Characteristics of near surface circulation patterns in the Benguela as derived from the ADCP (Acoustic Doppler Current Profiler).

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ABSTRACT

This study forms part of one of the Benguela Environment Fisheries Interaction and Training (BENEFIT) program projects, whose main objective is to implement effective and quality ADCP data collection in the Benguela region. The thesis has two main components, firstly it undertook to investigate and assess the data quality, processing methods and software of ADCP data that are used to collect and process the ADCP data available in the Benguela region. An inter-comparison was made between the two different formats for data collection, i.e. raw and RDI proprietary "TRANSECT"-processed data (which is more readily available in South Africa), to evaluate their respective accuracy in depicting current flow. The raw data were validated (edited and calibrated) using the CODAS software package before the current vectors could be drawn. TRANSECT-processed data could not be validated therefore vectors were drawn from the un-validated data. Data used here was collected during a monthly monitoring survey on 06-08 August 2001 on board one of the South African research vessel Algoa. The comparison results showed that TRANSECT-processed data includes unedited errors, noise and biases, which are already averaged into the data by the program and that the raw data presented a more realistic current flow. Secondly, the study undertook to apply the ADCP data collected to describe the state of oceanography of the Benguela region during the survey periods. Data from monitoring survey in 06-08 August 2001 was used to describe the southern Benguela while the second data set from a cruise conducted off Namibia in October 2000 was used to describe the oceanography of the central and northern Benguela. Most of the structures observed were in support of the literature and confirming previous studies of the region. In the southern region, the equator ward shelf jet off Cape Peninsula was observed to be forced offshore and entrained in an anticyclonic-like feature, which appeared to be part of a warm Agulhas filament. In northern Nambia, a strong poleward movement of the warm Angolan water was measured.

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CHAPTER 1

INTRODUCTION

Ship-borne ADCP (Acoustic Doppler Current Profiler) data are used to identify the dynamical and spatial structure of the ocean current flow. The use of these instruments to collect data in the Benguela region commenced in 1989 (Boyd *et al*, 1992) and has made a major contribution to the understanding of the flow patterns in the region. Much has been learned about the prevailing currents over the whole Benguela region using ADCP data and especially in South Africa, the data are used to elucidate the impact of ocean current on fish stocks with regard to fish movement and recruitment.

In the Benguela, the ADCP data collection from the research vessels has been mainly confined to the southern region (along the South African coast) due to lack of technical, financial and human capacity in Namibia and Angola. During the mid 90's the research was extended to the rest of the Benguela region with the collaboration between the three countries (i.e. South Africa, Namibia and Angola) and the Norwegian Nansen program on a bilateral agreement, conducting the Namibian Hake Ecology cruises on board *R/V Dr. Fridjotf Nansen.*

With the inception of the BENEFIT (Benguela Environment Fisheries Interaction and Training) program in 1997, a number of research vessels equipped with ADCP instruments were active in the Benguela region. BENEFIT is a multidisciplinary research programme involving the three countries bordering the Benguela current system (Angola, Namibia and South Africa). In the same year, 1997, the first BENEFIT survey took place in April/May. Research started aboard the Russian research vessel *Petr Kottsov* (chartered by German scientists from the research Institute Warnemünde, IOW) and the Norwegian *R/V Fridtjof Nansen,* which together investigated the Angola/Benguela front. These two vessels made use of vm-ADCPs (vessel mounted ADCP) to carry out current measurements. In addition to the vm-ADCP the *Kottsov* had another ADCP attached to a small catamaran towed 150m behind the vessel. This was used to measure current signals in the upper 50m (Lass and Schmidt, 1997). Another German research vessel *Poseidon,* investigated the northern Benguela in April/May 1999 overlapping areas studied by the *Kottsov*'s expedition. Apart from the usual vessel mounted ADCP the Poseidon was equipped with the LADCP (Lowered Acoustic Doppler Current Profiler). The LADCP was used to obtain full depth velocity of currents at each CTD station. The vessel was receiving ship position from two GPS with an ASHTEC GG24 receiver (Schmidt *et al.,* 1999).

Ship borne ADCP was used extensively during the dedicated BENEFIT training survey in June/July 1999, covering the whole Benguela region starting from Cape Town to Angola on board research vessels *Africana* and *Algoa* of South Africa and *Welwitchia* of Namibia. The two South African vessels were equipped with narrow band 150 kHz vm-ADCPs, receiving ship position and heading from the RACAL real-time differential Global Position System (DGPS) and ship gyro-compass respectively (Boyd *et. al* 2001).

In 2000, a dedicated survey was conducted with the help of the german research vessel *Meteor*. With five legs (M48/1-M48/5), the survey covered mainly the northern and central Benguela with only the fourth leg extending to the south. The vessel was equipped with a 75 kHz vessel mounted narrow band ADCP, receiving heading information from two gyrocompasses, a new fibre optical gyro and an Attitude Determination Unit (ADU2). Data from all the above-mentioned cruises have substantially contributed to the understanding of the structure and dynamics of the current in the region.

Good quality directly measured current data is required before serious analysis and interpretation can be done especially for transport estimates. Accurate velocity data is needed for estimation of full-depth transport. Transport estimates are highly sensitive to any bias in the estimate of transducer heading. Therefore, there is a need to find appropriate software, which can make the ADCP data scientifically accessible for oceanography, fisheries/environment interaction studies and modelling in the Benguela region. These in situ current measurement data can also be used to validate 3D-physical circulation models of the region.

In order to implement effective ADCP data acquisition, data processing, archiving and data management in the Benguela region, it is necessary that data collected throughout the region be analysed in a comparable way and stored in a database, which is accessible to research scientists in the whole region. This aim is a part of one of the BENEFIT projects[1]. Some of BENEFIT's environmental research goals are:

- To understand the natural environmental variability within the Benguela System.
- To understand the role of the variability on the living resources of the system.
- To understand how those resources respond in time and space to the variability in the system.

The main objective of this BENEFIT project is to implement effective ADCP data collection in the Benguela region. The key questions that this project will attempt to answer are:

- What is the quality of the data from the different ADCP units used in the BENEFIT programme under different conditions?
- What measures can be suggested to improve data quality within operational constraints?
- What steps are necessary to validate and correct biases that exist in data that have been collected already?
- What is the most appropriate software developments needed to make the data scientifically accessible?

It is therefore in line with these questions that this thesis study undertook to examine the following objectives:

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[1] http://www.benefit.org.na/

- To investigate and assess the data quality and the availability of software used to acquire, "clean" and process ADCP data in the Benguela region.
- To investigate steps necessary to validate and correct biases in the data.
- To analyse the structure and nature of the flow along the South African west coast and in the Namibian coastal ocean, where data exists.

This thesis has two distinct main components, in that it firstly conducted the inter-comparison between the two different formats for data collection, i.e. raw data, which could and was validated using the CODAS software and RDI proprietary "TRANSECT"-processed (un-validated) data, to evaluate their respective accuracy in depicting current flow. This was in order to assess the data quality, processing methods and software of ADCP data available in the region especially from the South African research component MCM (Marine and Coastal Management) whilst the second component of this thesis is to describe the oceanography prevailing at the time of the surveys. The first chapter of the thesis gives a brief description on the dynamics of the shelf circulation of the Benguela region as provided by several reviews (Shannon, 1985, Shannon and Nelson, 1996, Shillington, 1998). The second chapter, which presents the data and methodology, firstly describes the background of the ADCP instrument and its principle of operation and thereafter concentrates more on the processing of the data itself, putting more emphasis on comparing results from using ADCP raw data (validated and processed using CODAS software) files and "TRANSECT"-processed data files (un-validated). The validated data, which were believed to present more realistic results, were used to give a general description of the oceanography of the region during the study time in the third chapter.

CHAPTER 2

LITERATURE REVIEW

An understanding of the near-surface circulation is important in that it roughly coincides with the euphotic zone and it's features are therefore important to the biological processes in the upper ocean (Brink, 1983). Nelson and Hutchings (1983) defined the continental shelf (shelf break as commonly known) of the Benguela to be within the 200 m isobaths, narrowing in the north off southern Angola with the widest zones near Orange River, 180 km (Shannon, 1985) and Agulhas Bank, 230km (Shannon and Nelson, 1996). At some places for example near Walvis Bay (23°S latitude) very pronounced double shelf breaks are common with the inner and outer breaks beginning at depths of about 140m and 400m respectively (Shannon, 1985; Shannon and Nelson, 1996). The variable topography of the Benguela shelf is of particular significance for near shelf circulation.

In the past four decades oceanographic data have been collected along the whole coast in the Benguela region. Current data from different sources such as ship drift, hydrographic instruments (like CTD), satellite tracked buoys and drifters, satellite imagery, current meters and recently, data from ADCPs were used to help in describing the different aspects of the shelf circulation in the region. These aspects include:

i) Surface and near surface flow, which is largely influenced by the prevailing winds and oceanic forcing;

ii) Jet currents observed mainly in the southern Benguela propagating equatorward;

iii) Cross-shelf circulation, significant for nutrients and biological transport across the shelf zone and enforced by upwelling processes;

iv) Shelf and coastal-trapped waves believed to enhance the poleward motions;

v) Poleward flows recorded in the inner shelf along most part of the coast-line as well as at depth as an undercurrent and

vi) Inertial motions; these are circular motions, which flow anticyclonic in the southern hemisphere and are induced by strong wind impulses.

All these aspects will be discussed in more detail in the two shelf circulation sections below.

Water flow studies in the Benguela region started as early as 1960 with Hart and Currie (1960) describing the flow to be broadly northwestward. Shannon (1985) summarized work from several authors that describe the general physical characteristics and the dynamics of the current in the Benguela.

Satellite images were used to study and demonstrate existence of cold-water filaments, plumes and frontal eddies along the whole coast (Lutjeharms and Meeuwis, 1987; Lutjeharms and Stockton, 1987; Nelson *et al*, 1998 and Shillington *et al*, 1990).

Filaments have been mostly observed with extensive seaward penetration off the upwelling cells. Subsequent studies described locations and characteristics of these upwelling cells. Shannon (1985) identified six localized cells along the coast, two near Cape Frio (18°S), at Lüderitz (27°S), Namaqua (30°S), Cape Columbine (33°S) and Cape Peninsula (34°S). However, Lutjeharms and Meeuwis (1987), found an additional cell in the central region near Walvis Bay (23°S). The wind stress and the frequency of occurrence of these cells are more intense at Lüderitz where upwelling is more perennial than anywhere in the Benguela region. Upwelling filaments can last up to several weeks and are a characteristic of the Benguela oceanic front. Another candidate for the offshore forcing of the filaments could be detached Agulhas rings or eddies that shed from the Agulhas Current as it retroflects. A large filament captured by an Agulhas ring was measured at sea, and the surface circulation was determined using two adjacent satellite SST images (Duncombe Rae *et al*, 1992).

Apart from rings and some mesoscale eddies, which are seen to be generated by the Agulhas retroflection and advected northward into the Benguela system (Nelson and Hutchings, 1983; Shannon, 1985; Lutjeharms and Stockton, 1987; Lutjeharms and Gordon, 1987; Shannon *et al.,* 1990), some eddies are observed to be associated with main upwelling fronts. These fronts are known to be areas where jets are more energetic and biological activities mainly take place (Brink, 1987).

2.1 Shelf circulation in the Southern Benguela

The general shelf circulation in the southern Benguela, along the South African West coast (between Orange River, 29°S and Cape Agulhas, 35°S), is well documented, compared to that in the central and northern part of the region. Detailed observations of the surface features started in 1978 using satellite and radio tracked drifters (Harris and Shannon 1979, Lutjeharms and Valentine 1982, Nelson and Hutchings 1983 and Holden 1985) as well as subsurface features from current meter deployments (Nelson, 1985; 1989; Nelson and Polito, 1987; Holden, 1987 and Nelson *et al*, 1998). More recently, current flow off this region has also been measured using the ADCP on research vessels, and since the early 90's as part of SARP (Sardine and Anchovy Recruitment Programme) monitoring line (Boyd *et al*, 1992; Nelson *et al*, 1998; Boyd and Nelson, 1998).

Shannon (1985) described the dynamics of the southern Benguela region to be maintained by the mesoscale atmospheric perturbations, bottom topography and the influence of the Agulhas Current system. Studies done on the dynamics of the shelf along the South African west coast looked at many aspects including the baroclinic shelf edge jet, barotropic shelf waves and poleward motions.

The first direct measurements of the current started in the 70's (Bang and Andrews, 1974) when a strong equatorward baroclinic shelf-edge jet with an equatorward velocity of about 1.2ms^{-1}, west of Cape Town, was recorded. Nelson (1989) measured the velocity of this shelf edge jet to be ranging between 0.3ms^{-1} and 0.6ms^{-1}. This jet is confined to surface and subsurface layers down to 200m deep and is believed to be approximately 10 km wide (Shannon and Nelson, 1996). Using acoustic current meters, Nelson (1985) detected jet-like motions at other points near Cape Peninsula. Between Cape Columbine and Cape Peninsula, Nelson and Hutchings (1983), have recorded a jet with a speed of approximately 0.35ms^{-1} as a permanent feature, and its permanence was verified by Shannon and Nelson, (1996), using ship-borne ADCP current measurements. Near Cape Columbine the jet diverges into two branches, an offshore component flowing NNW and inshore component flowing northward alongshore (Shannon, 1985; Boyd *et al*, 1992, see Figure 2.1).

Induced by the combination of tidal motion and bottom topography, this jet is believed to be a mechanism for passive transport of the pelagic biota (Nelson and Hutchings, 1987), playing an important role in transporting the fish eggs and larvae from the anchovy and sardine spawning grounds on the western Agulhas Bank to the nursery areas near St. Helena Bay. It is still not yet known if the jet is continuous or if it exists in the central and northern Benguela. Nevertheless Gordon *et al.* (1995) suggested a jet like feature present in the upper 100m over the mid-shelf near Lüderitz, from ADCP measurements.

Shoreward of the jet, north of Cape Columbine the flow is weak and variable (Boyd *et al*, 1992) but it is dominated by the southward flowing current, mostly observed in winter. This flow was described as a compensation for the Ekman divergence by Hart and Currie (1960). However, Nelson, (1989) suggested that the flow was more extensive than that required as compensation for coastal upwelling. Poleward motions have been detected to be seasonal north of Cape Columbine corresponding to the seasonal upwelling wind, which has the maximum during summer while south of 33°S the flow is not seasonally dependent (Shannon and Nelson, 1996) and of a barotropic nature. These motions are influenced by the presence of poleward propagating coastal-trapped waves and are observed near the coast at a depth of about 30-40m. Currents measured over the shelf exhibit wave-like motion with a periodicity of about three to five days. When averaged to remove the low frequency signals, the flow is predominantly southward with a speed of about $0.06 ms^{-1}$ (Nelson, 1989; Shillington 1998). This inshore southward flow was also observed between Orange River and Cape Columbine at the depth of about 34 m from ADCP measurements (Iita *et al*, 2001) and at the depth of about 118m from the current meter deployed off Cape Columbine (Frantz and Nelson, 2001) during the BENEFIT training cruise in July 1999.

Satellite tracked, surface drifters deployed along the coast in the southern, central and northern Benguela region during the above mentioned BENEFIT training cruise, exhibited large variability both in time and space which can be interpreted as wind driven inertial motions (Largier and Boyd, 2001). Moreover, currents analysis from the ADCP data (Iita *et al*, 2001) suggested that these inertial oscillations are not only confined to the wind forced layer but also have a response in the lower layer. This was described by Simpson *et al*, (2002) using data from an upward looking ADCP mooring at 30° S which suggested a resonance observed at places where the diurnal wind forcing coincides with the local inertial frequency. This occurs in means places where the inertial period is close to 24 hours (in this case 30° S latitude). Largier and Boyd (2001) found that the same area was dominated by diffusive fluxes.

Another observed flow was the onshore movement near 30°S. This flow was also seen in the surface drifter reported by Largier and Boyd, (2001). Evidence of retained water over a small inner shelf region for a period of at least a week was reported in this area. North of Cape Columbine, near St. Helena Bay, some coastal trapped eddies were found, which were thought to be generated by the enhancement of onshore surface transport (Holden, 1985). It was found that frequent onshore flows could be also a mechanism of retention. Flow patterns favouring the retention were presented by Bailey *et al*, (2001) from their schematic diagram in their synthesis of the near surface current in the Benguela (Figure 2.2).

2.2 Shelf circulation in the Central and Northern Benguela

Although the general knowledge of the current flow in these regions was made available at the beginning of last century, most of the extensive work did not take place until the 70's, especially with the direct current measurements. The majority of this intensive work took place on the west coast of South Africa and did not extend up to the Namibian coast. Information on direct measurements of currents is particularly sparse off the Namibian coast. Key features of the near surface currents in this region are presented in a schematic diagram (Figure 2.2).

Flow along the Namibian coast has been described mainly using information from primitive methods like drift cards and ship drift as well as dynamic topography inferred from CTD measurements. These lack of direct currents measurements data contributed to the poor understanding of the dynamics of the flow and small-scale structure in the central and northern Benguela region. The first dedicated oceanographic survey along the Namibian coast took place in 1978, with the aim of understanding the relations between currents, winds and the hydrology of the region (Boyd, 1983). Shannon, in his review of 1985, has looked at the macro-scale structure of the water circulation in the Benguela region, and calculated the mean speed of the Benguela current to be $0.17 ms^{-1}$, with the surface transport of about 30 Sv of which only 21 Sv belongs to the Benguela Current with the other 9 Sv re-circulating further in the west (Stramma and Peterson, 1989).

