Monitoring the oceanic flow between Africa and Antarctica: Report of the first GoodHope cruise

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ABSTRACT

As a component of the Meridional Overturning Circulation (MOC), the Southern Ocean plays a major role in the global ocean circulation and it is hypothesised that it has an important impact on present day climate. However, our understanding of its complex three-dimensional dynamics and the of impact of its variability on the climate system remain to this day rudimentary. The newly constituted, international GoodHope research venture aims to address this knowledge gap by establishing a programme of regular observations across the Southern Ocean between the African and Antarctic continents.

The objectives of this programme are five-fold:

(1) *To gain a better understanding of Indo-Atlantic inter-ocean exchanges and their impact on the global thermohaline circulation and thus on global climate change;*
(2) *To understand in more detail the impact these exchanges have on the climate variability of the southern African subcontinent;*
(3) *To monitor the variability of the main Southern Ocean frontal systems associated with the Antarctic Circumpolar Current;*
(4) *To study air-sea exchanges and their role on the global heat budget, with particular emphasis on the intense exchanges occurring within the Agulhas Retroflection region south of South Africa, and*
(5) *To examine the role of major frontal systems as areas of elevated biological activity and as biogeographic barriers to the distribution of plankton.*

We present here preliminary results on the physical and biological structure of the frontal system using the first GoodHope transect that was completed during February – March 2004..

INTRODUCTION

The global oceanic thermohaline circulation, often referred to as the Meridional Overturning Circulation, is a vital link in the global transport of heat from the tropics to higher latitudes. The physical structure of this circulation belt and its efficiency in regulating climate is substantially influenced by the nature of water mass exchange between ocean basins[1,2,3]. The Antarctic Circumpolar Current (ACC) is by far the largest conduit for such exchange. Extending unbroken around Antarctica it is the primary means by which water, heat and salt are transferred between different ocean basins. As these exchanges play an important role in regulating mean global climate, sustained hydrographic observations are essential in order to describe and better understand the physical and dynamic processes, which are responsible for the variability of the ACC[4]. The major part of the flow associated with the ACC is concentrated at a number of circumpolar fronts, which act as boundaries separating zones of uniform water masses[5] (Figure 1). From north to south the fronts and associated zones of the Southern Ocean are: Subtropical Convergence (STC), Subantarctic Zone (SAZ), Subantarctic Front (SAF), Polar Frontal Zone (PFZ), Antarctic Polar Front (APF), Antarctic Zone (AAZ) and Antarctic Divergence (AAD).

South of Africa, the Southern Ocean plays a unique role in providing a source for the equatorward flux of heat into the South Atlantic. However, it has been suggested[3, 6] that water mass differences between the South Indian and Atlantic Ocean basins would be far more prominent were it not for various smaller inter-ocean links. South of Africa, water masses originating in the Indian Ocean are injected into the South Atlantic both by anticyclonic ring shedding processes at the Agulhas Retroflection region[7] and by filaments of Agulhas Current water[8] (Figure 2). Recent modelling studies on the global ocean circulation suggest that Indo-Atlantic interocean exchanges through the Agulhas Current system are far more important for the thermohaline circulation than the direct input of water from the Drake Passage[3, 6]. Estimates of the percentage of mode and intermediate waters entering the Atlantic via the Agulhas region is highly variable ranging from 0%[1] to 50%[9]. Therefore, in order to understand the role of this key component of the MOC on the global ocean circulation and its possible role in climate it is critical that the inflow of Indian waters into the Atlantic Ocean be properly quantified, and monitored.

The aim of the GoodHope programme is to establish an intensive monitoring platform that will provide detailed information on the physical structure and volume flux of waters south of South Africa, where the interbasin exchanges occur. A key component of this programme is the implementation of the high density XBT line AX25 that runs from Cape Town to Antarctica. The advantages of the GoodHope programme are four-fold:

(1) It runs approximately along with the TOPEX/POSEIDON – JASON 1 altimeter ground-tracks and will serve for ground-truthing of altimetry-derived sea height anomaly data;

(2) The southern fraction of this line (south of 50ºS) is currently monitored by a mooring array aimed at investigating the formation of deep and bottom water in the Weddell Sea deployed during the WECCON project by the Alfred Wegener Institute for Polar and Marine Research.

