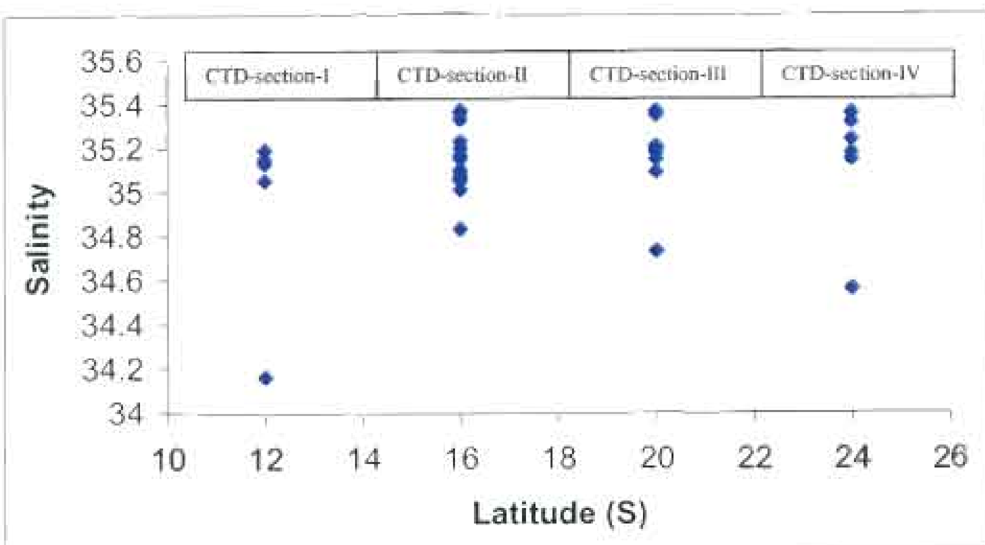


Table 5.1: Shows the variations in surface temperature and salinity as we move through the Mozambique Channel.

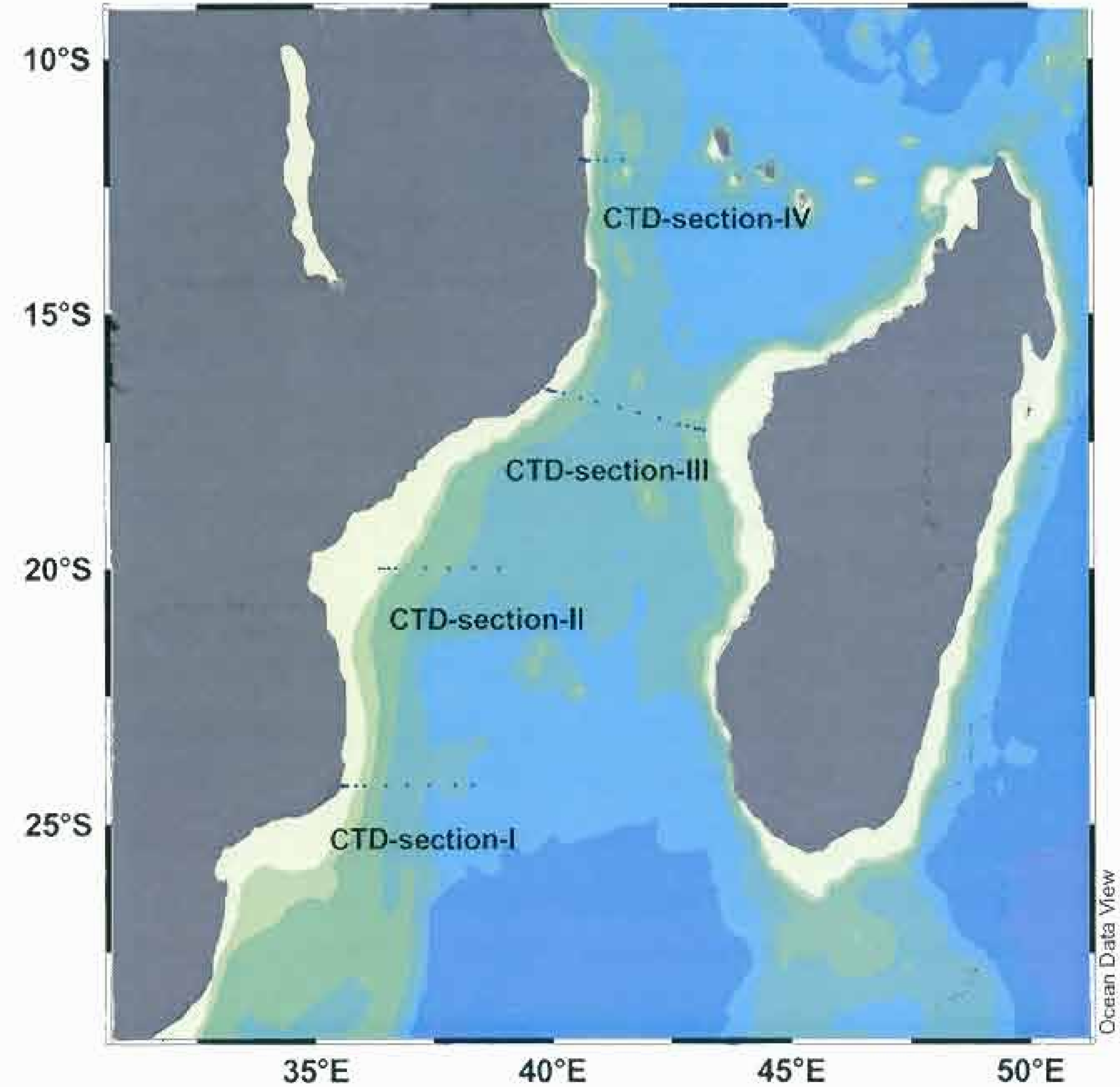


Figure 5.1: The distribution of the CTD stations occupied during the ACSEX-1 cruise.

ODV5.7: C:\Program Files\Ocean Data View\Data\SAVE\NewCol1; C:\Program Files\Ocean Data View\Data\SAVE\NewCol1.cfg - May/30/2003 20:46:07

Figure 5.2: Temperature and Salinity diagram across CTD-section-I.

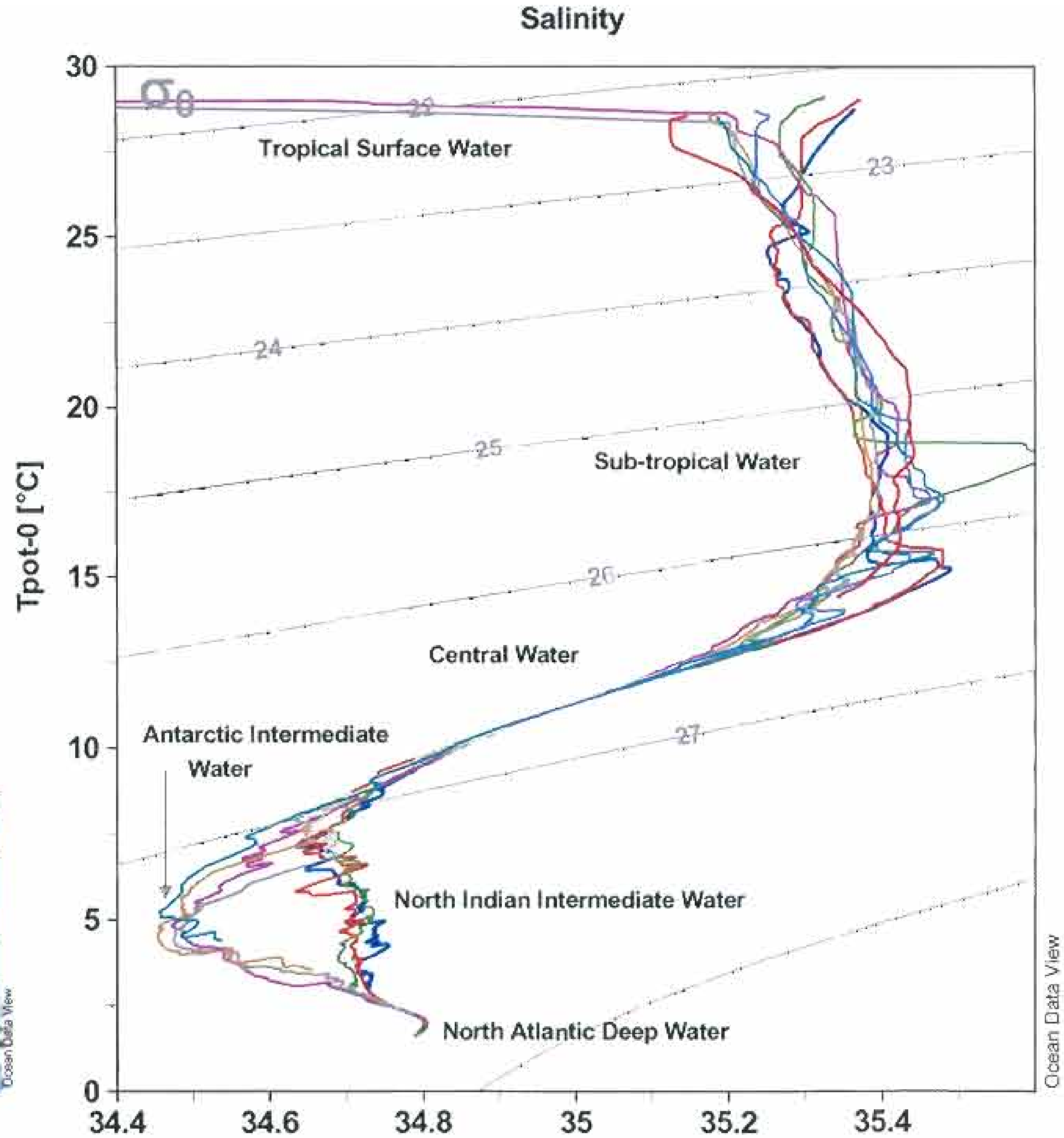


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Figure 5.3: Temperature and Salinity

diagram across CTD-section-II.

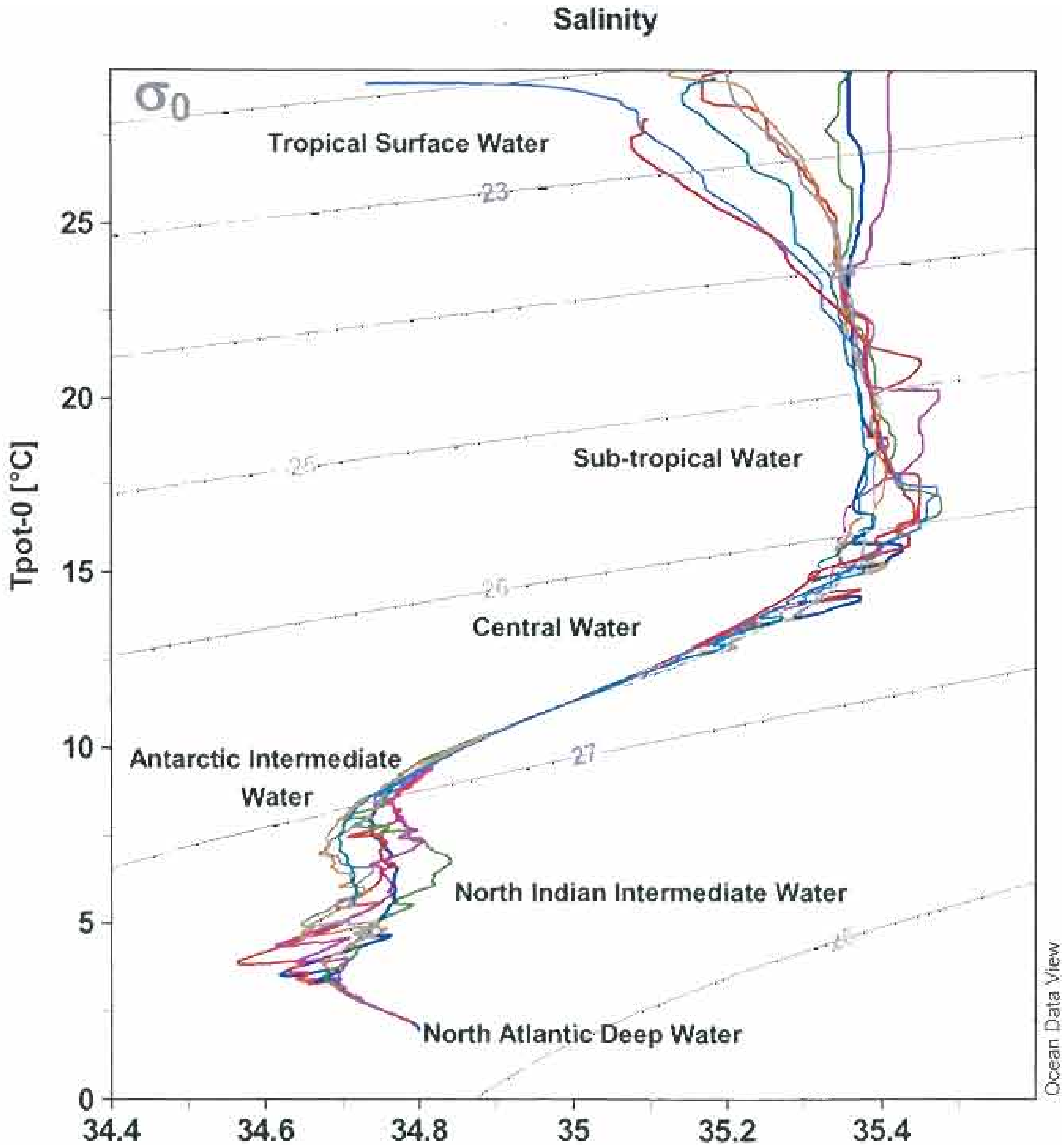

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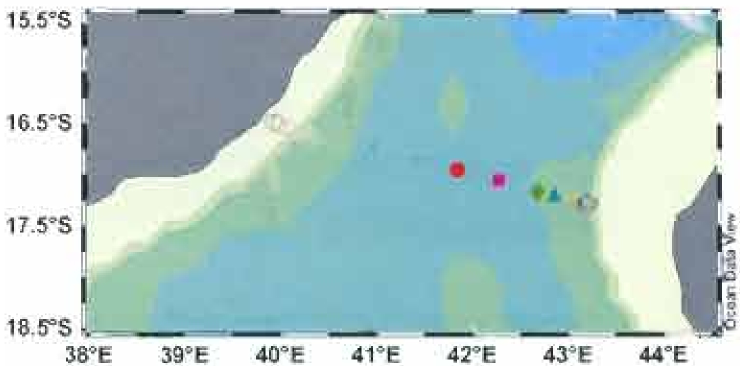
Figure 5.4: Temperature and Salinity diagram across CTD-section-III.



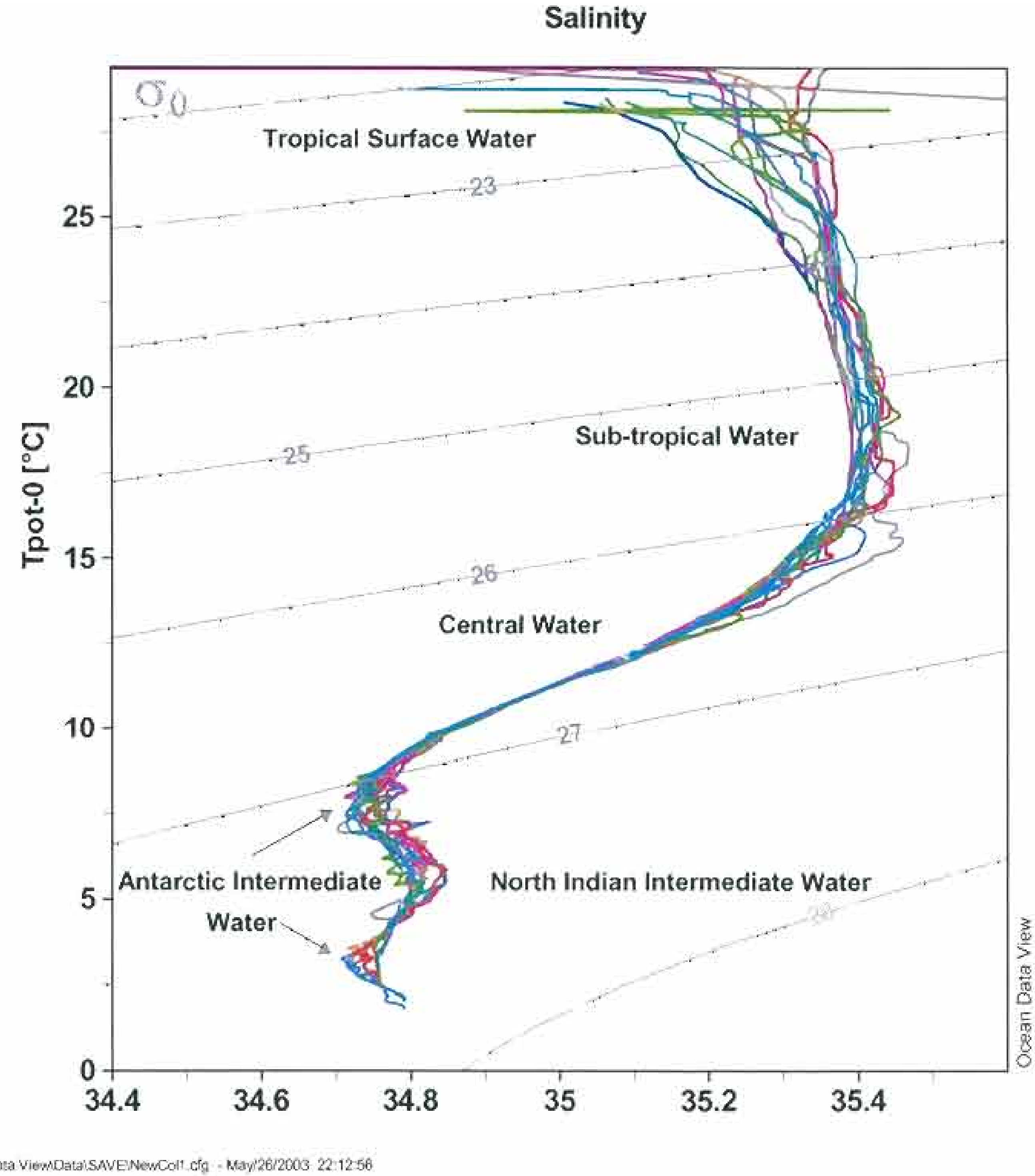
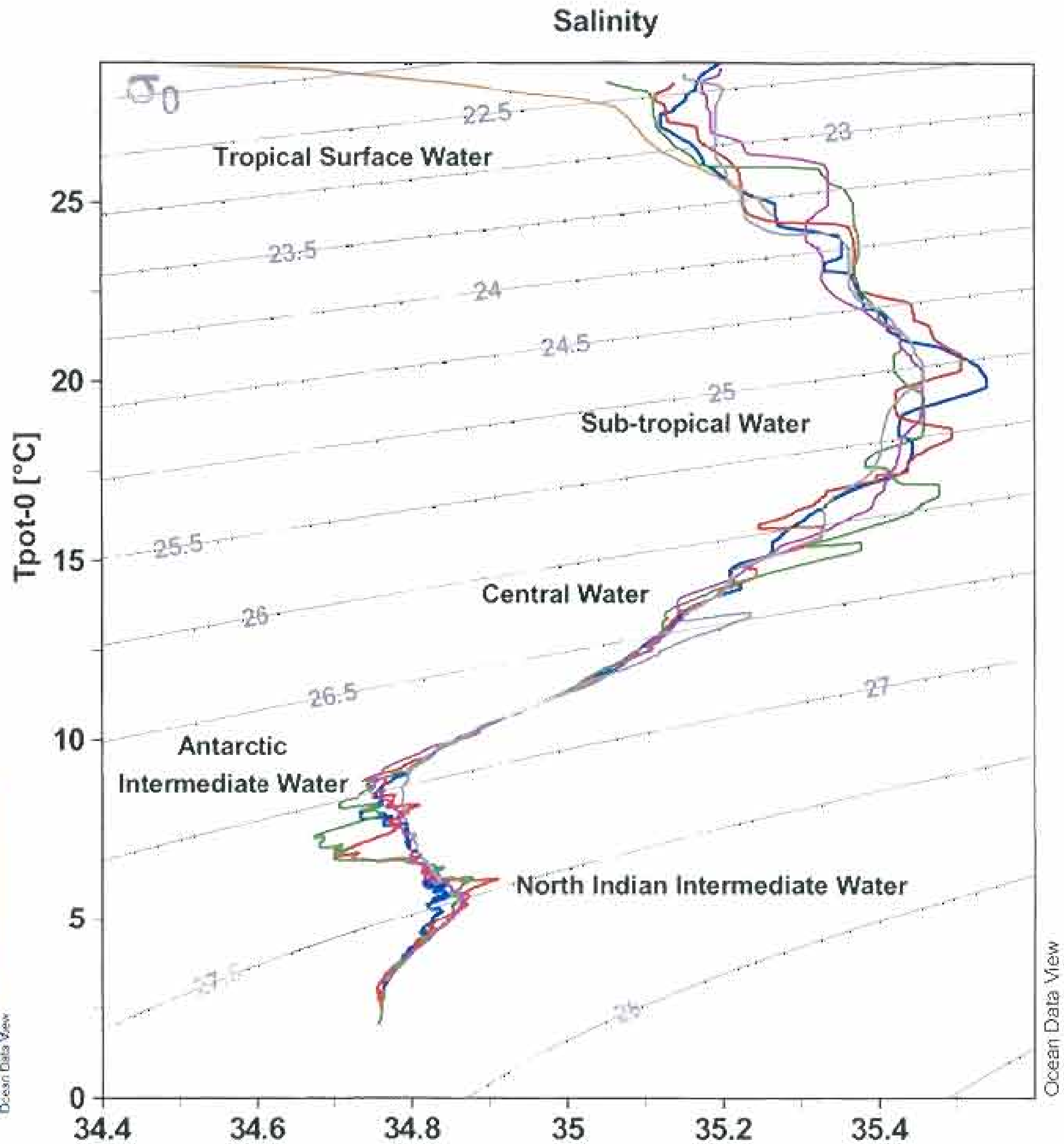
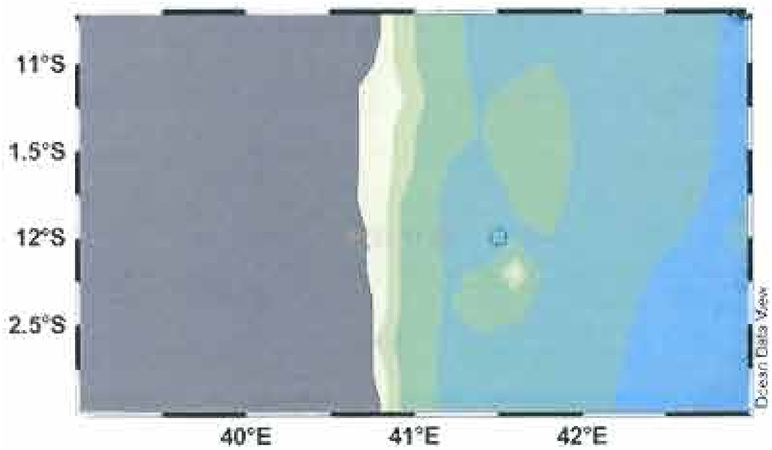


Figure 5.5: Temperature and Salinity diagram across CTD-section-IV.





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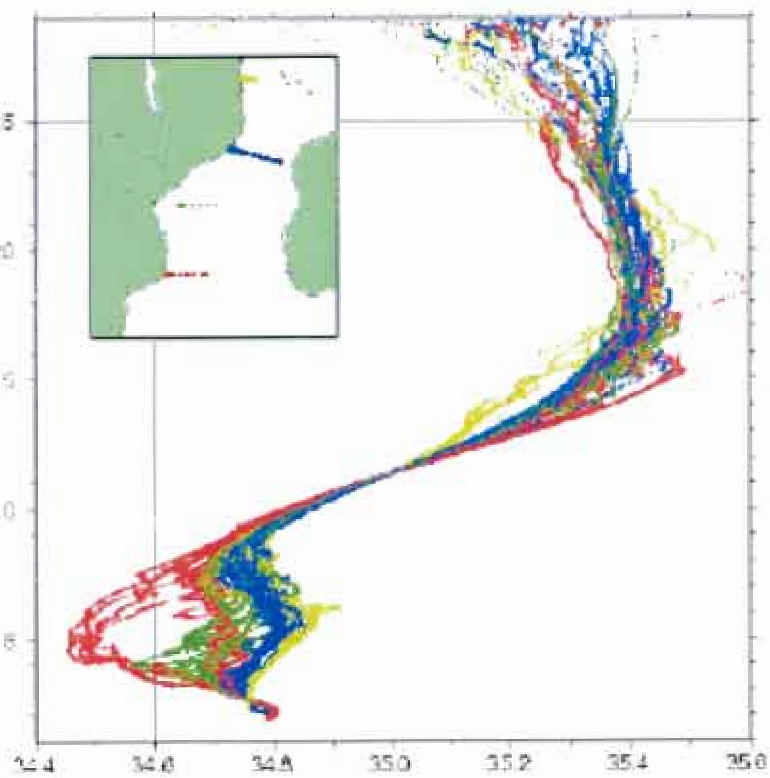
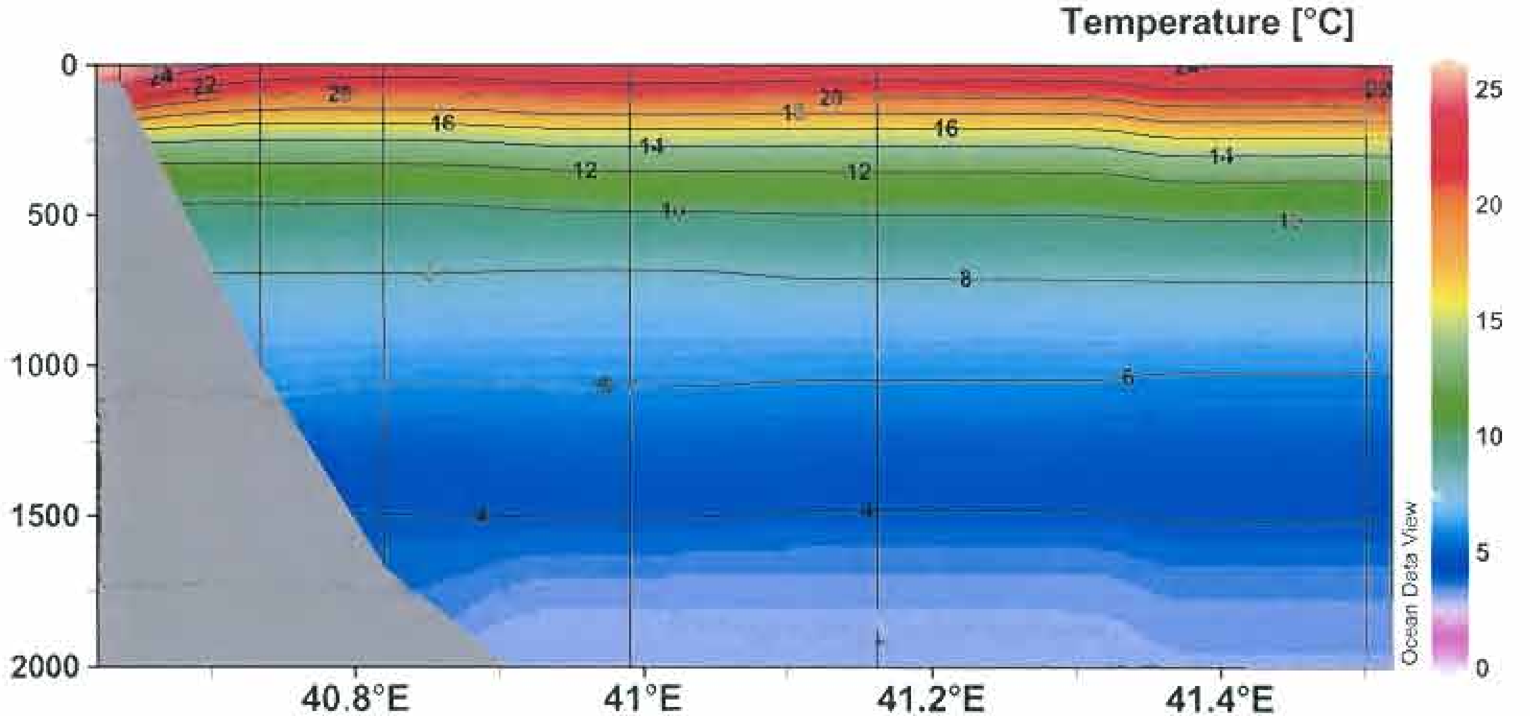
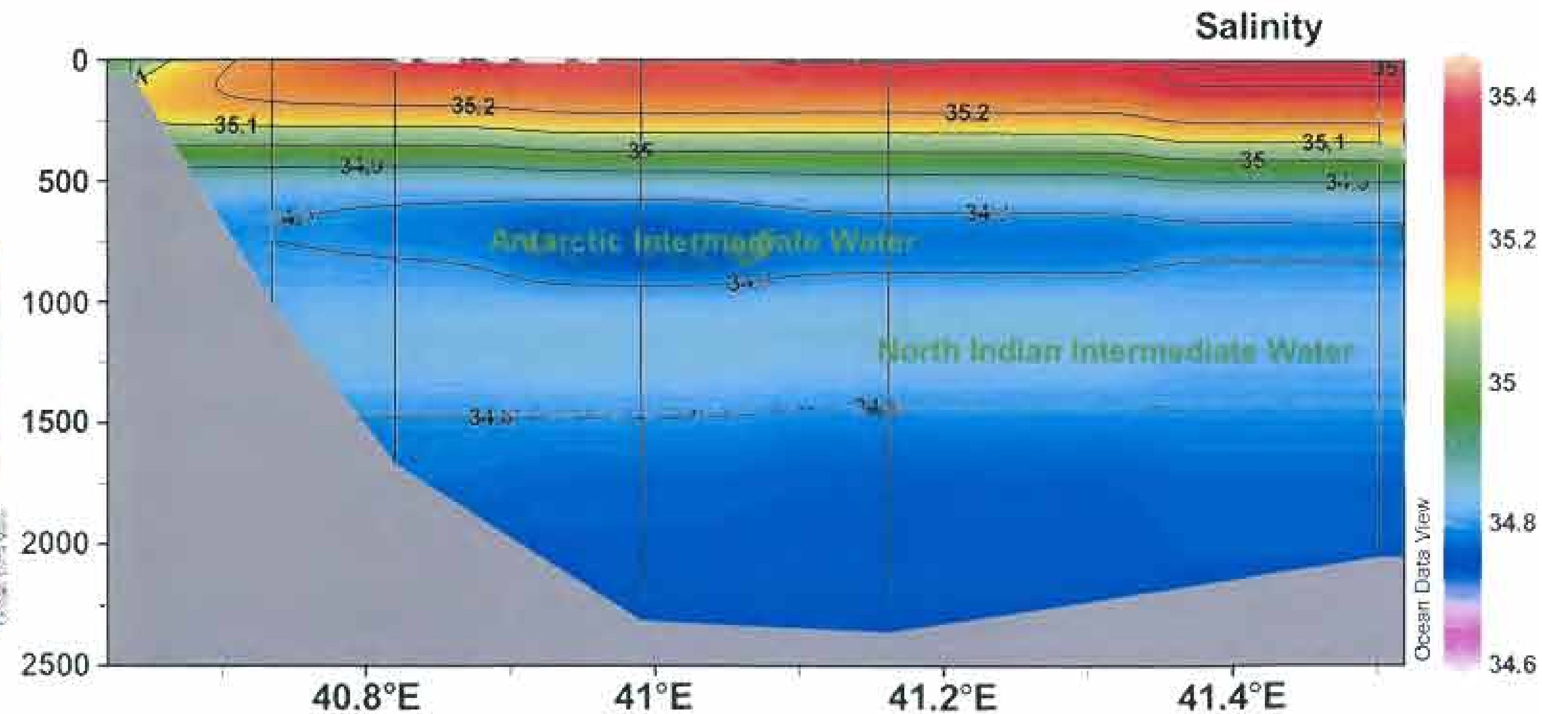
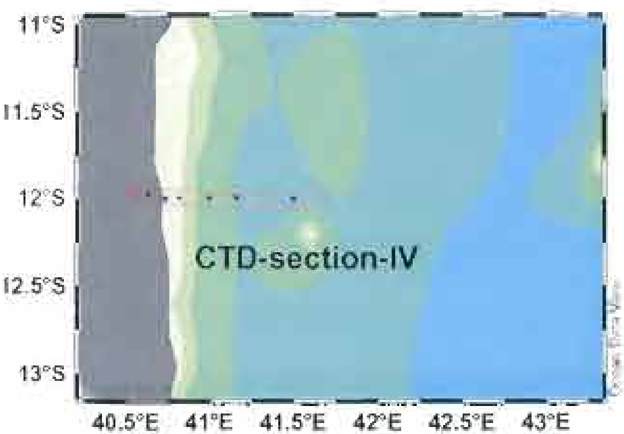