The Benguela is bordered by warm water on both the northern and the southern boundary of the system. In the north, the coastal upwelling boundary is marked by the Angola Benguela Frontal Zone (ABFZ). The ABFZ demarcates the area where warm, nutrient-poor Angola Current water and the cold, nutrient-rich Benguela Current water form a transition zone between the tropical ecosystem in the north and the upwelling-driven ecosystem in the south (Lass *et al* 2000). This is a permanent surface feature that penetrates down to 200m but is more intense in the upper 50 meters (Shannon *et al*, 1987; Shannon and Nelson, 1996). Its average width was found to be about 200km and sometimes multiple fronts might occur within this distance.

The front has been a focus of recent cooperative research between international and regional scientists. Research surveys were conducted on board foreign research vessels under the auspices of the BENEFIT program as described in the introduction section. Meteorological, hydrographical, biological oceanographic and chemical oceanographic data were collected and used to describe the dynamic of the frontal system. Using these data, Mohrholz *et al.,* (2001) found that on short time scales the ABFZ was directly driven by the local wind field. They found a strong correlation between the local wind field and consequently the coastal upwelling and the position of the southern frontal boundary.

The southern boundary of the front does not normally move south of 22°S except for those years when the intrusion of the tropical saline water of the Angola current into the Benguela penetrates as far as 25°S (Mohrholz *et al,* 2001). Referred to as Benguela Niños, several such events were recorded in the Benguela in 1934, 1963,1984 and the most recent one in 1995 (Shannon *et al*, 1986; Gammelsrød *et al*, 1998). These intrusions are in addition to the seasonal intrusion of saline water that penetrates southward along the Namibian coast with the maximum penetration recorded in late summer and early autumn (O'Toole, 1980; Boyd, 1983).

On average, the surface current flows in the northwestward direction with a speed ranging between 0.10-0.20m.s^{-1} (Shannon 1985; Gründlingh, 1999), before turning westward opposite Lüderitz (Harris and Shannon 1979; Boyd *et al,* 1998). This flow path was confirmed by satellite-tracked drogues that were released at Cape Town (Harris and

Shannon, 1979; Nelson and Hutchings, 1983), showing how the path of these drogues followed the bathymetry closely up to Lüderitz where they turned offshore. This was again demonstrated by recent observations from satellite drifters (Gründlingh, 1999; Largier and Boyd, 2001).

Surface and near surface currents over the Benguela region are largely influenced by prevailing local wind (Shannon, 1985; Boyd *et al.,* 1998), especially by the diurnal winds (Boyd *et al.* op cit.). This flow is characterized by coastal upwelling especially in the central and southern region, caused by the equatorward wind stress. The extent of the upwelling is determined by the wind field which is responsible for the formation of the upwelling cells combined with change in bottom topography and the orientation of the coast (Nelson and Hutchings, 1983; Shannon, 1985; Hocutt and Verheye, 2001). This wind stress is strongest at 27°S, creating a perennial upwelling cell near Lüderitz (Stander, 1964), with a maximum recorded during spring, with some slackening during autumn. The extensive upwelling zone is characterized by cold surface water, weak stratification and high turbulence, which appear to be an important determinant of the biology of the system. This zone appears to act as a barrier to the migration of small pelagic fish such as sardine and anchovy and seems to effectively divide the Benguela Current System into northern and southern sub-systems (Shannon, 1985).

The current is variable in the area of low velocities especially off Walvis Bay (Iita *et al,* 2001). In these areas of weak flow, currents are found to be complex, depth dependent and alternating north and southward (Boyd *et al*, 1998; Iita *et al,* op cit). Between Cape

Frio and Walvis Bay, the flow is dominated by weak and variable currents, and at times a southward flow can be observed close to the coast and below 30m. Meso-scale structures such as anticylonic eddies are found in this region especially when upwelling is relaxed (Nelson and Hutchings; 1983; Boyd, 1987; Barange and Boyd, 1992; Bailey *et al* 2001). Evidence of these eddies was observed in the ADCP measurements during July 1999 (Mouton *et al*, 2001). The nearshore poleward flow was not detected during that survey. By examining the geostrophic circulation of the area, the dynamical signature of these eddies was detected down to 100m. These eddies are also found in the south off Lüderitz, with radii of about 25 -60km (Salat *et al*., 1992),

Small-scale variability was recorded in the surface in some areas along the Namibian coast. This variability could be driven by diurnal wind and tidal forcing or inertial oscillation (Boyd *et al.,* 1998). These variations were found to be important in vertical movement of nutrients across the thermocline (Boyd *et al.,* 1998).

In areas where the wind is relatively calm and current velocities are low, inertial oscillations have been recorded (Gründlingh, 1999). Recently, these oscillations have been measured in the south, off Orange River and have been reported to be responsible for the diffusive transport that causes strong cross-shelf fluxes of plankton in these regions (Largier and Boyd, 2001). Cross-shelf circulation has been associated with wind-driven coastal upwelling. These flows are usually weaker than the alongshore flow, but they can be important in helping redistribution of water properties, nutrients, sediments and other constituents. Boyd, (1983), studied currents in the central Benguela region and used the satellite-tracked drogues to measure the surface flow in central Namibia. The periodicities of these drogues were estimated at four depths and found it to be in the agreement with that of the theoretical value of the inertial motion.

The poleward undercurrent was documented from as early as 1960 by Hart and Currie (1960). It was confirmed by several authors such as Shannon, (1985); Chapman and Shannon, (1987) and Nelson, (1989), and the flow was described as a compensation for the Ekman divergence. The flow was recorded offshore in northern Namibia off Cape Frio. Moreover it also occurs inshore sometimes and referred to at times as the counter current to the surface northward flow measured over the shelf (Boyd *et al.,* 2000). Carrying South Atlantic Central (thermocline) water into the Benguela region (Gordon *et al.* 1995), this current could be detected penetrating to Lüderitz (Shannon 1985, Chapman and Shannon, 1985), and was observed as far south as Cape Columbine (Nelson and Hutchings, 1983; Nelson, 1989). The flow has been directly observed in a number of cross sections with an average speed of 0.05-0.06 $m.s^{-1}$ (Shannon and Nelson, 1996). It is part of a more extensive poleward motion that stretches from the coast across the bottom of the shelf (Nelson, 1989).

This poleward motion is believed to transport the oxygen-depleted water southward. There are two aspects that have been suggested as sources of this oxygen deficient water (Chapman and Shannon, 1985). A mass of low oxygen water with concentration of less than 1ml/l is found at around 300-400m depth and originates from a source area off Angola (possibly the Angola gyre) whilst on the shelf, the near-bottom water is oxygen depleted due to bio-chemical processes which occur in the northern Benguela between Cunene River and Lüderitz. This water lies over the shelf and is influenced by the local upwelling resulting in anoxic conditions in the central Benguela. The occurrence of low-oxygen water is not only important in terms of the chemistry, but plays a key role in controlling the distribution and abundance of several marine species. Subsequent studies have shown that low oxygen conditions can exist at times on the shelf further south, for example near the Orange River, in St Helena Bay and even at some sites on the Agulhas Bank (Hart and Currie 1960; Andrews and Hutchings 1980).

Little is known about the exchange of surface and subsurface water between the southern and the northern Benguela. This is due to the lack of direct flow measurements in the vicinity of Orange River. The area around the Orange River is one of the least investigated in the Benguela region. The general picture that exists today of the current regime especially in the central and northern Benguela is based upon a combination of ship drift data, geostrophic calculations from hydrographic data, estimates of surface drift based on Ekman dynamics, a few satellite tracked drifter and very few moored current observations. The amount of actual direct current measurements in this region is rather sparse. The use of ADCP data has contributed more to the understanding of the flow pattern especially in the Southern Benguela where these data have been used extensively. If used correctly, these data can be used to provide finer resolution in both space and time, which is needed to resolve smaller spatial scales associated with shear, internal wave mixing and cross-frontal exchange.

ADCP data have also been used to estimate the abundance and distribution patterns of zooplankton (Flagg and Smith, 1989) with high spatial resolution and over large areas (Postel *et al*, 2002) and river discharges (Simpson and Oltamann, 1993).

In the future, numerical models will dominate as a tool to simulate large circulation and to resolve mesoscale features that develop over the coastal area, as the collection of data remains expensive and time consuming. Models of this nature need some direct physical measurements for validation. Correctly collected ADCP data can be used for this purpose. Consequently it can also be utilized for three-dimensional biophysical models to study the physical processes, which affects the recruitment of pilchard and anchovy (Penven, 2000) as well as the advection of pelagic recruitment in the region.

CHAPTER 3

ADCP INSTRUMENT, DATA PROCESSING, DATA MEASUREMENTS AND CASE STUDIES

3.1 ADCP Instrument

ADCPs have been used from vessels since 1984. Its predecessor, the Doppler speed log was an instrument that measures the speed of the vessel through the water or over the sea bottom. The Research Development Instrument Company (RDI) produced its first ADCP in 1982, which was a self-contained instrument and in 1983 the first vessel mounted ADCP was produced (RD Instrument, 1996). The first generation of ADCPs used a narrow–bandwidth with five different frequencies between 75 –1200 kHz available.

For most of the time the RDI Narrow Band (NB) Vessel-mounted (VM) 150kHz ADCP was the instrument of choice. Its relatively small size and 400 meter profiling range made a good general-purpose current profiler. However, many users need greater profiling range. As a possible successor the RDI developed Broad Band ADCPs. In 1996, RD Instruments introduced its latest vessel-mounted ADCP package called the Ocean Surveyor (OS). The Ocean Surveyor combines the capabilities of the Narrow Band ADCP and the Broad Band ADCP in a single package. Although there are other companies that produce ADCP instruments, such as AANDERAA and SonTek, most of the ADCP instruments used in the Benguela region, if not all, are manufactured by the RDI Company.

The ADCP measures ocean currents at various depths from a moving vessel by means of acoustics. The data is used to identify the dynamical structure and the spatial distribution of the ocean current flow. In addition to flow measurements ADCPs have been used for a variety of purposes. Physical oceanographers use the instruments to estimate wind speed by interpreting surface backscatter from upward looking deployments (Brown *et al.*, 1992; Zedel *et al.*, 1996). Recently, high-frequency ADCPs have been used to investigate turbulence (Gargett, 1996; Stacey *et al.*, 1998), while biological and chemical oceanographers have also begun to exploit ADCP measurements both for assessing advective effects on their point measurements and in estimating zooplankton biomass (Flagg and Smith, 1989).

The instrument has become common, and is found on most modern oceanographic research vessels (New, 1992). Measuring velocities relative to the earth both vertically and horizontally as a function of depth, the ADCP employs the Doppler principle to measure the relative radial velocity in the water column between the instrument and scatterers (for example plankton, sediments and other solid particles drifting with the water currents).

The ADCP instrument has four acoustic beam transducers (only three beams are the minimal requirements), which transmit acoustic pulses vertically along narrow beams at a known frequency and subsequently receives and processes echoes returning from scatterers in the water (see Figure 3.1).

Using the ship's compass, the beam coordinate velocities are converted into orthogonal earth coordinates system (the east-west, north-south and vertical velocity components). With the four beams the instrument can compute (measure) the error velocity from the estimated difference between the two pairs of beams measuring the vertical velocity.

Data are produced by range-gating the echo signal, which means the echo is broken into successive segments called depth bins. The operator configures the length of each depth bin and the transmit pulse, which determines the degree of averaging in the vertical, depending on whether one is interested more in vertical resolution or profile penetration. The 150 kHz vessel mounted ADCP has vertical range and resolution of typically 300m and 8m respectively, with a standard deviation of 0.11 ms^{-1} for a single-ping horizontal velocity component estimate.

Since the use of ADCPs has become widespread in the last 15 years, current data are now generally collected along a survey grid and/or at fixed stations. The data now offer the same advantages of a real-time coverage as an oceanographic survey, but also still suffer the same problem of non-synopticity. This can distort, alias or even create some spurious oceanographic features. Directly below a moving ship the basic assumption of a horizontally homogeneous flow is violated due to the current fields generated by the interference of both the bow and stern wave of the moving ship. This causes a significant bias of the ADCP measurement down to a depth of about half of the ship's hull.

In order to understand our analysis of these instruments' performance, it is necessary to understand some of its principles of operation. There is also a need to understand the quality and limiting factors of the data and what influence these factors have on measurements.

There are two kinds of errors in the velocity data collected by an ADCP instrument:

(a) Random error

Random error is referred to sometimes as short-term uncertainty and defined as the error in single-ping ADCP data. The size of random errors can range from $0.001ms^{-1}$ to $0.5ms^{-1}$ depends on number of pings, depth cells size and the ADCP frequency (RDI Instrument, 1996). There are some external environmental factors, which can influence these errors as well; this includes turbulence, internal waves and the (ship) instrument's movements. Random error can be estimated by computing the standard deviation for the error velocity and the error can be reduced by averaging multiple pings.

(b) Bias error

The bias error, which is sometimes called the systematic error, is the error that remains in the data after random error has been essentially eliminated/reduced by averaging. It has a magnitude ranging between 0.05 and 0.1ms^{-1}. This error can be influenced by several factors such as temperature, mean currents speed, beam geometry etc.

Other possible sources of errors and uncertainties in the data that limit the determination of water velocity's accuracy are:

(i) The performance of the ADCP in measuring the motion of the upper few hundreds of meters of the water column relative to the ship (which can be affected by among others; state of the sea, trapped bubbles etc.),

(ii) The navigation (this is the accuracy of the ship's position) and

(iii) The short and long term accuracy of the ship's, and therefore ADCP's heading (King and Cooper, 1994).

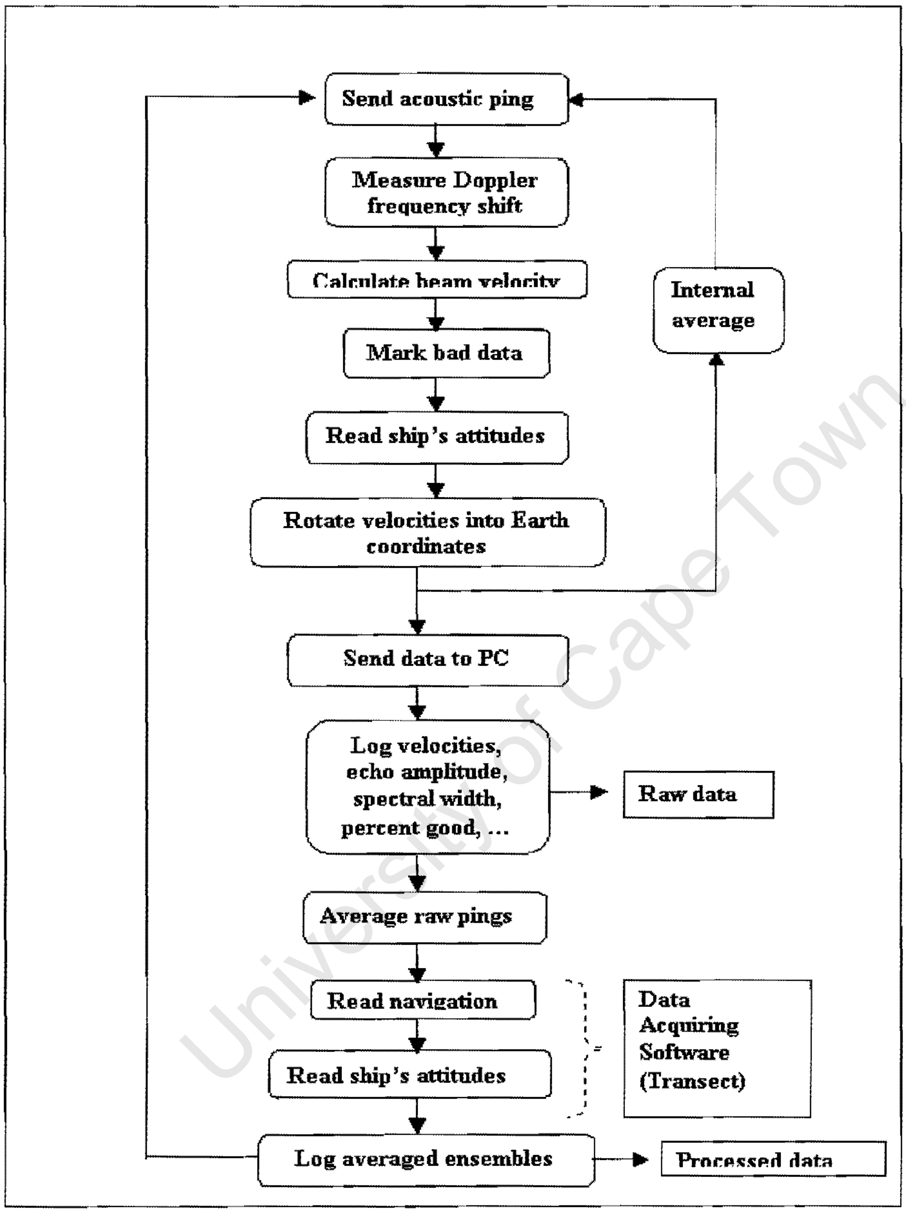
The data in the upper layer is often contaminated by ship's perturbations and reliable data are normally found at depth greater than 20m (Mohrholz *et al* 2001) depending on the depth of the ship's hull and the turbulence created by it. During moderate and severe (seas) weather, the quality of the data may be poor, because of the trapping of bubbles beneath the ship's hull (New, 1992), which can act as a shield blocking the transmission of sound frequency. This might cause a spurious near-surface flow in the direction of the ship's motion. It can be avoided if it is possible to mount the ADCP below the bubble layer.