(3) The northern section of the GoodHope line also overlaps the region being studied by the USA - ASTTEX programme, enabling observations in the Southern Ocean to be linked with data collected within the Benguela region and the west coast of Southern Africa. ASTTEX examines the fluxes of heat, salt and volume entering the South Atlantic Ocean via the Agulhas Retroflection, thereby providing a quantitative, Eulerian measurement of the strength and characteristic scales of the volume and mass transport of the Agulhas Current into the South Atlantic. It has been estimated that up to half of the Agulhas-South Atlantic exchange is contained in mesoscale rings and eddies[10] and that the strength of the mesoscale fluxes could potentially have a very large temporal variability. Results from altimetry observations have shown that Agulhas rings are shed intermittently with periods of several months when there is no ring formation. However, this remains to be confirmed by a single, consistent set of in-situ and hydrographic observations[10]. GoodHope will provide additional support in determining the nature and scale of the injection of Indian Ocean water into the southeastern South Atlantic via the Agulhas Retroflection, and,

(4) GoodHope will support and contribute to the data collected by two Pressure Inverted Echo Sounder (PIES) mooring already deployed along this line.

Sustained observations such as repeat transects along AX25 will provide the only means to monitor the vertical structure and to investigate the variability of the fronts in this region. The GoodHope programme will investigate year-to-year and longer period variability in the fluxes, such as those related to the Antarctic Circumpolar Wave. Such intense and periodic monitoring has been underway in the Drake Passage[11] and south of Tasmania[4] since the 1970s. A repeat transect between South Africa and Antarctica, the third Southern Ocean “choke point”, has only this year been implemented.

In this study, we describe the frontal structure in the upper ocean as determined from underway surface and XBT (expendable bathythermograph) measurements during the first GoodHope transect along AX25, relating our findings to total chlorophyll-a concentrations as well as air-sea interaction along this transect.

DATA

The first GoodHope transect was conducted onboard the R.V. SA Agulhas between the 25 February and 6 March 2004. A total of 188 Sippican Deep Blue XBTs were deployed between 33º59’S, 17º50’E and 69º05’S, 04º10’W enroute to Georg von Neumayer station, the German station on Antarctica. The XBTs were deployed at intervals of 90 minutes (~ 15 nm) increasing to every 60 minutes (~ 10 nm) over the main frontal regions associated with the ACC (Figure 3). Prior to their deployment each probe was placed in a water bath in order to minimise the difference between the storage temperature of the probe and expected sea surface temperatures (SST). In total, 20 XBTs (11%) failed; mainly as a result of strong winds and sea swell blowing the running signal wire against the hull of the ship resulting in XBT wire stretching and, thus, insulation leakages. Surface temperature and salinity data were recorded continuously by the shipboard thermosalinograph. These data were averaged into 20 minute intervals in order to reduce noise levels but to retain adequate information to identify the main frontal characteristics. The exact clarification of surface fronts based on exact temperature and salinity definitions is difficult because of the variable nature of surface waters and the influence of precipitation, especially at mid latitudes[12]. We use here the surface definitions provided by Belkin and Gordon[13] (Table 1) as a guide in determining the surface expression of the main fronts.

In the remote regions of the Southern Ocean, the monitoring of changes in upper ocean temperature and salinity structure is only possible using drifting platforms due to the lack of routes of merchant ships. For example, profiling floats containing temperature and salinity sensors provide a cost-effective means of monitoring such regions. Along the first transect, 12 PROVOR CTF2/CTS2 floats were deployed at selected intervals (Figure 3). Each float descended to a “parking depth” of 1900m before profiling the upper 2000m, a cycle that is repeated every 10 days. In addition to these floats, 7 SVP surface drifters were deployed at predetermined locations along the GoodHope transect (Figure 3). These surface drifters are drogued at a depth of 18 m and are able to measure surface temperature, velocity and geographic position, which are relayed to ARGOS ground stations. SVP drifters are designed to have a drag area ratio of ~40 (i.e. the ratio of the drag area of the drogue to that of the tether and surface float), which yields a wind slippage of <1 cms^{-1} [14]. Satellite tracked drifters have become invaluable tools for studying ocean circulation and provide mixed layer velocity and temperature observations over 5 year periods in all major ocean basins. Data can be obtained from the Drifting Buoy Data Assembly Centre at http://www.aoml.noaa.gov/phod/dac/ for the SVP drifters and at http://www.ifremer.fr/coriolis/ for the PROVOR profiling floats.