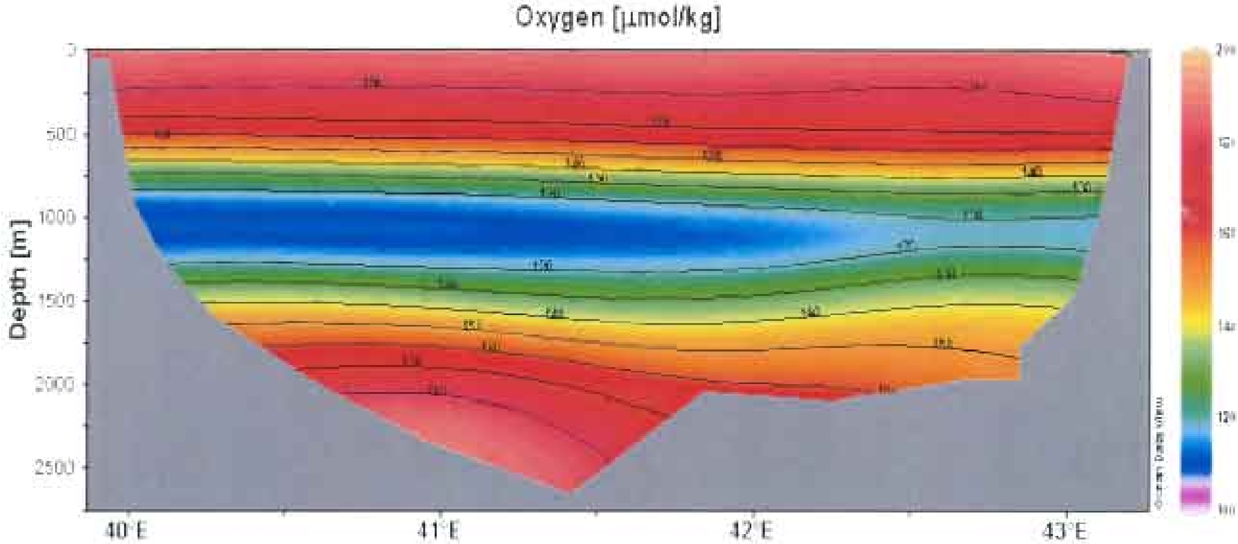
Figure 5.6: Temperature and salinity diagrams for the four hydrographic sections of which the locations are shown in the inserted figure (Schouten et al, 2001).

Figure 5.7: Vertical sections of temperature and salinity across CTD-section-IV.









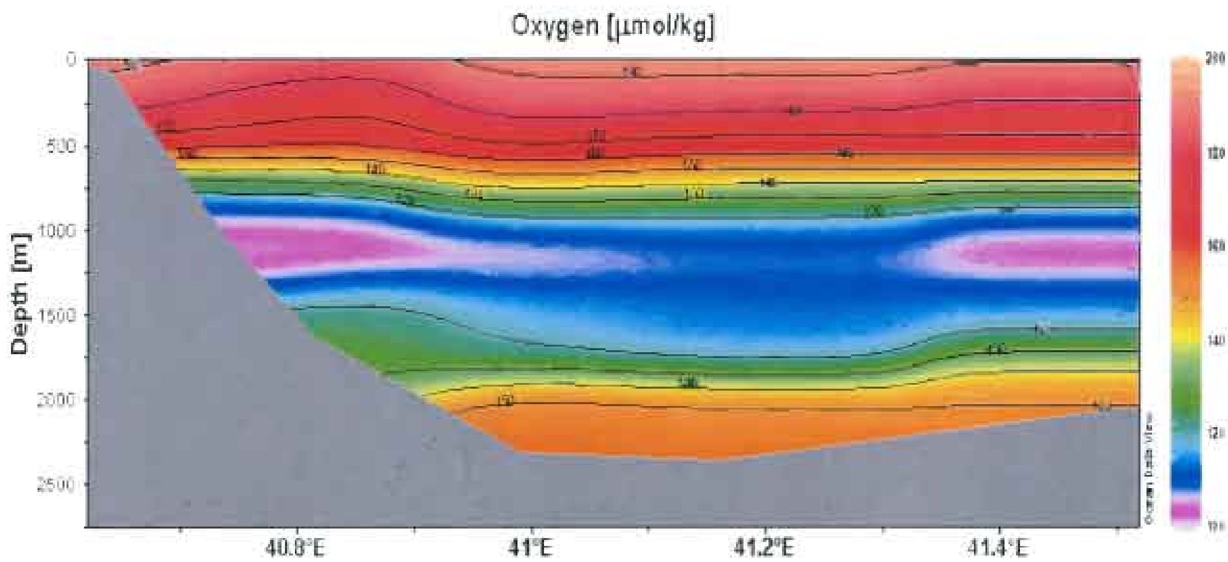
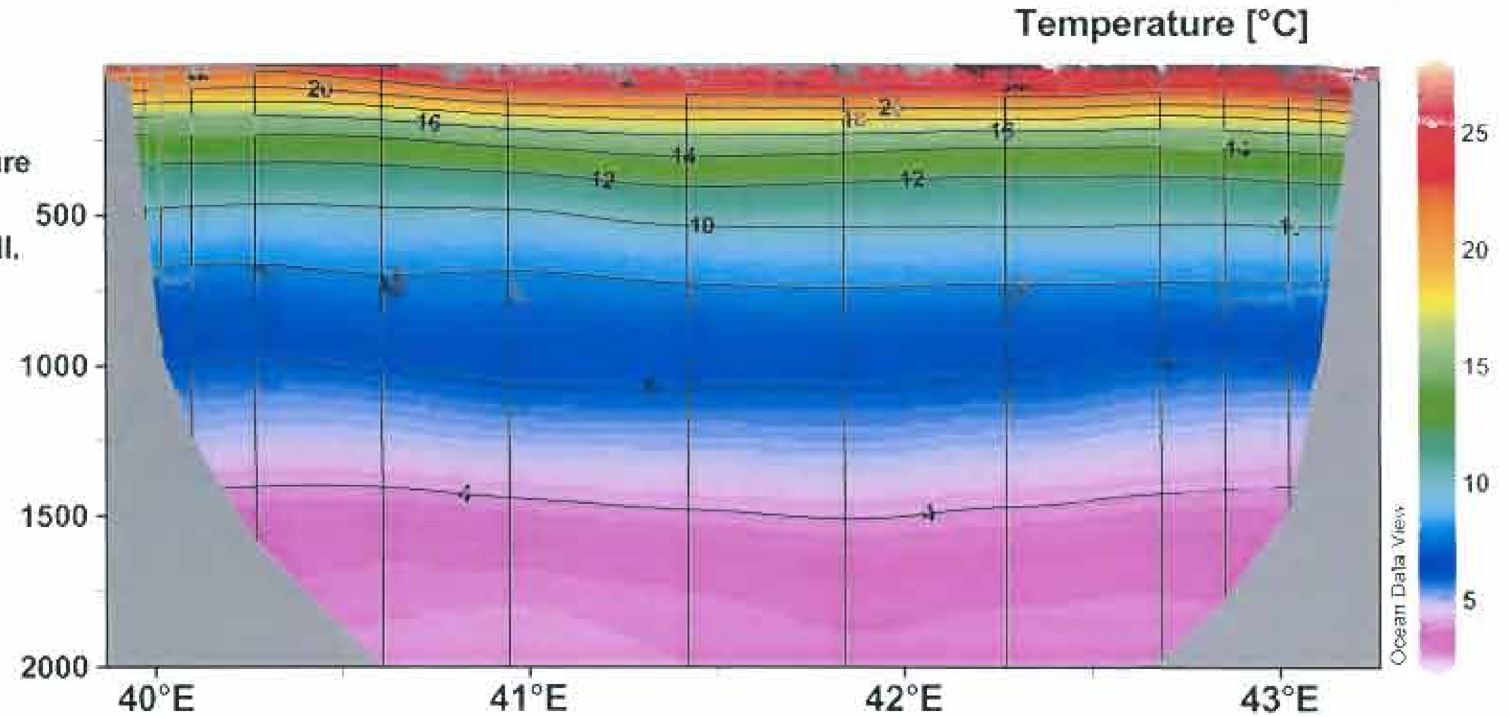
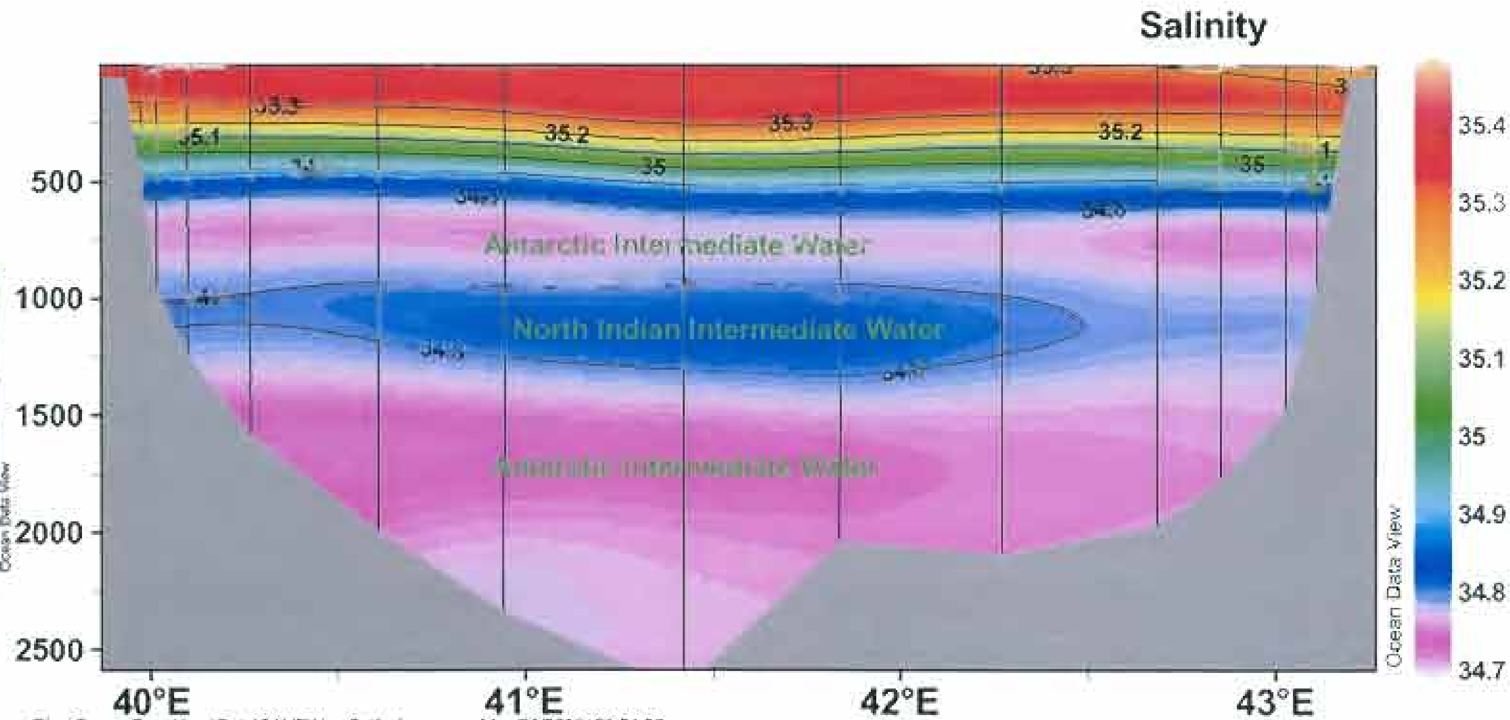
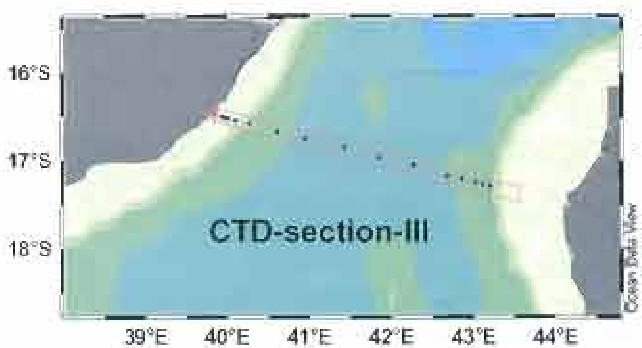


Figure 5.8: Oxygen sections across CTD-section-III (top) and CTD-section-IV (top).

Figure 5.9: Vertical sections of temperature and salinity across CTD-section-III.







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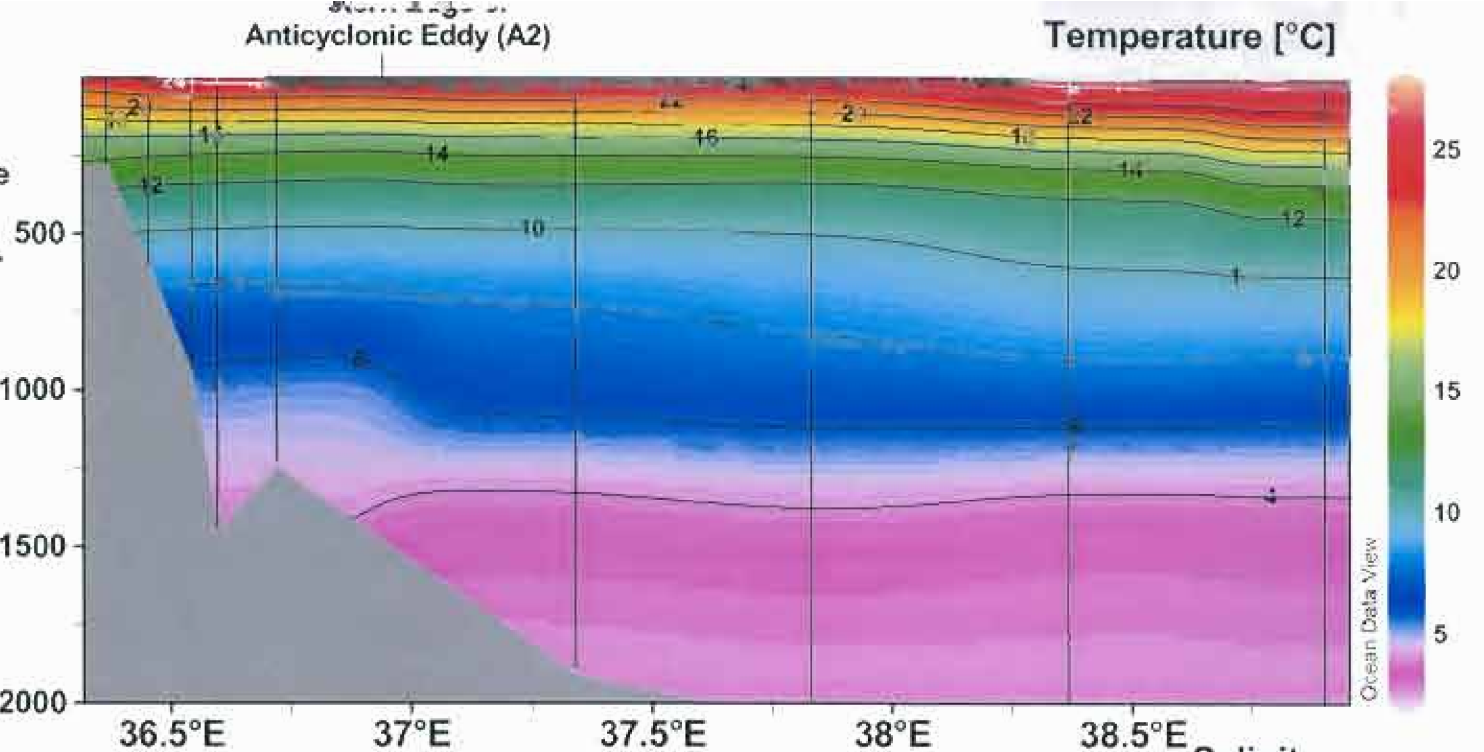
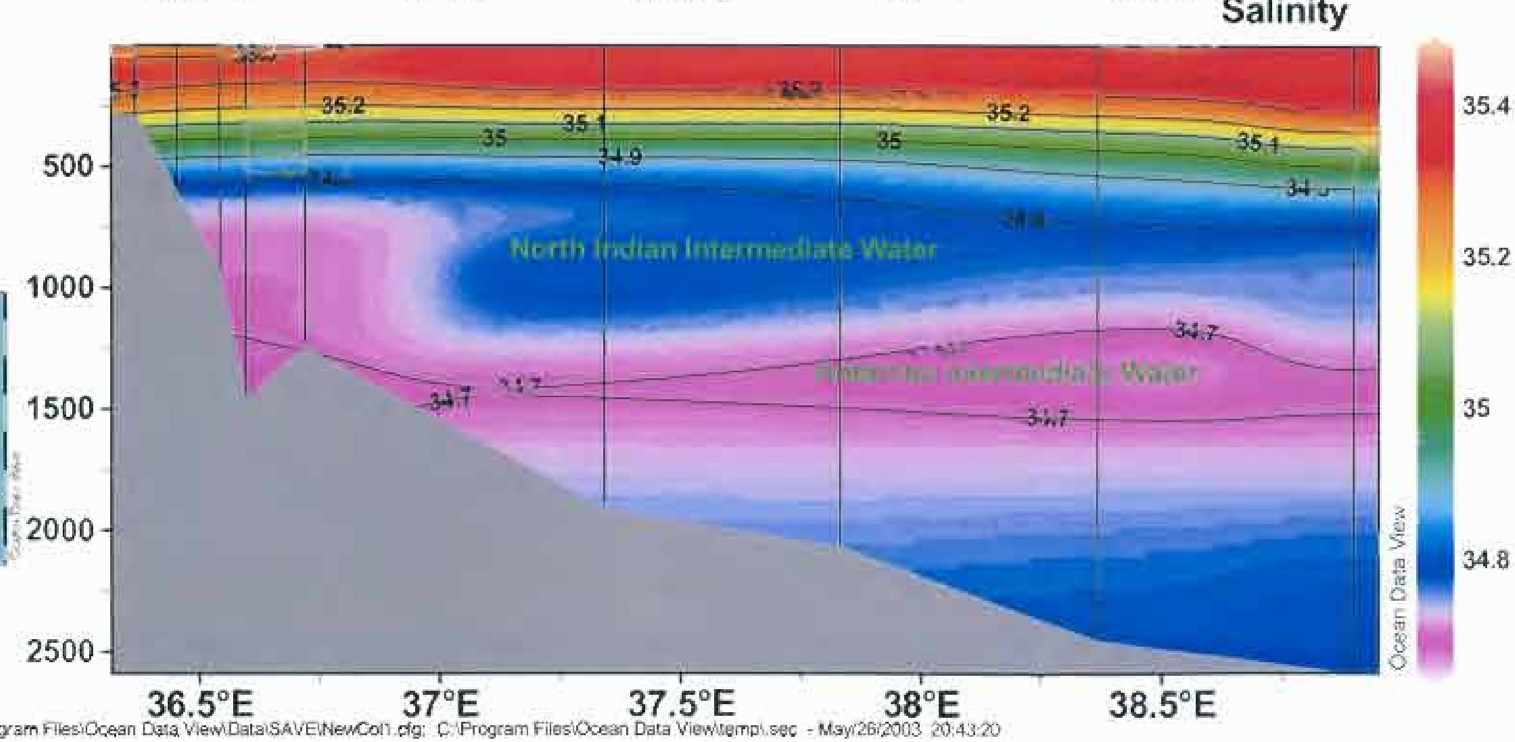
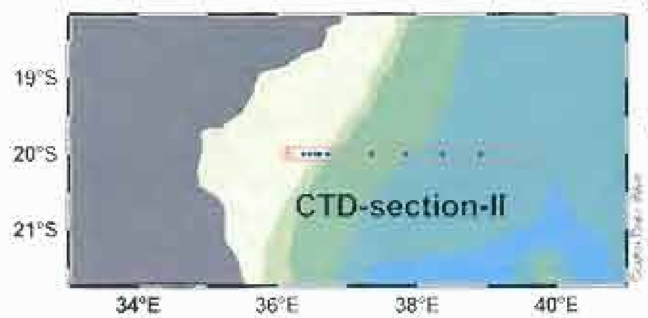


Figure 5.10: Vertical sections of temperature and salinity across CTD-section-II.





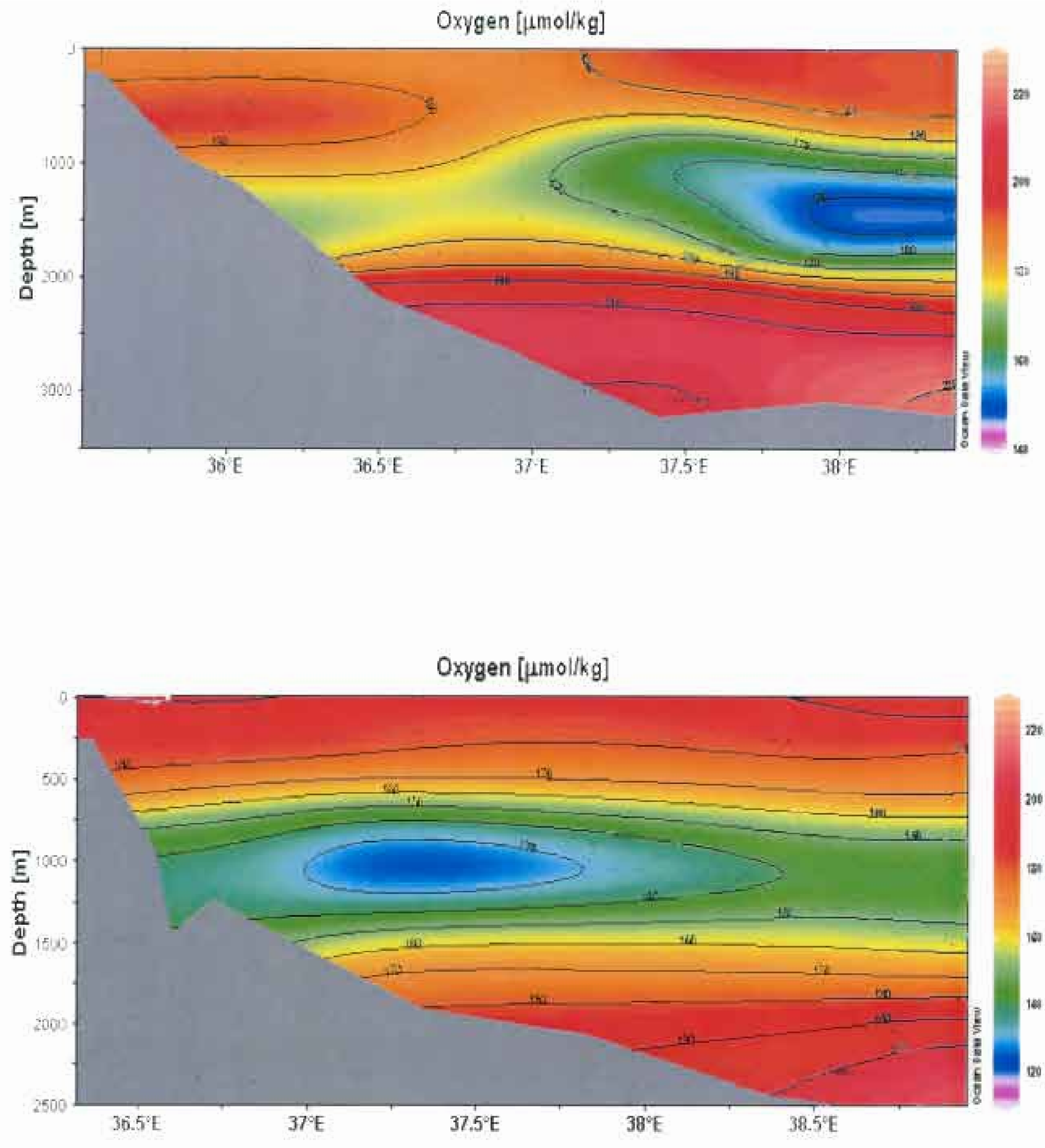
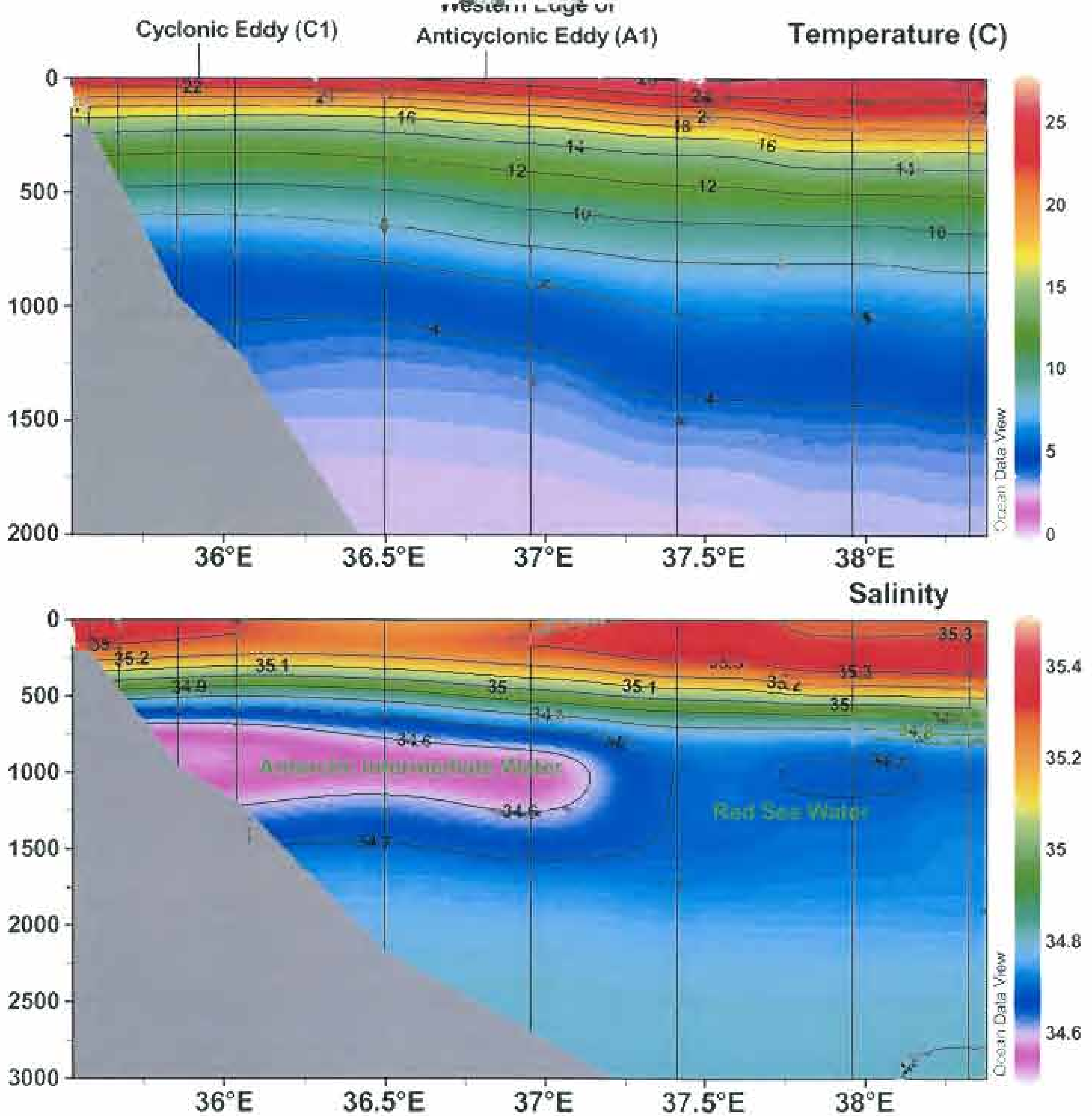
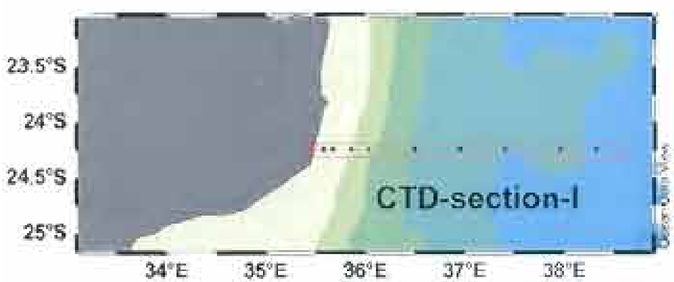


Figure 5.11: Oxygen sections across CTD-section- I (top) and CTD-section-II (bottom).