The last two types of errors, (ii) and (iii) can be reduced by using the ship gyro - compass and the GPS to determine the vessel position and heading accurately. The gyro - compass typically has an error of about 1° for a vessel moving at 10 knots, which can result in the ADCP current measurements having errors of about $\pm 0.1 ms^{-1}$. With the introduction of real-time Differential Global Position System (DGPS) position fixing and GPS attitude measurements, these errors can be reduced to $\pm 0.01 ms^{-1}$ ADCP measurements collected over 10 min (King *et al.* 1996). The GPS system computes ships heading to within 0.05 of a degree in real time. The error introduced by the gyro, combined with the mounting angle error is referred to as the misalignment error. This error can be estimated (Joyce, 1989; Pollard and Read, 1989) and significantly reduced during the post-processing of the data (Osinski, 2000).

There are two different methods of obtaining absolute current velocities using the ADCP instrument, i.e bottom track and water track. Using the water track method, the absolute current velocities over a fixed depth range (reference layer) are obtained by subtracting the average of the ship velocity relative to a reference layer (i.e. ADCP velocities) from the absolute ship velocity over the ground (from navigation, i.e., GPS or bottom track). This is a critical step in the processing of ADCP data in that the ship's velocity is at least one order of magnitude larger than the absolute currents. With the bottom-track method, the ADCP transmits a special acoustic pulse to measure the movement of the ship relative to the bottom, which is the negative vector of the ship's velocity. The bottom-tracking mode is usually preferred to using navigation reference, because there is no need for external devices such as GPS, which could introduce errors (Gordon, 1996; Osinski, 2000). There are limitations to this option, in that it is only applicable within the 300-400 - metre depth range (for 150kHz narrow band ADCP), when the ADCP acoustic pulse can reach the bottom.

3.2 Data measurement

Shown below is a schematic diagram of the ADCP data measuring.



3.3 Data Processing

3.3.1 Data acquiring (RDI TRANSECT) and processing (CODAS) software packages

Although processing ADCP data well is not a trivial job, it is not so difficult that it should limit the collection and/or use of the data. There are a number of different software packages and computer programs developed to acquire, process and graphically display ADCP data.

Since the use of the ADCP instrument was introduced in South Africa, the collection of these data at Marine and Coastal Management (MCM), have been mostly done using the RDI TRANSECT software. From the RD Instruments Company, this is a program that runs only in DOS mode on a PC. It is mainly used to acquire and visually present the ADCP data in time and space. There are some limitations to this program in that it will not run on fast new generation computers. Although the RDI Company has since introduced the Windows version (Win ADCP), the DOS version remains the most used program on board the two main South African research vessels, *Africana* and *Algoa.*

This program performs processing by averaging individual ping profiles in real-time. It generates raw data and averaged (processed) data files. The difference between raw data files and processed files is that raw data contain the original data read directly from the

ADCP and this allows several post-processing capabilities on the files whilst processed data are affected by information set in the user-specified configuration file. This file contains scaled data, which is based on the offsets settings for some parameters, (such as transducer misalignment, compass offset and magnetic variation) and processing options.

Due to the fact that the raw data are very large files and subsequently the lack of vessel's PC's capacity, surveys conducted by the MCM mostly archive only "TRANSECT"-processed ADCP data files without saving the original raw data.

TRANSECT has an ASCII-output playback mode that creates ASCII files, but some further processing has to be done so that the velocities are converted into earth-coordinates instead of beam-coordinates. At MCM before the year 2000, this conversion was done using the Underway Mapping System (UMS) software of the MCM but the data had to be converted first to a UMS readable files by a Norwegian written ADCP2UMS program, which was also giving some problems. The UMS software became very outdated, as it was not Y2K complaint, and is therefore no longer functional. In the meantime, software such as Surfer and Generic Mapping Tool–GMT are used temporarily for vector plotting of the ADCP data results, from the "TRANSECT"- processed files.

Most of the data collection software defaults from the instrument's manufacturer are not adequate for high quality scientific processing of ADCP data. As TRANSECT is more of a data acquisition program than a data processing program, there is a need to investigate more appropriate and effective processing software.

It is against this background that this study undertook to investigate the use of CODAS for processing ADCP data. CODAS (Common Oceanographic Data Access System), was developed by a group at the University of Hawaii led by Eric Firing[2]. CODAS consists of a database system for ADCP and other oceanographic data such as CTD, and a set of programs for ADCP data processing. This set of machine-independent subroutines can run on a number of computing platform and operating systems for PC as well as in UNIX environments (Firing *et al.*, 1995). The CODAS distribution comes with an extensive list of utilities for processing data from Vessel Mounted Acoustic Doppler Current Profilers (VM-ADCP). It also provides a series of MATLAB analysis routines for post-processing and plotting ADCP velocity. Although CODAS was developed with an emphasis on working with data collected using Data Acquisition Software (DAS 2.48) and the University of Hawaii (UH) "user exit" program, it can also handle RDI's TRANSECT collected data.

Additional CODAS tools (GFI Extensions) have been developed at the Geophysical Institute, University of Bergen by Pierre Jaccard[3] (personal communication). These were added as utilities for scanning, viewing and averaging of Narrow Band ADCP Raw files acquired with RDI's TRANSECT as well as files for loading the "TRANSECT"-processed data files into the CODAS database for post-processing.

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[2] http://currents.soest.hawaii.edu/software/codas3/
[3] http://www.gfi.uib.no/~jaccard/gficodas/

CODAS software allows the user to perform routine processing such as data editing, calibration and navigation calculation (Figure 3.2). The first step is to create the database and scan the data for readability before loading them into the CODAS database. This is then followed by the processing routine (editing, calibration and navigation).

1. Data editing, - This is done in many ways for example verifying the speed of sound used during the acquisition of the data; setting thresholds for bad bins/profiles that have been contaminated by the interference with the bottom or some physical object such as hydro wire as well as rejecting data not in the water column and eliminating bad GPS fixes. Editing of the data starts by determining the parameters to flag bad data. The basic editing parameter is the percent good determined by the ADCP and recorded along with the velocity data. The other editing parameters are:
    - Amplitude- corresponds to the depth-varying amplification used by the ADCP profiler to maintain a constant signal level for all vertical bins. It is generally used as a measure of signal strength. It is used to edit the ADCP profiles for bottom interference (only useful with bottom-track method when the bottom is within ADCP range).
    - Error velocity- used to detect interference of physical object in the path of the acoustic beams.

- Variance of the vertical velocity (W)- variance is calculated of the entire profile and is used to indicate shallow depths. When the water is shallower than 50m the variance is large.
- Second derivatives of U, V and W- when the second derivatives of W and at least one of U or V is high, it indicates physical intrusion in the path of the beams. It also detects 'spikes' in the relative velocities.

These parameters flag interference from the bottom, instrumentation suspended from the ship and large aggregations of fish or acoustic scatterers. Therefore individual profiles of velocity have to be examined visually and in the light of these flagging parameters.

2. Calibration, - by applying a correction to the gyrocompass using GPS heading data. The heading offset (phase) and amplitude scale factors are required for the calibration of the transducer's orientation and velocity. These are obtained by using the water track and/or bottom track methods to calculate the net transducer offset. This is the correction of the "angle" error due to the misalignment of the transducer.

3. Navigation and the calculation of absolute velocity, using the smoothed reference layer to reduce the effect of noise in the position fixes.

4. Data extraction in various formats, with various gridding schemes.

Some of the advantages of the CODAS software package is that data are saved together with instrument set up; cruise information and post-processing information. The database is built in such way that data can be easily and quickly retrieved. And most importantly, most of the post-processing information is saved separately, and applied to data only when these are retrieved, therefore original measurements are untouched and can be re-examined or re-processed at a late date if needed.

3.3.2 Case Study 1: Description of the data from the *Algoa* (C098 Survey)

This data set was collected during the routine monitoring survey of the South Africa SARP line and St. Helena Bay monitoring line (SHBML) on board research vessel *Algoa* on 06-08 August 2001 (Figure 3.3). This vessel was equipped with a 150-kHz narrowband RD Instruments ADCP mounted on the ship's hull at about 4 m depth. The instrument received ship's heading from a real – time differential GPS (DGPS) and the ship's gyrocompass.

As mentioned earlier most of the available ADCP data collected from the South African continental shelf area are mainly "TRANSECT"-processed files. Little or no data are available in the original raw data format. This is due to the lack of disk space on the data acquisition PC because the raw data are very large files. During the August 2001 survey, data were collected continuously both underway and on stations and acquired using TRANSECT and an effort was made to collect and save all available data.

In addition to the usual collected "TRANSECT"-processed data files, the raw (ping) files were also saved. No further editing or calibration and hence no validation can be performed on the processed data after collection. The raw data can be validated during the processing. For the purpose of calculating the absolute reference layer velocities, navigation data were also collected.

One of the objectives of the BENEFIT ADCP project, of which this study is a part, is to assess the quality of the data collected as well as the software used to acquire, clean and process the ADCP data in the Benguela region. An attempt was made here to compare the un-validated "TRANSECT"-processed data with the "TRANSECT" raw data, which was validated, collected during this survey. Current vectors from both these data sets were drawn using the CODAS software package. Firstly, the raw data were loaded into the CODAS database using the GFI Extension files then using the original CODAS routines data were validated, edited and calibrated before the vectors were plotted.

A constant speed of sound of 1500ms^{-1} was used during this survey. A better value was estimated from a constant salinity value of about 35.4 psu and temperature values as measured by the thermistor at the transducer's head. Editing parameters were derived using the CODAS editing system. Individual profiles of velocity and backscatter were examined visually and in light of these flagging parameters. The editing statistical analysis used the following values to identify the bad data (see Table 1).

Parameters	**Threshold values**
Reference layer bins	4-12
w variance	30000 $mm^2 s^{-2}$
w 2nd derivatives	260
uv 2nd derivatives	360
Error velocity	200 mms^{-1}
amplitude	20 counts

Table 1. Thresholds values to set flags for bad ADCP data during the R/V *Algoa* cruise

The calibration was performed by correcting the gyro heading, before the ship-ADCP misalignment angle was corrected from the ADCP heading which was calculated from bottom track calibration. The ADCP uses the beam 3-4 axis as its heading reference and assumes that beam 3 points in the same direction as the heading reference. Any misalignment of this axis gives the ADCP incorrect information from the ship's gyrocompass. The offset of the transducer mounting must be accounted for in the software and in setting of the configuration file. Analysis of the bottom track information while the ship is underway and maintaining a steady course will provide the magnitude of this offset. The phase angle between the ship and ADCP heading was found to have an offset of about 140° (see Table 2 below).

Parameters	Bottom track
Amplitude (mean)	0.9764
Amplitude (stdev)	0.0127
Phase (mean)	139.96 °
Phase (stdev)	0.3812°

Table 2: Calibration values for phase and amplitude before data rotation (*Algoa* cruise)

The data was then rotated by 140° to correct for the angle misalignment and the correction was applied to the whole database. The results after the data rotation are shown in the table below.

Parameters	Bottom track
Amplitude (mean)	0.9963
Amplitude (stdev)	0.0130
Phase (mean)	-0.0441°
Phase (stdev)	0.3863°

Table 3: Calibration values for phase and amplitude after data rotation (*Algoa* cruise)

The "TRANSECT"-processed data were loaded into the CODAS database and some limited editing was performed. These data had to be rotated as well before the vectors could be drawn, despite the fact that the bottom track feature was used for the entire cruise. The obvious spikes especially when the vessel's speed changes during the stations were manually removed from the data.

In addition to current measurements, hydrographical (temperature, oxygen and salinity), data were also measured during the survey using a Seabird CTD and vertical profiles were contoured using the Surfer version 7 and the Generic Mapping Tools (GMT) programs. CTDO stations were only conducted along the St. Helena Bay Monitoring line (north of Cape Columbine) at the station spacing of 2 miles, 5 miles then every 10 miles until station 12, approximately 100 nautical miles offshore (Figure 2.3). On the SARP line only particle size and fluorescence were sampled using a "Magnum" down to 100m, which also measured temperature in the water column. Additional information on surface features was gained from high-resolution NOAA AVHRR satellite infrared SST and SeaWiFs imagery. These images were processed and provided by the Satellite Application Centre (SAC). Wind information was also obtained from ocean surface winds at a 10m height derived from near real-time wind data collected by NASA's SeaWinds scatterometer aboard the QuikSCAT and processed by NOAA, for wind forcing processes[4].

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[4] http://orbit212.wwb.noaa.gov/quikscat/

3.3.3 Case Study 2: Description of data from the *Meteor* Cruise (M48/5)

The data set used here was collected from the northern part of the Benguela region on board the German research vessel *Meteor* (cruise M48/5) from 12 October to 23 October 2000. The survey covered the area in the central Namibian coast from 18°45'S, south of Cape Frio, to 25°S just north of Lüderitz upwelling cell (Figure 3.4). The main objective of this survey was to investigate and understand the impact of meso-scale physical structure and processes on zooplankton with reference to fish recruitment.

Apart from a number of different biological instruments that were used for phyto-, zoo- and ichthyo-plankton sampling, hydrographical parameters were measured with SeaBird 911 (conductivity temperature depth probe) CTD at each station. The CTD was equipped with oxygen, fluorometer sensors. These data were supplemented by underway measurements from a weather station giving meteorological data, the thermosalinograph to measure surface salinity and temperature, and the vessel mounted ADCP for current measurements. The ADCP used during this survey was a 75 kHz narrow broad mounted in the hull of the vessel at 5m depth. Current data were collected in the water-tracked mode with automatic bottom track and time-averaged as current profiles every 5 minutes.

The primary data acquisition was performed by a PC running RDI's Data Acquisition Software (DAS) version 2.48. With the present RDI DAS, integrating navigation into the ADCP system requires a "user exit" program that effectively becomes part of the DAS, therefore the DAS used the UH's program, version "ue4" for data acquisition.

Information on the ship's heading, pitch and roll was provided by an Ashtech Attitude Determination Unit (ADU), whilst the two gyro compasses were available for ship's heading. Additional heading information was provided by a fibre optical gyro. The heading information was used to calibrate the ADCP data for the correction of the ADCP misalignment.

ADCP data was validated using the CODAS software package. Its editing and calibration routines were performed on the data with a few modifications made on some MATLAB routines. A speed of sound of 1500ms^{-1} was used during the data collection. During the processing a better value was estimated from the temperature and salinity data collected with the thermosalinograph. Parameters used to set flags for outliers and bad data values in profiles are given in the table below.

Parameters	**Threshold values**
Reference layer bins	4-10
W variance	10000 mm ^{2} s^{-2}
w 2nd derivatives	200
uv 2nd derivatives	250
Error velocity	70 mm s^{-1}
amplitude	10 counts

Table 4. Error thresholds to flag bad ADCP data during the *Meteor* cruise

The ADCP heading for the ship-ADCP misalignment angle correction was calculated from both bottom and water track calibrations. And the calibration coefficients from these bottom and water track methods yielded consistent results for the amplitude and phases value (results are shown in the table below).

Parameters	Bottom track	Water track
Amplitude (mean)	1.0028	0.9976
Amplitude (stdev)	0.0055	0.0086
Phase (mean)	-1.4492	-1.3768
Phase (stdev)	0.2653	0.5953

Table 5: Calibration value for amplitude and phase (*Meteor* cruise)

Mean values for both the amplitude and phase of 1.00 and –1.41° respectively were used for the calibration coefficients and applied to the whole database.

CHAPTER 4

RESULTS

4.1 RDI "TRANSECT"-processed data versus raw data

During the August 2001 monitoring survey, in addition to the usual processed data files, raw data files and raw navigation files were saved. This was in order to compare and see the difference, if any, between the current velocities from "TRANSECT"-processed data and that from the original raw data files. This would make it possible to assess the quality of the historical ADCP data, which has been collected since the introduction of the ADCP into the Benguela region, mainly by the region's two only research vessels (*Algoa* and *Africana*) equipped with ADCP instruments. It should be stressed here that this cruise was part of a monitoring survey and was not designed for a specific physical oceanographic investigation. It was therefore not the ideal cruise for a total accurate ADCP data quality evaluation.

It should be mentioned here that results from ADCP raw data files acquired using the RDI TRANSECT program, which processed (edited and calibrated) and presented using the CODAS software package would be referred to as validated data. While un-validated data will refer to results from "TRANSECT"-processed data, which used CODAS only for presentation.