ALTIMETRIC FIELDS

The large variability in the upper ocean dynamics in the region makes the use of sea height anomaly fields derived from satellite altimetry observations a very valuable tool. These fields mainly respond to changes in the steric, salinity, baroclinic, and barotropic components in the upper ocean. Blended alongtrack data from the Geosat Follow-On and JASON-1 altimetric missions are used here to construct gridded fields using a Gaussian interpolation radius of 0.5 degrees. The field corresponding to the period 25 February – 5 March 2004, is used in this work together with other observations. Current jets associated with the APF and SAF have been identified in the ACC using GEOSAT altimetry observations[15]. We use along cruise track sea height anomaly fields to investigate the surface height signals associated with the jets and fronts of the currents during the first transect. We expect that the future transect will aid in the development of techniques to allow altimetry to continue the monitoring of these fronts and currents.

BIOLOGICAL OBSERVATIONS

Primary production in the sun-lit upper layer contributes to the biogeochemical fluxes in the ocean, is able to modify the ocean-atmosphere exchange of gases, and provides food supply for the upper trophic levels[16]. Whereas production is potentially high in the Southern Ocean due to the abundance of nutrients, observed rates of primary productivity and the concentrations of phytoplankton biomass are low. Possible reasons to explain this include insufficient light for plankton growth, lack of trace nutrients such as dissolved iron[17] and zooplankton grazing[18]. In contrast, increased phytoplankton biomass occurs at the main frontal bands of the ACC, notably at the APF[19]. Maximum chlorophyll concentrations appear to correlate to mesoscale frontal dynamics, in particular cross-frontal exchange as a result of baroclinic instability in these regions.

The role of frontal systems as regions of increased biological activity and as biogeographic barriers to the distribution of the plankton (mainly phytoplankton and mesozooplankton) in the Southern Ocean is now well established [20, 21]. The elevated biological activity in the region of fronts is largely attributed to localised elevation of phytoplankton production rates due to increased water column stability and macronutrient availability[22, 23]. Due to the increase in food availability, frontal systems are generally characterized as areas of elevated secondary and tertiary production. Studies conducted in various sectors of the Southern Ocean suggest that there is marked spatial and temporal variability in the importance of the main frontal systems as biogeographic barriers to the distribution of plankton and as areas of enhanced biological activity. The variability in the role of the frontal systems as biogeographic barriers is thought to be attributed to mesoscale variability in the physical environment including meanders in fronts, the formation of eddies and cross frontal mixing[24]. These processes facilitate the transfer of plankton across the fronts. The absence of biological enhancement in the waters in the frontal waters is generally believed to reflect the temporal variability in the stability of the water column. Shifts in the intensity and geographic position of major frontal systems resulting from global climate change are thus likely to coincide with dramatic changes in the distribution of species and total productivity within the Southern Ocean.

A total of 188 surface chlorophyll-a and 75 phytoplankton stations were occupied in conjunction with each XBT deployment (Figure 3). Chlorophyll-a was filtered passing 250 ml water samples obtained from the shipboard scientific seawater supply through serial filtration. Phytoplankton samples of 200 ml were collected from the shipboard scientific seawater supply and preserved in 2% buffered formalin and Lugols solution.

METEOROLOGICAL OBSERVATIONS -

The Southern Ocean is characterized by strong cyclonic atmospheric development in the region between South Africa and Antarctica[25, 26]. These Mid-latitude Cyclones (MCs) sweeping over the Southern Ocean from west to east are frequently associated with strong surface winds and rough seas that develop as a result of negative air-sea fluxes of momentum (wind stress). MCs over the Southern Ocean differ from those in the Northern Hemisphere where the mid-latitudes (approximately 50^{o}-70^{o}N) are mostly covered by land. Southern Ocean MCs mostly develop and propagate over a marine environment that encircles the entire Antarctic continent. These systems are exposed to strong meridional oceanic and atmospheric temperature gradients that contribute to their strength[27]. The impact of sea-air fluxes on MCs is not yet well understood. Positive surface heat fluxes might either strengthen MCs by encouraging convective activities, or weaken them by reducing temperatures in the cold air sector behind the cold front. The latter might affect the propagation velocity of MCs. In addition, cyclonic rotation in MCs might be slowed down by negative fluxes of momentum, and positive fluxes of mass (water vapour) might alter thermodynamic properties, cloud bands and rainfall in MCs[28].