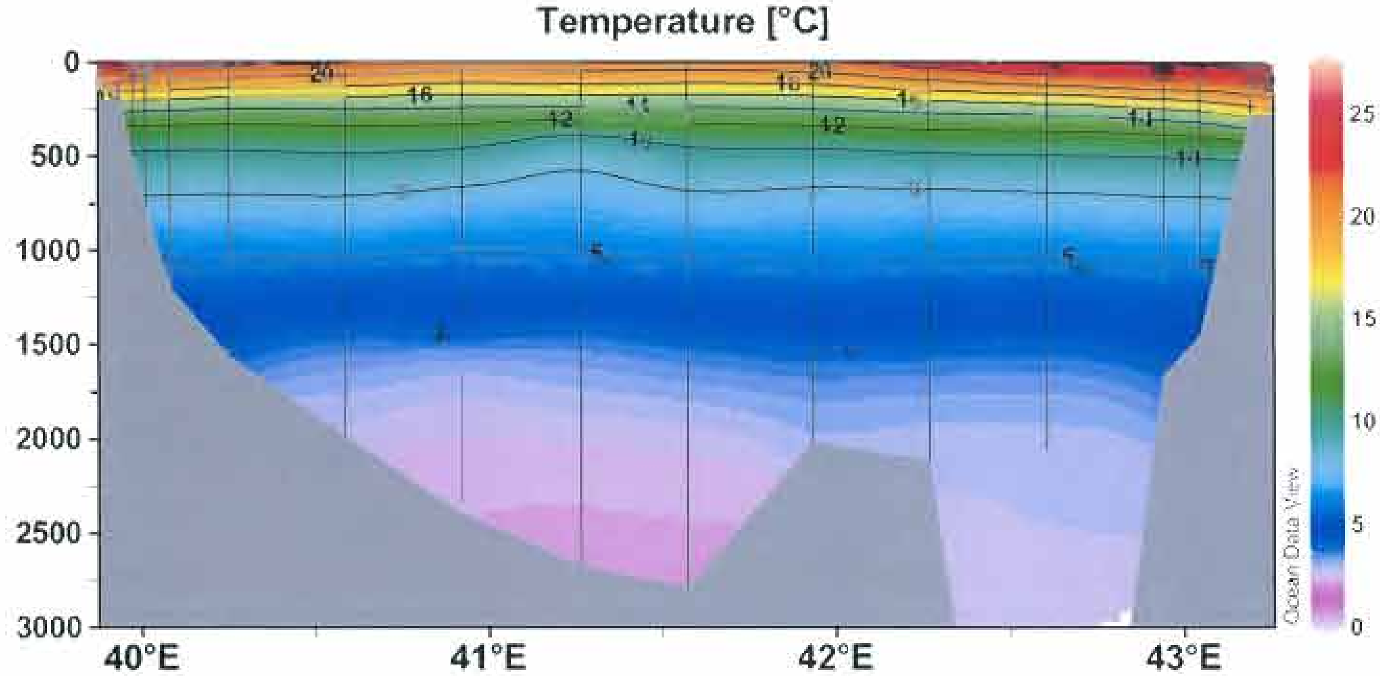
Fig 5.12: Vertical sections of temperature and salinity across CTD-section-I.

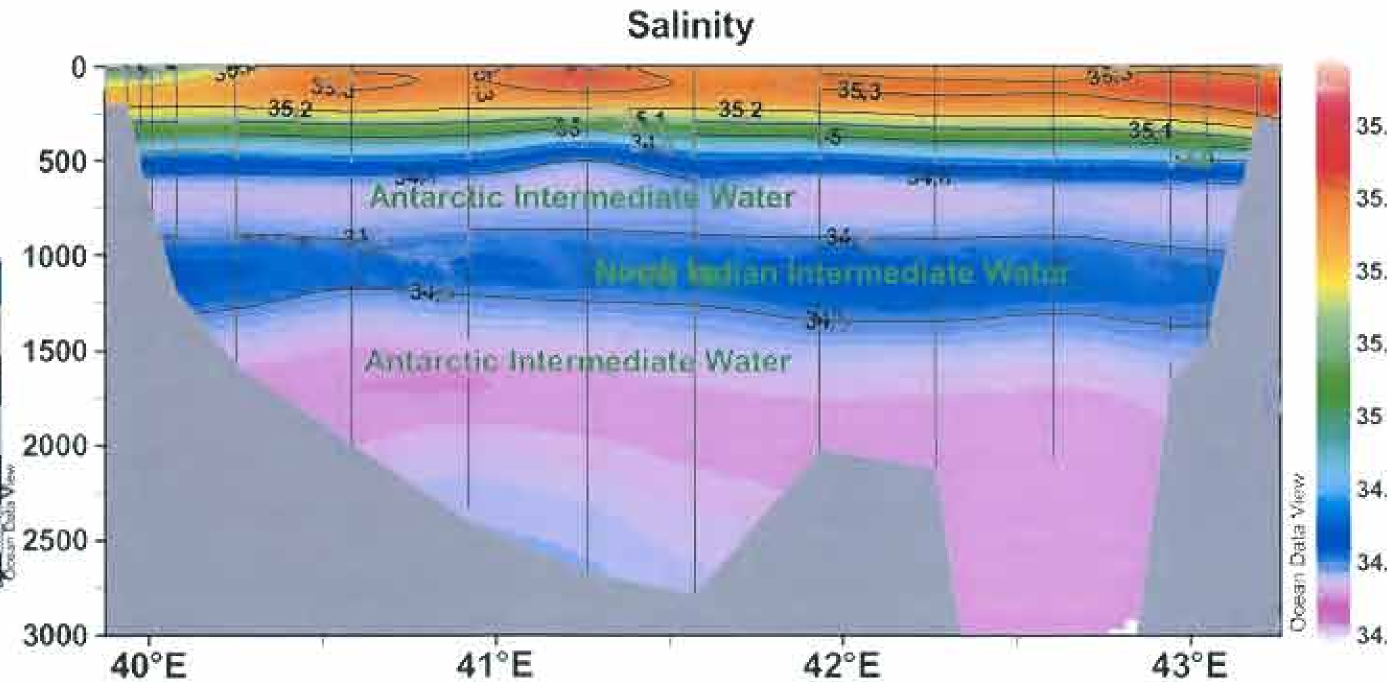


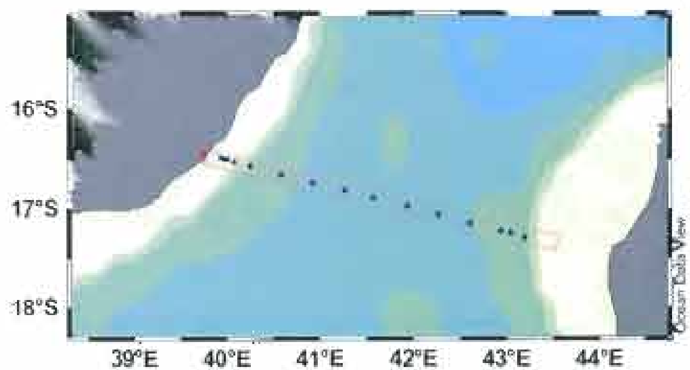


ODV5.7: C:\Program Files\Ocean Data View\Data\SAVE\NewCol; C:\Program Files\Ocean Data View\Data\SAVE\NewCol.cfg; C:\Program Files\Ocean Data View\templ.sec - May/26/2003 20:12:54

Figure 5.13: Vertical sections of temperature and salinity, taken from the ACSEX-3 cruise, across the narrows of the Channel.







Chapter 6
Hydrography, Geostrophic Currents and Altimetry

In order to address the research questions adequately, the first ACSEX cruise was specifically designed to intercept the purported trajectory of the Mozambique Current as seen in most previous publications (De Ruijter *et al.*, 2002; Lutjeharms *et al.*, 2000). Simultaneously, by using real-time altimetric information, we intended to investigate the main regions of high mesoscale activity in the channel. In this way we are now able to compare the altimetric images with hydrographic data collected on the cruise.

Using Ocean Data View (ODV) to plot vertical sections of temperature, the slope associated with the isotherms will indicate in which the direction the current is flowing. For instance, if the isotherms slope upwards, it represents an eastward/northward flow, while a downward slope represents a westward/southward flow. Eddies can also be identified by there characteristic 'v-shaped' appearance on the temperature section.

Also in this chapter we mention the observations of drifting buoy data. For a more detail description of their drift movements in the Mozambique Channel, refer to Chapter 7.

During the **CTD-section-I** the western edge of a strong and well-define anticyclonic eddy (A1) was identified at 24.24 °S; 36.75 °E (fig. 5.12). The position of the positive anomaly (+10 cm) observed from the altimetric image forms an almost exact fit with the anticyclonic eddy (A1) identified from the hydrographic data (fig. 6.1). Observations from the drifting buoy data (Buoy 17343 and 17442) also confirm the presence of an anticyclonic eddy at this position (figs. 7.3 and 7.4; chapter 7). Using data from the WOCE cruises, DiMarco *et al.* (2001), also reported an anticyclonic eddy at the same position. However, he observed that the eddy disappeared below 1000 m. The temperature section (5.12) also reveals the existence of a weak cyclonic eddy (C1) around 37 °E. This is confirmed by the altimetry data, which shows a cyclonic anomaly (-10 cm) centered at 37 °E, just inshore of the anticycloic anomaly (fig. 6.1). By using data collected onboard the *Nikolay Resheneyak*, Saetre and Jorge da Silva (1984) also identified a cyclonic eddy at this position.

The width of the anticyclonic eddy could not be determined since the CTD line did not cross the entire eddy. However, altimeter data reveals that the eddy appears to have been over 300 km wide. We could determine from ADCP data (fig.6.2) however, that it was a deep anticyclonic eddy penetrating all the way to the bottom, where swirl velocities are still around 0.1 m/s. Results from the geostrophic velocity section (fig. 6.3) shows a predominately southerly flow with a maximum geostrophic surface velocity of 80 cm/s at 37 °E. This eddy (A1) appears to be surface intensified. However these velocities are substantially higher than the 24 to 68 cm/s velocities reported by Nehring *et al.* (1987) for a similar feature observed here. A shallow northward current was also observed along the coast, with surface velocities between 10 and 40 cm/s. ADCP observations measured from on board the ship (fig 6.4) also show a northward flow along the coast. But as we move further offshore the flow patterns indicate a southerly flow, confirming the results of both geostrophic and hydrographic observations.

In addition, current observations from the ACSEX-1 cruise, using a Lowered Acoustic Dipolar Current Profiler (ADCP) have revealed a significant undercurrent structure below the thermocline (De Ruijter *et al.*, 2002), along the Mozambique continental slope (fig. 6.2). Observations reveal that the undercurrent is found inshore of the eddies and appears to move water equatorward. It has two cores, one at intermediate level between 700 and 1200 m depth, and the other core below 2000 m depth. Observations from both salinity (fig. 5.12) and t-s diagrams (fig. 5.2) reveal that the undercurrent core at intermediate level consist of AAIW, which stands out clearly by its marked salinity minimum of less than 34.5. Furthermore, ADCP observations (fig. 6.2) reveal that the undercurrent at intermediate level flows northwards, carrying with it AAIW, with speeds ranging between 10 and 20 cm/s along the continental slope. The other core is found below 2000 m depth, where a deep western boundary current is observed with maximum along slope equatorward speeds near 20 cm/s (De Ruijter *et al.*, 2002). Observations from both the oxygen (5.11) and t-s diagram (5.2) along 24 °S, reveal that the core below 2000 m contains relatively high salinity and oxygen concentrations, which is consistent with

NADW. According to De Ruijter *et al.* (2002) the total equatorward transport in the Mozambique undercurrent was, roughly estimated, 5 Sv at 24 °S, of which 2 Sv is in the NADW core. AAIW probably enters the Indian Ocean inshore of the Agulhas Current as part of an intermediate depth undercurrent that traverses the South Atlantic around 35 °S and focuses into a western boundary undercurrent of the South Indian Ocean (Schmid *et al.*, 2001). DiMarco *et al.* (2001), using data collected from the WOCE cruises at 25 °S, also observed a strong northward undercurrent flow along the African coast. Thus, these authors agree that this undercurrent system is most probably a continuation of the Agulhas undercurrent observed recently by Beal and Bryden (1997).

Continuing northwards and using the results from the XBT-temperature section, we observe additional evidence of the presence of anticyclonic eddy (A1) at this position (fig. 6.5). Along this line shipboard ADCP observations (fig. 6.4) reveal a strong westerly flow, which is consistent with an anticyclonic eddy at this position. We also encounter a very shallow (500 m) but well-define cyclonic eddy (C2) at 21.5 °S. Unfortunately, this feature could not be identified from the altimetric data.

Results from the **CTD-section-II** show that the vessel crossed the western edge of a strong and well-define anticyclonic eddy (A2) situated at 20 °S; 37 °E (fig. 5.10). Once again a positive anomaly (+20 cm) was identified from the altimeter data, where the warm anticyclonic eddy (A2) was encountered (fig. 6.1). Additional evidence of the existence of this eddy can be seen in the drift patterns of buoy 17377 and 17378 (figs. 7.6 and 7.7). Furthermore, the *Commandant Robert Giraud* in 1960 and 1962 and *Almirante Lacerda* in 1964 (Seatre and Jorge da Silva, 1984), occupied similar hydrographic sections across the Mozambique Channel along 20 °S. Their results also show the characteristic feature of an anticyclonic eddy at the same position. ADCP (fig. 6.6) and hydrographic observations further reveal that the eddy appears to penetrate all the way to the bottom. Geostrophic velocity (fig. 6.7) as well as shipboard ADCP (fig. 6.4) calculations inside the eddy, reveal a strong southward flow with a maximum surface geostrophic velocity of 60 cm/s. A shallow (100 m) and weak northward counter current was also observed, with velocities ranging between 10 and 20 cm/s closer inshore. Observations from the ADCP (fig. 6.6) reveal an undercurrent structure along the

Mozambican continental slope at 20 °S as seen in CTD-section-I to the south. Once again there are two cores. One is at intermediate level, around 1000 m depth, weakening northwards. The other core also flowing northwards is found below 2000 m depth.

Results from the northbound XBT-temperature section (fig. 6.8) provide additional evidence of an anticyclonic eddy (A2) at this position.

At the **CTD-section-III,** observations from both satellite altimetry (fig. 6.1) and hydrographic data (fig. 5.9) reveal that an anticyclonic eddy (A3) was situated between 40.2 °E and 42.5 °E. ADCP (fig. 6.9) and hydrographic observations reveal that the anticyclonic eddy observed (A3) was deep, penetrating to the bottom, while being roughly 350 km wide. Results from ADCP data (fig. 6.9) confirm the presence of an anticyclonic eddy in the center of the narrows. Although the geostrophic velocity results (fig. 6.10) also confirm the presence of an anticyclonic eddy, we do observe differences in the velocities of the two methods. The reason lies in the fact that the geostrophic velocity was calculated, using ODV, with a reference depth of 2500 m. By choosing a reference surface at a depth of 2500 m, one makes the assumption that the velocity at this depth is zero. If lower, then the whole water column even below 2500 m moves in the same direction and the calculated velocity will be an underestimate. By contrast, if the water column below 2500 m is moving in the opposite direction to that above 2500 m, then the geostrophically calculated velocity in the upper 2500 m will be an overestimate. In our case the ADCP results (fig. 6.9) show the eddy motion extending to the sea floor, here it is to be expected that the geostrophic results would be too low. In addition, both methods also show substantial counterflows near both coasts. Along the coast of Mozambique we observed a relatively strong northward flowing current (> 40 cm/s). Nehring *et al.* (1987), on the other hand, claimed to have found evidence of both a Mozambique Current, with a mean geostrophic velocity of 68 cm/s, and a relatively strong northward flowing countercurrent along the coast. Saetre and Jorge da Silva (1984) also found evidence of an inshore northward flow, which seems to be present along most of the Mozambican coast. However, they deduced that it was probably as a result of the cyclonic eddies. Along the Madagascar coast we observed a relatively strong southward moving current (> 50 cm/s). Such a southward flow was deduced by

Lutjeharms (1971) and apparently confirmed by Lutjeharms *et al.* (1981). Soares (1975) regarded the current as the eastern margin of a cyclonic vortex east of 40 °E. Saetre and Jorge da Silva (1984) also observed this southward moving current near the coast of Madagascar.

At the narrows of the Channel ADCP observations (6.9) still reveal an undercurrent system around 2000 m depth, but it had weakened considerably, from 2 Sv at 24 °S down to approximately 1 Sv in the narrows (De Ruijter *et al.*, 2002). In figure 5.8, a core of high (values greater than 200 μmol/kg) oxygenated water can be seen at 2000 m depth, confirming the presence of an undercurrent system. According to De Ruijter *et al.* (2002), the main part is probably steered by bottom topography across the channel, leaving it south of Madagascar. It might also be temporary reduced in strength by the presence of the eddy.

Continuing northwards along the XBT line, we enter the northern half of the anticyclonic eddy (A3) centered at 16.85 °S (fig. 6.11). The position of this eddy compares well with the position of the positive anomaly (+10 cm) observed from the altimetric data (fig. 6.1). The presence of an anticyclonic eddy in the northern mouth of the Mozambique Channel has been observed by several authors (Donguy and Piton (1969), Nehring *et al.* (1987) and Donguy and Piton (1991)). As we continue heading in a northerly direction, we encounter another anticyclonic eddy (A4) centered at 13.25°S. However, according to the temperature results (fig. 6.11) this eddy was very shallow, reaching only down to 300 m and extending to a width of about 250 km. It is possible that this was a very weak eddy and therefore the reason why it was not evident in the altimetric images (fig. 6.1).

At **CTD-section-IV** observations from ADCP data reveals a predominately southward flow along this line (fig. 6.12). It also reveals an along-slope boundary current with velocities ranging between 30 and 60 cm/s in the upper 200 m, decreasing to 20 cm/s at depths between 400 and 800 m, and still around 10 cm/s at 2000 m (De Ruijter *et al.*, 2002). We also find nothing of interest in the altimeter data (fig. 6.1).

Heading back southwards towards the narrows of the Channel, we once again encounter the edge of the same anticyclonic eddy (A3) at 15.85 °S (fig. 6.13). It therefore appears that the anticyclonic eddy observed (A3) at 16°S; 42.25 °E was quasi-stationary. It is also possible that this eddy could have been topographically induced as suggested by Saetre and Jorge da Silva (1984).

De Ruijter *et al.* (2002) have calculated that the resulting total transport across 12 °S, is about 30 Sv, of which 15 Sv is in the upper 450 m layer of Indian Central Water. Furthermore, he calculated that the intermediate layer, between 250 and 1500 m depth, carried 11 Sv and the remaining 4 Sv transport Deep Water south. The net transport estimates through the Mozambique Channel calculated by De Ruijter *et al.* (2002) for the ACSEX-1 cruise, lie within the range of historical and model estimates for this region (table 1).

To obtain a better understanding of the movement of these eddies over a longer time period we refer to the work of Schouten et al. (2001). By analysing 8 years of TOPEX/Poseidon altimetry data, they have shown that, triggered by incoming Rossby waves from the eastern Indian Ocean, generally 4 eddies are formed in the Mozambique Channel per year. He also observed that these eddies travel southward through the Channel at an average speed of about 4.5 km/day causing a net poleward transport of about 15 Sv. As a result, a continuous train of 3 anticyclonic eddies is always present in the Channel. This in turn produces a southward current at the Mozambique side of the Channel and northwards towards the Madagascar side. The Mozambique eddies themselves may be connected to processes further east in the Indian Ocean, as Rossby waves are observed to cross the Indian Ocean over the full zonal extent with frequencies close to that of the observed eddies in the Mozambique Channel and on the offshore edge of the Agulhas Current (Schouten *et al.*, 2001). Both to the north and south of Madagascar, interaction of these Rossby waves with local currents (the South Equatorial and East Madagascar Current respectively) may result in the shedding of eddies (Schouten *et al.*, 2001). However, the origin of the frequency of 4-5 per year and the forcing mechanism resulting in the Rossby waves at this frequency is not yet identified. Further study is presently underway to identify the origin of this phenomenon.

Model results have shown considerable seasonal variability in the Mozambique Channel. Although the model data supports the idea of a southward flow through the Channel, only a comprehensive measurement program that include a time series of direct measurements across the narrow, central portion of the Channel will ultimately determine the Channel transport's variability and seasonality (DiMarco *et al.*, 2001). Thus we await the results of the recent Dutch current meter deployments across the Channel with interest.

Transport (Sv)	Reference (m)	Data Source	Reference
20-26 south	1000	hydrography	Duncan, 1970
10 south	2500	hydrography	Harris, 1972
6 south (15°S)	1000	hydrography	Zahn, 1984
5 north (26°S)*	1000	hydrography	Zahn, 1984
19.4 south (Feb/Mar)	500	hydrography	Donguy and Piton, 1991
9.4 south (Mar)	500	hydrography	Donguy and Piton, 1991
14 south (July)	500	hydrography	Donguy and Piton, 1991
5 south	1000	hydrography	Stramma and Lutjeharms, 1997
15 south #	1500	lowered ADCP	De Ruijter et al., 2001
6 south	1500	inverse model	Fu, 1986
0.3 north	2000	inverse model	MacDonald and Wunsch, 1996
16 north to 35 south	full depth	LANL POP model	Maltrud et al., 1998
10 north to 20 south	full depth	3.5 layer model	Ji and Luther, 1998
3 north to 22 south	full depth	Kiel MOM	Biastoch and Krauss, 1999
14 +/- 6 south	full depth	inverse model	Ganachaud and Wunsch, 2000
15 +/- 6 south	2500 m	inverse model	Ganachaud et al., 2000
14 +/- 9 south	full depth	inverse model	Ganachaud et al., 2000
29.1 south	variable	hydrography	WOCE I2 - DiMarco et al., (2001)
21.5 south	1000	hydrography	WOCE I2 - DiMarco et al., (2001)
23.3 south	2000	hydrography	WOCE I2 - DiMarco et al., (2001)
5.9 south	variable	hydrography	WOCE I4 - DiMarco et al., (2001)
4.5 south	1000	hydrography	WOCE I4 - DiMarco et al., (2001)
19.0 south	2000	hydrography	WOCE I4 - DiMarco et al., (2001)

* did not extend to coasts

\# rectified transport in a Mozambique Channel ring

Table 6.1. Historical and Model Estimates of Volume Transport in the Mozambique Channel (DiMarco et al., 2001)

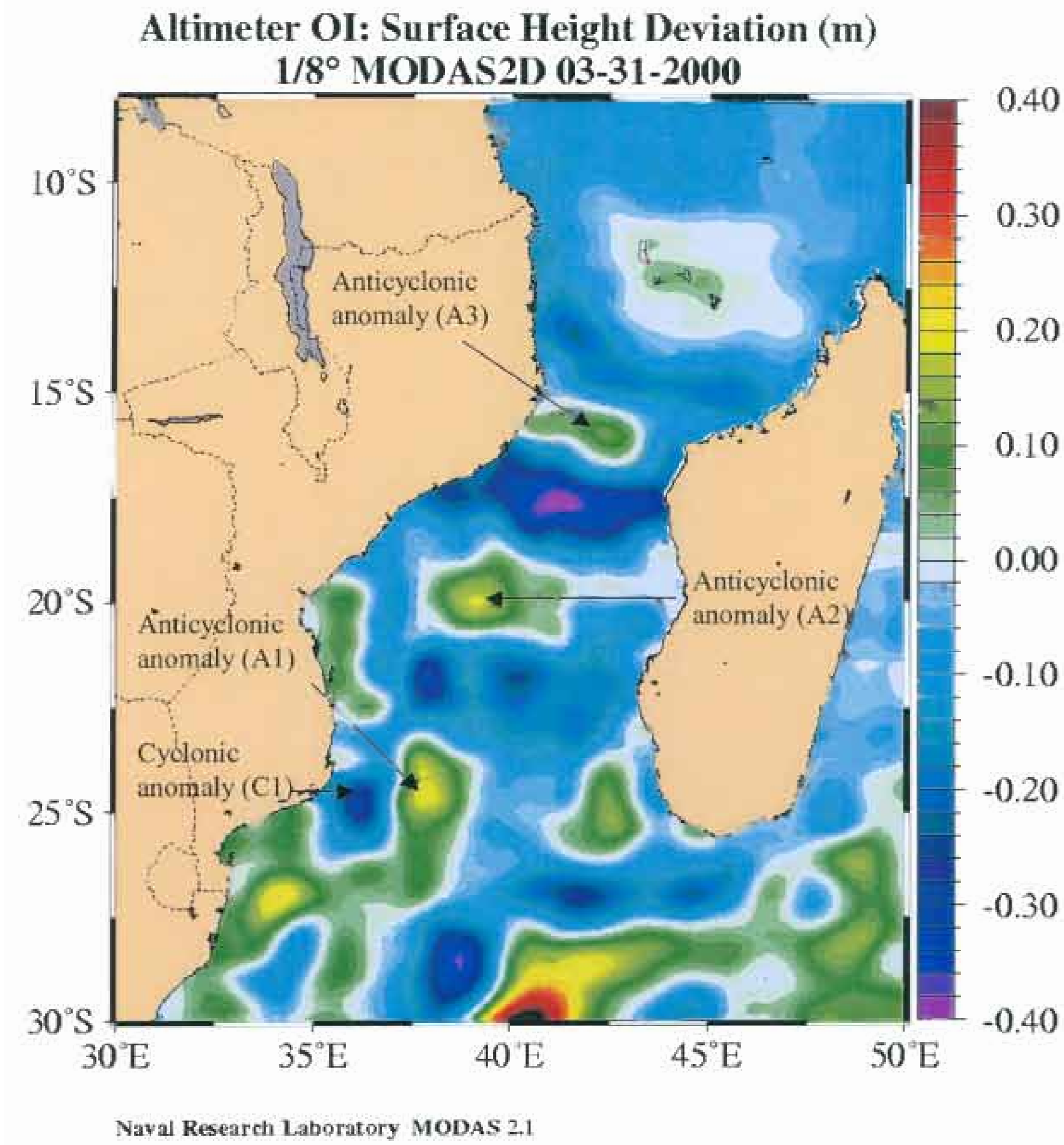


Figure 6.1: MODAS sea surface height imagery of the Mozambique Channel. The coloured regions indicate anticyclonic anomalies (red, yellow, green) and cyclonic anomalies (blue).