These results of validated current data and un-validated current data files are shown in Figures 4.1 (a-c). Firstly differences in the results between the validated (Figure 4.1a) and un-validated data (Figure 4.1b and c) were looked at before discussing the possible causes of these differences. It can be clearly seen that the un-validated data show very noisy results giving an unrealistic representation of the water flow of the study area (Figure 4.1b). Differences were more pronounced especially along the two cross-shelf transects, where stations were conducted (see cruise track Figure 3.3) at all depth ranges, especially on the southern most (SARP) line. This was because of sudden changes in the vessel's speed and direction (ship's turns) before and after oceanographic stations, which affects the gyro offset. Good quality ADCP data can be collected if the vessel speed and course is kept constant or with minimal turns. Pollard and Read (1989) recommended that 10-15 minutes of ADCP data should be discarded after a start of each turn as these data could be contaminated by short period errors of up to 2°. This would then mean that most of the data collected along the SARP line were of poor quality and had to be discarded because stations were only an hour away from each other (10 mile apart).

Results indicate that the validated data (Figure 4a) shows clear distinct features, which are not clearly observed from the un-validated data (Figure 4b). For instance, close inshore where the velocities were relatively weaker, there was a difference in current vectors. Figure 4.1a shows a very distinct divergence in the flow at around 33.4°S but this divergence is not clear in Figure 4.1b. Nevertheless, results showed agreement in the flow on the alongshore transects when the vessel was underway with the prominent features observed to be very consistent.

In an attempt to smooth out the 'noise' from the un-validated data (Figure 4b), all vectors that seemed to give unrealistic velocity flow were manually deleted. The result of this exercise is shown in Figure 4.1(c). Comparing it to Figures 4.1(a and b) it is obvious that there is an improvement and it was easier to see the similarities in the flow. Considerable differences were still evident at some places. The most noticeable difference was on the south cross-shore transects (SARP line). From Figure 4(c), in the upper 100 m mid-shelf, the current was shown to be flowing onshore while in Figure 4.1(a) the flow was going offshore. "TRANSECT"-processed data files contain the scaled data based on the offsets and processing options from the user-specified configuration file. Errors found in these processed data could be due to, inaccurate information in the configuration file. This can exist if for example, the navigation configuration is not correct for the instrument (gyro) and data-acquiring programme (in this instance RDI TRANSECT), but mostly if the bottom-track method is not used.

Ageostrophic motions (tidal and inertial periods) especially in the surface layer can also contribute to the noise found in the data. Spatial averaging done by the ADCP as well as by TRANSECT is not over long enough period to remove these periods. The CODAS software has a way of computing and extracting this information from ADCP raw data. The advantage of collecting raw data is that it enables the user to diagnose errors and hence validate the data through calibration and editing.

4.2 Oceanography along the west coast of South Africa during 06-08 August 2001

4.2.1 Hydrography and meteorology

Near real-time surface wind data from NASA's SeaWinds scatterometer were obtained, for the two days of the survey (07 and 08 August 2001) and are shown in Figures 4.2(a, b) and 4.3(a, b), measured in the mornings and in the afternoons. Around the study area (between 32°S and 35°S) the wind was generally light on both days, not exceeding 15 knots with a direction from southerly in the morning on the 7th to a more upwelling favourable south-easterly in the afternoon, which persisted until the following morning. In the afternoon of the 8th, the wind direction changed dramatically to a weaker northerly direction.

SeaWiFs images showed high concentrations of chlorophyll *a* along the coast (Figures 4.4 (a) for 06 August 2001 and Figure 4.4 (b) for 07 August 2001) that seemed to indicate some strong upwelling events, which had occurred especially near St. Helena Bay (north of Cape Columbine). These images showed an increase in the chlorophyll *a* concentration from the 6th to the 7th of August. This could be due to the change in direction of the wind from southerly to a more upwelling favourable south-easterly direction on the 7th of August. Indications of weak upwelling filaments penetrating offshore were evident in both images west of Cape Town.

The sea surface temperature during the 06 August 2001 is given in the satellite image presented in Figure 4.9 (will be discussed later). Close to the coast the water was relatively cooler, with sea surface temperature ranging between 18°C and 19°C, confirming weak upwelling signals. There is a thermal front more noticeable north of Cape Columbine with warmer water seen to be pushed relatively more seaward. This could be due to the upwelling and the Ekman offshore transport. A warm filament was observed with an anticyclonic feature near Cape Town, penetrating further northward and moving parallel to the shelf. This filament could be possibly detaching off the Agulhas Current (not shown here). The feature was confirmed by SeaWIFs images that showed a weak filament moving north eastward which seemed to persist till the following day (Figures 4.4 a & b). Advections of warm water from the Agulhas Bank (Nelson *et. al*, 1998) are a norm of the southern Benguela region as a result of the shear in the Agulhas retroflection area (Shannon, 1985).

Vertical structure for temperature, salinity and oxygen from the cruise along the St. Helena Bay line (SHBML) cross-shore transects are shown in Figure 4.6. The water column showed vertical stratification, suggesting the lack of strong wind and consequently weak surface coastal upwelling along the transect. Water column upwelling was suggested by the uplift of 10°C isotherm and 34.8psu isohaline at around 30km offshore. The oxygen profile also indicated upward displacement of low oxygen water in the same area.

In the midshelf (~95 km offshore), a frontal feature trapping a body of less saline, cooler and oxygenated water was observed (seen in the vertical profiles Figure 4.6), coinciding with the divergence motion recorded in the current flow (Figure 4.1a). This coincides as well with the thermal front, which was observed in the satellite image in Figure 4.9.

The oxygen profile showed a region of oxygen-saturated water (>7ml/l) in the surface, which roughly coincided with the frontal feature observed in temperature and salinity profiles. The profile showed several pockets of low oxygen area throughout the water column and especially along the shelf. An area of very low oxygen, possible an indication of anoxic condition was measured between 50-100m depths in the bottom close to inshore (layer of about 40m thick).

4.2.2 Current measurements

During this cruise there were no current meter measurements available. There were not enough data collected from the CTD casts for detailed geostrophic calculations to be made. Thus, the results of the vertical shear obtained from the ADCP data could not be compared with the geostrophic shear. Nevertheless, it seemed that information given from the ADCP raw data and processed with the CODAS software (validated data) were more reliable than the one from the "TRANSECT"-processed (un-validated) data. The description of current flow below was based on results from the former.

Due to perturbations by the ship, data from the few upper meters are normally contaminated and not reliable, therefore only results from 30 down to 200 meters depths were presented in this study. The horizontal current distribution in this depth range (30m to 200m) is given in Figure 4.1a showing the synoptic features at those depths. In the upper 50m over the inner shelf–zone, the flow was variable off Cape Columbine and there was a hint of divergence at around 33.2°S with a weak net poleward motion of water recorded from 33.5°S down to the Cape Peninsula moving parallel to the bathymetry. This poleward flow was observed down to 100m deep. The flow became very strong near 34.2°S, reaching maximum speed of about $0.6ms^{-1}$. The vertical profile of the currents along the line off Cape Peninsula (SARP line) showed an onshore tendency in the surface flow (south-east) close inshore in the upper 80m (Figure 4.7). The flow then turned southerly to south-westward a little further offshore before it completely turned to join the north-westward motion over the mid-shelf. There was a clear front around 18.2°E evident from the current measurements along this line with two alternating flows. The inner-shelf water was moving poleward while the mid-shelf component moved equatorward forming part of the shelf edge jet motion and both flows seemed to be baroclinic, relatively strong in the surface. Both motions were detected down to 200m (though weakening) and with a maximum speed of about $0.5ms^{-1}$ in the near surface, the mid-shelf flow was believed to be part of the well-documented baroclinic shelf edge jet (Bang and Andrews, 1960; Nelson, 1989; Shannon and Nelson, 1996). The strong front indicated in the current measurements was not clearly observed from the chlorophyll profile but was detected in the temperature subsurface measurements (below 30m) close to inshore (Figure 4.5).

In the offshore alongshore transect, the jet was observed moving north westerly before leaving the shelf at about 33.8°S entrained into the warm Agulhas filament (Figure 4.9). Moreover, this offshore movement was observed to be of a barotropic nature with anticyclonic motion, which seemed to have a velocity of about 0.5ms^{-1}.

The sea surface temperature imagery shown in Figure 4.9 was obtained earlier than the current measurements superimposed on to it, therefore there seemed to be an offset on the observed anticylonic features. Another thing is that the current measurements are from 30m depths and not from the surface as the image.

Along the St. Helena Bay line (north of Cape Columbine) in the mid-shelf, the flow suggested a divergence motion in the surface (Figures 4.9) and near surface (upper 100m) at around 17.5°E (Figures 4.1a). This was confirmed by the presence of the frontal feature (between 70-100 km offshore) seen in the temperature and salinity vertical profiles (Figure 4.6). From the satellite image it was seen that the divergence had taken place at the thermal front indicating the warmer water moving with the offshore branch of the jet whilst the cooler water moving with the onshore branch of the jet. There seems to be an eddy-like motion with an anticyclonic motion below 100m, in the mid-shelf with a weak velocity of about < 0.1ms^{-1}(Figure 4.1a).

4.3 Oceanography off the Namibian Coast during the R/V Meteor cruise M48/5 in October 2000

The study area during this survey covered the coast off central Namibia from 25°S to 18°45' S. During the survey, five major cross-shore transects and a transect along the 200m isobath were sampled (see Figure 3.4 for the cruise track). For this study only two cross-shore transects were considered; one in the central Namibia, off Walvis Bay (23°S), the Namibian monthly monitoring line, and the other just north of Lüderitz, (along 25-25.5°S), which is the main upwelling region.

4.3.1 Hydrography and Meteorology

Horizontal distributions of sea surface temperature (SST) and sea surface salinity (SSS) are shown in Figure 4.10. There was a clear evidence of upwelling inshore close to 25°S depicted by the cooler (12°C) and less saline (34.8 psu) water during the survey. This could also be observed and confirmed in the vertical distribution of these parameters along 25.5°S latitude (Figure 4.12). In the extreme northwest of the study area, warmer (>16°C) and more saline (35.4 psu) water were observed. This could be an indication of the southward intrusion of the warmer and saline Angolan water penetrating into the Benguela region. Unfortunately, this surface southward movement of water could not be confirmed by remote sensing as most of the SST and SeaWiFs images captured during this survey were covered by clouds. The current flow obtained from the vessel mounted

ADCP measurement suggested a strong southward movement of the surface water along the Namibian coast (see section 4.3.2 below). Such warmer saline water of a tropical origin has been detected on the surface moving down south intruding into the northern and central Namibia in a number of occasions with a maximum penetration in late and early summer (O'Toole, 1980; Boyd and Thomas, 1984; Boyd *et al.*, 1987).

Vertical profiles for both salinity and temperature along the two sections off Namibia are shown in Figures 4.11 (23°S) and 4.12 (~25.5°S). The water column in both sections showed a fairly regular stratification at depth. The salinity profile suggests some signature of oceanic water from the west pushing through towards the coast.
It is clear that the water was cooler and less saline inshore in the south (25°S). This was due to strong coastal upwelling recorded in the region depicted in the temperature profile by the uplift of the 12°C isotherm over the inner shelf from the depth of approximately 180m. At the northern section off Walvis Bay, the upwelling signals were relatively weak.

4.3.2 Current measurements

Figure 4.13 shows a horizontal distribution of current flow at different water depths measured using the vessel-mounted ADCP during the *Meteor* (M48/5) cruise. In the surface (upper 100m), the flow was weak and variable especially in the central Namibia. Current measurements seemed to give a general northward flow north of Walvis Bay within the 200m isobath and beyond this isobath a poleward flow in the offshore direction was recorded. Below 100m, the flow was moving southward more strongly in the north with the highest value of about 0.35 ms^{-1} was measured. This could be the suggested poleward undercurrent first documented by Hart and Currie (1960) and many other authors thereafter, which is believed to transport the oxygen-depleted water off Angola into the Benguela region. The poleward motion was confirmed by the presence of the warmer saline Angolan water, which was observed in the SST and SSS distribution at the northwest edge of the study area (Figure 4.10).

To examine the vertical distribution of the current flow, two lines namely: 23°S (Figure 4.14) and 25.5°S (Figure 4.15) were also used in this regard. The profile along the section 23°S, in the central Namibia, showed very weak velocities more so in the surface with the inshore highest values of about 0.05ms^{-1}. The flow, however, improved slightly in the midshelf region reaching the speed of 0.1ms^{-1}. On the southern most transect (~25°S), the current showed a typical and expected cross shelf circulation in an upwelling area. The surface layer showed an offshore water movement, whereas an onshore compensation flow occurred in the deeper layer. This behaviour seemed to confirm the upwelling observed in the temperature profiles in Figure 4.12.

CHAPTER 5

DISCUSSION AND CONCLUSION

This thesis was not designed on the basis of a typical research study, where a specific oceanographic aspect or hypothesis is being investigated, that allows the design of a concise survey to collect and analyse the data accordingly and discuss the findings. The approach adopted here was mainly due to the lack of suitable research ship availability in the Benguela. The study forms part of a larger on-going Benguela Environment Fisheries Interaction and Training Program (BENEFIT) project, which aims to implement standardised quality ADCP data collection in the Benguela region. This is important in order to make available good data for physical oceanography, biophysical modelling and multidisciplinary studies. Consequently, this study was formulated along the objectives of the aforementioned larger BENEFIT project. An important aspect of the BENEFIT Program is the training of young scientists, and the appropriate technology transfer.

5.1 ADCP data quality

As a result, the main components of the thesis are firstly to investigate and assess the data quality, processing methods and software of ADCP data, which can also be used for data validation. This was done using data collected on a three-days cruise on board the research vessel *Algoa*. It should be noted, however, that this survey forms part of monthly monitoring cruises and was not specifically designed to assess ADCP data quality.

Nevertheless, an inter-comparison was made between the two different formats for data collection, i.e. raw and RDI proprietary "TRANSECT"-processed data, to evaluate their respective accuracy in depicting current flow. It should be stated, at this point, that the latter data format is more readily available for ADCP current measurements around South Africa. As a consequence, processed data were assessed in more detail in order to establish whether it is adequate for high quality scientific analysis and interpretation.

The inter-comparison results showed that the underlying and general flow presented in the vectors agree in principal although the flow details were different. The agreement was most evident at areas where current flow was stronger and uniform as well as when the vessel was underway, moving at a constant speed. But where currents were weaker and variable, the flow differed considerably. It seems though that most of the differences shown in the vectors were mainly along transects where stations were conducted, that means when the ship changes it's course and/or when it decelerates and accelerates before and after the oceanographic stations are conducted. This would pose serious problems when the data are averaged before the error vectors could be removed or reduced especially in the case of "TRANSECT"-processed data files and this could bias the flow. Motions (tidal and inertial periods) especially in the surface layer can also contribute to the variability found in the data, if these specific processes are not removed (e.g de-tiding the data). Spatial averaging done by the TRANSECT program is not over long enough time to remove these periods. Fortunately, the tidal currents on the South African shelf tend to be small ~0.1m^{-1} (Schumann and Perrins, 1982; Shillington, 1998).

Another problem, which was encountered, was of the misalignment error. During this survey a misalignment angle of about 140° was detected for the vessel mounted ADCP on the *Algoa*. The misalignment sometimes occurs due to the incorrect mounting of the transducer beam 3. The ADCP uses the beam 3-4 axis as its heading reference and assumes that beam 3 points in the same direction as the heading reference. The beam's mounting angle should be zero (meaning 3-4 axis corresponds to the earth's north-south axis) otherwise the offset has to be accounted for in the setting up of the configuration file. A second source or contributor to the misalignment angle could be errors due to variations in the gyrocompass-ship's heading calibration. In their papers, (Joyce, 1989; Pollard and Read, 1989) gave the estimation of this angle, while (Osinski, 2000) described how to correct the angle error during the post-processing of the data.

The error in misalignment angle would introduce bias into the transport perpendicular to the ship's track. Transport estimates are very sensitive to any bias in the transducer heading estimates. This angle would pose a serious problem especially when the ADCP is not within bottom range and the acoustic bottom tracking is not possible to derive current measurements. The result is that absolute water velocity has to be calculated using GPS and the gyrocompass. This, if affected by ship turns as described before, will introduce errors in the velocity measurements. It is essential to estimate this error though as it has very serious consequences on the velocity. For example, a bias of 0.5° in the ship's gyro leads to an error of about 1% in the ship's velocity (King and Cooper 1993). At the ship's speed of $5ms^{-1}$, the error will be $0.05ms^{-1}$. This misalignment error can only be detected during the data calibration, which is performed on the raw data. It is almost impossible to detect this error from the processed data.

There is a need for adequate training of ADCP instrument operational personnel in order to avoid such errors and achieve the highest quality of data collection during research cruises. It is important also to pay attention to all aspects of the data collection process especially when setting the ADCP instrument's configuration file, which will consequently enhance the quality of the obtained data significantly. During the processing and cleaning up stages, careful attention to the processing and use of appropriate software can improve the reliability of data. A recommendation is that due attention should be paid to the collection and processing of the ADCP data regardless of what data format is to be collected.

It is clear from the results that "TRANSECT"-processed data includes unedited errors, 'noise' and biases, which are already averaged into the data by the program, hence it is difficult if not impossible to completely remove or edit out these errors. As a consequence, it would be difficult to validate and completely correct for errors that are in the existing data available in South Africa, as these data are all in "TRANSECT"-processed files format. These can be minimized during the data collection by using a corrected configuration file as mentioned earlier.

The raw data collected on the recent *Algoa* cruise, presented a more realistic current flow. Since one of the advantages of collecting raw data is that it enables the user to validate the data through calibration and editing, it is therefore recommended that, original ADCP raw data files should be always collected/saved in conjunction with the processed data to allow for validation and if necessary, post-processing of the data before analysis using the CODAS software package.