Higher-level wind, air temperature and relative humidity measurements were made continuously during the transect. These higher-level values were recorded by instruments located on the main crane on the bows of the R.V. SA Agulhas at an altitude of approximately 17m above sea level. Data were collected at 10 minute intervals. Corrections according to ship speed and direction were made to obtain true or absolute wind vectors. In addition, incoming short-wave and long-wave solar radiation were recorded at one-minute intervals by using an Eppley pyranometer and a pyrgeometer, which were also installed on the shop crane. Data were written to two Campbell Scientific CR10X data loggers, and routine downloads took place on a daily basis. The purpose of these measurements was to investigate surface properties of MCs and to determine the magnitude of sea-air fluxes[29] along the cruise line between Cape Town and the Georg von Neumayer research station (Figure 3). Recorded surface pressure and wind speed values as measured in 10-minute intervals from 26 February to 8 March (day 1 to 12) along the first GoodHope transect (Figure 3) are depicted in Figure 4. Note how periods associated with lower pressures, presumably MCs, are associated with stronger winds and therefore larger negative fluxes of momentum towards the ocean and rough seas. The deep trough in near-surface pressure (<970 hPa) experienced on day 9 of the cruise (Figure 4), accompanied by the strongest wind gusts measured during the period (>20 ms^{-1}), is of particular interest. Much calmer winds occur in events associated with higher pressures. Fluxes of momentum might even alter the horizontal propagation of ocean surface temperatures, emphasizing the importance of energy and mass exchange between atmospheric weather systems and the underlying ocean surface.

FRONTAL LOCATIONS

The Southern Ocean is characterised by the strong zonal nature of its main frontal bands, and its spatial structure is strongly determined by the position and flow regime of a number of frontal system separating different ACC zones[13]. Extensive measurements have been made in the South Atlantic and South Indian sectors of the Southern Ocean over the past 3 decades[30-33]. Full depth CTD measurements have been made during AJAX[34] SR2 WOCE (Roman, MSc thesis) and on an opportunistic basis enroute to the ice edge. Unlike other regions of the Southern Ocean where frontal systems display high bands of variability with enhanced eddy activity such as at the Drake Passage and South Georgia[35], at the South-West Indian Ridge[36-38] and south of Australia[4, 39], the frontal characteristics in the region of the Greenwich Meridian line are less intense and variable, as can be inferred from altimetry and from historic hydrographic data[40].

Identification of the main ACC fronts is essential in order to trace the upper level circulation associated with the baroclinic shear. However, accurate identification of the fronts is not always simple, especially in regions where they remain merged. One major difficulty is the various definitions that have been given for the characterisation of the fronts bordering the Antarctic Circumpolar Current. Depending on authors, these definitions are based on either surface or subsurface property values, whereas others have used phenomenological definitions[38]. Definitions for both surface and subsurface ranges are given in Table 1, however, in order to unambiguously place the fronts before describing the frontal features observed along the GoodHope I transect, each front will be defined using their representative subsurface axial values at 200m where generally each front is marked best. The definitions used for this study are taken from Belkin and Gordon[13].

Subtropical Convergence

The Subtropical Convergence (STC) marks the boundary between warm, salty subtropical surface water and cooler, fresher Subantarctic Surface Water to the south. It is the most northerly front associated with the ACC (Figure 1) and the most prominent surface thermal front. XBT data collected from over 70 crossings of the STC have shown that in the South Atlantic the STCs mean position lies at 41º40’S[33]. The surface expression during GoodHope I of the STC was found between 39º39’ – 40º54’S and the subsurface core, identified by the 10ºC isotherm at 200m, at 40º42’S (Figure 5). Previous studies in the South-east Atlantic sector of the Southern Ocean[41] have identified two separate fronts associated with the Northern (NSTC) and Southern boundaries (SSTC) of the STC. These observations have been made from over 10 datasets extending across the South Atlantic from the Brazil Current at 42ºW to the Agulhas - Benguela region at 11ºE. Surface temperature and salinity definitions given by Belkin and Gordon[13] cover the range 14.0 –16.9ºC, 34.87 – 35.58 for the NSTC and 10.3 – 15.1ºC, 34.30 – 35.18 for the SSTC. Examination of the thermosalinograph data collected during GoodHope I (Figure 6) reveal two distinct surface frontal features between 39º49’S- 40º06’S and between 40º20’S – 41º15’S where surface temperatures drop from 18.83º - 15.16ºC, 35.49 – 34.02 and 16.13º – 11.13ºC and 34.665 – 34.045 respectively. Providing further support in the belief that in the SE Atlantic the STC may exist as two separate bands[13].