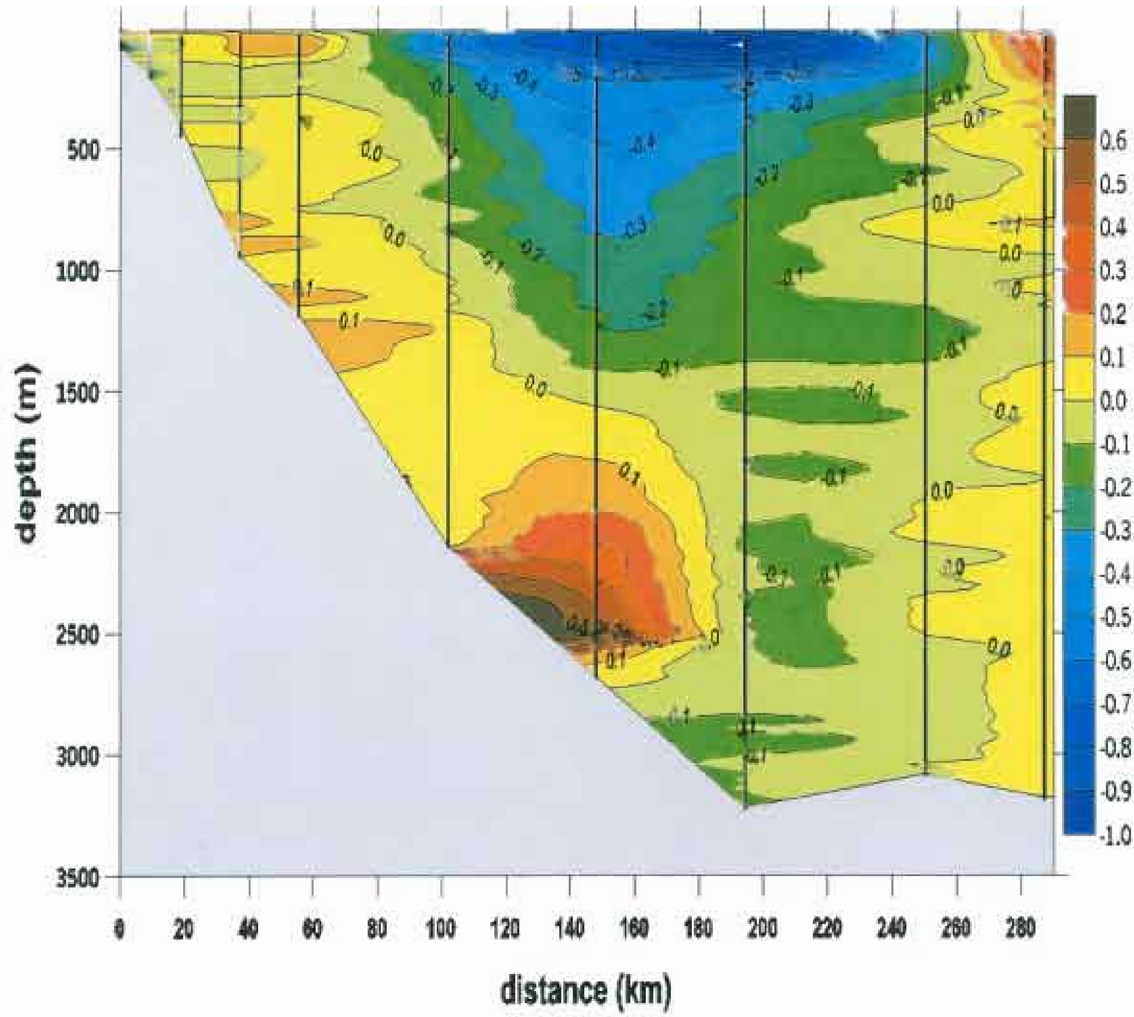


Figure 6.2: Absolute velocities across the southern entrance to the Mozambique Channel (CTD–section–I). The centre of the eddy is about 260 km off shore. Clearly, the eddy penetrates to the bottom. The Mozambique Undercurrent hugs against the continental slope, with a northward flow of NADW at 2500 m and a core AAIW flowing into the Mozambique Channel around 1000 m (De Ruijter et al., 2002).

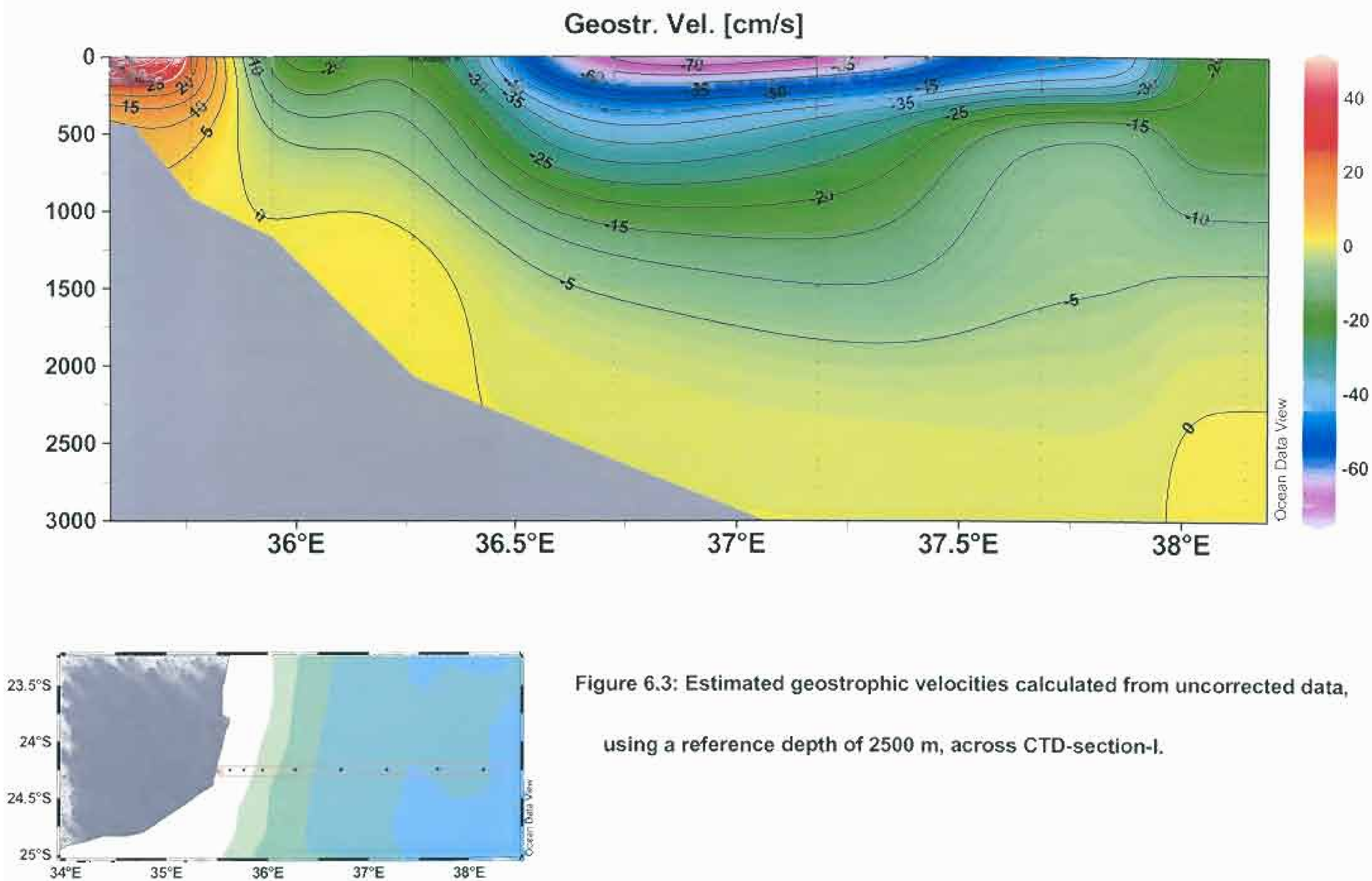


Figure 6.3: Estimated geostrophic velocities calculated from uncorrected data, using a reference depth of 2500 m, across CTD-section-I.

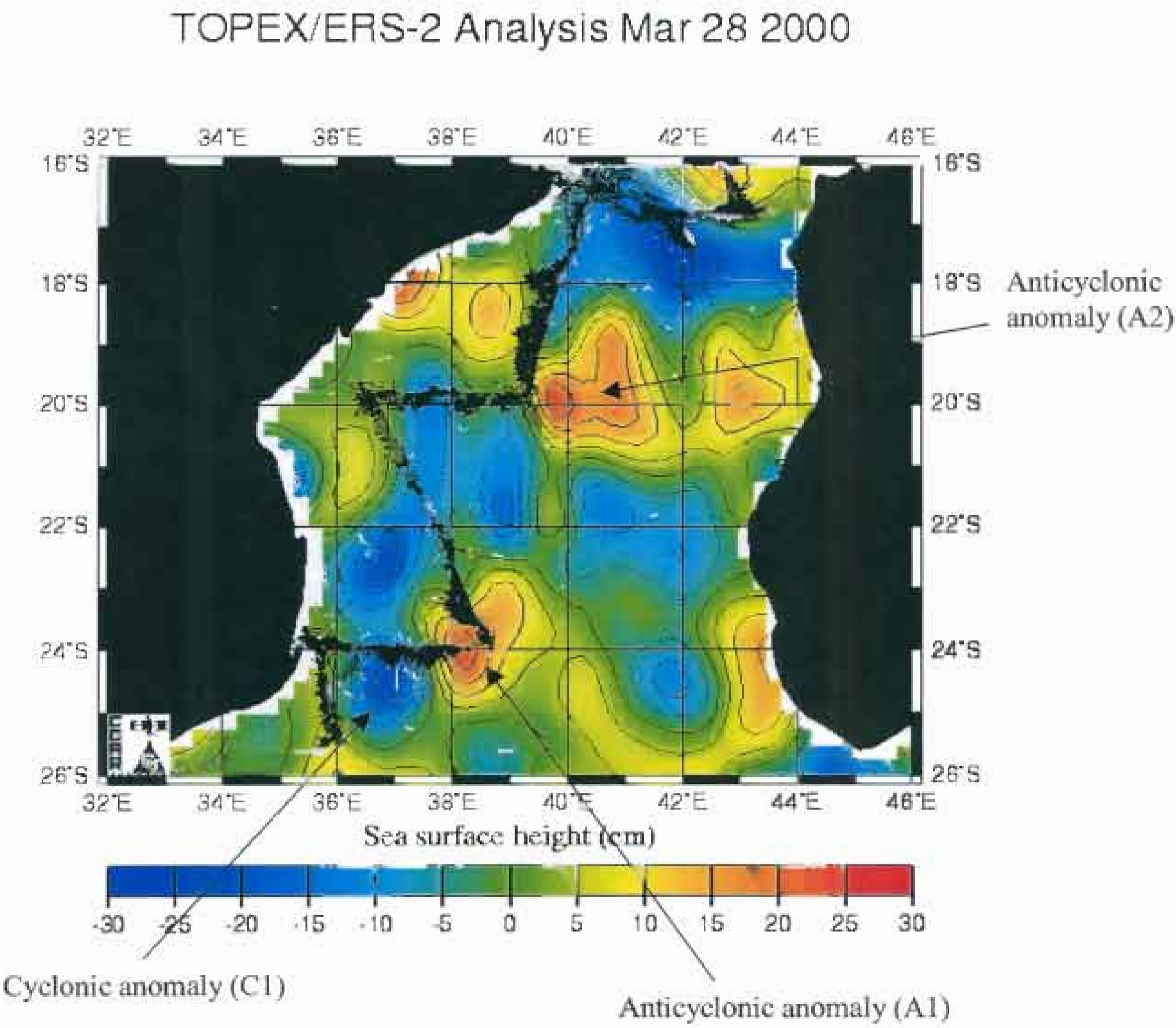
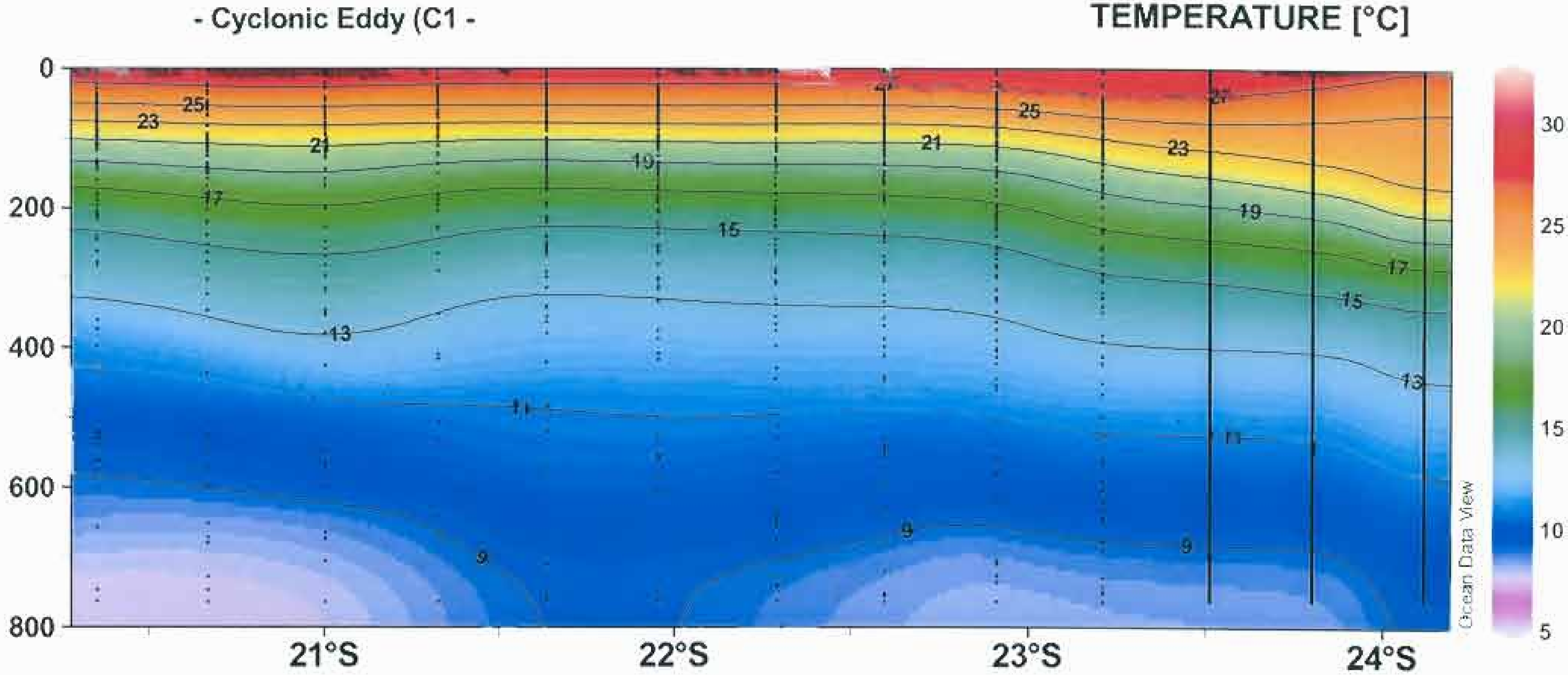


Figure 6.4: The cruise track of the ACSEX-1 cruise in the Mozambique Channel. The arrows along the track donate uncorrected drift as measured from on board ship established by dead reckoning. The coloured regions indicate positive (orange) and negative (blue) anomalies of sea surface height from altimetric observations from TOPEX/Poseidon satellite.



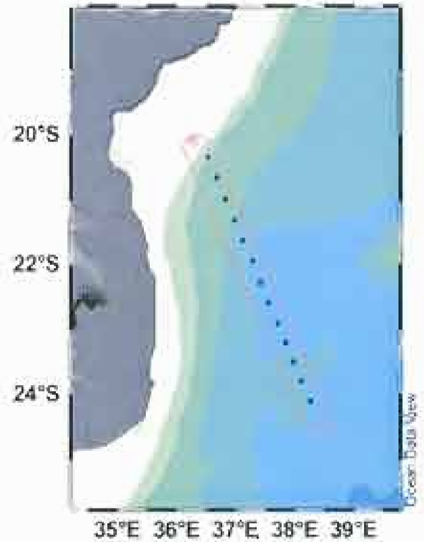


Figure 6.5: XBT- temperature section linking CTD-section-I to CTD-section-II.

ODV5.7 C:\Program Files\Ocean Data View\Data\SAVE\NewCol1; C:\Program Files\Ocean Data View\Data\SAVE\NewCol1.cfg; C:\Program Files\Ocean Data View\temp\.sec - May/29/2003 20:53:19

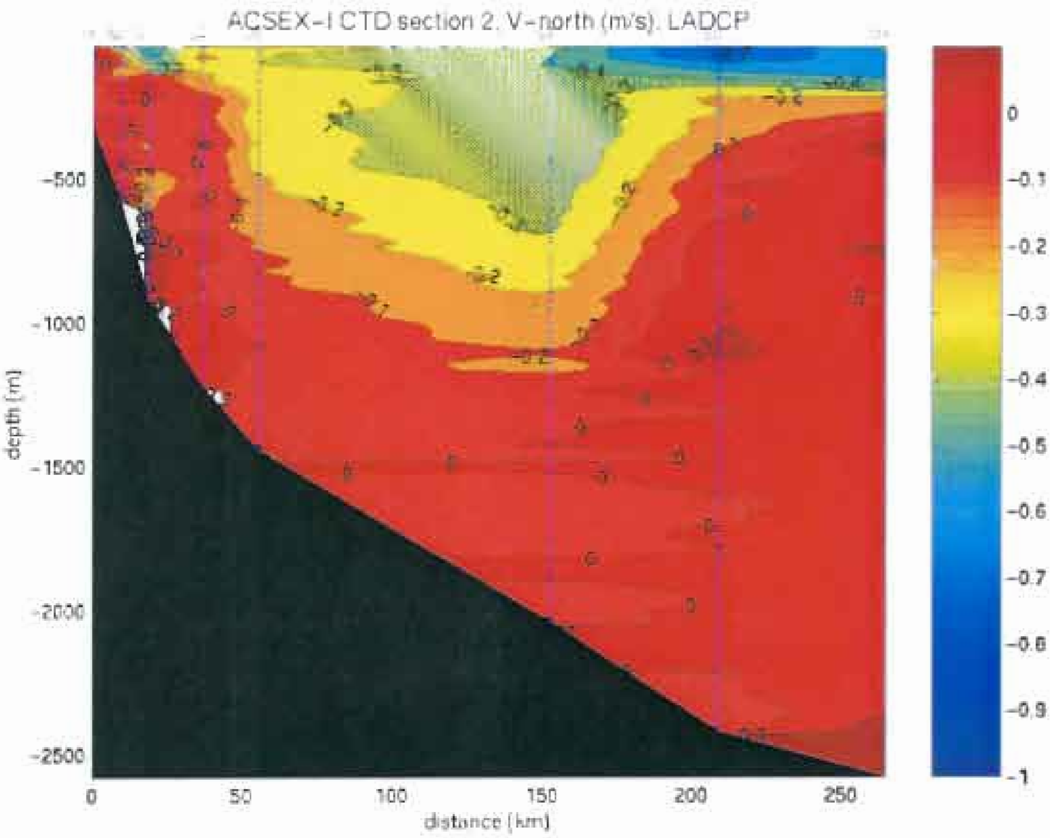
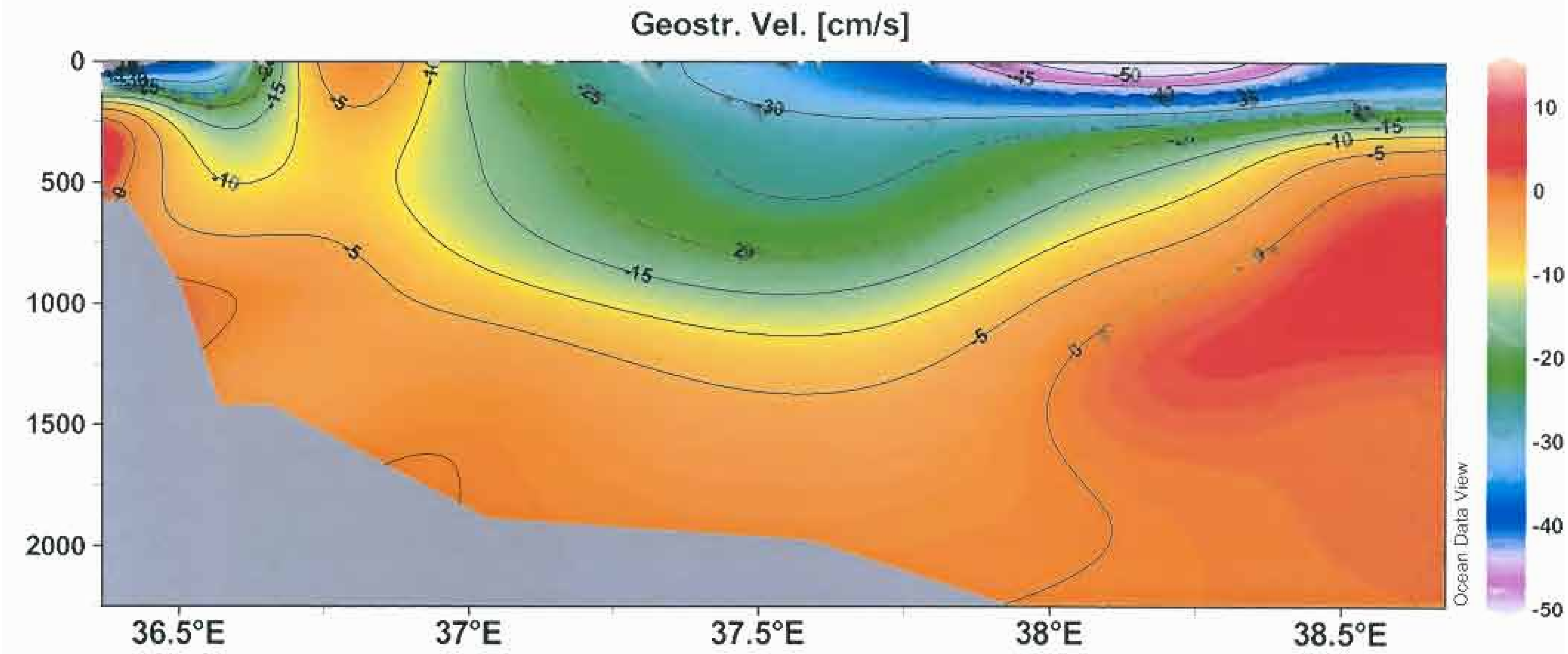


Figure 6.6: Absolute velocities across the CTD-section-II (20 °S) in the centre of the Mozambique Channel.



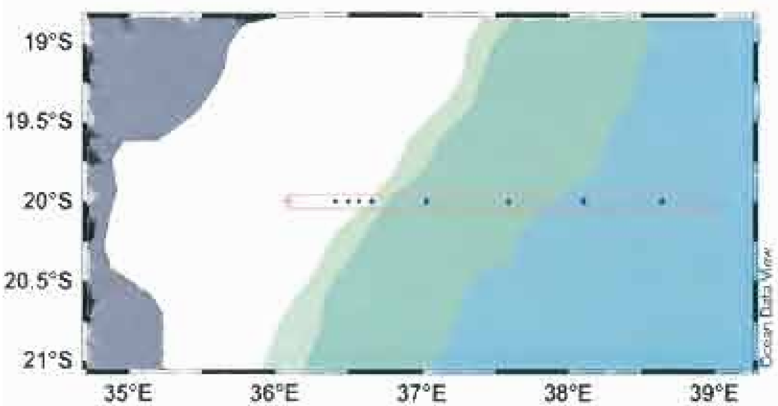


Figure 6.7: Estimated geostrophic velocities calculated from uncorrected data, using a reference depth of 2500 m, across CTD-section-II.

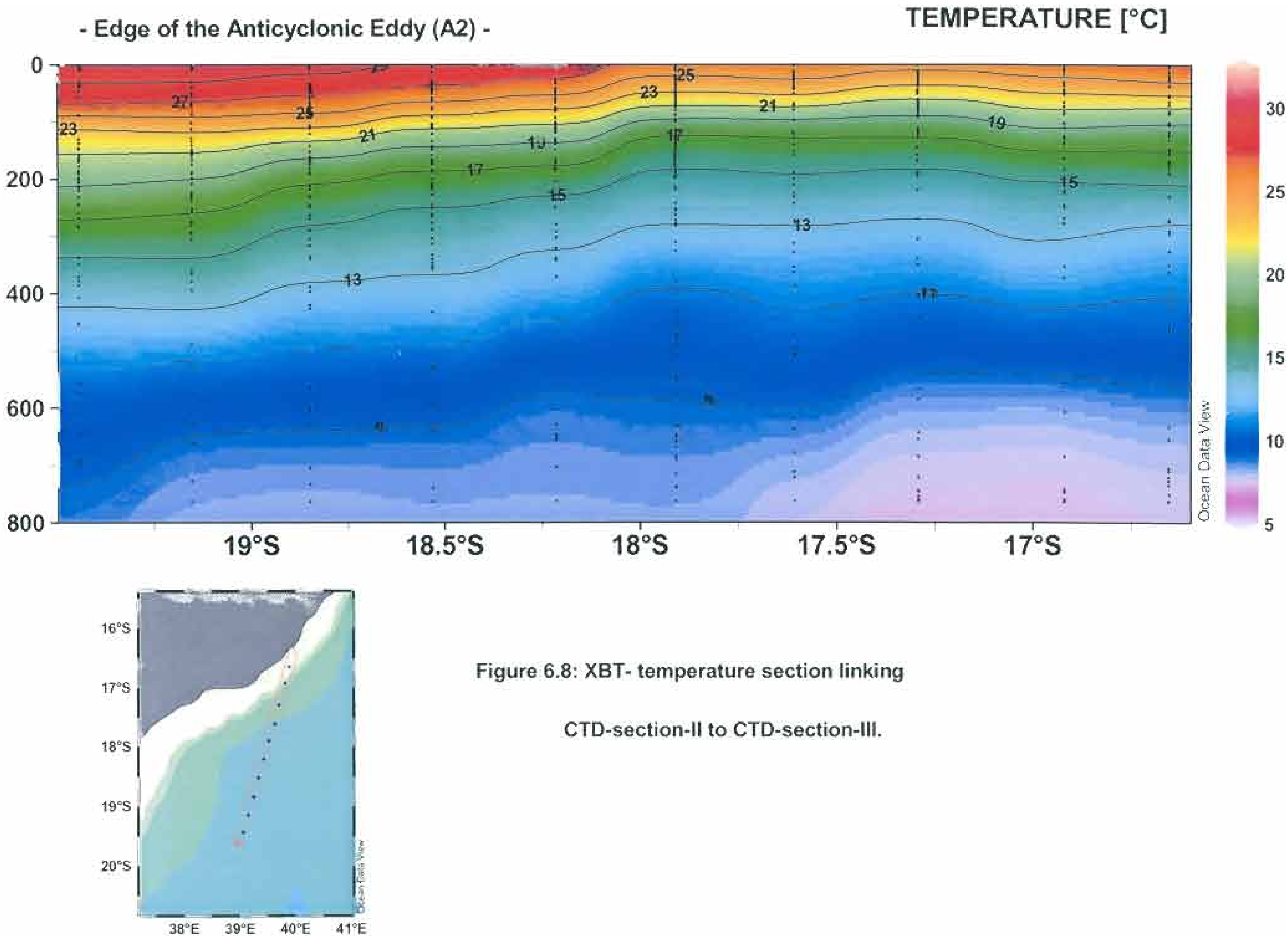


Figure 6.8: XBT- temperature section linking

CTD-section-II to CTD-section-III.