This thesis study does not intend to disapprove entirely the quality of the existing data, but rather to show that there is a need for improved data archiving and processing procedures if high quality current flow studies are to be conducted. Using a data processing system such as the CODAS package helps in eliminating and reducing a lot of random errors and 'noise' that exist in the data before the final presentation. Moreover, it should be emphasized here again that the data used was from a monitoring survey; therefore there is a need for an accurate ADCP data quality assessment. A fully dedicated survey needs to be designed specifically to look at the quality of the acquiring software and consequently data quality (formats) in the region and this should be coupled with other types of flow measurement to validate the measured flow.

5.2 Circulation on the shelves

The second major component of the thesis undertook to apply the ADCP data collected to describe the oceanography of the Benguela region during the survey periods. Data from a monitoring survey in August 2001 was used to describe the southern Benguela. A second dataset collected in October 2000, a cruise conducted off Namibia was used to describe the oceanography for the central and northern Benguela.

5.2.1 Southern Benguela

Most of the structures observed were in support of the literature and confirmed some of the previous studies of the region. In the southern Benguela, a net subsurface poleward flow, with average velocities of 0.04ms^{-1} - 0.06ms^{-1}, has been observed close to the shore along the entire west coast (Boyd and Oberholster, 1994) at depths below 40m (Nelson, 1989). The flow was observed here down to a depth of 100m at speeds of roughly 0.1ms^{-1} and was not continuous from Cape Columbine to Cape Peninsula. The strongest poleward flow was recorded off Cape Peninsula, possibly influenced by southward propagating shelf waves. Generated by the variable atmospheric processes (e.g. coastal low), these waves are sometimes seen formed near Cape Columbine. The presence of this wave could not be confirmed by the available data at hand. Nevertheless, barotropic shelf waves (Holden, 1987) and poleward propagating coastal-trapped waves with a periodicity of roughly three days were sometimes measured over the coastal strip (Boyd and Nelson, 1998) and a little further offshore with velocities up to 0.6 ms^{-1} (Nelson and Polito, 1987).

The divergence observed in the current flow during the survey off Cape Columbine could be the indication of the branching of the jet shown by Boyd *et al*., (1992) on a schematic current flow field off southern Benguela using vessel mounted ADCP data (Figure 2.1), while Shannon (1985), recorded the divergence zone at around 17.5°E and referred to it as the 'Columbine Divergence'. During the survey the jet was recorded splitting in two parts just north of Cape Columbine, probably as a result of the thermal front observed there. The inshore branch was recorded moving inshore into St. Helena Bay carrying relatively cooler water and the warmer saline water pushing offshore aided by the Ekman transport as a result of the midshelf upwelling. The area of divergence coincided with Shannon's 'Columbine divergence' (17.5°E).

The equatorward shelf edge jet off Cape Peninsula was not recorded flowing continuously along the shelf, but was seen diminished and forced offshore entrained in an anticyclonic-like feature. A strong baroclinic jet is often observed southwest of Cape Town in the sub-surface and surface water with a mean speed of 0.58 $m.s^{-1}$ (Bang and Andrews, 1974) and it is believed to be a semi-permanent feature (Shannon and Nelson 1996; Boyd and Nelson, 1998). It has also been shown that the jet is sometimes variable and not always continuously present between Cape Peninsula and Cape Columbine (Nelson *et al*, 1998). At times the jet is seen diminished and entrained into the mesoscale features spinning from the Agulhas currents (Nelson *et al.*, op cit).

The southern Benguela is often forced by sporadic advection of warm water from the Agulhas Bank (Nelson *et al*, 1998). Water originating from the Agulhas current often intrudes and extends to the west coast of South Africa in the form of rings, eddies and filaments (Shannon, 1985; Shillington *et al.*, 1992). One such feature observed off Cape Town showed an anticylonic eddy-like motion as it left the Agulhas current and continued moving north westward into southern Benguela. This warm Agulhas filament, which could be frontal eddy (Lutjeharms 1981; Lutjeharms and Matthysen, 1995), was seen entraining the shelf edge jet. This feature was also identifiable from the SeaWiFS images, although observed relatively weaker; it persisted to the following day. Its existence was confirmed by the strong current flow on the northwestward direction, southwest of Cape Town before the flow turned in the offshore direction. Evidence of such an eddy-like flow feature has been observed from the chlorophyll satellite image by Nelson and Hutchings (1983), who suggested that the westward flow might not be permanent but occurs when the jet accelerates.

Filaments play an important role in transporting warm surface water from the Agulhas into the Benguela. This surface movement of water is also important to the biology of the area in that it transport eggs and larvae of pelagic fish from the Agulhas Bank where they spawn to the nursery grounds (Boyd *et al*, 1992; Nelson *et al,* 1998), while frontal eddies are believed to play important roles in cross-frontal mixing (Lutjeharms and Stockton 1987).

5.2.2 Central and Northern Benguela

The flow off the Namibia coast strongly confirmed the presence of the poleward movement of the warm Angolan water (Boyd *et al*., 1987; Salat *et al*., 1992). Noticeable over the mid shelf extending beyond 22°S in surface and subsurface (below 100m) but penetrating as far south as 26°S in the deep layer.

Although there is a distinct poleward undercurrent especially over the midshelf, the flow in the surface is rather variable and weak particularly inshore. Currents off central Namibia are often complex and variable mainly due to mesoscale features often found there. The available data did not capture any of those features probably because of the nature of the sampling. Nevertheless, mesoscale processes develop in the area during the period when the coastal upwelling is relaxed (Salat *et al.*, 1992). The coastal upwelling during this survey was only observed off Walvis Bay and in the south of the study area. The southern most sampled transect was just north of the Lüderitz upwelling cell. This is a semi-permanent cell, which is believed to divide the Benguela region into the southern and northern section (Shannon and Nelson, 1996). The coastal upwelling at this region is the most intense and perennial in the whole Benguela region and is one of the most active cells in the world. Relatively less intense coastal upwelling occurs off Walvis Bay as well (Lutjeharms and Meeuwis, 1987), with complex processes at times, which seem to be influenced by some eddies, (Salat *et al.*, 1992). The upwelling around Walvis Bay was detected to be more intense in winter when it broadens its alongshore extent into the Lüderitz cell (Lutjeharms and Meeuwis, 1987).

The surface flow in the inner shelf, within the 200m isobath is predominant northward north of 23°S and southward beyond the 200m isobath. The northward flow in the surface is induced by the wind driven coastal upwelling, whereas the southward subsurface flow may be the continuation of the poleward undercurrent, which is fed by the subsurface branch of the Angola current, which crossed the Angola Benguela Front below the thermocline.

In conclusion, the ADCP data, if used properly will significantly contribute to the understanding of the characteristics of the flow and features in the Benguela region and help in elucidating the impact of ocean current on fish stocks with regard to fish movement and recruitment. In South Africa, systematic use of these data has provided much information about prevailing currents over the shelf. The data have been useful in interpreting fisheries data collected during joint cruises, and have already been used in biophysical advection models of pelagic fish recruitment. This can be extended to the rest of the Benguela region.

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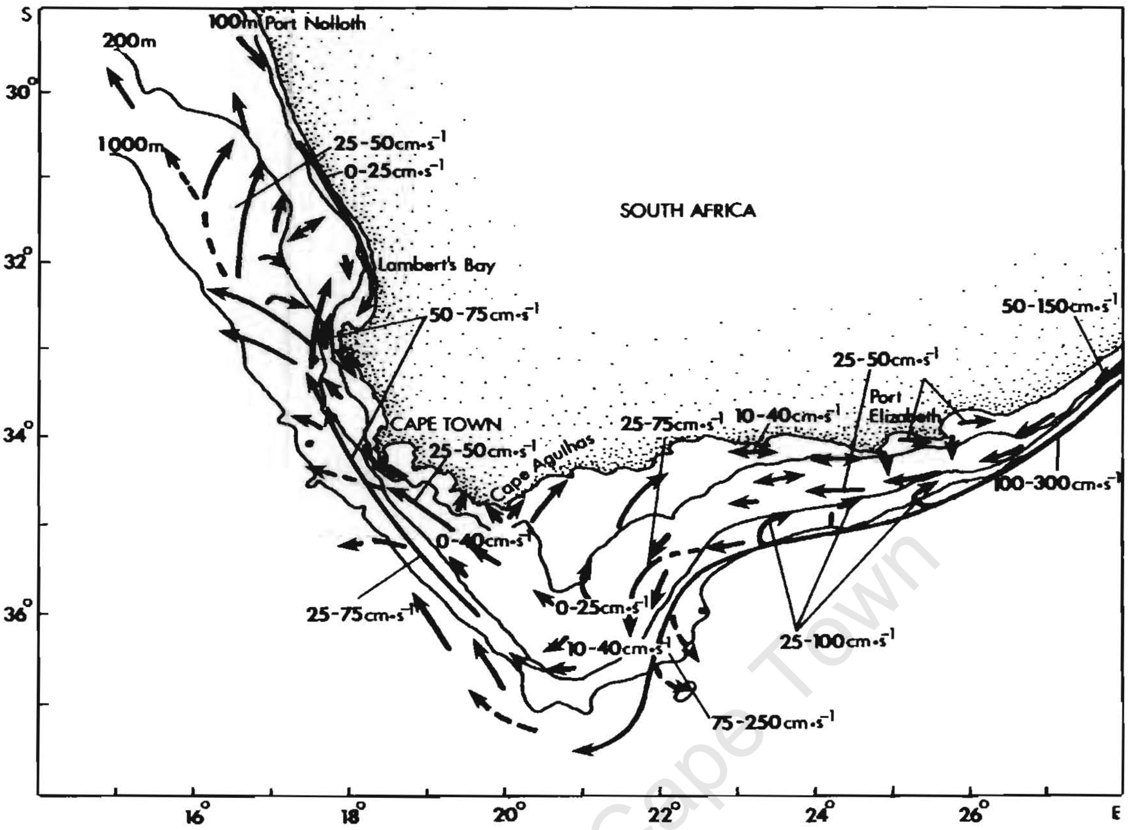


Figure 2.1: Schematic flow field of near-surface currents based on ADCP data collected between November 1989 and January 1992 (From Boyd *et al*, 1992).

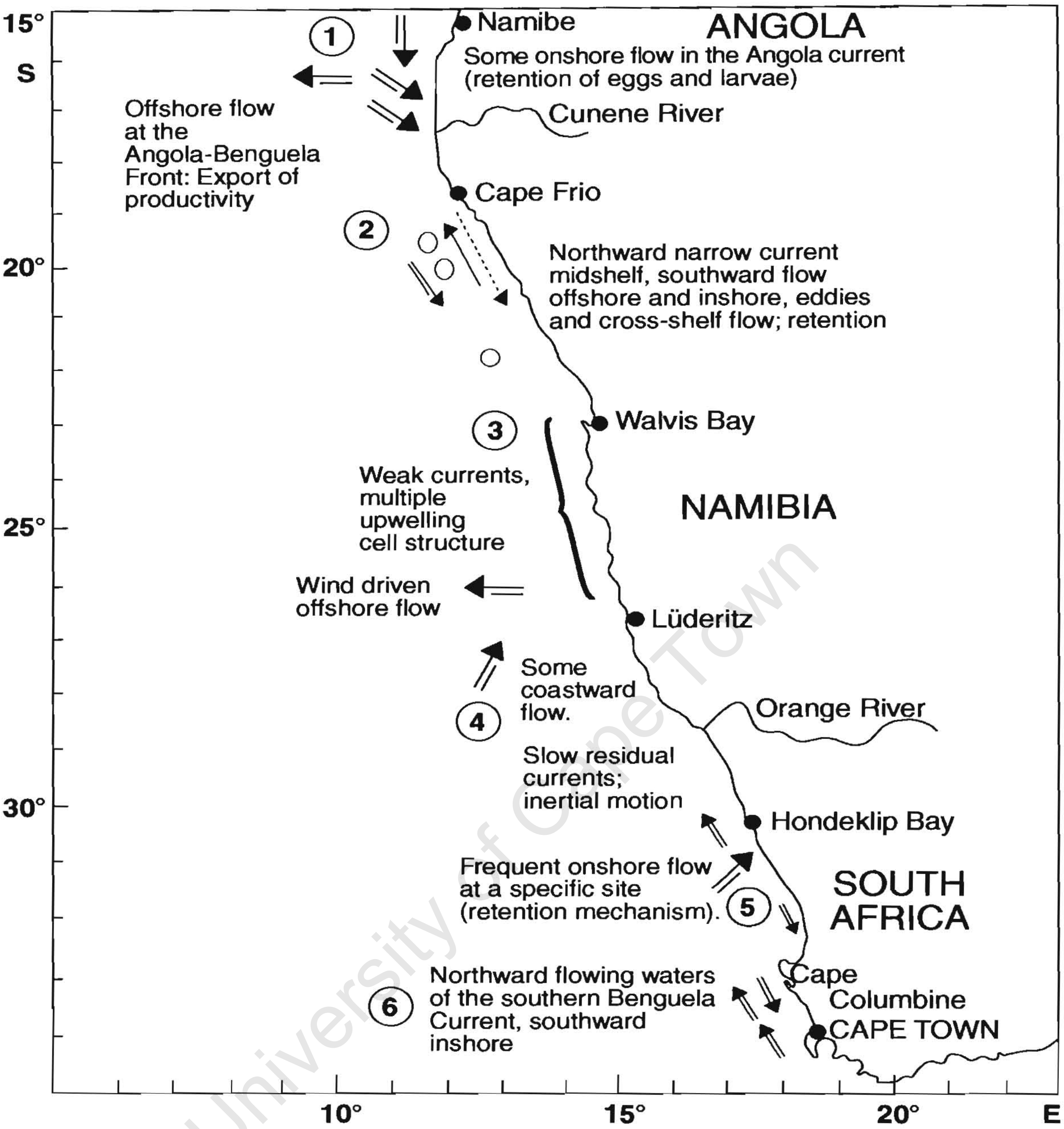


Figure 2.2: Schematic representation of key features of the near-surface currents in the Benguela. (From Bailey *et al*, 2001).