Subantarctic Front

The Subantarctic Front (SAF) marks the northern boundary of the Polar Frontal Zone (PFZ), which is a transitional zone between SASW and AASW. In comparison to the STC, which is clearly characterised by a sharp and consistent gradient in both surface and subsurface expressions, making identification extremely easy[32-33], the SAF is less clear in its surface expression. The exact boundaries of the PFZ can therefore be difficult to identify due to the weak nature of this front. The SAF is predominantly a subsurface front and can be defined by the most vertically orientated isotherm within a temperature gradient lying between 3ºC and 5ºC, while it’s surface expression extends between 8ºC and 4ºC[33]. Lutjeharms and Valentine[32] have identified the SAF as having a mean position of 46º23’S south of Africa. Using the criteria described by Belkin and Gordon[13] in which the subsurface temperature range between 4.8 - 8.4°C and 34.11 - 34.47 at 200m, with axial values of 6°C and 34.3, we observed the subsurface axis of the SAF at 44º07’S during GoodHope I transect (Figure 5). Thermosalinograph data places the surface expression of the SAF between 44º05’S – 49º16’S (8.51 - 4.24ºC, 34.031 – 33.618) (Figure 6). This appears to be considerably wider than in other studies in this region of the Southern

Ocean[13]. However, recent investigations[41] have shown that in the South Atlantic, the SAF is often found as a broad frontal band extending over 250km (45º54'S - 48º42'S). Closer examination of the SST and in particular the SSS (sea surface salinity) data reveal a number of narrow reversals between 44º43'S (33.854 – 33.7) and 46º38'S (33.666 – 33.598) (Figure 6). This observation is in agreement with Holliday and Read[12] who have identified a number of surface steps related to both temperature and salinity inversions. The exact cause of these inversions is not known, however Lutjeharms and Valentine[32] and Wexler[42] have ascribed these inversions to either wind-induced upwelling or the poleward shedding of eddies.

Antarctic Polar Front

The APF marks the northern limit of the Antarctic zone and the subsurface expression of the APF is historically identified by the northern limit of the 2ºC temperature minimum at a depth of 200m [5, 13]. In some instances this is not coincident with the surface expression of the APF[32] and instead the surface expression can be identified by the maximum temperature gradient between 6ºC and 2ºC. The APF is characterised by a shallow temperature minimum associated with the remnants of Winter Water, which lies at depths between 50 – 150m. It is seasonally variable; in winter it is nearly homogenous extending to 250m, while in summer the mixed layer extends only to between 50 - 100m. Temperatures for this water mass range from -1.8 – 6°C at the APF and salinity from 33.4 - 34.2. During GoodHope I the subsurface expression of the APF was found to lie at 50º22'S (Figure 5). The surface expression, identified from the thermosalinograph lay between 50º14'S – 52º51'S (4.7 – 1.46ºC, 33.796-33.894) (Figure 6).

Southern Antarctic Circumpolar Front (SAACF)

Orsi et al.[43] have identified an additional ACC front, which they have termed the Southern ACC Front (SACCF) and described as a circumpolar, deep reaching front lying south of the APF. The position of this front corresponds to the position of the atmospheric low-pressure belt Antarctic trough, which separates the easterly and westerly wind belts at ~65ºS. In contrast to the other fronts associated with the ACC, the SACCF does not separate distinct surface water masses, instead it is defined by the temperature and salinity characteristics of the Upper Circumpolar Deep Water (UCDW)[12]. Two branches of the SACCF, marked by a high salinity gradient 33.80 – 33.63 at 63.4ºS and 33.78 - 33.09 at 64.7ºS between 0.9 –0.7ºC, were observed by Holliday and Read[12] in the SE Atlantic from their RRS Discovery dataset. South of Australia[4] the SACCF has been identified by the location of the 0ºC isotherm along the T_{min}, which places the front at a mean position of 63º48'S. Increase in air temperatures between December – February results in the warming of the surface mixed layer and the northern extent of the TML cooler than 0ºC forming a reliable indicator of the position of the SACCF[43]. Using this definition, places the SACCF during GoodHope I between 53ºS and 55º44'S (Figure 5). In this region the T_{min} formed by the presence of the remnants of Winter Water average 80m in thickness and centred at 150m.