ODV5.7 C:\Program Files\Ocean Data View\Data\SAVE\NewCol1; C:\Program Files\Ocean Data View\Data\SAVE\NewCol1.cfg; C:\Program Files\Ocean Data View\temp\.sec - May/29/2003 21:05:26

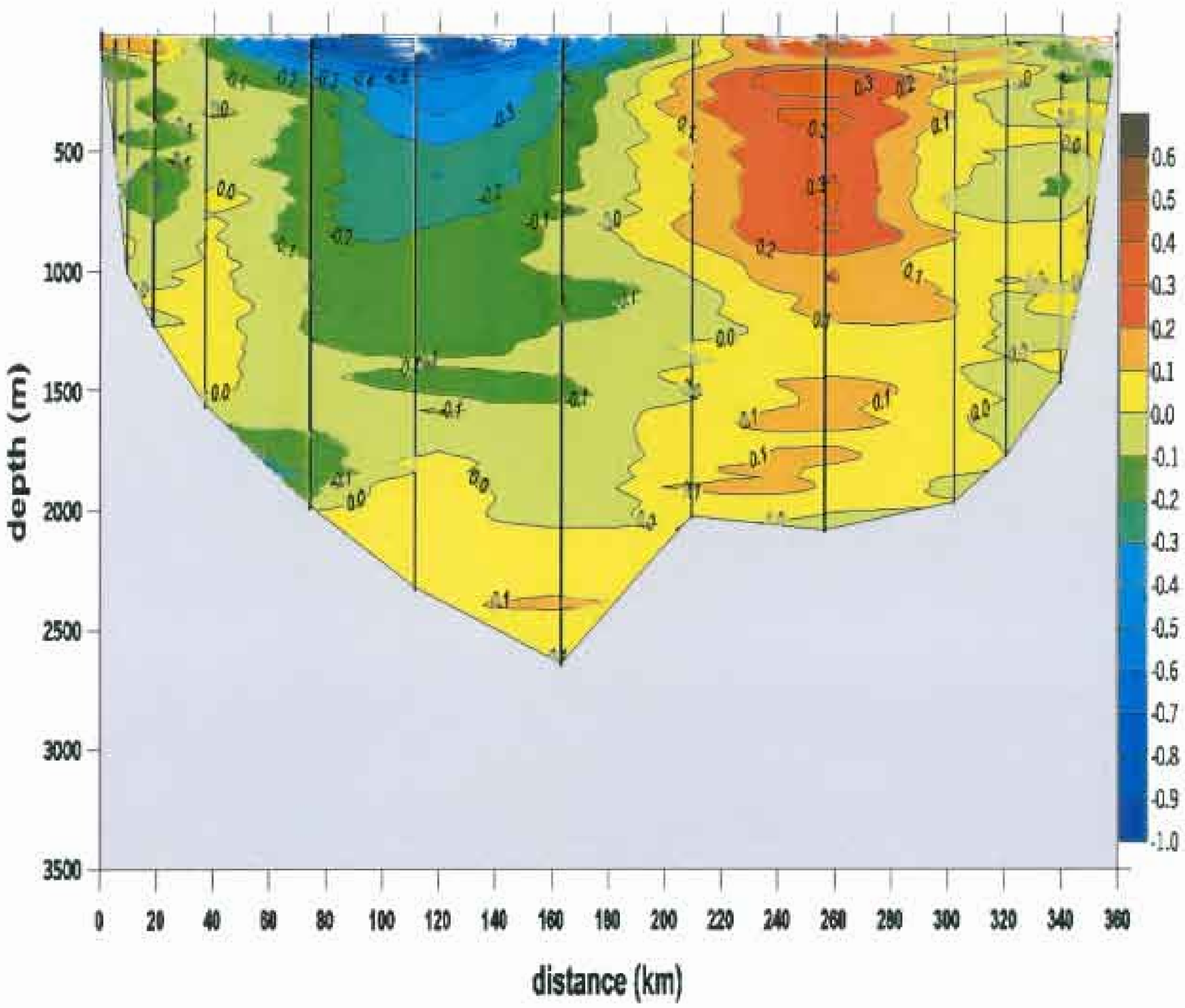
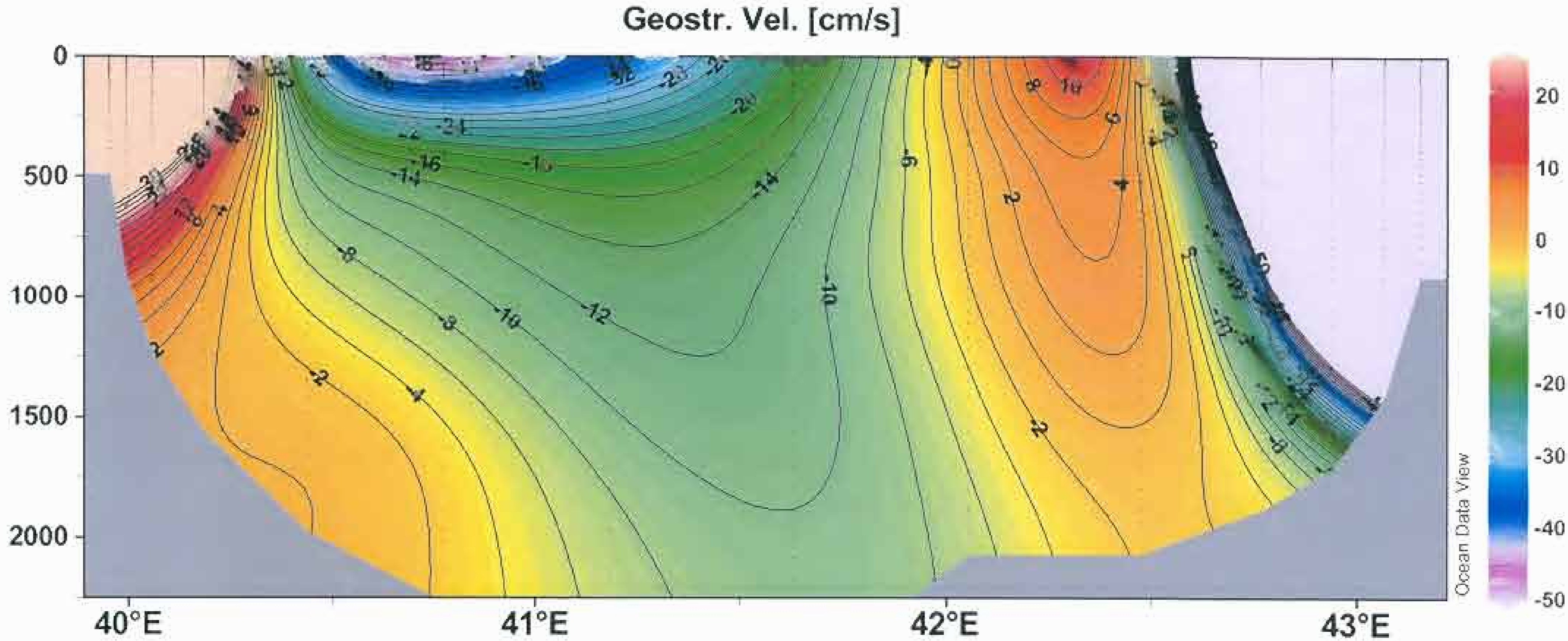


Figure 6.9: Absolute velocities across the narrow part of the Mozambique Channel. Observations were taken using a Lowered Acoustic Doppler Current Profiler. Positive values indicate northward velocities, negative ones are southward. An anti-cyclonic eddy appears to fill almost the full cross section of the channel and to penetrate to the bottom. Below 2000 m a (weak) northward flow of North Atlantic Deep Water (NADW) still exists, while along the African continental slope, around 1100 m depth, a continuation of an equatorward undercurrent carries Antarctic Intermediate Water (AAIW) northward (De Ruijter et al., 2002)



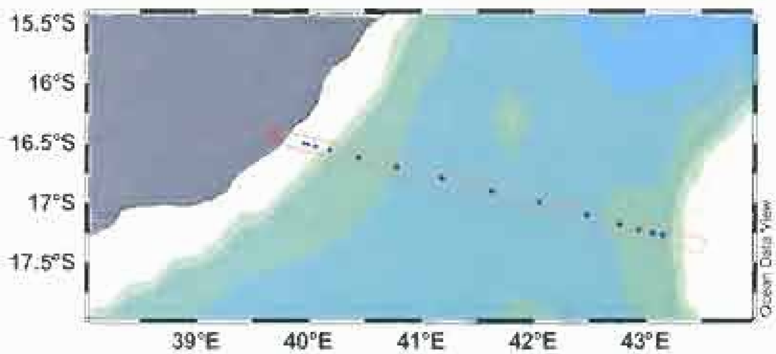
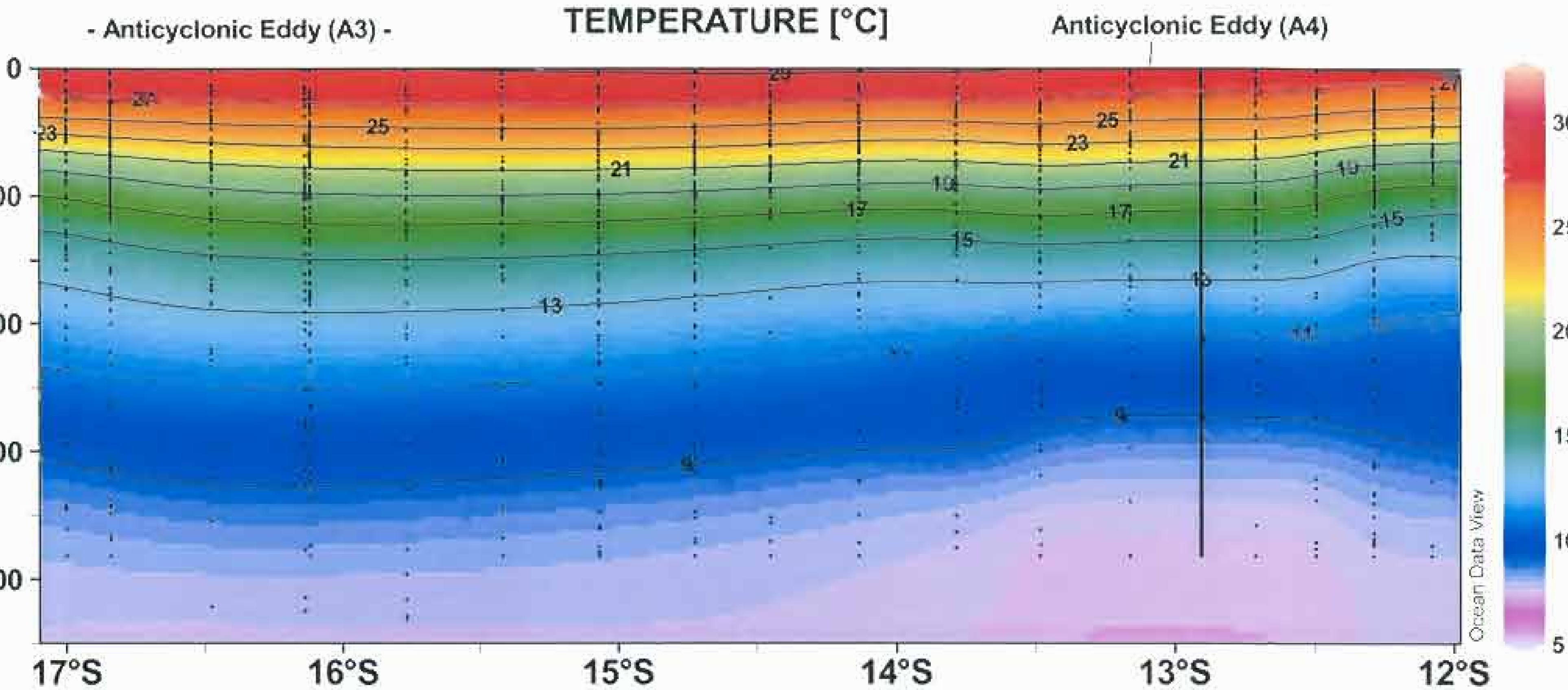


Figure 6.10: Estimated geostrophic velocities calculted from uncorrected data, using a reference depth of 2500 m, across CTD-section-III.



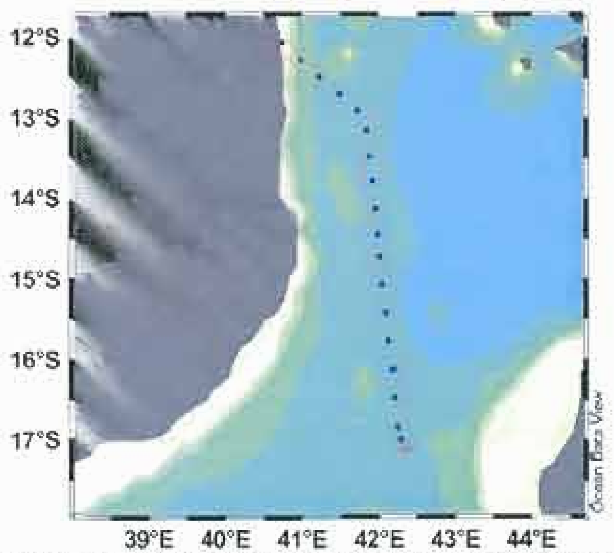


Figure 6.11: XBT- temperature section linking CTD-section-III to CTD-section-IV.

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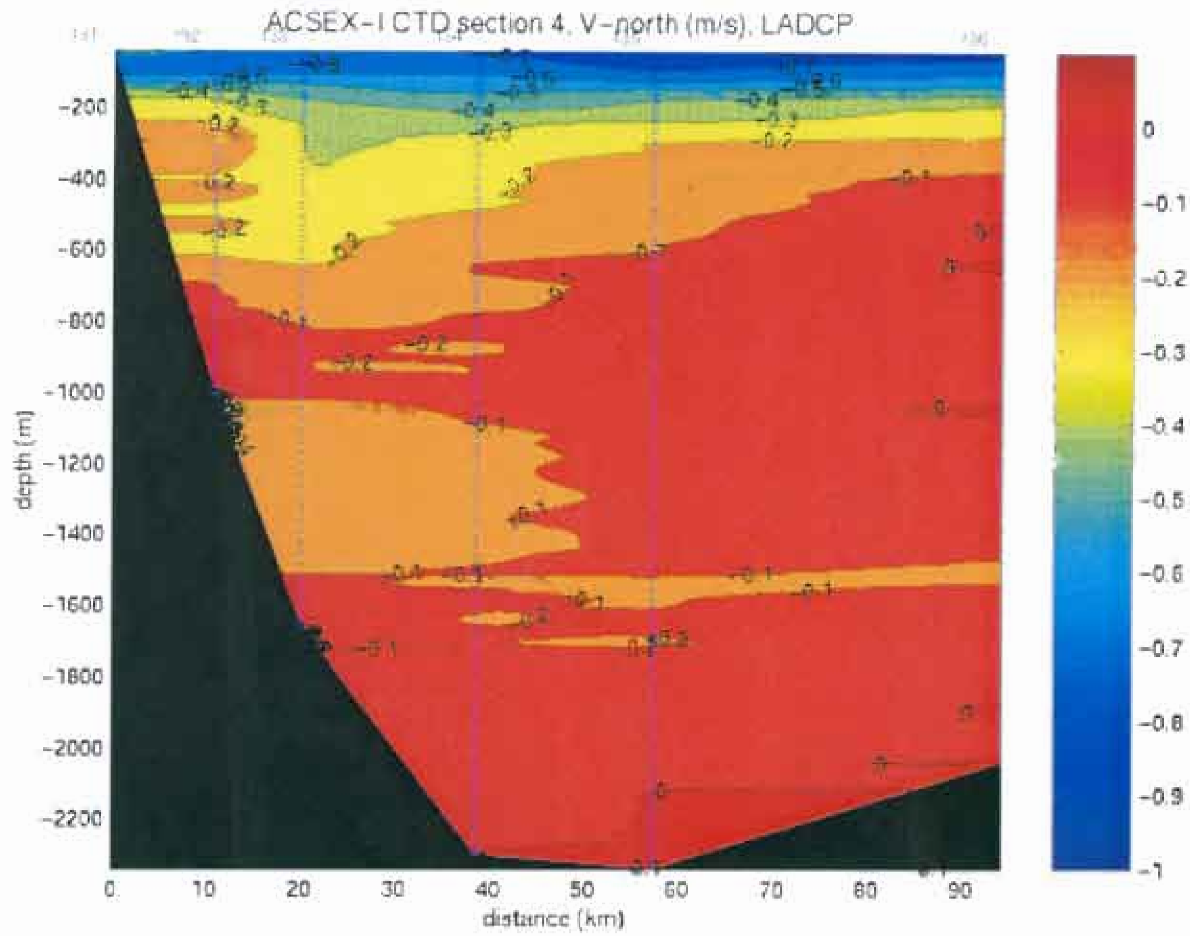
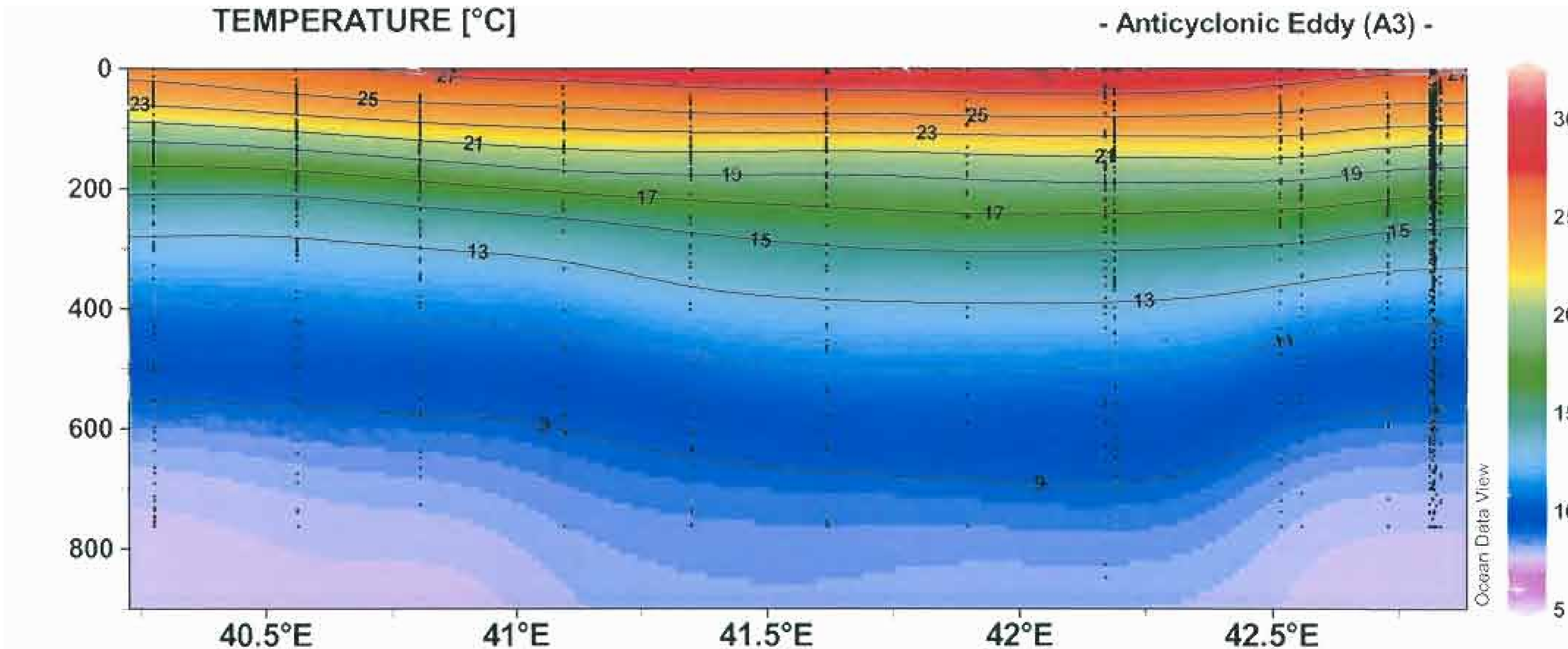


Figure 6.12: Absolute velocities across CTD-section-IV (12 °S) in the northern mouth of the Mozambique Channel.



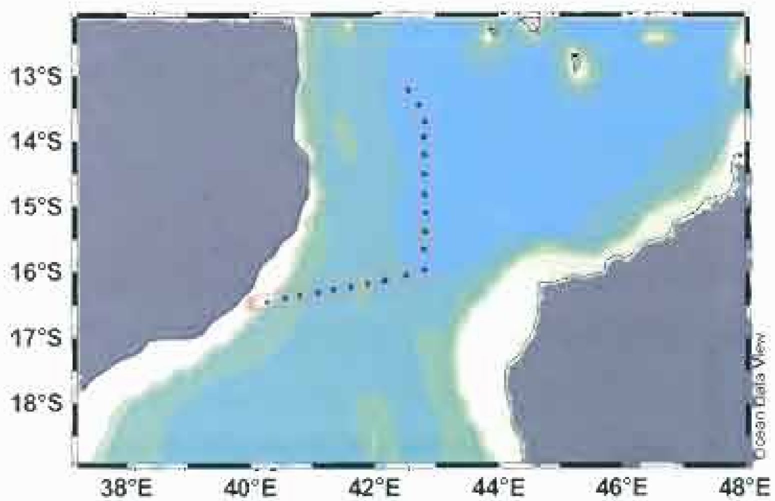


Figure 6.13: XBT- temperature section linking CTD-section-IV to CTD-section-III.

ODV5.7: C:\Program Files\Ocean Data View\Data\SAVE\NewCol1; C:\Program Files\Ocean Data View\Data\SAVE\NewCol1.cfg; C:\Program Files\Ocean Data View\temp\.sec • May/29/2003 21:14:20

Chapter 7
Drifting Buoy Data and Altimetry

The general utility of using satellite-tracked drifting buoys to trace circulation patterns in parts of the ocean that are relatively unstudied, such as the southwest Indian Ocean, has been recognized for some time (Gründlingh, 1977; Lutjeharms *et al.*, 1981). When combined with a study of hydrographic data from the same area, analyses of the drift of buoys have shown to be particularly revealing (Lutjeharms *et al.*, 1981).

During the ACSEX-1 cruise seven ARGOS satellite-tracked buoys were deployed within the channel (fig. 7.1). We should also point out that the drifting buoys **were not blindly** deployed. The aim of this project was to deploy the buoys inside or as close to the Mozambique Eddies. In addition, the drifting buoy data were broken down and then superimposed on the altimeter data. This was done in order to firstly, gives us a better idea of the circulation within the Mozambique Channel and secondly, to verify the accuracy of the altimeter data images. Thus satellite altimetry was first consulted before each deployment in order to achieve this goal.

Unfortunately, one of the main problems with comparing the SSH-altimetry data with drifter tracks is that the SSH data is "wired" together using multiple altimeter tracks with several days of scattered multi-channel SST measurements, so a precise and synoptic comparison is not possible. Drifters could also be influenced by surface, wind-driven currents making a direct comparison somewhat difficult.

<u>Buoys deployed in the southern mouth of the channel:</u>

Observations from satellite altimetry data show that **buoy 17343**, launched on 27 March at 24 °S; 37.4 °E, was launched in the centre of a large anticyclonic anomaly (fig. 7.2a). These observations compare well to the hydrographic data (fig. 5.12), which confirms the existence of an anticyclonic eddy (A1) at this position. During its drift southwest of 24 °S, buoy 17343 was entrained into a series of anticyclonic circulation patterns (fig. 7.3).

Between March 27 and June 10, buoy 17343 described a sequence of 9 anticyclonic motions in all with an average period of 4.6-days, before entering the core of the Agulhas Current on the 12 June. By superimposing the altimetry on the drift patterns of buoy 17343 (figs. 7.2b and 7.2c), we are able to track the southward movement of the anticyclonic anomaly down the coastline from 24 °S to 32 °S, were it eventually enters the Agulhas Current on 25 May. Between 26 May and 12 June the drift track had an almost jet-like appearance, reaching a maximum drift speed of 254 cm/s. Gründlingh (1977), using the *Nimbus IV* satellite-tracked buoys also recorded similar drift speeds (228 and 260 cm/s) in the Agulhas Current. The buoy then moved in a southwesterly direction into the Agulhas Retroflection area (fig. 7.5a). From 1 July onwards, the buoy started its easterly trajectory in the Agulhas Return Current (fig. 7.5b). Buoy 17347 had an average drift speed of 33 cm/s between 12 °E and 28 °E. These results are very similar to those reported by Gründlingh (1977), who also recorded drift speeds of 28 cm/s in the Agulhas Return Current. On 28 July the buoy arrived at the western edge of the Agulhas Plateau. However, instead of being swept northwards around the plateau, altimetry shows that the buoy was caught in a small cyclonic anomaly and therefore drifted southwards around the plateau (fig. 7.5c).

Buoy 17442 was launched on 28 March at 24 °S; 38.33 °E (fig. 7.2a) inside the same anticyclonic eddy (A1) as buoy 17347. From its drift tracks we observe the exact same behavior that was experienced by buoy 17343. Between the 28 March and 13 May, buoy 17442 drifted in a southwesterly direction experiencing a number of anticyclonic motions with an average period of 6.2-days. It described a sequence of 7 cycles before all signals were lost (fig 7.4).

Buoys deployed in the centre of the channel:

Buoy 17378 was launched on the 8 April 2000 at 17.17 °S; 42.7 °E (fig. 7.6) at the edge of a cyclonic anomaly. After deployment the buoy set off in a southerly direction. After drifting south for a week at an average current speed of 39 cm/s, the buoy underwent a 90° change in direction of drift and started moving westwards. These observations further confirm that the cyclonic anomaly, observed from the altimeter data, does exist (fig. 7.8). This change in direction also compares well with the surface circulation scheme presented by Donguy and Piton (1991) (fig. 2.8b:chapter 2). Figure 7.9 shows that during its drift west, buoy 17378 was drawn into a large anticyclonic anomaly with current speeds approaching 145 cm/s between 37 °S and 40 °E. The anticyclonic anomaly observed here compares well to the hydrographic data (5.10), which confirms the existence of an anticyclonic eddy (A2) at this position. The buoy then spent the next 38 days entrained in the eddy and circled it 3 times with a consistent average period of 11 days, before drifting off at much reduced speeds in a southward direction. On 12 June, 12 days after being expelled from the anticyclonic eddy, a smaller anticyclonic eddy can be observed from its drift patterns (fig. 7.10). The buoy appears to circulate an anticyclonic eddy once. However, also from figure 7.10, one can clearly see that the buoy drifted into the eastern edge of a cyclonic anomaly, thereby forcing the buoy to head back north before drifting in a westerly direction towards the Mozambique coast. Before reaching the coast, buoy 17378 switches direction again and swings from a westerly to a southwesterly direction. Between 26 June and 2 July, the buoy's tracks followed a small cyclonic motion on the continental shelf at 25.15 °S, before continuing southwestward (fig. 7.10). The data of Lutjeharms and Jorge da Silva (1988) and Gründlingh (1977) showed the existence of a small cyclonic eddy at this position, which they found to be a topographically-induced, semi-permanent phenomenon. We find that satellite altimetry confirm the existence of a cyclonic anomaly at this position but shows it to be rather large (fig. 7.10). At 26.61 °S, buoy 17378 switched direction again, drifting northwards, entering a small cyclonic eddy at 26 °S. After leaving the eddy the buoy heads for the coastline and remains there, apparently caught in the surf (fig. 7.10).

Buoy 17377 was launched on the 30 March at 38.96 °E; 20 °S in the centre of a large anticyclonic anomaly. These observations compare well to the hydrographic data (5.10), which confirms the existence of an anticyclonic eddy (A2) at this position. The buoy then spent the next 34 days (March 30 - June 3) entrained in the eddy and circled it 7 times, with an average period of 6 days, before moving southwards (fig. 7.7-stage1). This eddy (A2) appears to be the same feature as the one observed from the drift tracks by buoy 17378. However, 3 days later on June 6 at 37.45°E; 22.48°S, the buoy switched direction again, drifting northeastwards, entering the large anticyclonic eddy again and remaining there (Fig. 7.7-stage2).

Buoy 17234 was launched on March 29 at 36.68 °E; 20 °S (fig. 7.11), in an area where we hoped to find the Mozambique Current. Unfortunately this was not the case. After deployment the buoy meandered off in a general westerly direction at an average speed of 13 cm/s towards the Mozambique Coast. Five days later, on April 3, the drift track switched to a northeasterly direction continuously increasing in speed (15 cm/s) and moving closer towards the Mozambique coast (fig. 7.13). This northward current is also observed in the geostrophic velocity results (fig. 6.7) in chapter 6. The drift tracks also shows that between May 1 and July 26, buoy 17234 remains virtually in the same spot.

Buoy 17444 was launched on the 31 March in a very large cyclonic anomaly, which covered the entire narrows of the channel, at 16.5 °S; 40 °E (fig. 7.12). After deployment the buoy set off in a northeasterly direction at an average speed of 24 cm/s, keeping close to the coastline. Four days later the drift track switched to a southeasterly direction, drifting into the centre of the Mozambique Channel. The buoy continued to head in this direction for 5 days continuously increasing in speed (83 cm/s) until it reached 17.51 °S; 42.8 °E, before switching to a southerly direction. After drifting south for 3 days, the buoy underwent a 90 ° change in direction of drift and started moving westwards (fig. 7.8). By observing the drift patterns of buoy 17444 until now, we notice that it followed a cyclonic motion, thereby confirming that the large cyclonic anomaly identified from the altimetry data did exist. During its drift westwards buoy 17444 was drawn into a large anticyclonic anomaly with current speeds approaching 73 cm/s between 36 °E and 39 °E (fig. 7.9). This anomaly is the same anticyclonic eddy (A2) observed in the drift tracks of buoy 17378 and 17377. The buoy spent the next 45 days circling the eddy only once. Until this point the drift patterns observed by buoy 17378 and 17444 are quite similar. Also, the surface drift patterns of these two buoys are quite similar to the surface circulation scheme presented by Donguy and Piton (1991). However, after being expelled from the eddy and instead of continuing southwards like buoy 17378, buoy

17444 drifted in an eastward direction until it reached 19 °S; 41 °E. At this point buoy 17444 switched direction again and headed in a northeasterly direction at an average speed of 34 cm/s, into the northern mouth of the Mozambique Channel. Twelve days later, on the 20 June, the buoy switched direction again and swung into a southeasterly direction, heading closer to the Madagascar coast. Four days later buoy 17444 switches direction again and heads back into a northeasterly direction. Between the 3 July and 1 September, buoy 17444 described a sequence of 4 cyclonic motions, with consistent average periods of 11 days, before drifting off into the centre of the Mozambique Channel. These observations compare well with the altimeter data, which shows the presence of a large cyclonic anomaly in the area (fig. 7.14).

Buoys deployed in the northern mouth of the channel:

Buoy 17446 was launched in the northern mouth of the Mozambique Channel at 40.8 °E; 12 °S on the 3 April. After deployment the buoy drifted in a southerly direction keeping close to the Mozambique Coast at an average current speed of 43 cm/s. According to Donguy and Piton (1991), buoy 17446 appears to be caught in the southward flowing Mozambique Current. However, from the altimeter data we observe that buoy 17446 was deployed in an anticyclonic anomaly (fig. 7.15). In addition, instead of crossing the channel at the narrows as the portrayal by Donguy and Piton (1991) would have it, on April 9, the drift direction abruptly swung from a southerly to a northerly direction, meandering slowly (14 cm/s) towards the Mozambique Coast.

In conclusion we find that drifting buoy data supports the theory that the Mozambique Channel is a region strongly influenced by the presence of eddies, some propagating southwards quite quickly while others move at a much slower pace.

In addition, we have also created drifting buoy animations for the drift tracks of buoy's 17343, 17378, 17444, 17234 and 17446 using the combination of drifting buoy data and MODAS ssh images. These animations can be found on the attached CD ROM.