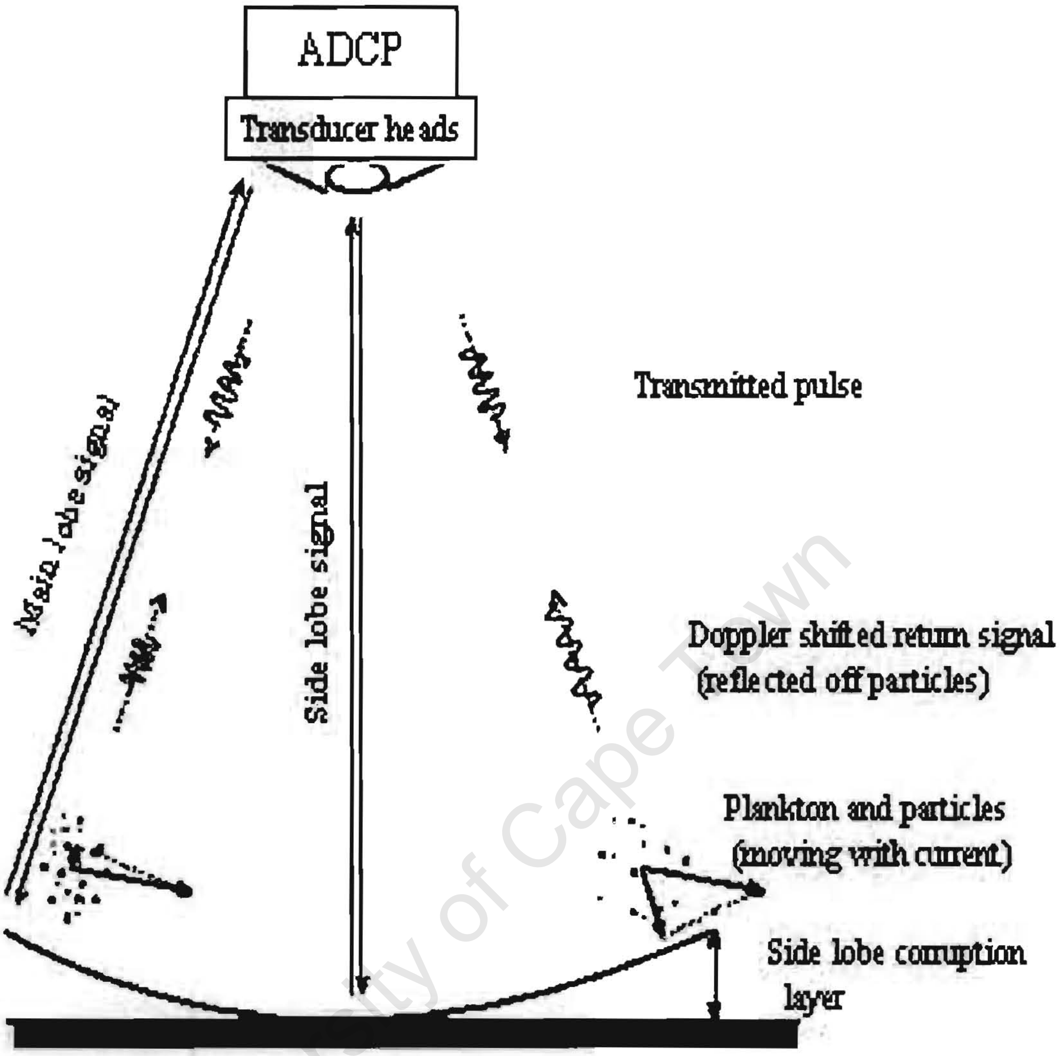
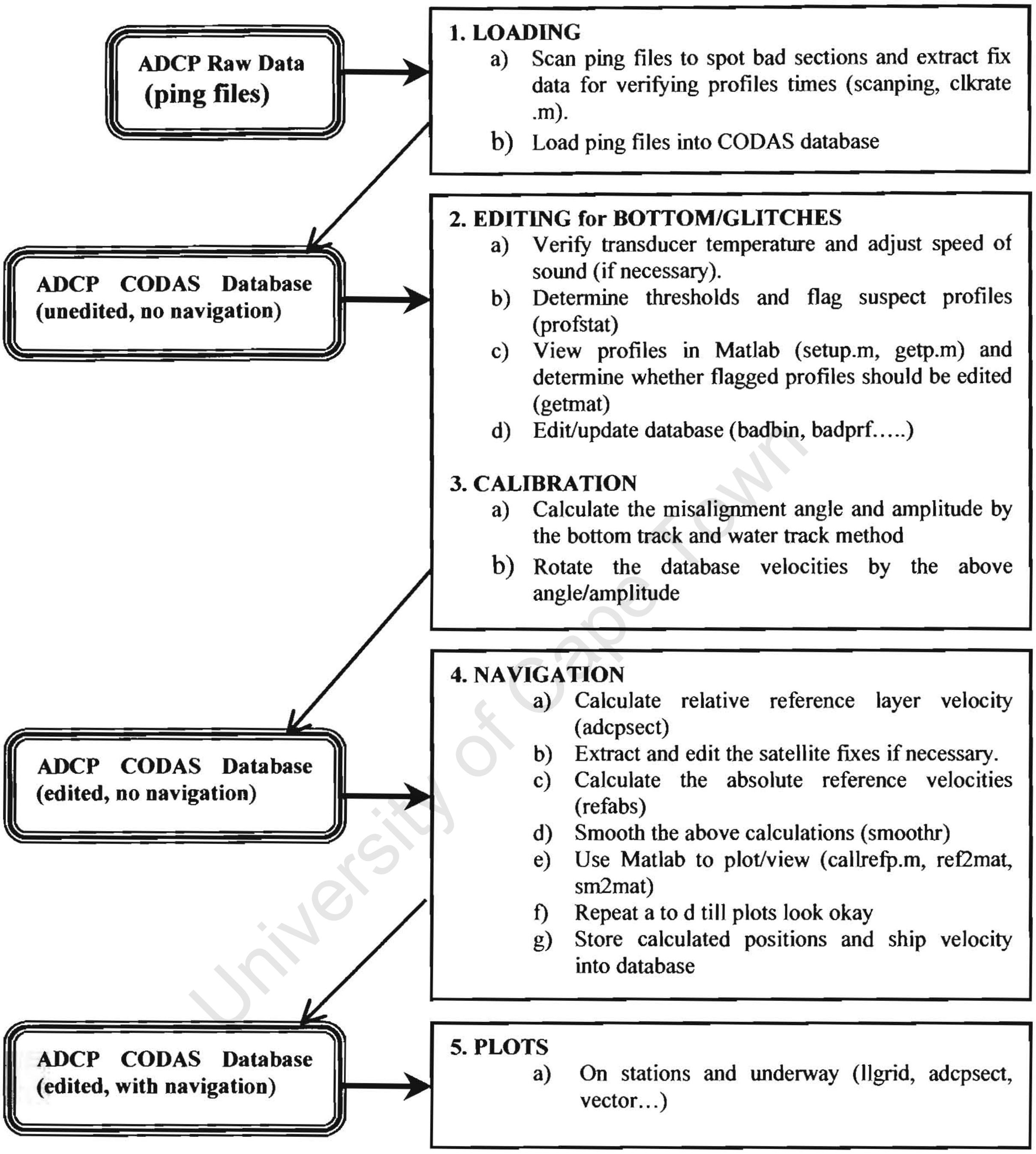


Figure: 3.1. ADCP uses Doppler effect by transmitting sound at a certain frequency and listening to echoes returning from the scatterers in the water (From de Madron, 1999).

ADCP DATA PROCESSING SYSTEM USING CODAS SOFTWARE PACKAGE



1. LOADING

- a) Scan ping files to spot bad sections and extract fix data for verifying profiles times (scanping, clkrate .m).
- b) Load ping files into CODAS database

2. EDITING for BOTTOM/GLITCHES

- a) Verify transducer temperature and adjust speed of sound (if necessary).
- b) Determine thresholds and flag suspect profiles (profstat)
- c) View profiles in Matlab (setup.m, getp.m) and determine whether flagged profiles should be edited (getmat)
- d) Edit/update database (badbin, badprf.....)

3. CALIBRATION

- a) Calculate the misalignment angle and amplitude by the bottom track and water track method
- b) Rotate the database velocities by the above angle/amplitude

4. NAVIGATION

- a) Calculate relative reference layer velocity (adcpsect)
- b) Extract and edit the satellite fixes if necessary.
- c) Calculate the absolute reference velocities (refabs)
- d) Smooth the above calculations (smoothr)
- e) Use Matlab to plot/view (callrefp.m, ref2mat, sm2mat)
- f) Repeat a to d till plots look okay
- g) Store calculated positions and ship velocity into database

5. PLOTS

- a) On stations and underway (llgrid, adcpsect, vector...)

Figure. 3.2 Summary of ADCP processing steps (Adapted from Firing *et al.,* 1995)

For the general overview of ADCP data processing using the CODAS see the figure above, however for a full detailed description of the processing refer to the CODAS software MANUAL[2] (*http://currents.soest.hawaii.edu/software/codas3/*).

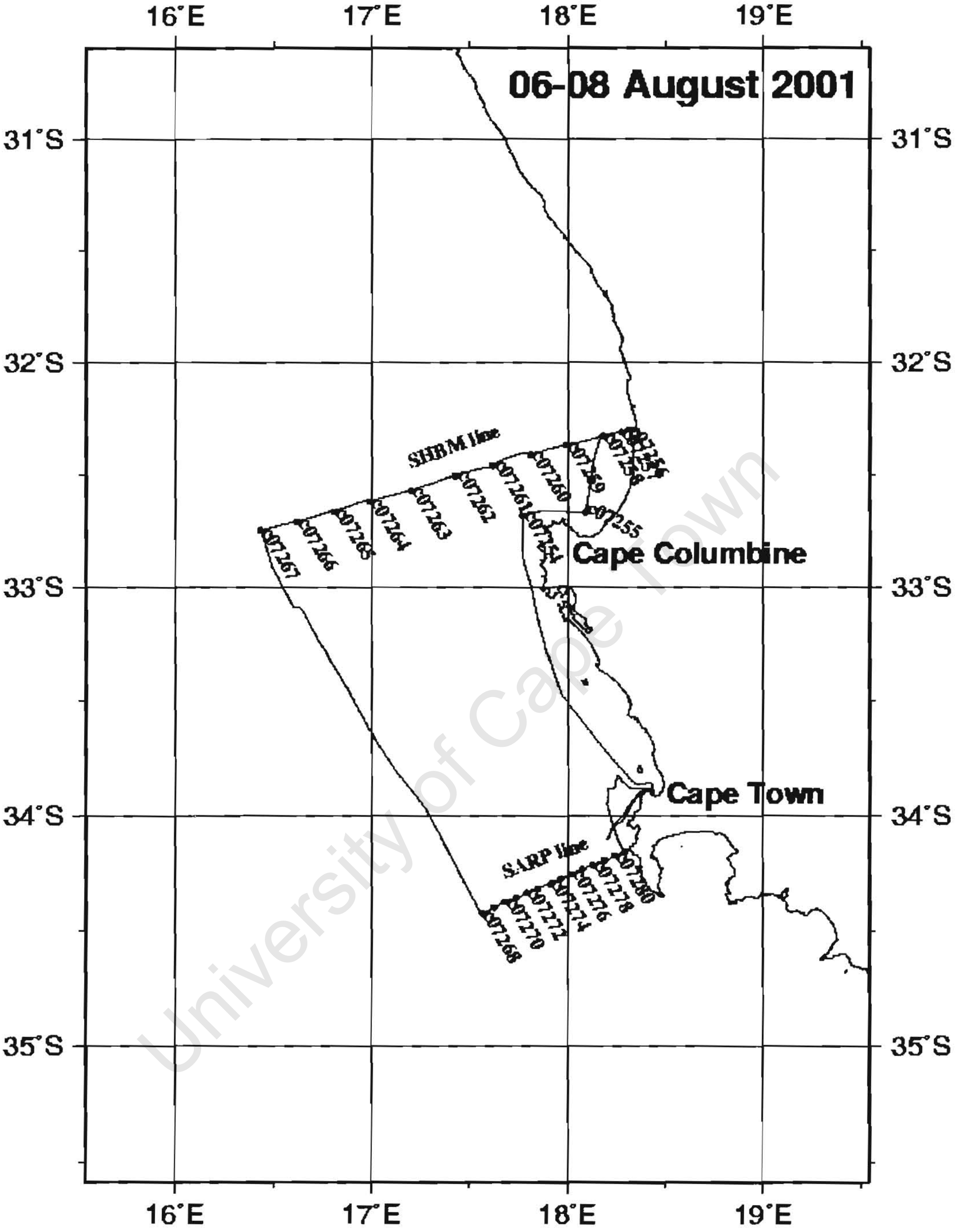


Figure 3.3 Cruise track during the August 2001 *Algoa* (C098) cruise.

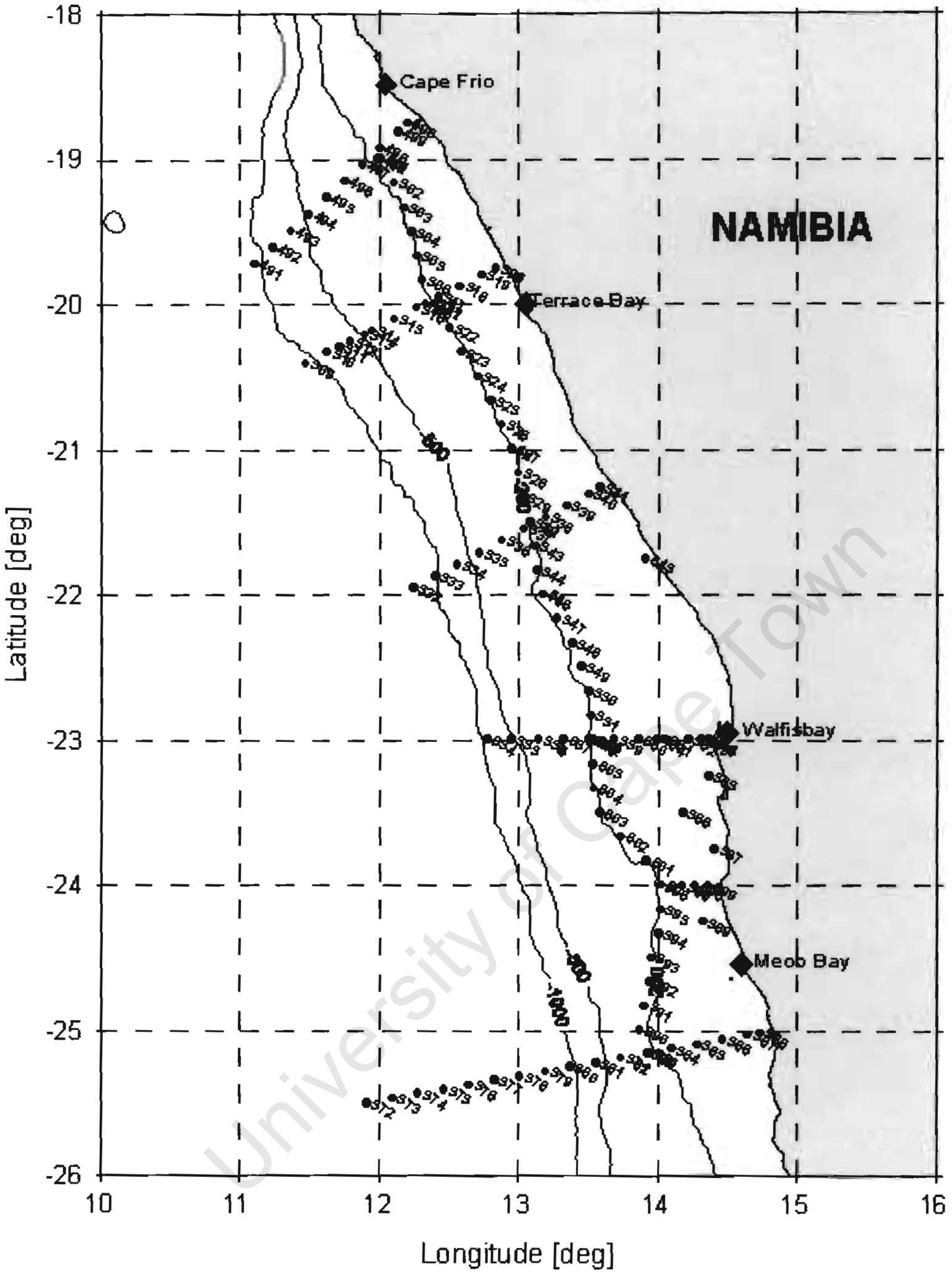


Figure 3.4. Cruise track and hydrographic stations during the R/V *Meteor* cruise (M48/5)

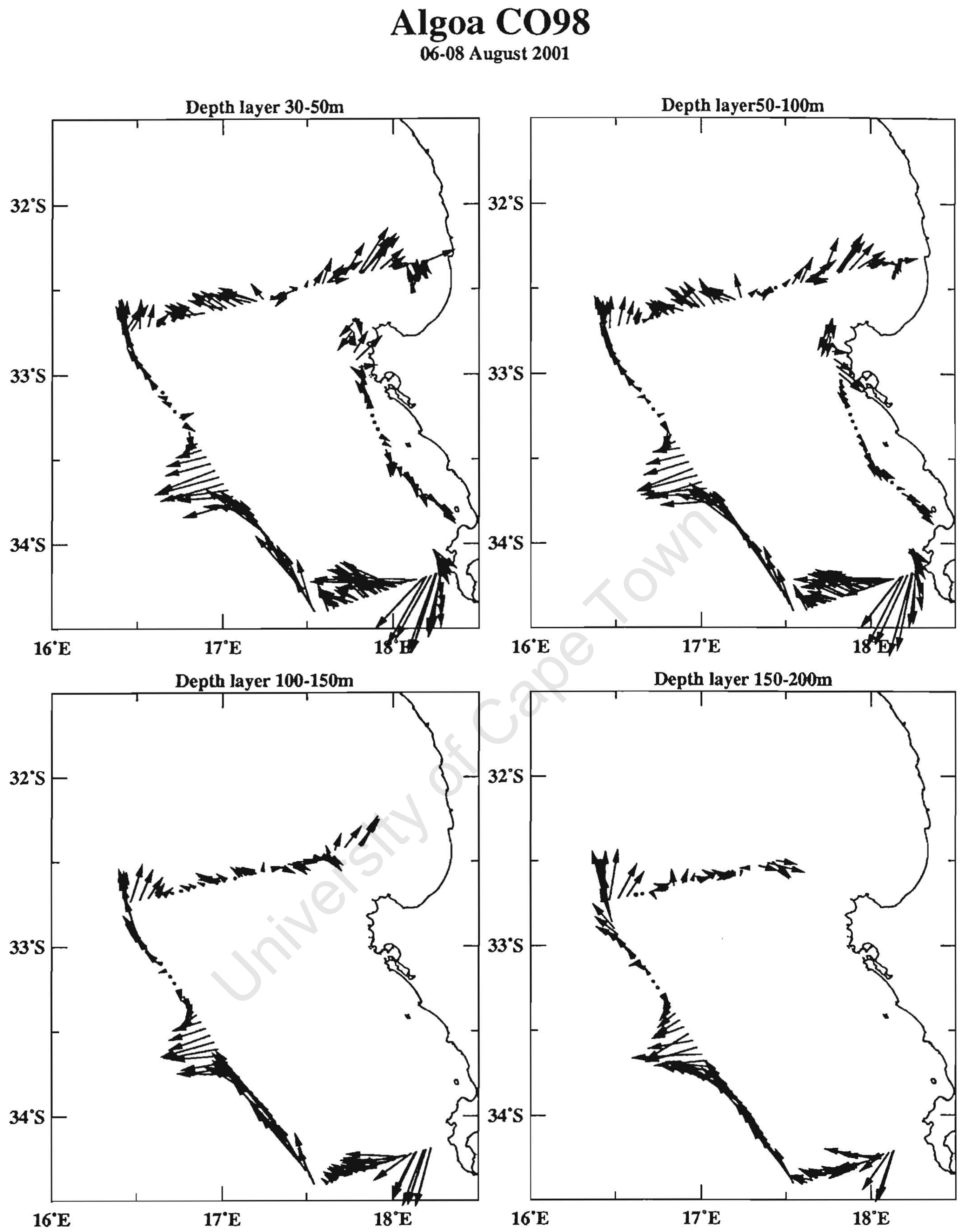


Figure 4.1: (a) Validated current vectors at different depths as measured by VMADCP during the *Algoa* (C098) cruise and drawn from TRANSECT raw data using