Total chlorophyll-a (chl-a) concentration during the cruise ranged from 0.07 to 2.81 mg m^{-3}. Peaks in total chl-a concentration were recorded in the continental shelf water south of Africa (>2.8 mg m^{-3}), at stations occupied in the vicinity of the major oceanic frontal systems and in the neritic waters of Antarctica (Figure 7). The highest concentration in chl-a in the Southern Ocean >0.75 mg m^{-3} was observed between stations 106 and 109 at 50º54'S and 51º22'S and are associated with the APF. In addition, a further peak in total chl-a concentration (0.7 mg m^{-3}) was located at stations occupied in the region of 58°S (Station 140). Similar patterns in total chl-a concentrations have been observed in the South Atlantic[16] and appear to be associated with melt-water lenses left behind by the retreating ice edge. At these stations total chl-a concentration always exceeded 0.5 mg m^{-3}. At stations occupied within the inter-frontal regions total chl-a concentrations were in the range 0.07 to 0.35 mg m^{-3}.

CONCLUSION

The Antarctic Circumpolar Current forms an important link in the global thermohaline overturning circulation. Modifications in the saline characteristic of water masses associated with the ACC play a vital role in maintaining both global heat and salt budgets. Determining the transport flux of the ACC south of South Africa has been an observational goal for many years. Such observations have been conducted during the World Ocean Circulation Experiment (WOCE) during the 1990s in which repeat transects across the ACC were restricted to 3 chokepoints. Intense and periodic monitoring of both the Drake Passage and south of Tasmania have continued since WOCE, however a regular monitoring line between South Africa and Antarctica has only commenced earlier this year.

Our understanding of how and why this transport varies with time and season remains incomplete due to the severe lack of observations. The sources, pathways and characteristics of these exchanges are not well-enough established to allow their influence on the climate system south of South Africa, to be quantified. The aim of GoodHope is therefore to establish an intensive monitoring line that will provide new information on the volume flux of the region south of South Africa, in particular the Indo-Atlantic exchange. An investigation studying the empirical relationship between upper ocean temperature and the baroclinic transport stream from repeat hydrographic sections across the ACC, south of South Africa is now currently underway. Application of this empirical relationship to all the past and future observations will be necessary to monitor the variations and variability of the ACC south of South Africa. By further defining a second empirical relationship between surface dynamic height and cumulative transport (following Rintoul et al.[44]) it will be possible in future to extrapolate the ACC behaviour, in particular its seasonality and inter-annual variability, through satellite altimetry.

This is the start of a new and exciting multi-national and inter-disciplinary endeavour aimed at integrating high-resolution physical, biological and atmospheric observations with along-track satellite and model data. With the first GoodHope transect already completed, a second line consisting of high resolution CTD stations is scheduled for November 2004. It is hoped that the outcome of the GoodHope project will result in a clearer understanding of the Indo-Atlantic inter-ocean exchange in this region of the Southern Ocean and its impact on both regional and global present day climate changes.

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FIGURE LEGENDS

Figure 1: Schematic diagram showing the average position of the subsurface temperature expressions of the STC (10ºC), SAF (6ºC) and APF (2ºC) south of South Africa.

Figure 2: (A) Along track sea surface height data (cm) for the GoodHope region showing the inter-basin leakage of Agulhas anomalies into the SE Atlantic Ocean. The ground paths of the Geosat Follow-On and JASON-1 missions have been superimposed onto the diagram. (B) Dynamic height (cm) of the SE Atlantic Ocean at the time of GoodHope I. The track of the first GoodHope transect is clearly shown on both images.

Figure 3: GoodHope I, which was occupied between February and March 2004. Blue dots represent the deployment location of each PROVOR float, green represent SVP drifter deployments and red dots represent XBT deployments and all underway chl-a stations.

Figure 4. Surface pressure in hPa (top) and wind speed in ms^{-1} (bottom) as measured in 10-minute intervals from 26 February to 8 March 2004 (day 1 to 12) along the first GoodHope transect. Lower pressures (presumably associated with Mid-latitude Cyclones or MCs) are associated with stronger winds and therefore larger negative fluxes of momentum are recorded due to poor sea conditions.

Figure 5: Temperature section from XBT data along GoodHope I. The dashed isotherms represent the subsurface axis of the STC (blue- 10ºC), SAF (red – 6ºC) and APF (white – 2ºC).

Figures 6: Thermosalinograph (A) SST and (B) SSS data collected at 20 minute intervals during GoodHope I.

Figure 7: Total chlorophyll-a concentration along GoodHope I. The position of the main frontal systems has been determined from the XBT data.