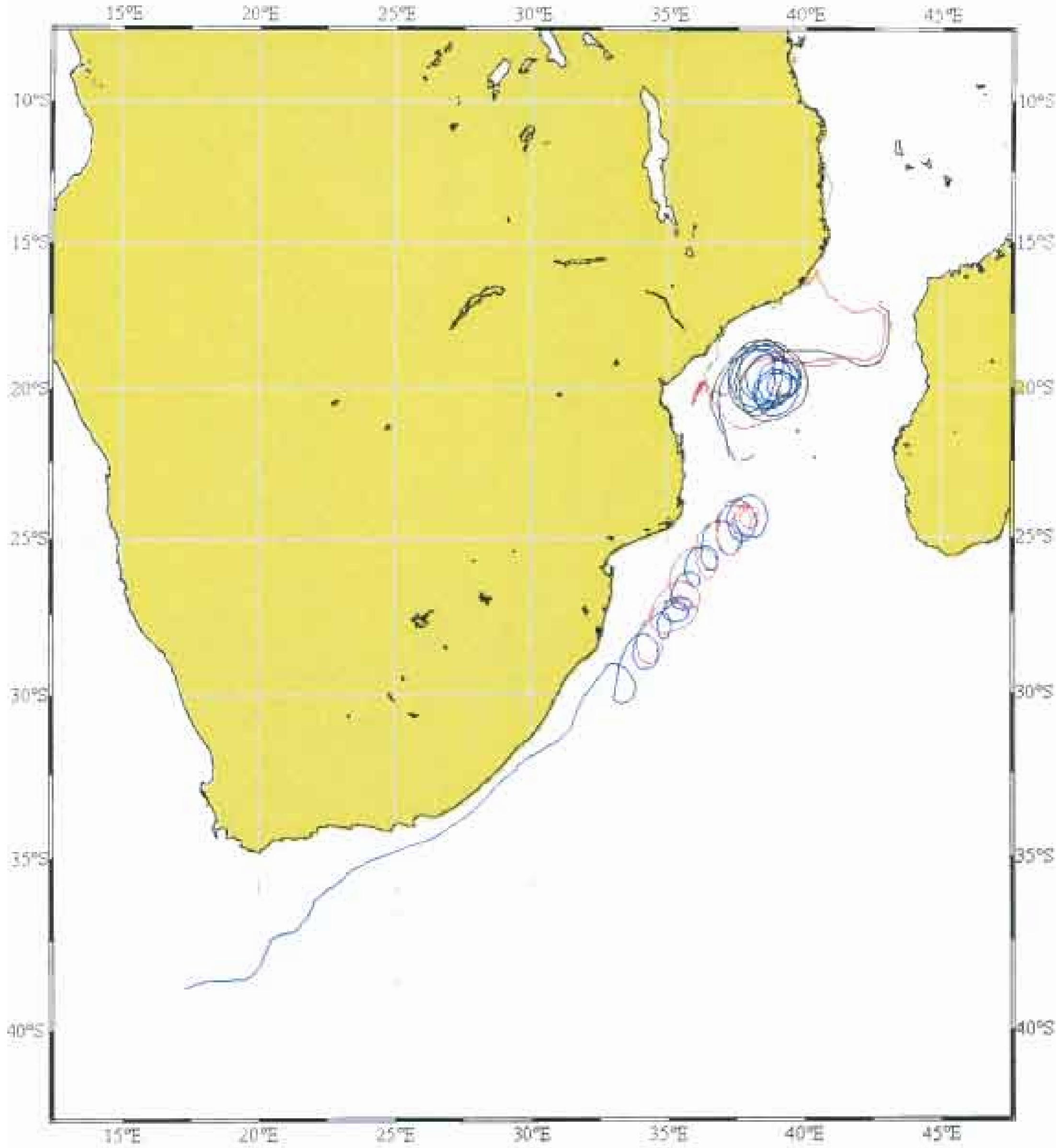


Figure 7.1: Drift tracks of the seven ARGOS satellite-tracked buoys deployed in the Mozambique Channel.

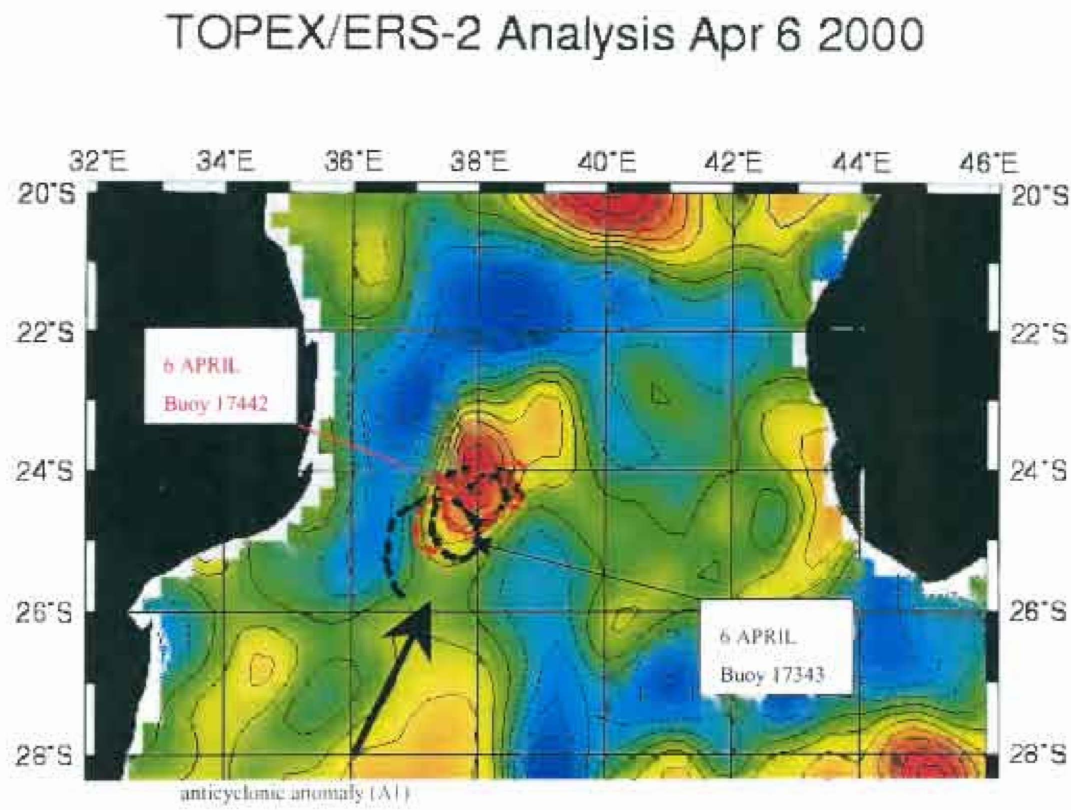


Figure 7.2a

Figure 7.2b

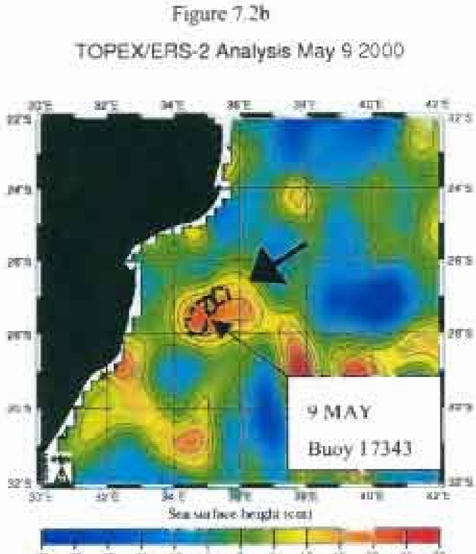


Figure 7.2c

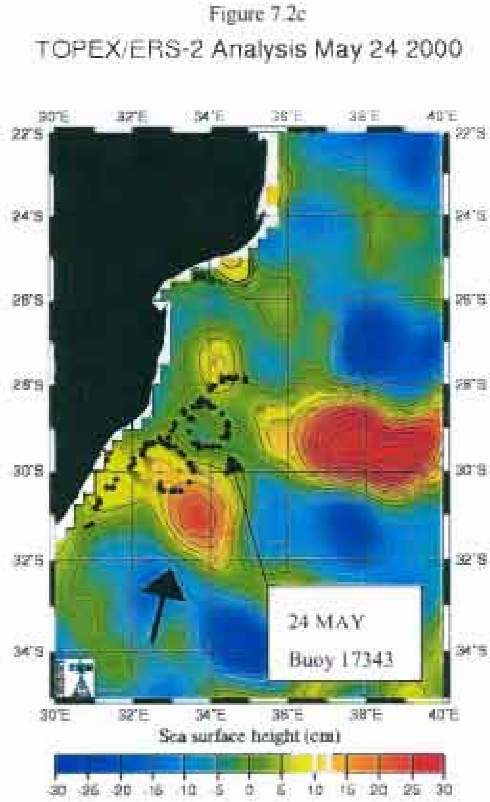


Figure 7.2a, 7.2b, 7.2c: Shows the drift tracks of buoy 17343. By superimposing the altimetry on the drift tracks, we are able to track the southward movement of the anticyclonic anomaly down the coastline from 24 S to 32 S.

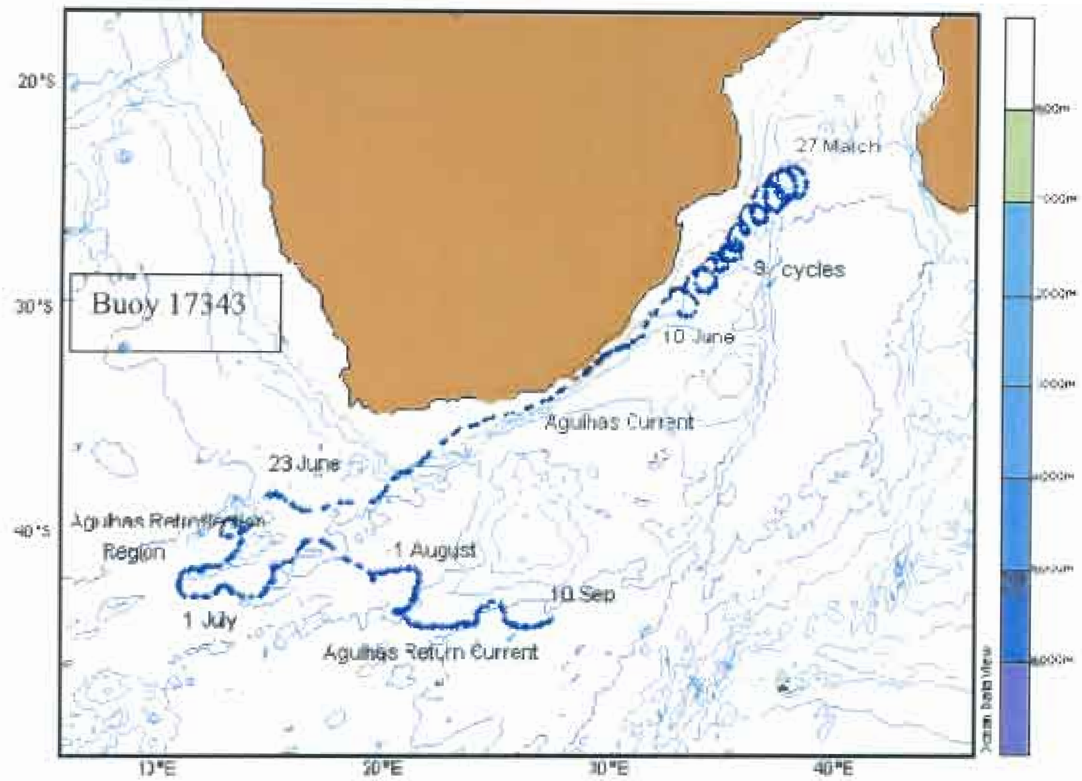


Figure 7.3

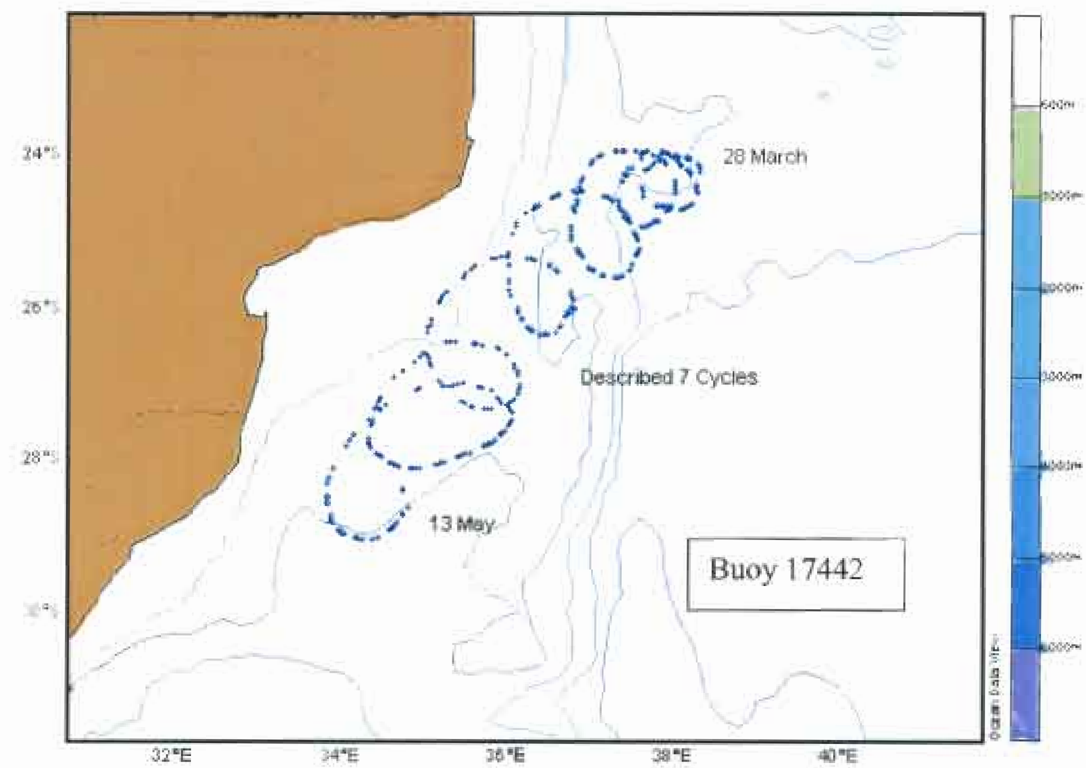
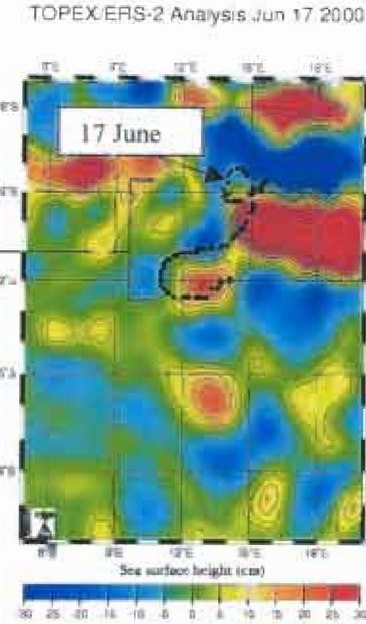


Figure 7.4

Figures 7.3 & 7.4: Drift tracks of buoys 17343 (top) and 17442 (bottom).

Figure 7.5a



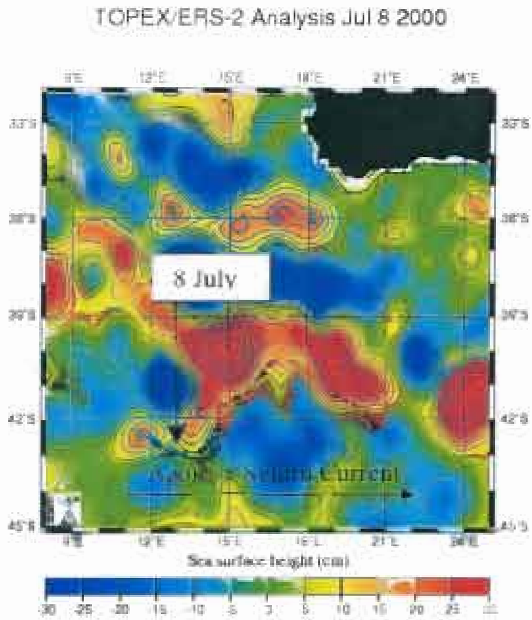


Figure 7.5b

Figure 7.5c

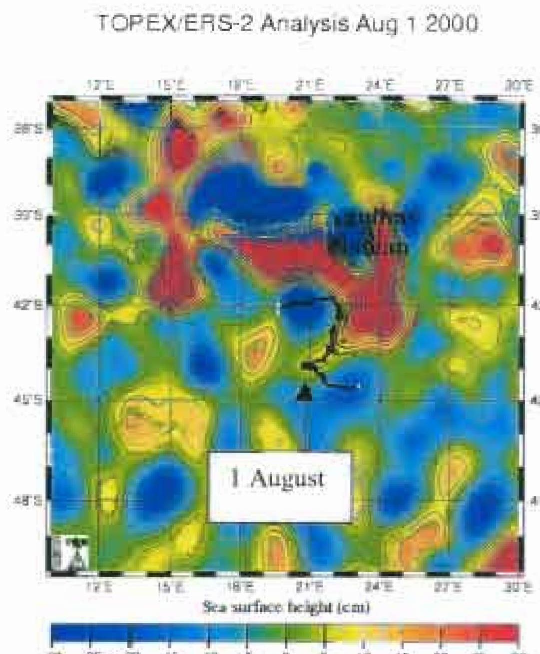


Figure 7.5a,b,c: Shows the drift tracks of Buoy 17343 (15 June-10 August) indicating the Agulhas Retroflection and the easterly flow of the Agulhas Return Current.

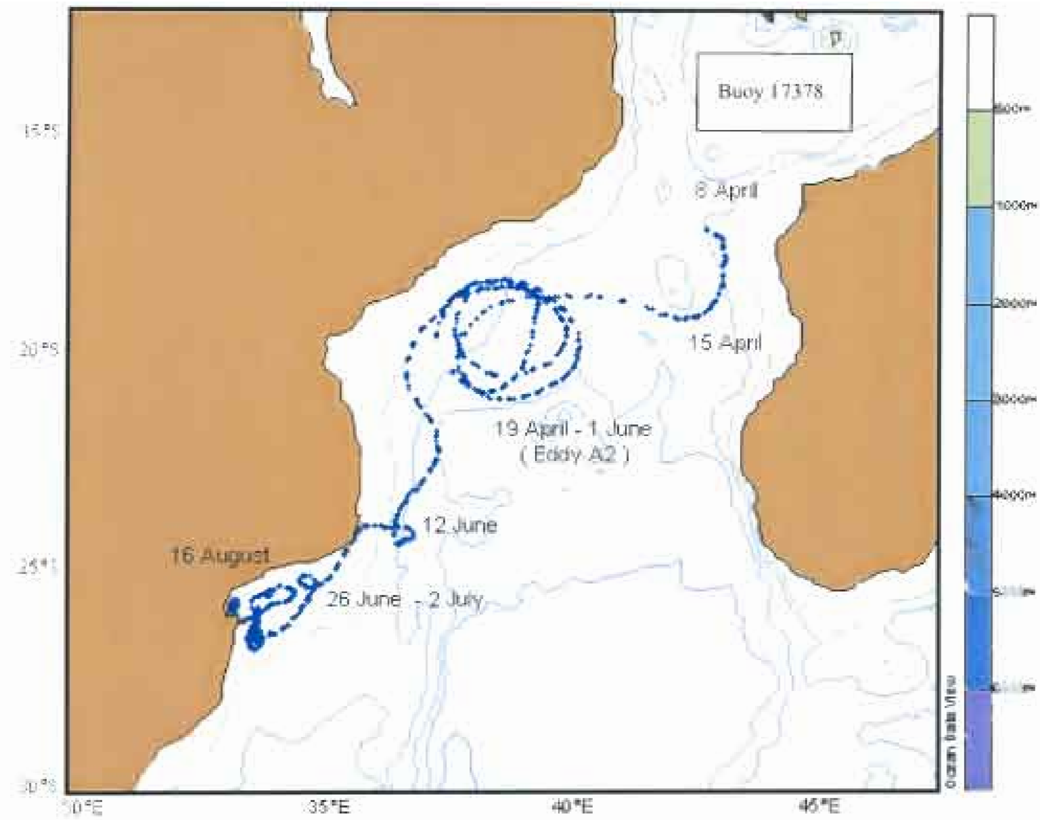


Figure 7.6

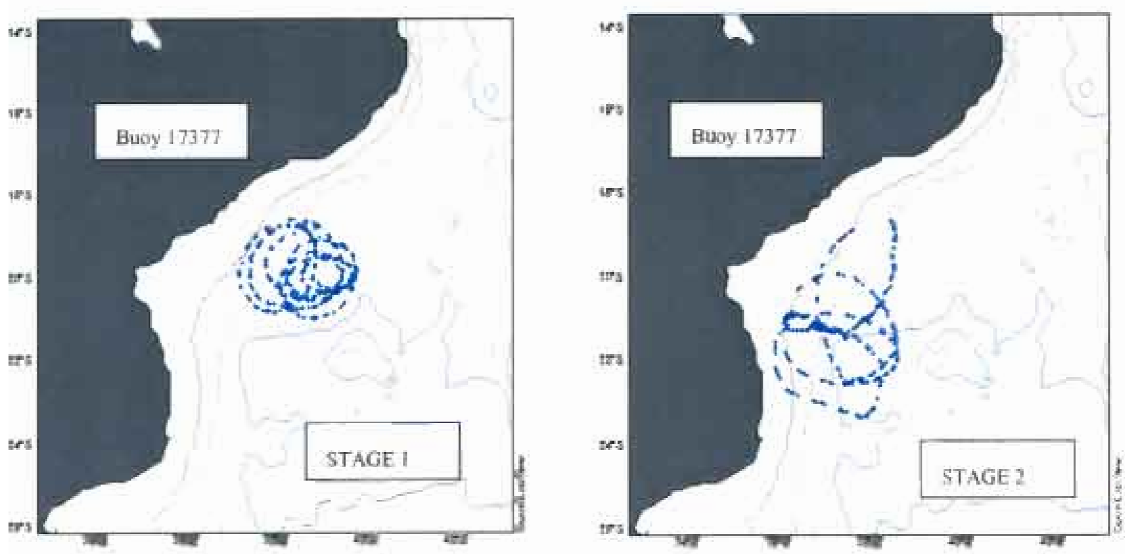


Figure 7.7

Figure 7.6 & 7.7: Drift tracks of buoys 17378 (top) and 17377 (bottom). The drift tracks of buoy 17377 were broken into 2 stages. In stage 1, we find the buoy entrained in a eddy for 34 days (March 30 - June 3). In stage 2, the buoy is expelled from the eddy. However, 3 days later the buoy changes direction and enters the eddy again.

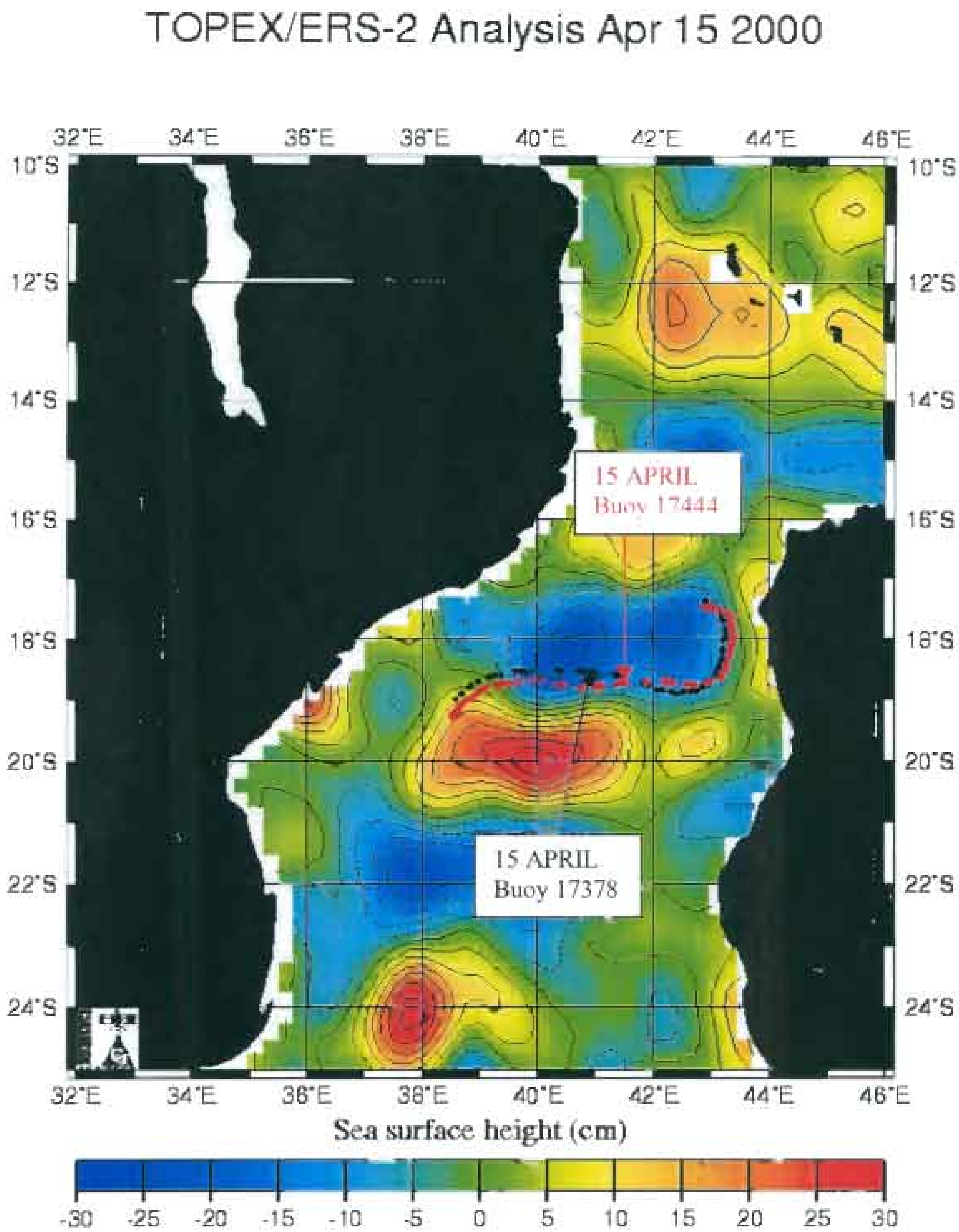


Figure 7.8: Drift tracks of buoys 17378 (black) and 17444 (red) for the first 20 days of drifting.

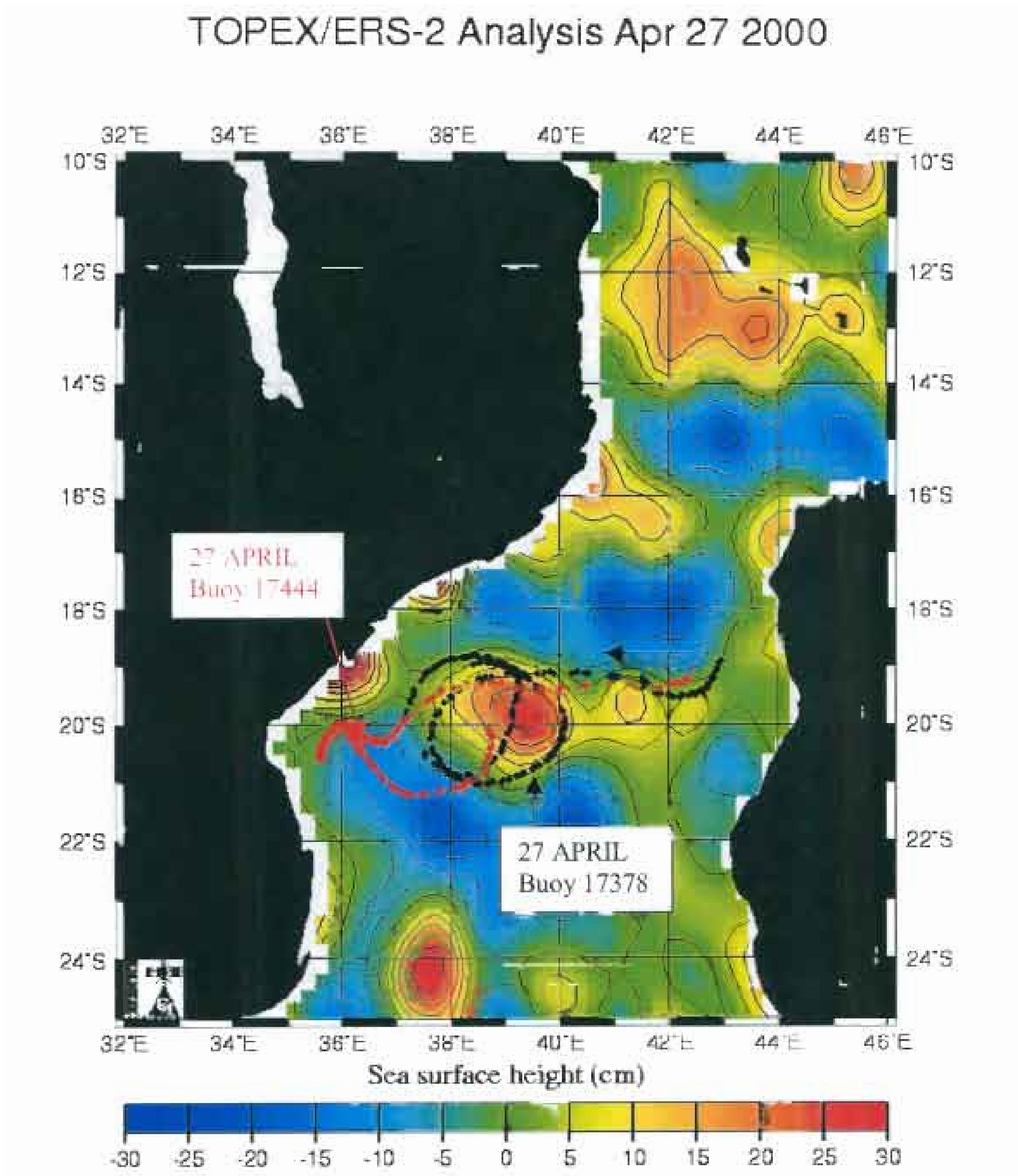


Figure 7.9: Drift tracks of buoys 17378 (black) and 17444 (red) for the next 70 days of drifting.