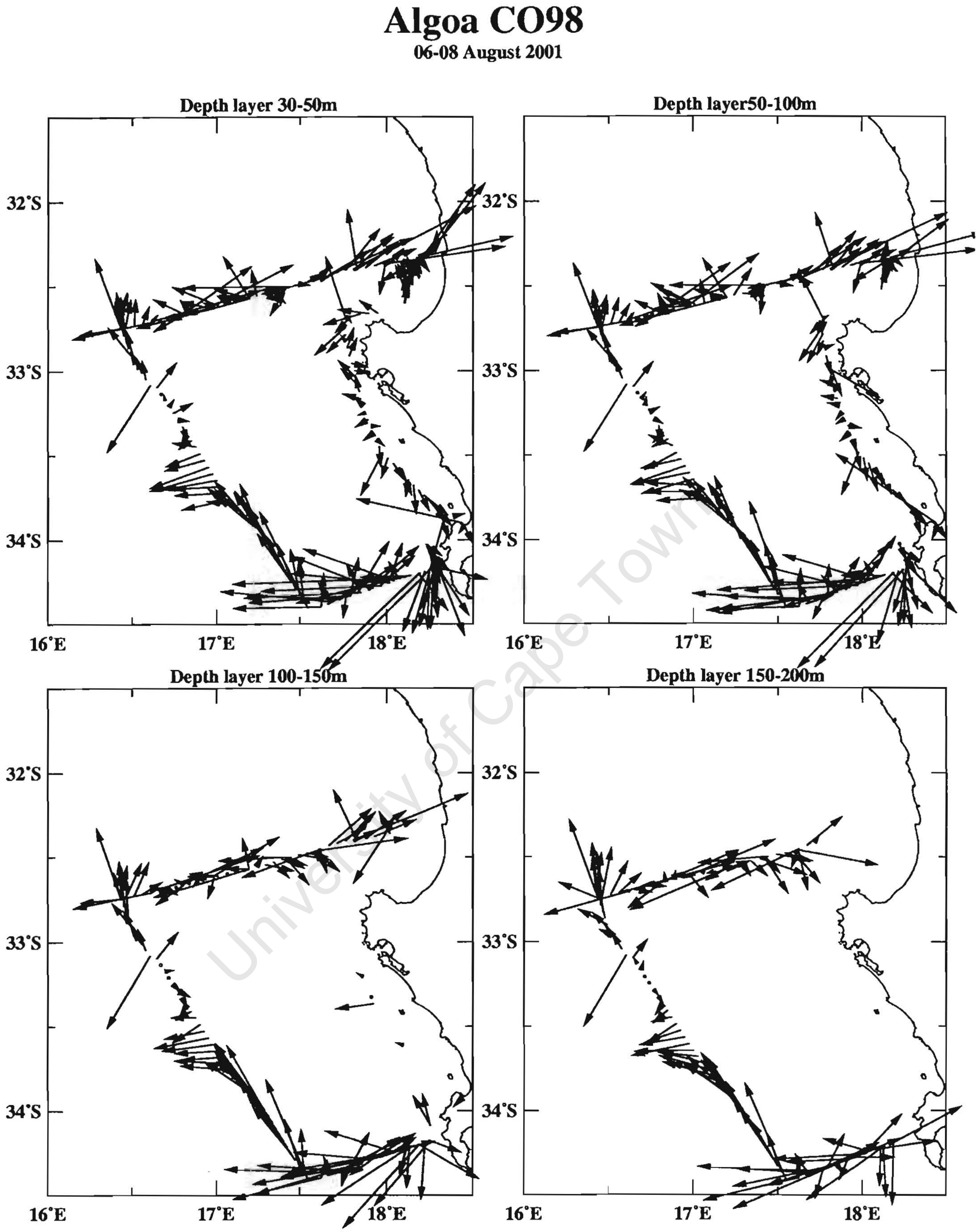


Figure 4.1: (b) Un-validated current vectors at different depths as measured by VMADCP during the *Algoa* (C098) cruise and drawn from "TRANSECT"-processed- data using CODAS

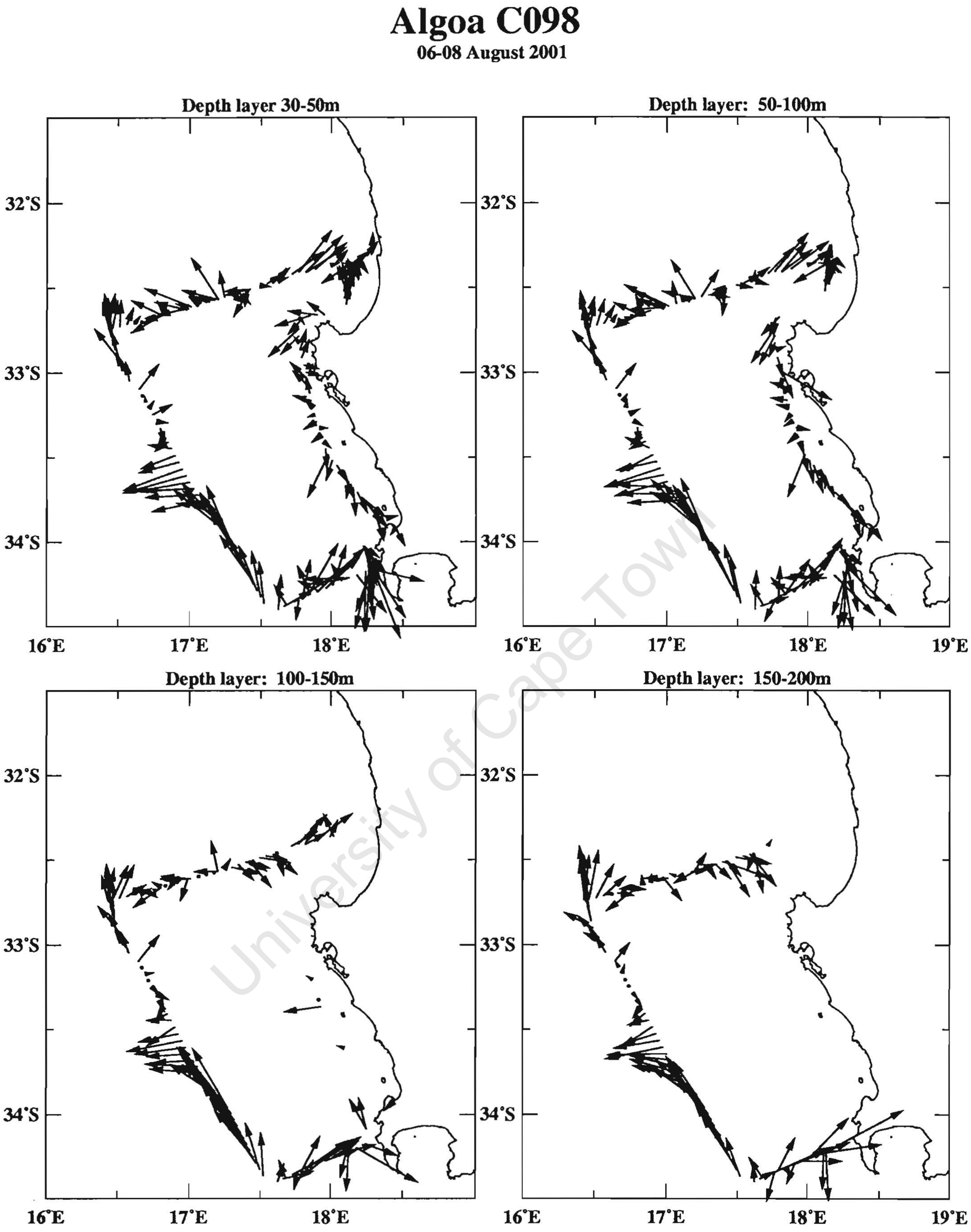


Figure 4.1: (c) Un-validated current vectors at different depths drawn from "TRANSECT"- processed data using CODAS (manually edited)

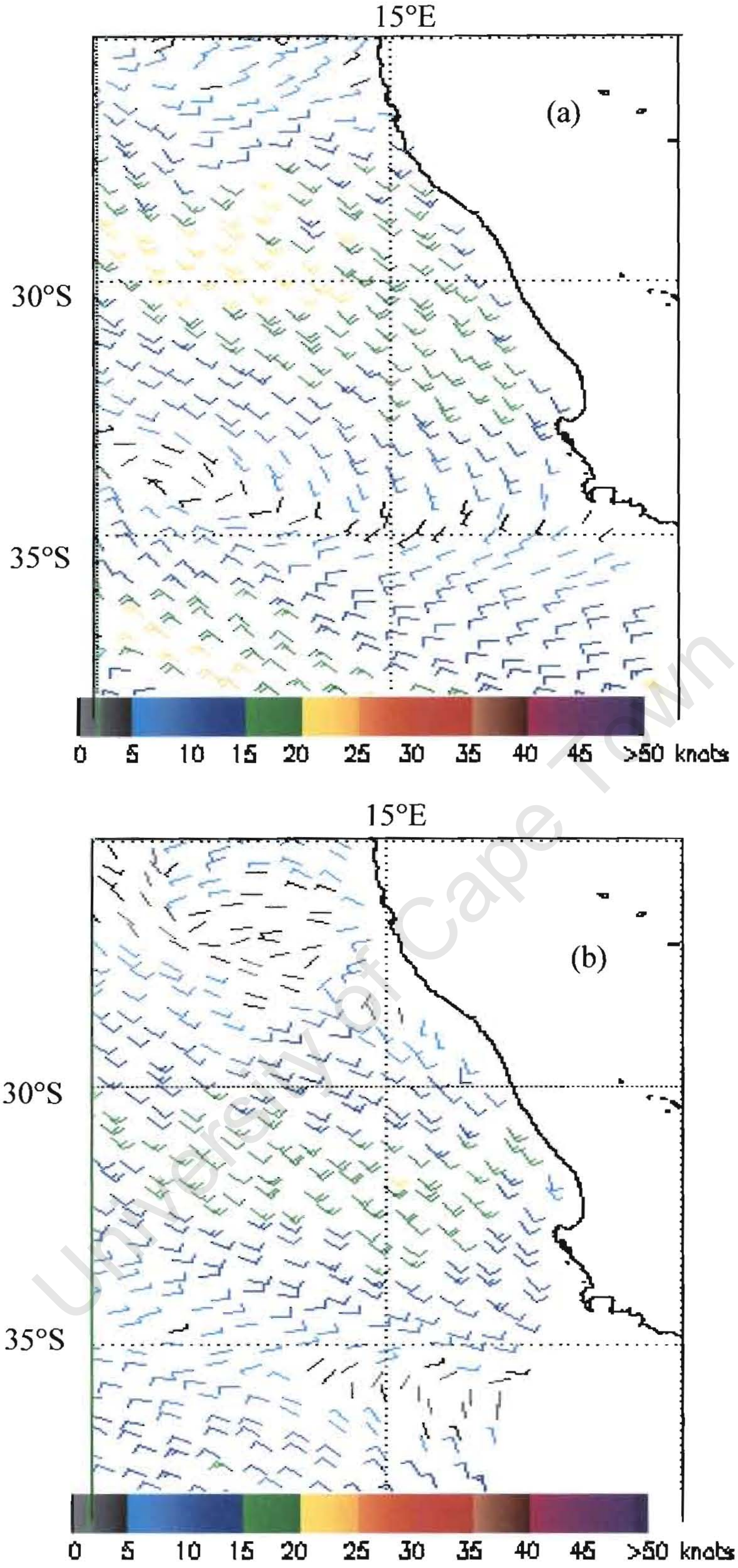


Figure 4.2. QuikSCAT Ocean surface winds at a 10m height from SeaWind Scatterometer on near real-time data (knots) at (a) 05:44 hrs GMT (b) at 16:58 hrs GMT on 07 August 2001

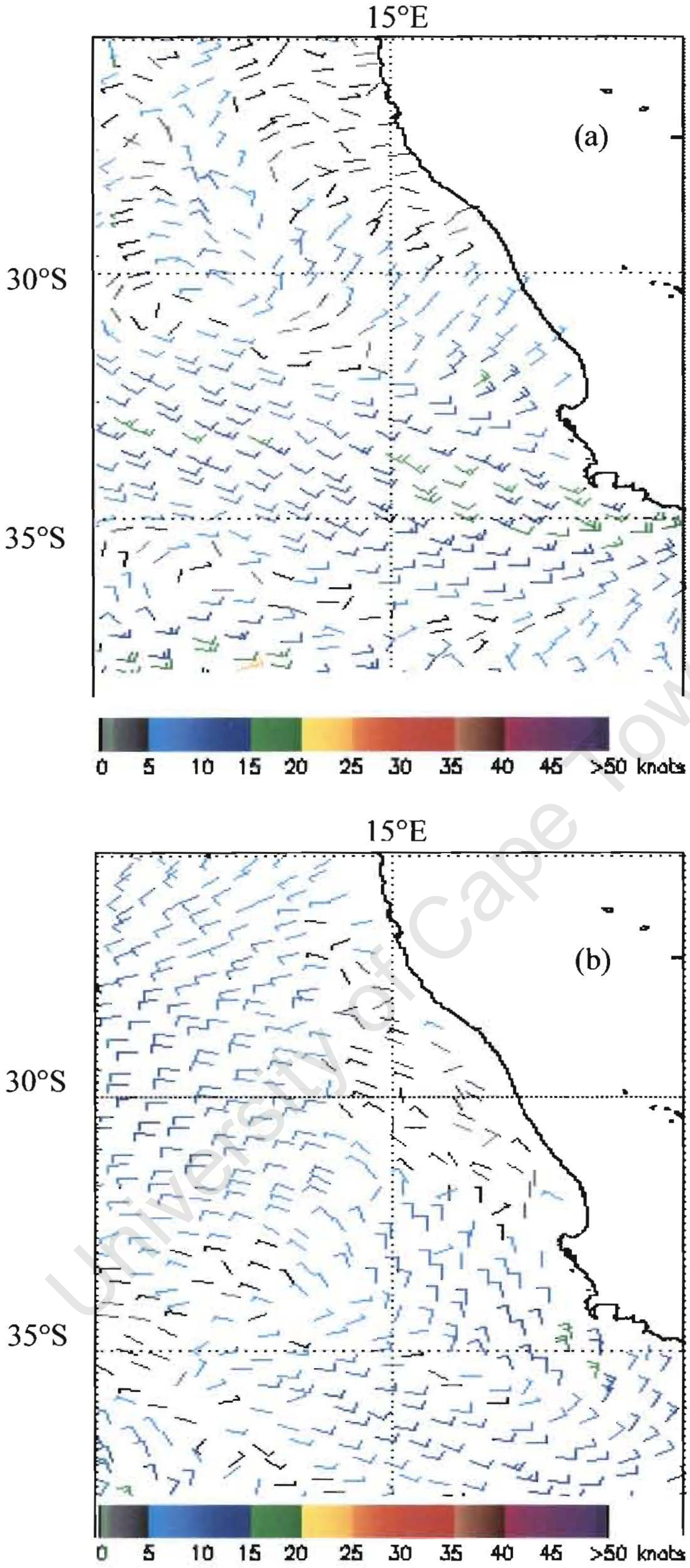


Figure 4.3 QuikSCAT Ocean surface winds at a 10m height from SeaWind Scatterometer on near real-time data (knots) at (a) 05:19 hrs GMT (b) at 16:33 hrs GMT on 08 August 2001

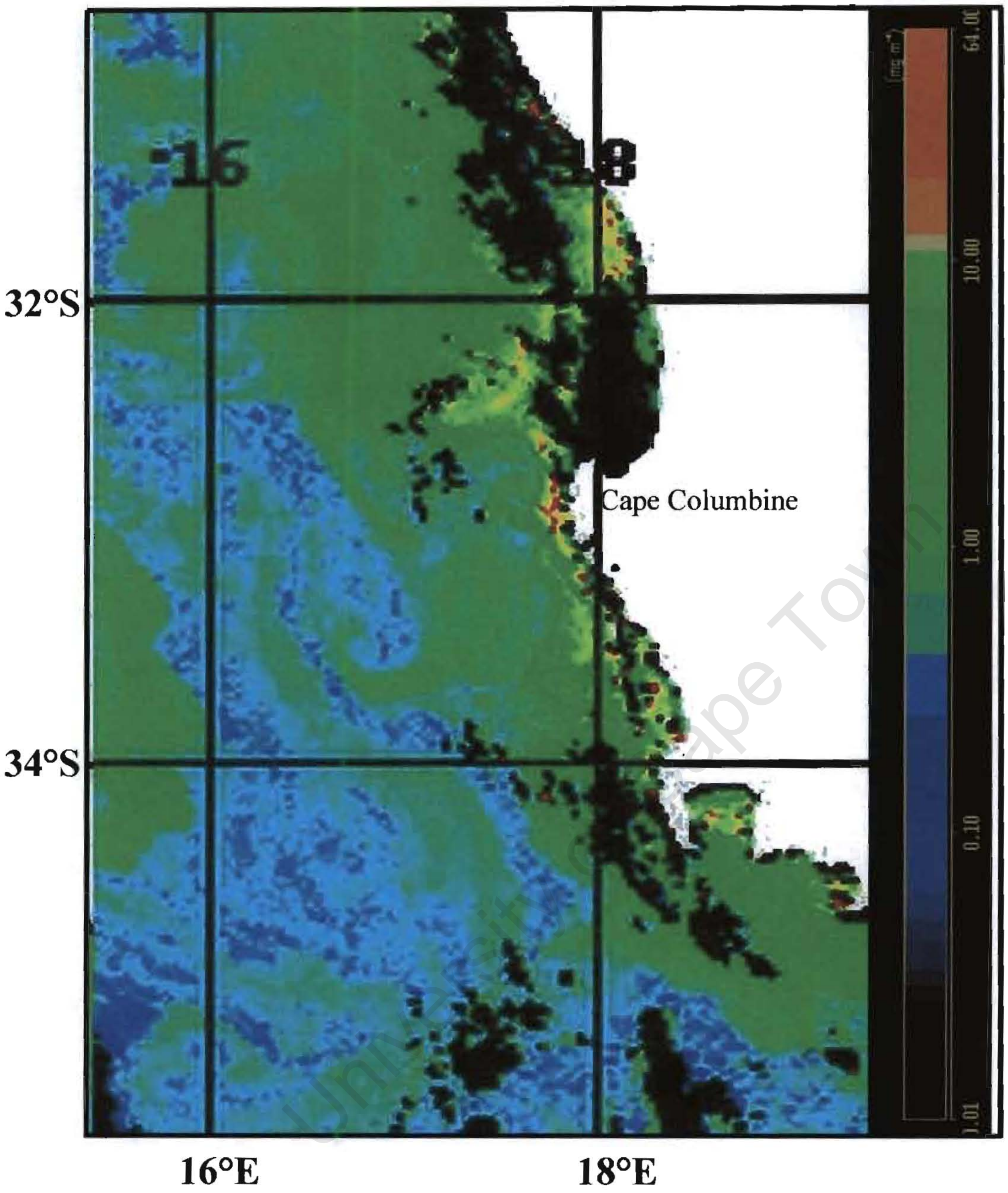


Figure 4.4 (a) SeaWIFs image showing chlorophyll concentration (mg m^{-3}) for 06 August 2001.

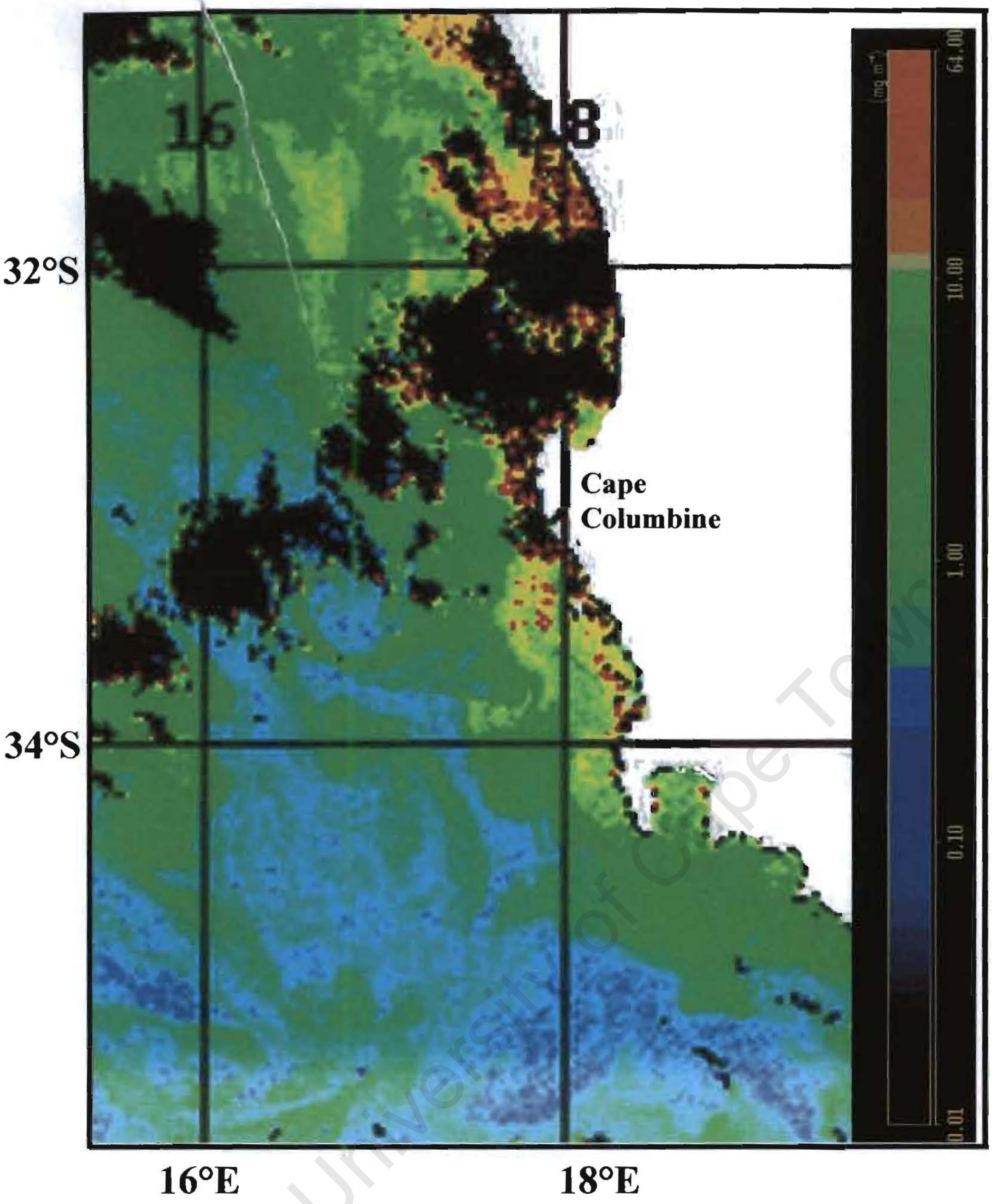


Figure 4.4 (b) SeaWIFs image showing chlorophyll concentration (mg m^{-3}) for 07 August 2001.

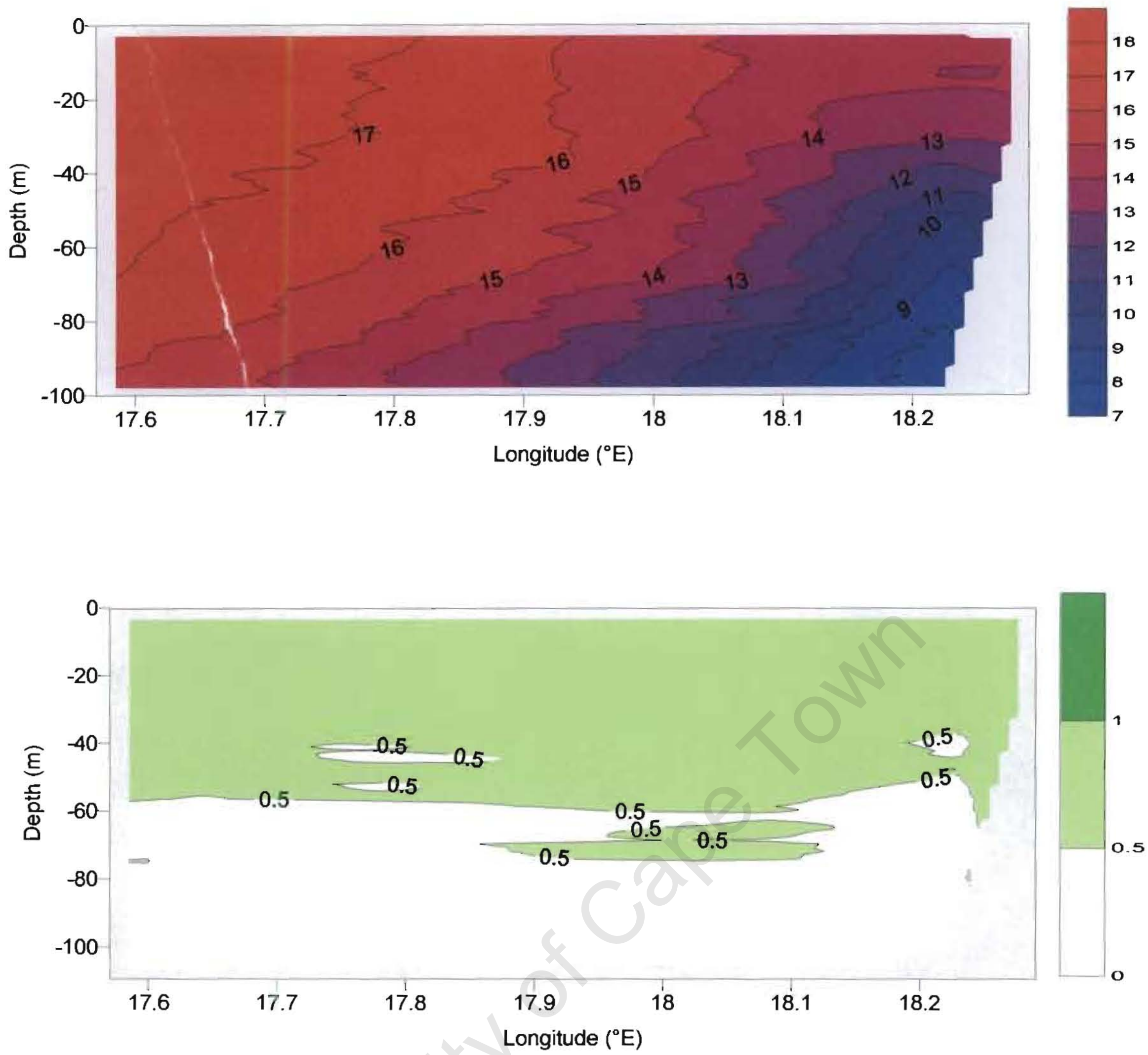


Figure 4.5: Vertical profile of temperature in °C (top) and chlorophyll in mg m^{-3} (bottom) along the SARP line during the *Algoa* (C098) Cruise.

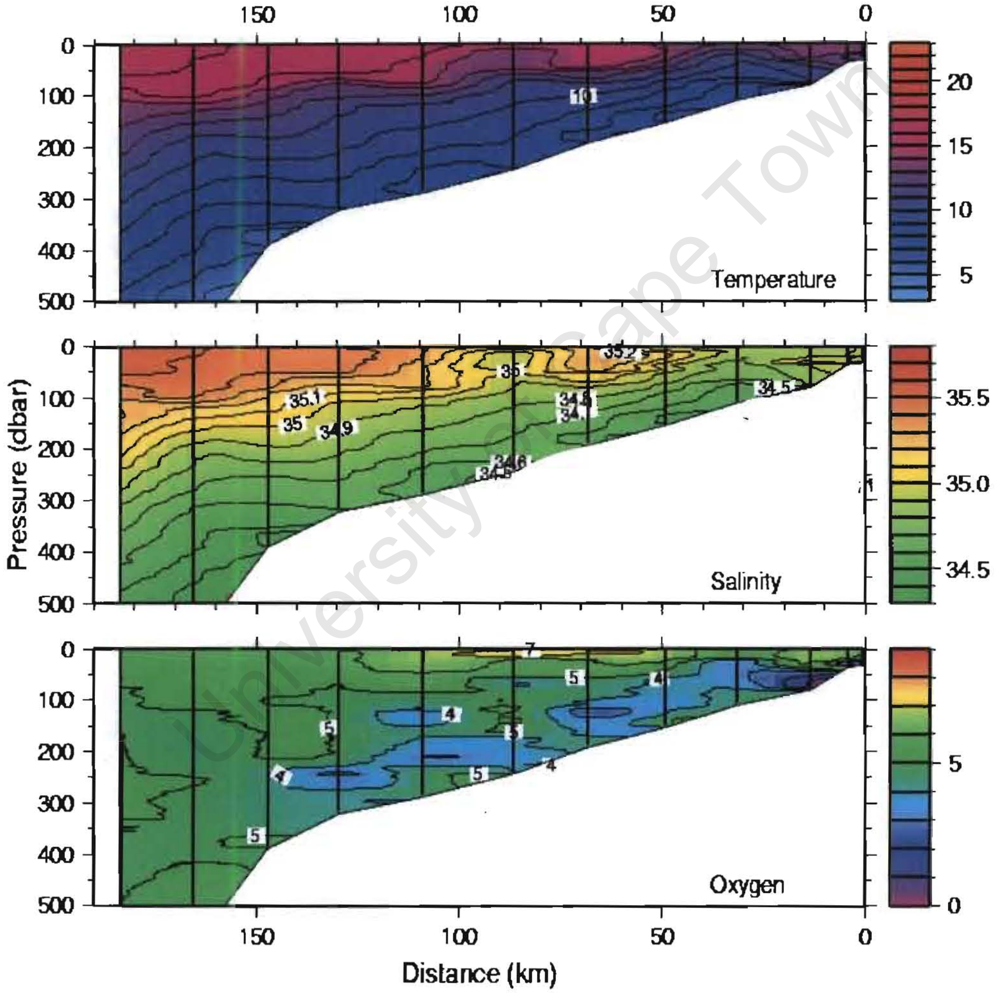


Figure 4.6. Vertical profile for temperature (°C), salinity (psu) and oxygen (ml/l) measurements along the SHBM line (~32-33°S) during the *Algoa* Cruise.

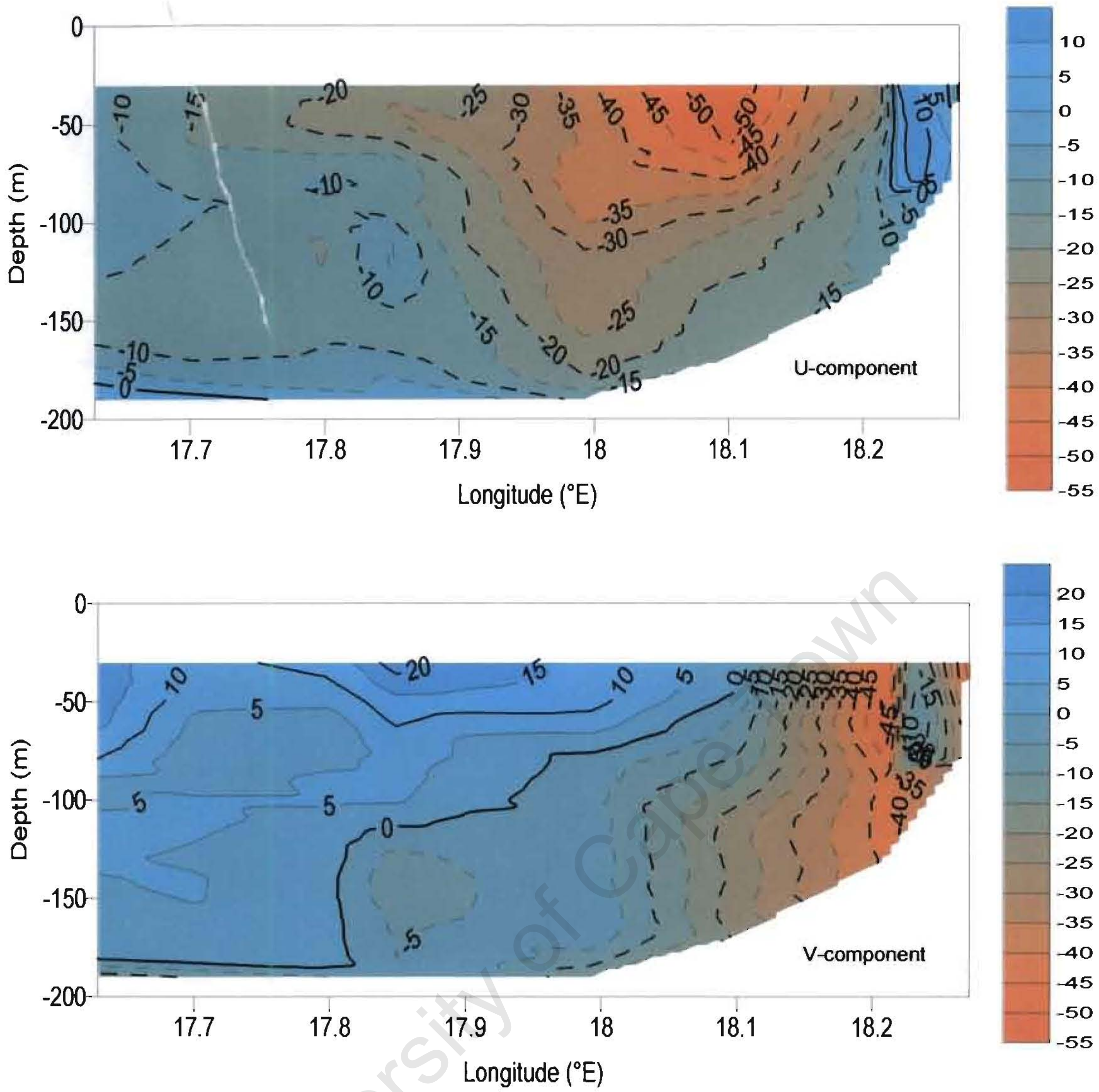


Figure 4.7 Vertical profile of current velocity (cm/s) along the SARP line during the *Algoa* (C098) cruise