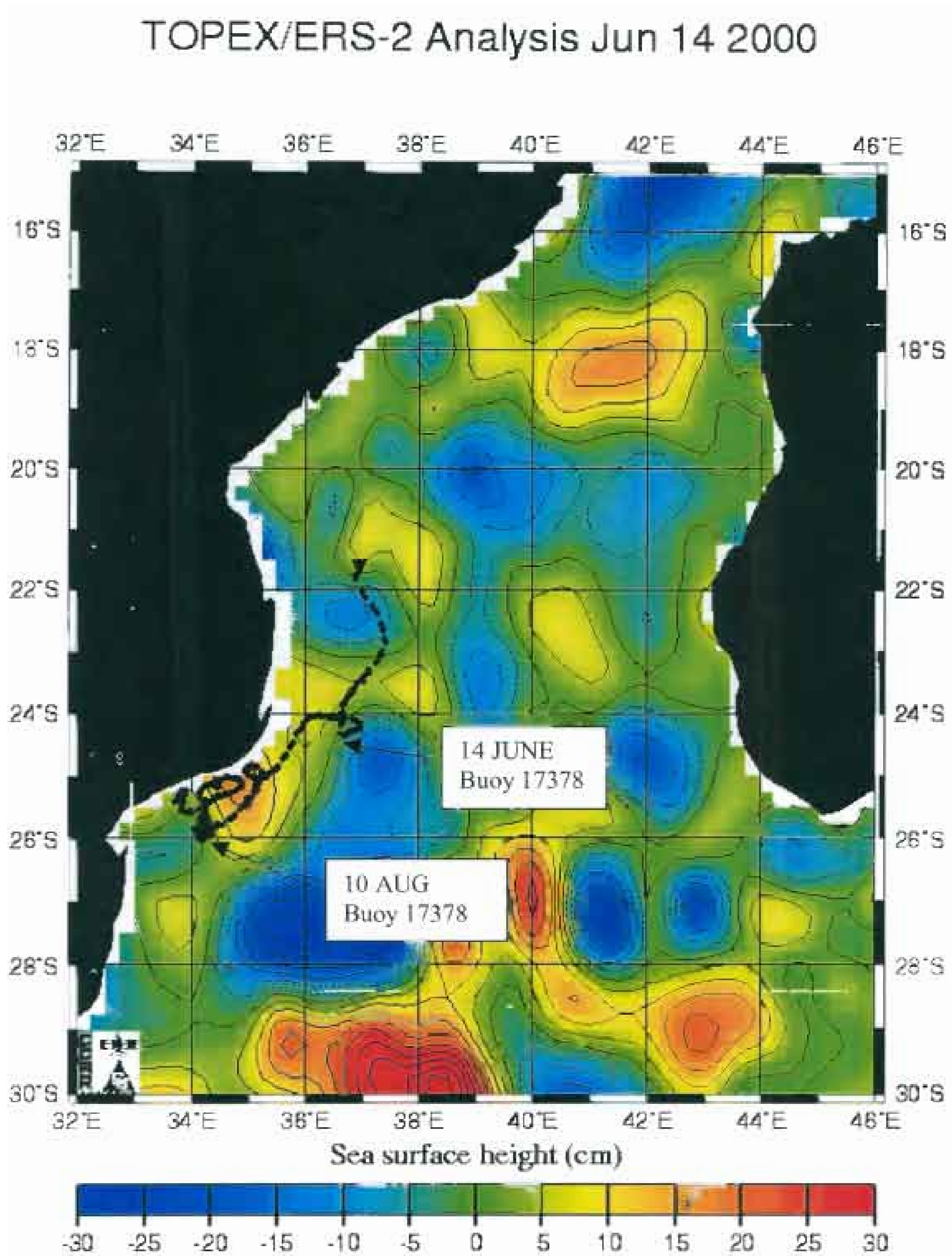


Figure 7.10: Drift tracks of buoy 17378 for the last 60 days of drifting.

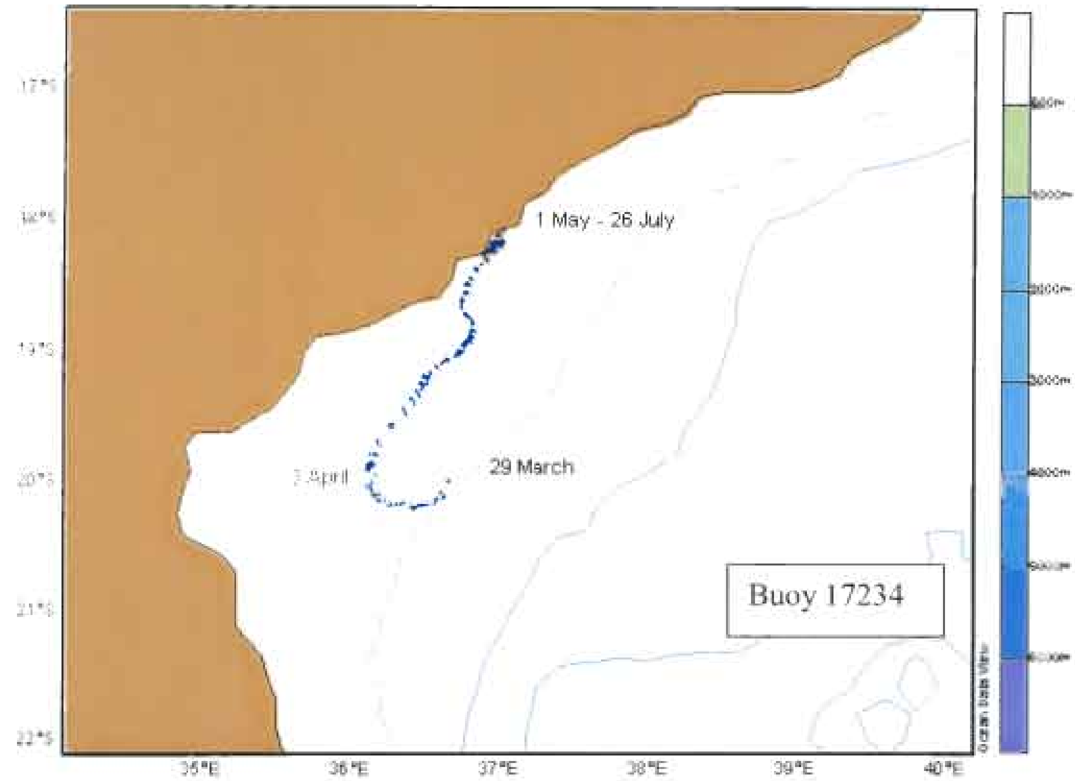


Figure 7.11

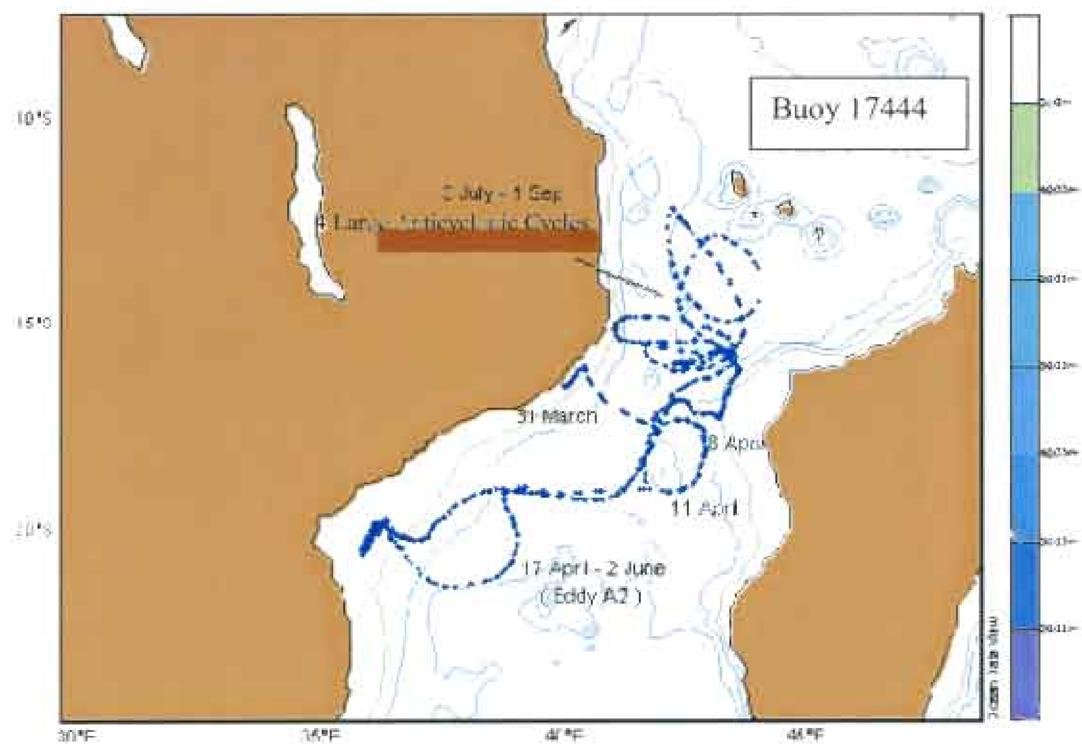


Figure 7.12

Figures 7.11 & 7.12: Drift tracks of buoys 17234 (top) and 17444 (bottom).

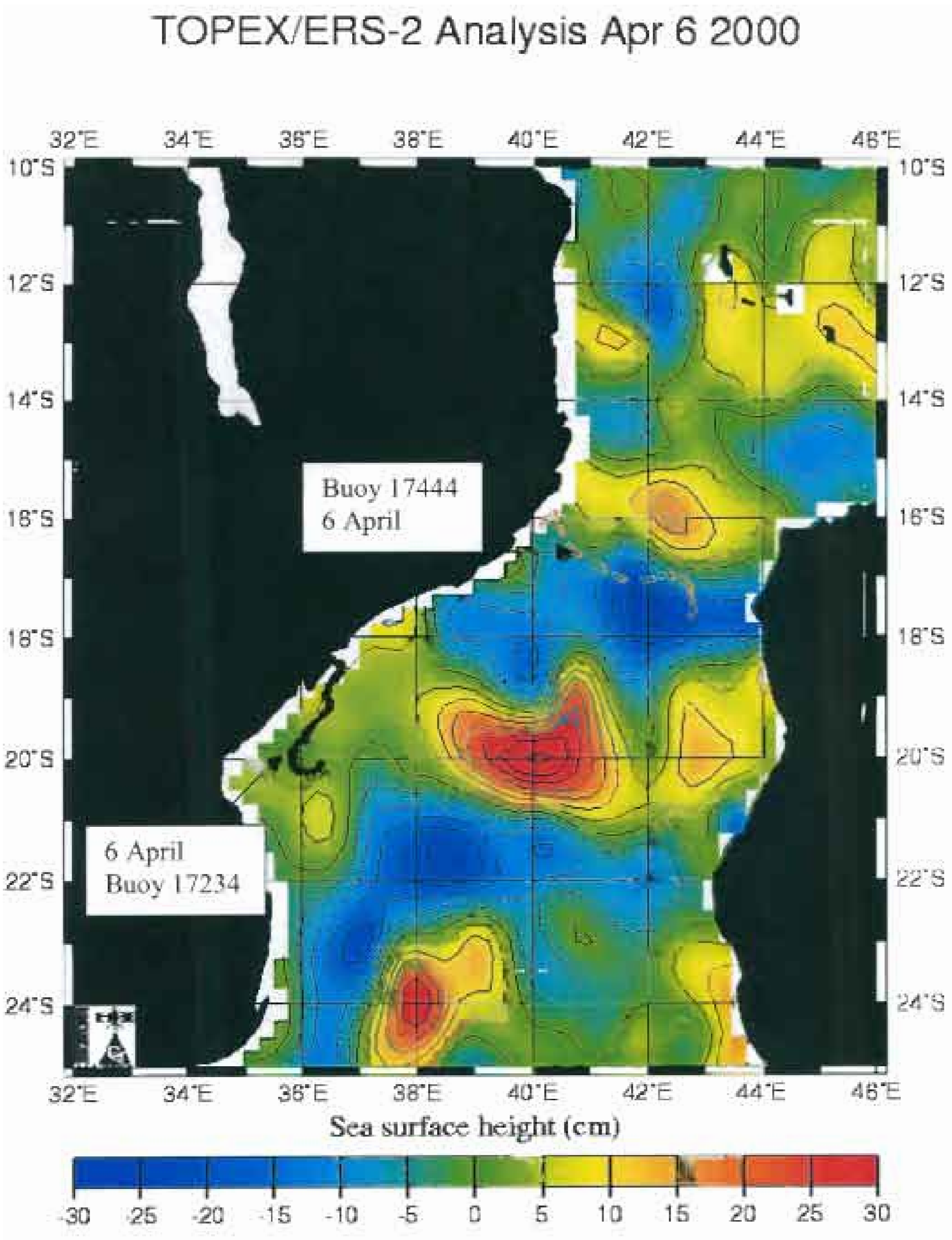
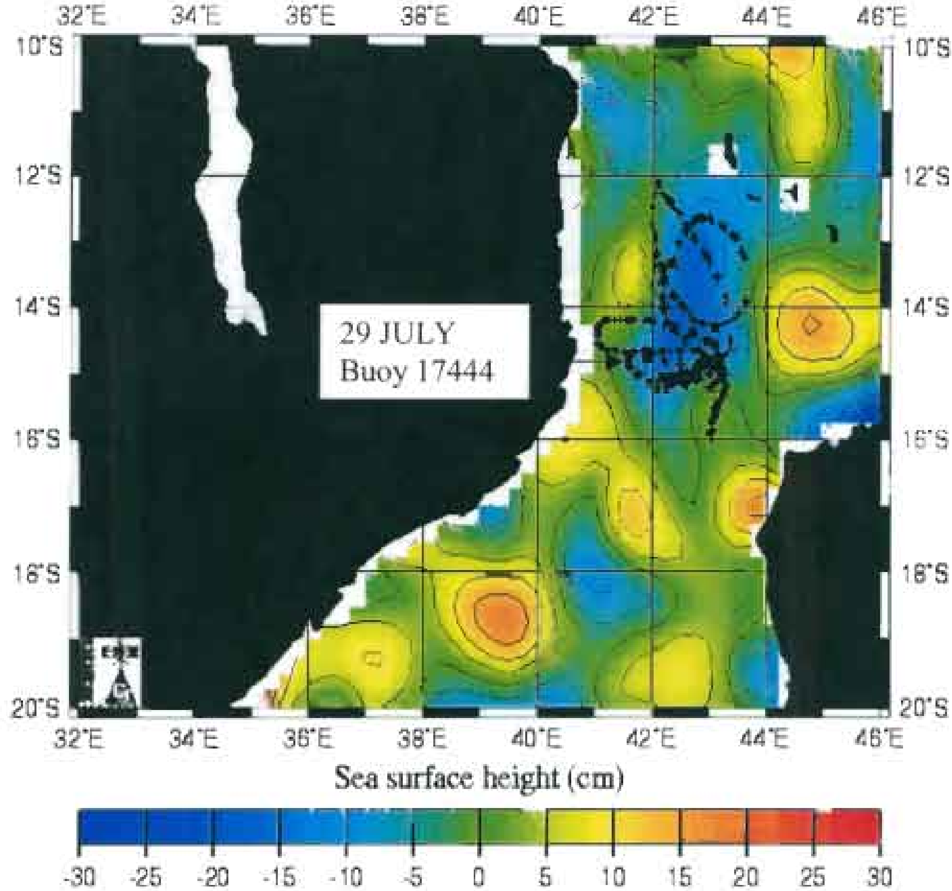


Figure 7.13: Drift tracks of buoys 17234 and 17444.

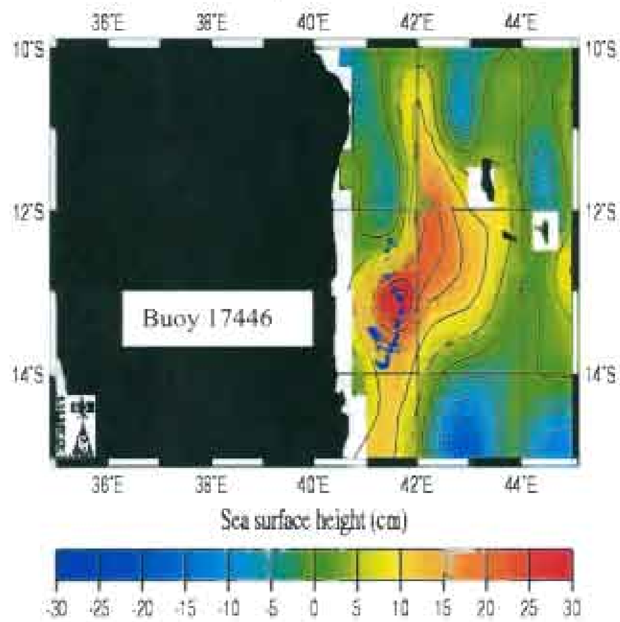
TOPEX/ERS-2 Analysis Jul 29 2000

Figure 7.14



TOPEX/ERS-2 Analysis Apr 9 2000

Figure 7.15



Figures 7.14 & 7.15: Drift tracks of buoys 17444 (top) and 17446 (bottom) in the northern mouth of the channel.

Chapter 8
Nutrient Distributions

From our results, we observe that throughout the Mozambique Channel the phosphate, nitrate and silica distribution with depth was characterized by (i) a nutrient deficient surface layer; (ii) a region of increasing concentrations forming a nutricline and (iii) a region of maximum contents which lay roughly at 1500 m (figs. 8.1-8.4).

According to Nehring et al. (1987), the vertical distributions of these nutrients is related to characteristic water types found by the classification of the water masses in the Mozambique Channel.

Generally surface nutrient values in this area are found to be higher near the coast and decrease steadily seaward (Orren 1963; Nehring et al., 1987). However, our results show that the Mozambique eddies carry nutrient rich water down the Mozambique coastline. As a result of this we observe an opposite effect i.e. surface nutrients are lower at the coast and increase seawards.

Results show that concentrations of the phosphate, nitrate and silica are higher at the bottom and lower at the surface i.e. we observe an increase in nutrients with depth (fig. 8.5). Throughout the Mozambique Channel we find a nutrient deficient layer that extends down to a depth of 70 - 100 m, followed by a slowly and relatively uniform increase in the discontinuity layer. We also find that below 1500 m, i.e. below the discontinuity layer, there is a slight decrease in the nutrient levels with depth. However, in the northern mouth of the Channel and on the west coast of Madagascar the silica concentration shows no signs of decreasing with depth (fig. 8.6). Instead they show a steady increase in concentration all the way to the bottom.

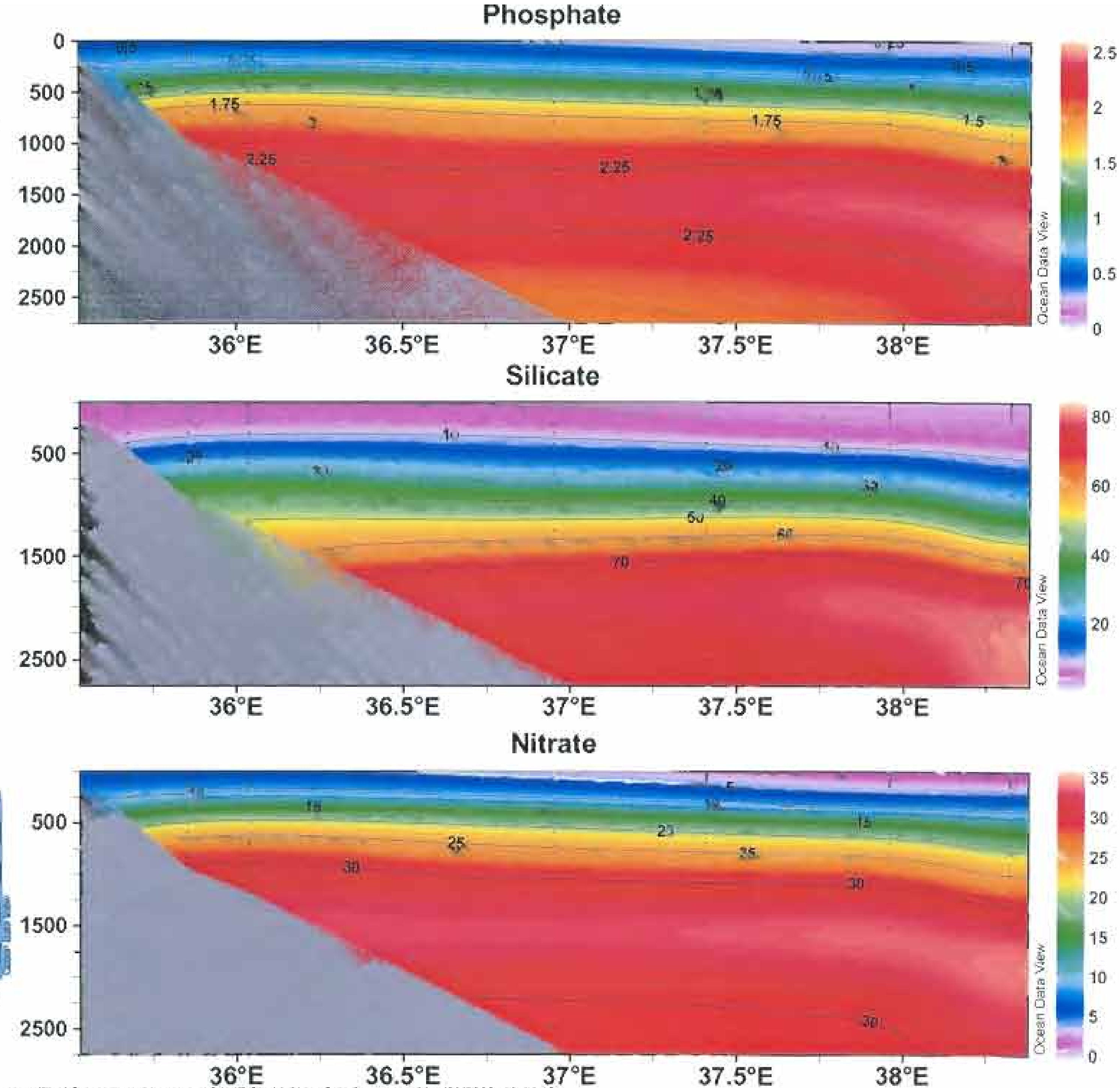
We also find that the silica concentration for the northern part of the Channel and on the west coast of Madagascar shows a steady increase in concentration with a decrease in temperature. However, for the rest of the Mozambique Channel we observe a nutrient maximum at 4 - 5 °C (fig. 8.7). This maximum coincides with the depth of North Indian Intermediate Water in the Mozambique Channel. The reason why we find a higher nutrient concentration in this water mass is because it originates in the nutrient rich waters of the Red Sea. Furthermore, if we compare this to the oxygen results, we find an oxygen minimum at this depth (fig. 8.8). Thus we observe an inverse relationship between the level of nutrients and oxygen in the Mozambique Channel. We also find that the temp/nutrient graphs shows no other significant changes as we move south through the channel.

Within the Mozambique Channel, our results also show that there are no major differences in the concentration of nutrients between the northern and southern part of the channel. Wyrtki (1971) has reported similar results. However, these results do not compare favourably with the work of Nehring et al. (1987). He reported somewhat higher concentration of nutrients in the southern part of the Mozambique Channel.

We also observe that the nitrate to phosphate ratio was near zero in the nutrient deficient surface layer. The ratio increased in the discontinuity layer and was characterized by a 14 : 1 in the layer of the Indian Central Water. These results compare well with the work of Nehring et al. (1987). However, Nehring et al. (1987) reported that the ratio decreased again the in the AAIW and below it reaching values of 12 to 13 : 1. Our results show no such decrease with depth in the values and the ratio remains constant at 14 : 1.

We already know that seasonality plays a role in the water circulation in the Mozambique Channel. However, what we don't know is how much the nutrient conditions may vary seasonally and what the resulting effect may be in this region. In addition, Nehring et al. (1987) have also reported cells of upwelling along the Mozambique coast. Unfortunately, we have not observed these upwelling cells from our results nor do we observe any upwelling from deeper areas.

Figure 8.1: Vertical sections of phosphate, silicate and nitrate across CTD-section-I.



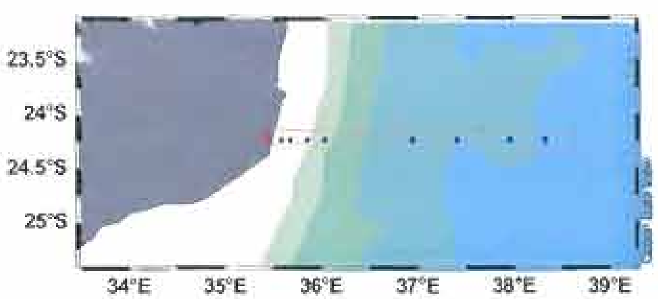


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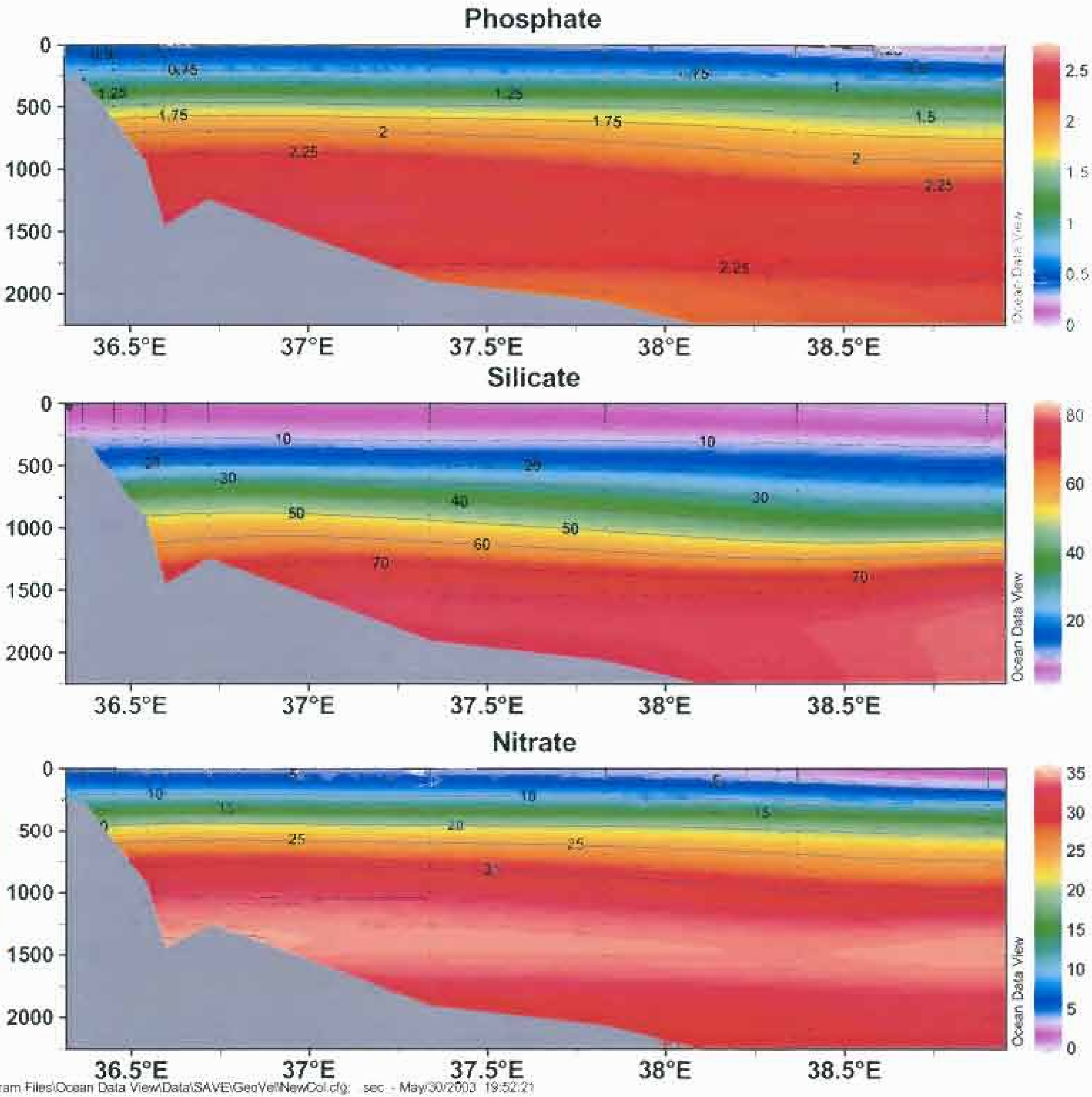
Figure 8.2: Vertical sections of phosphate, silicate and nitrate across CTD-section-II.



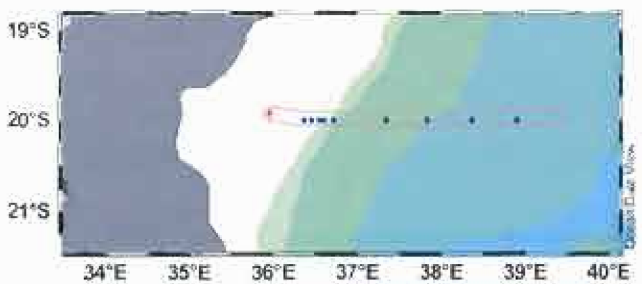
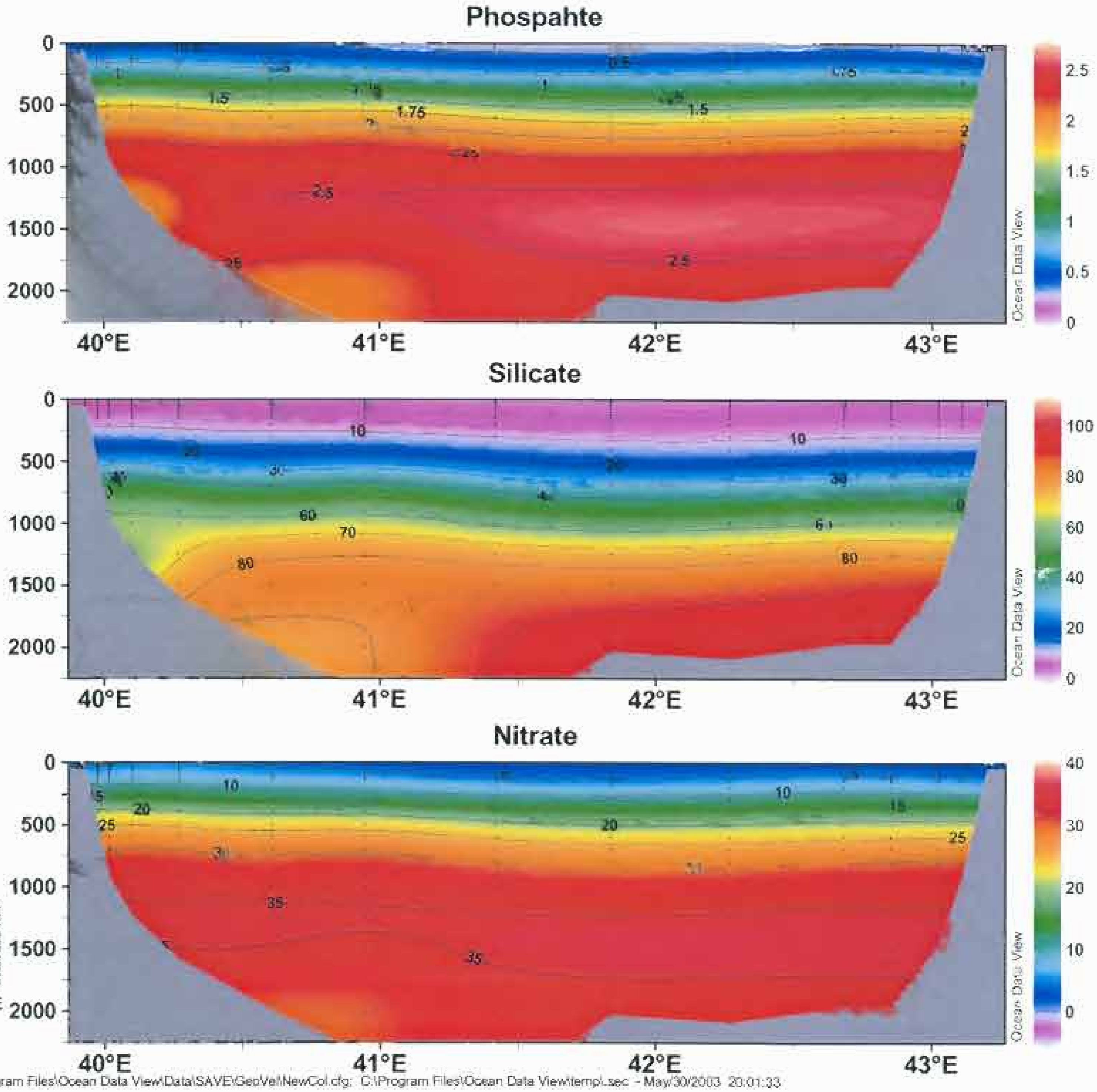


Figure 8.3: Vertical sections of phosphate, silicate and nitrate across CTD-section-III.



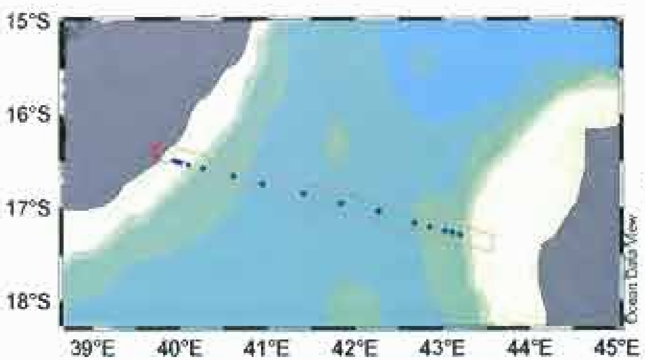
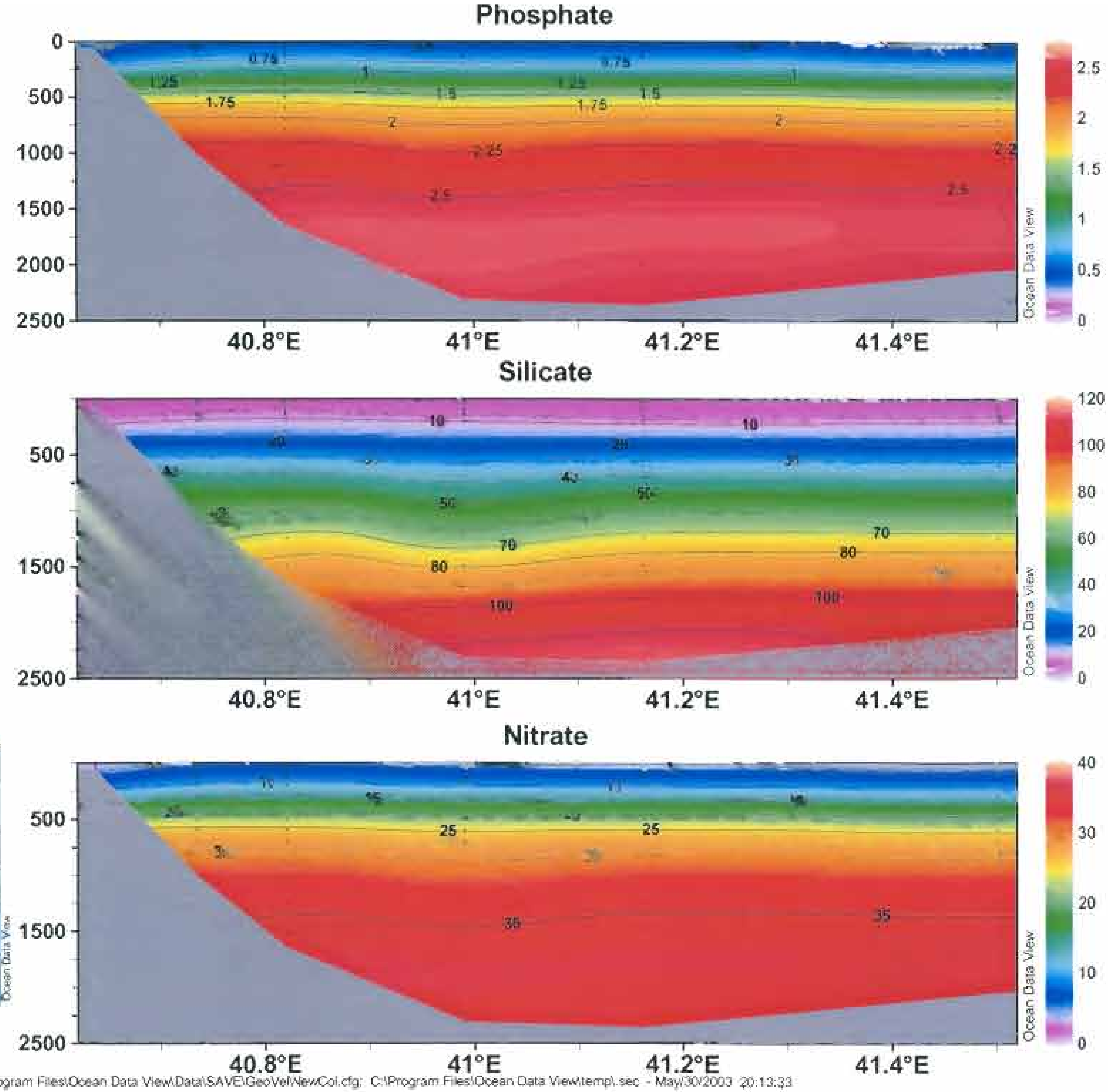
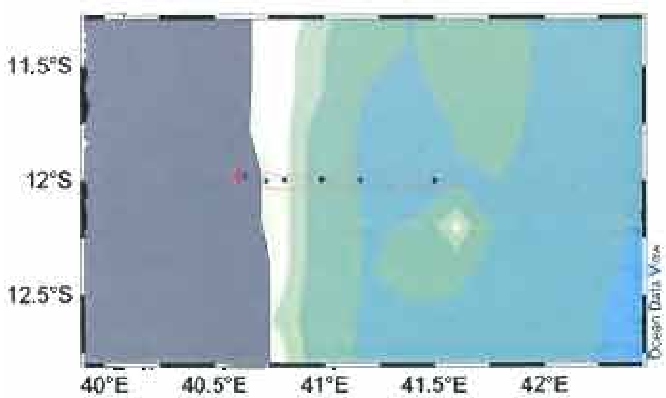
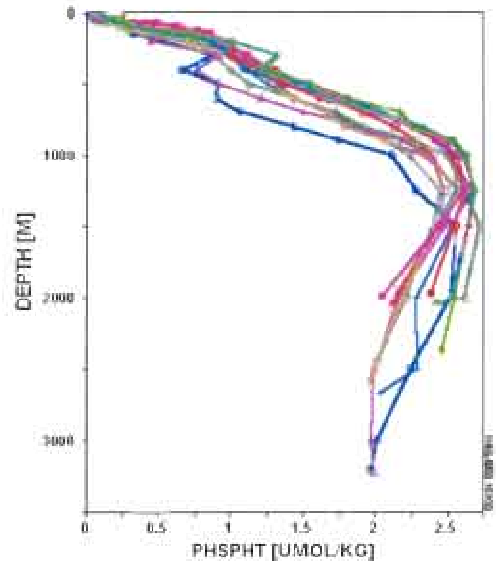
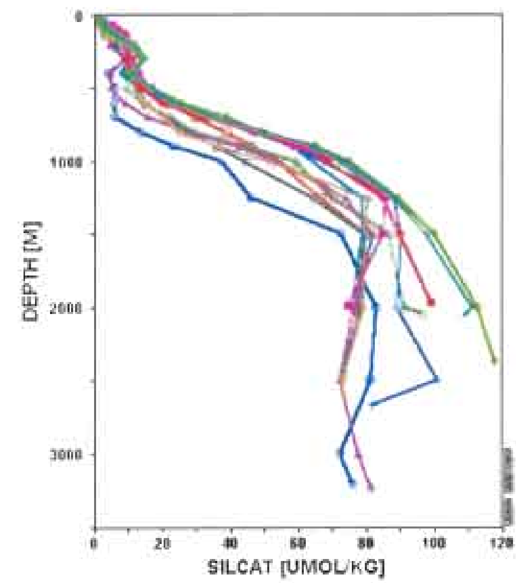


Figure 8.4: Vertical sections of phosphate, silicate and nitrate across CTD-section-IV.









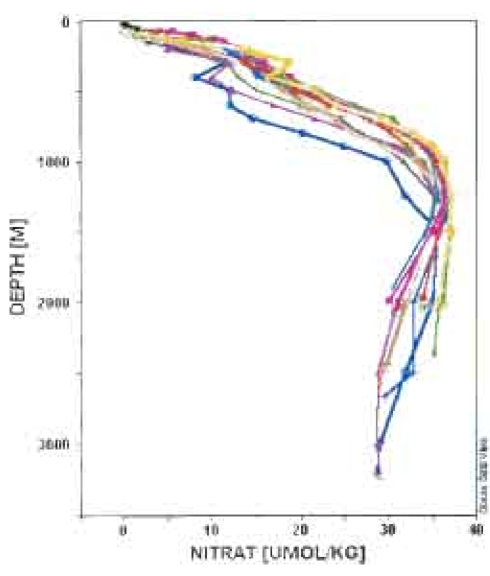
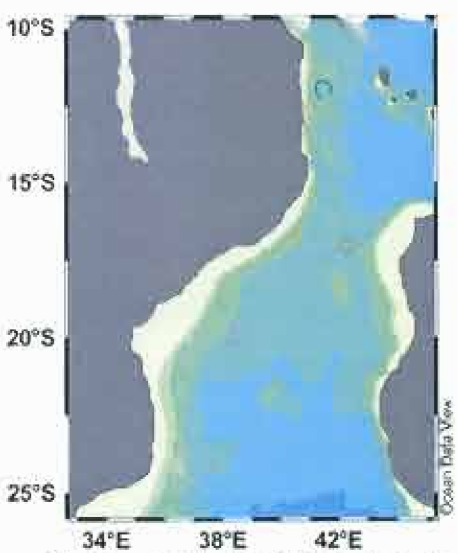
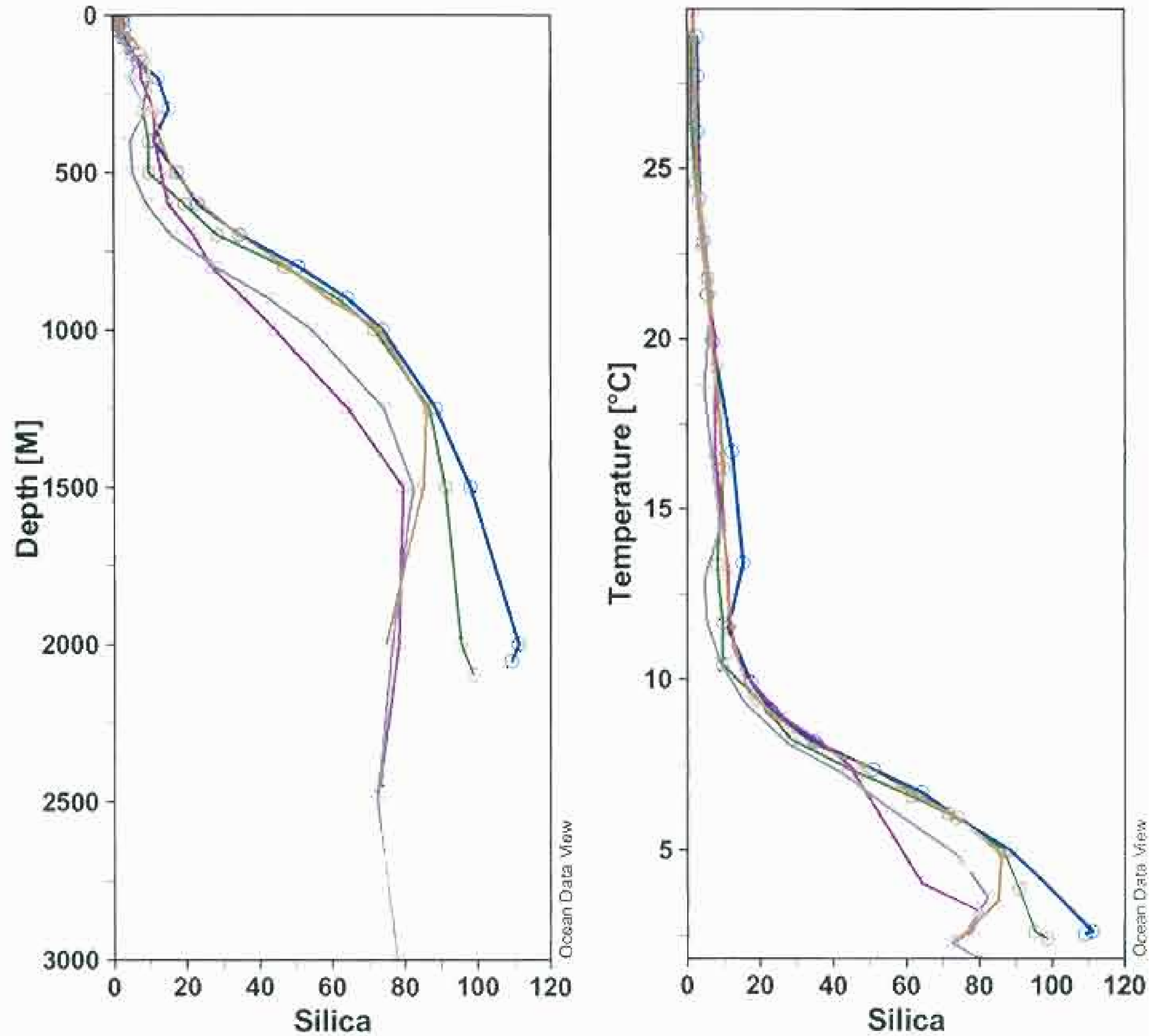


Figure 8.5: Vertical sections of phosphate, silica and nitrate with depth across all 4 hydrographic sections in the Mozambique Channel

Figure 8.6: Vertical sections of silica with depth (A) and temperature (B). The blue and green lines in the diagram identify the northern mouth of the Channel and the west coast of Madagascar.





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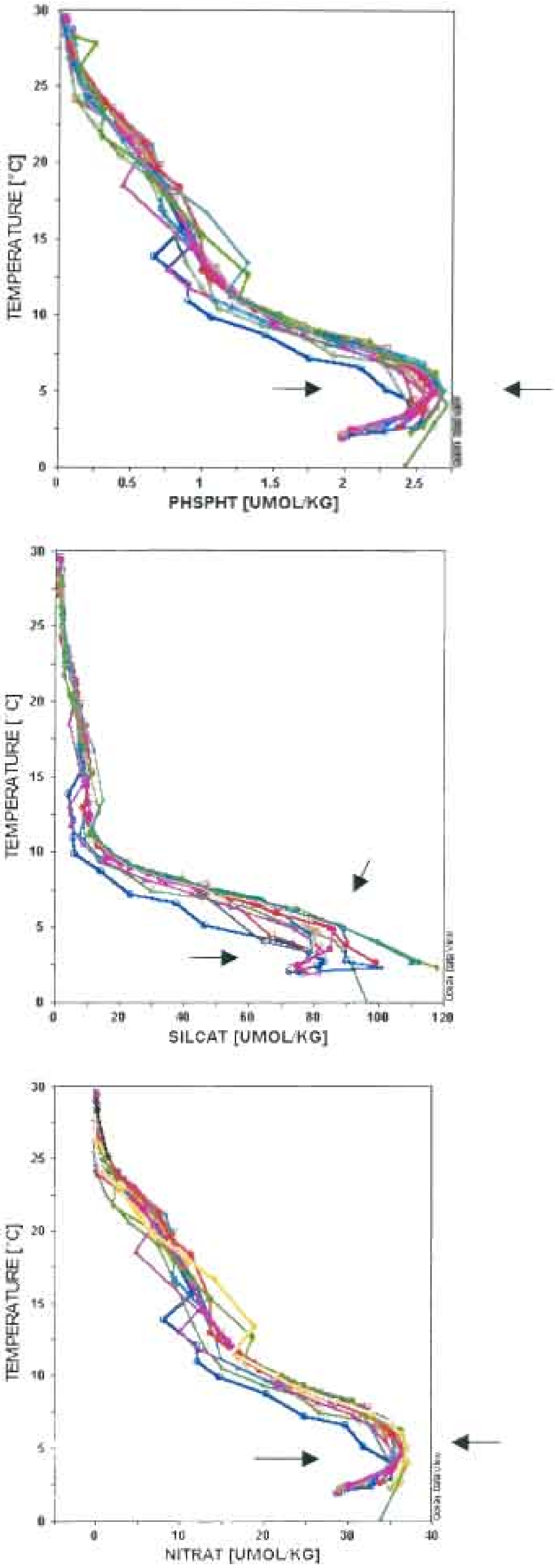

Figure 8.7. Vertical profiles of phosphate, silica and nitrate with temperature, showing the relative vertical position (arrows) of the nutrient maximum at 4-5 °C, across all 4 hydrographic sections in the Mozambique Channel.

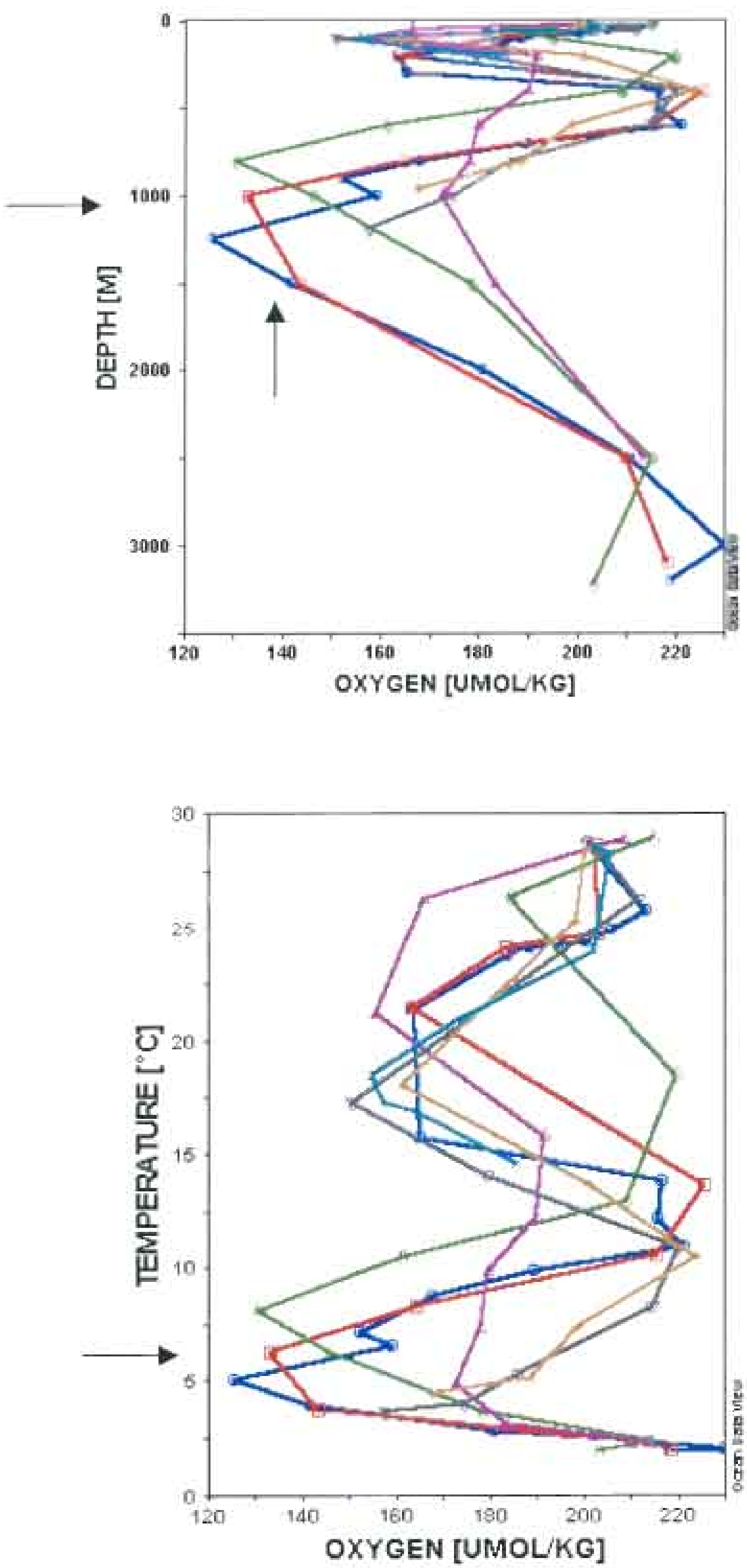

Figure 8.8: Vertical profiles of oxygen with depth (top) and temperature (bottom), showing the relative position (arrows) of the oxygen minimum at 4-5 °C and 1000 m depth, across all 4 hydrographic sections in the Mozambique Channel.

Chapter 9
Conclusions

Although the Indian Ocean has been extensively studied through the IIOE and WOCE programs, the Mozambique Channel remains surprisingly poorly investigated. Satellite altimetric and other modern observations as well as eddy permitting models have all revealed very high variability in the Mozambique Channel. Unfortunately, the lack of data prevents an accurate validation of these datasets.

The purpose of this thesis is therefore to establish a reliable hydrographic profile of the Mozambique Channel from the ACSEX-1 CTD and XBT datasets, and in doing so to address the key research questions, outlined in RESEARCH OBJECTIVES.

1) Does a continuous, consistent Mozambique Current along the shelf edge of Mozambique exist?

Geostrophic velocity results (chapter 6) reveal no evidence of a consistent boundary current at any crossing of the Mozambican continental slope. Instead the results reveal a very weak and shallow northward counter-current along the shelf edge. Further evidence can be seen in figure 9.1, which shows the superimposition of observed surface current speeds, averaged over the top 200 m, on sea surface height anomalies. No evidence of a continuous poleward Mozambique Current along the shelf break can be seen.

All the results available to us from the ACSEX-1 cruise, therefore lead to the conclusion that a coherent and persistent Mozambique Current along the shelf edge of Mozambique does not exist. We can only presume that this long-standing concept may have originated as a result of averaging flow induced by southward moving, anticyclonic eddies.

2) Does the Mozambique Current consist of a train of eddies?

In chapter 7 we find that the Mozambique Channel is strongly influenced by the presence of eddies. Several drifters launched during the cruise clearly show the rotating path of water inside an eddy. The drifters also show that eddies in the southern mouth of the channel tend to propagate southward from the channel. However, the drift tracks of drifters deployed in the center of the channel have a less consistent behaviour. We find that they will either propagate southwards or northwards or remain in the center of the channel. We also find that during this study the satellite altimetry data and drifting buoy data are in good agreement with each other.

In chapter 6 we identified the hydrographic characteristics of the anticyclonic eddies from the hydrographic data. The most notable feature of these eddies is that in their cores, at intermediate level, we find relatively salty, low oxygen water (NIIW) of Red Sea origin. Thus by looking at a N-S hydrographic section and using salinity and oxygen as a tracer, we found that the core of the NIIW spreads southwards through the channel. In addition, an analysis of a 3-month animation created using MODAS ssh images has shown that these eddies travel southwards through the channel (attached CD-ROM). Thus all the results combined lead to the conclusion that the flow in the Mozambique Channel is dominated by a train of large anticyclonic eddies that propagate southwards carrying NIIW towards the Agulhas Current.

3) What are the characteristic water properties within the Mozambique Channel?

At the surface, we find very salty and warm tropical and thermocline waters. These waters are formed throughout the Mozambique Channel, in particular both inside and outside the eddies. We anticipate that these waters propagate southwards. Two distinct types of intermediate water, AAIW and NIIW are found in the Mozambique Channel. They are carried southward through the Channel by the Mozambique Channel eddies. Traces of AAIW are found throughout the channel. ADCP and hydrographic data in chapter 6 reveal that the Mozambique Undercurrent carries the AAIW from the south. However, Saetre and Jorge da Silva (1984) and Wyrtki (1971) suggested that AAIW enters the Mozambique Channel from both the south and the north. Unfortunately, we have no hydrographic stations at the northern tip of Madagascar and therefore cannot confirm these observations.

Results from chapter 5 also show that the Mozambique eddies have a very distinct water mass properties. The Mozambique eddies have a trace of AAIW but their distinctive feature is the presence of NIIW. It is clear that the Mozambique Channel eddies are effective transporters of NIIW and its associated salt towards the Agulhas Current. With the absence of a Mozambique Current, we now believe that the poleward propagating Mozambique Channel eddies provides the significant link in the global ocean circulation system. At all stations taken in the Mozambique Channel, the T-S profiles reflect a strong, along isopycnal, mixing between the AAIW, from the northward undercurrent, and the southward moving NIIW, except at 24 °S. Here we observe that these two water masses appear to be separated by well define interfaces. However, the most interesting feature observed during the water properties analysis can be seen in the narrows of the Channel. Here we identified two layers of AAIW separated by the southward intrusion of NIIW. A full explanation of this feature will await further observations and research.

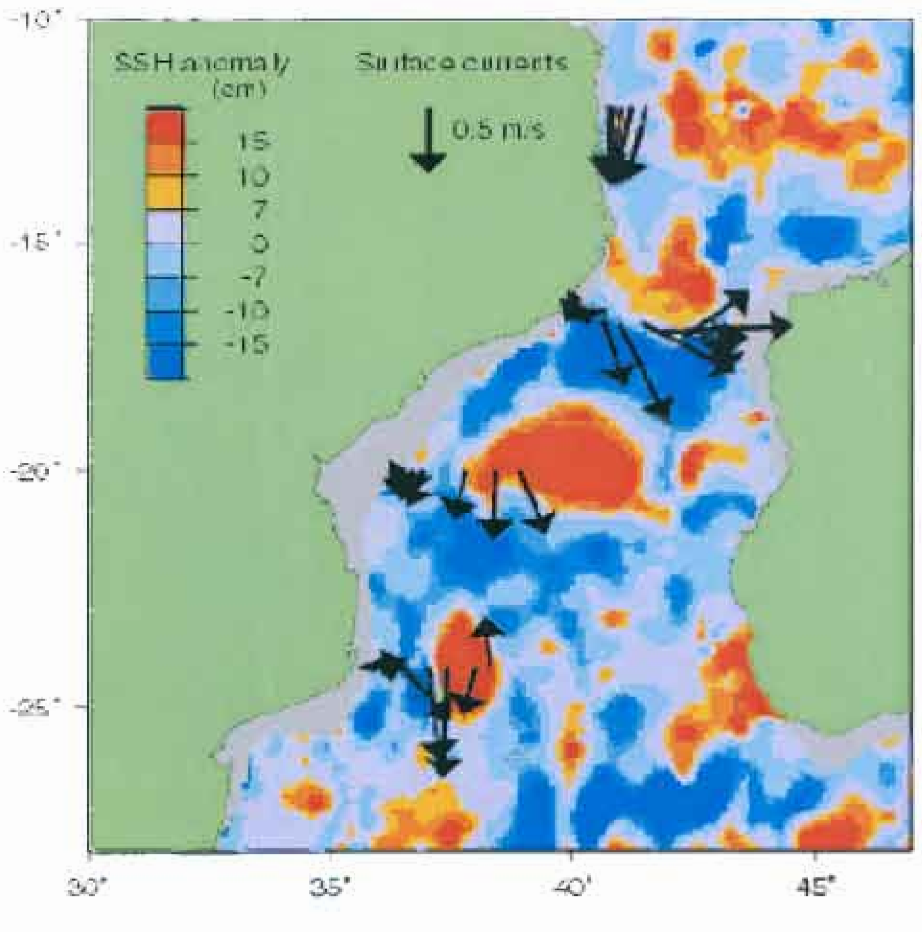

Figure 9.1. Surface currents and sea surface height anomalies during the ACSEX I cruise in the Mozambique Channel (20 March-13 April 2000). Arrows denote current speeds, averaged over the top 200 m of the water column. The currents have been directly observed using a Lowered Acoustic Doppler Current Profiler. Current vectors are superimposed on sea surface height (ssh) anomalies, derived from satellite altimetry over the cruise period. Both currents and ssh anomalies confirm the existence of a train of anticyclonic eddies in the Channel. A continuous poleward Mozambique Current along the shelf break (indicated by the 200m depth contour) was not observed (Schouten et al., 2001).

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