Table 1: Definition of the fronts bordering the Antarctic Circumpolar Current

FRONT	SURFACE RANGE	SUBSURFACE (200 m) RANGE
STC	10.6 – 17.9ºC: 34.3 – 35.5	8.0 – 11.3ºC: 34.42 – 35.18 Axial value: 10ºC, 34.8
SAF	6.8 – 10.3ºC: 33.88 – 34.36	4.8 – 8.4ºC: 34.11 – 34.47 Axial value: 6ºC, 34.3
APF	2.5 – 4.1ºC	Axial value: 2ºC

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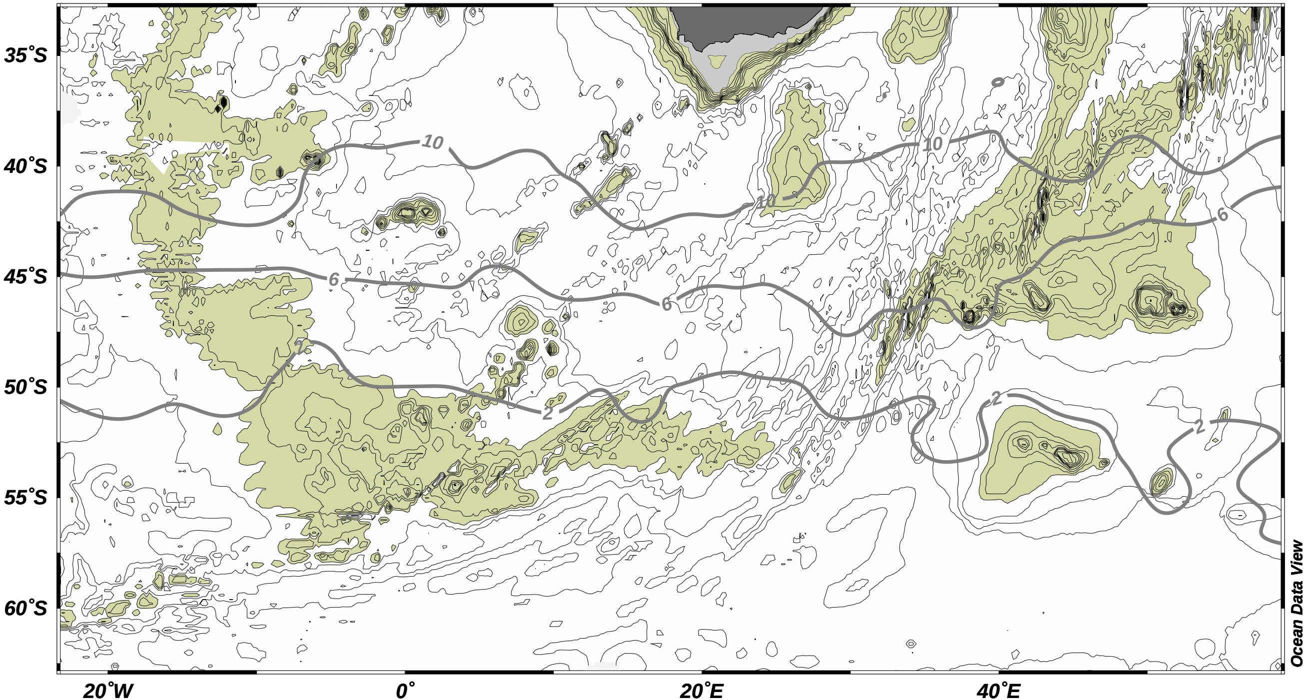
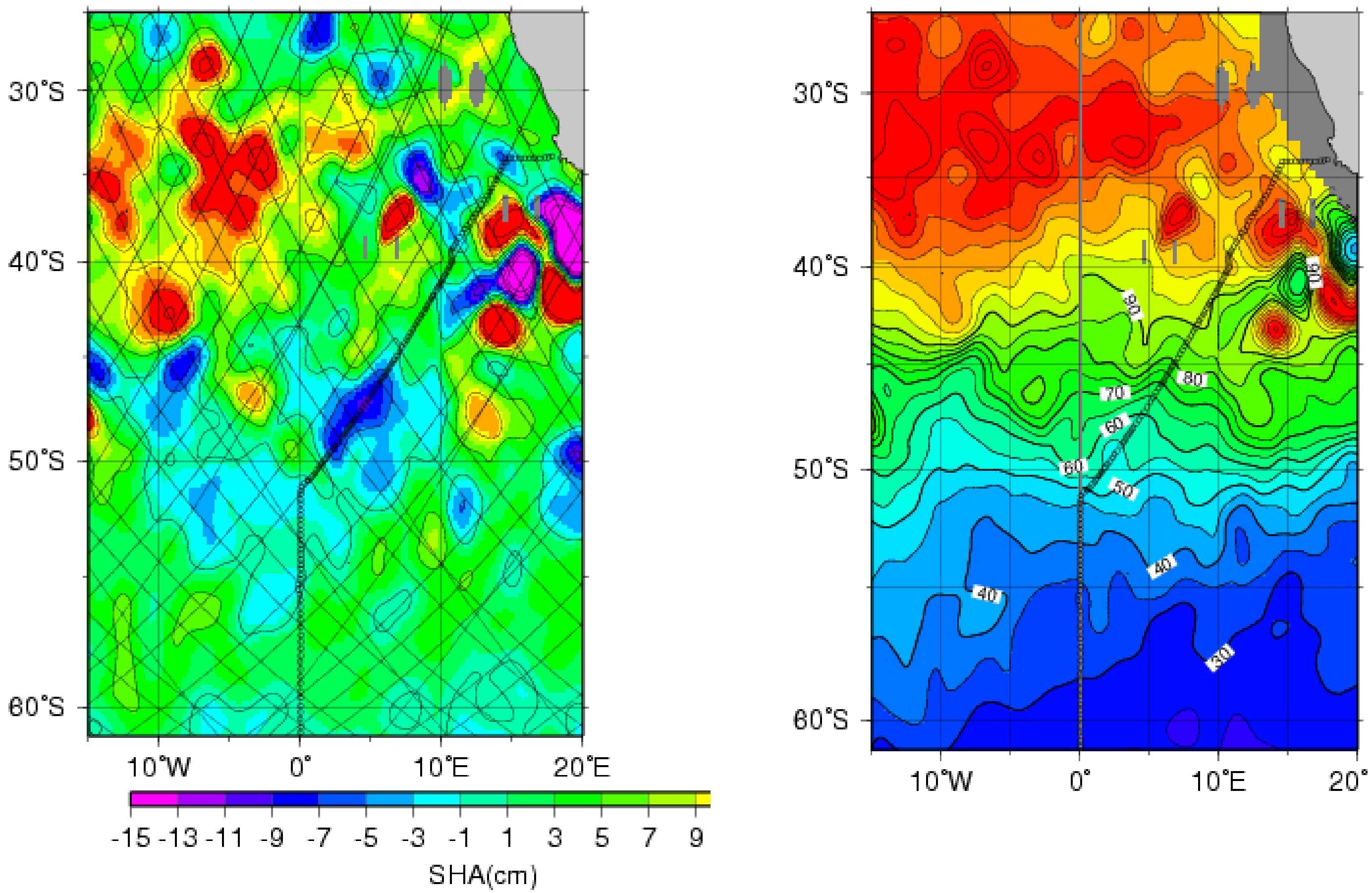
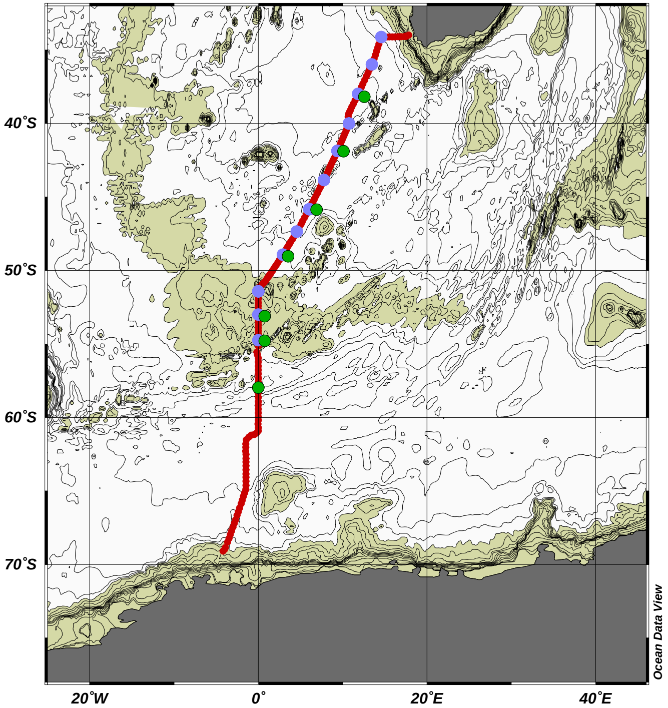


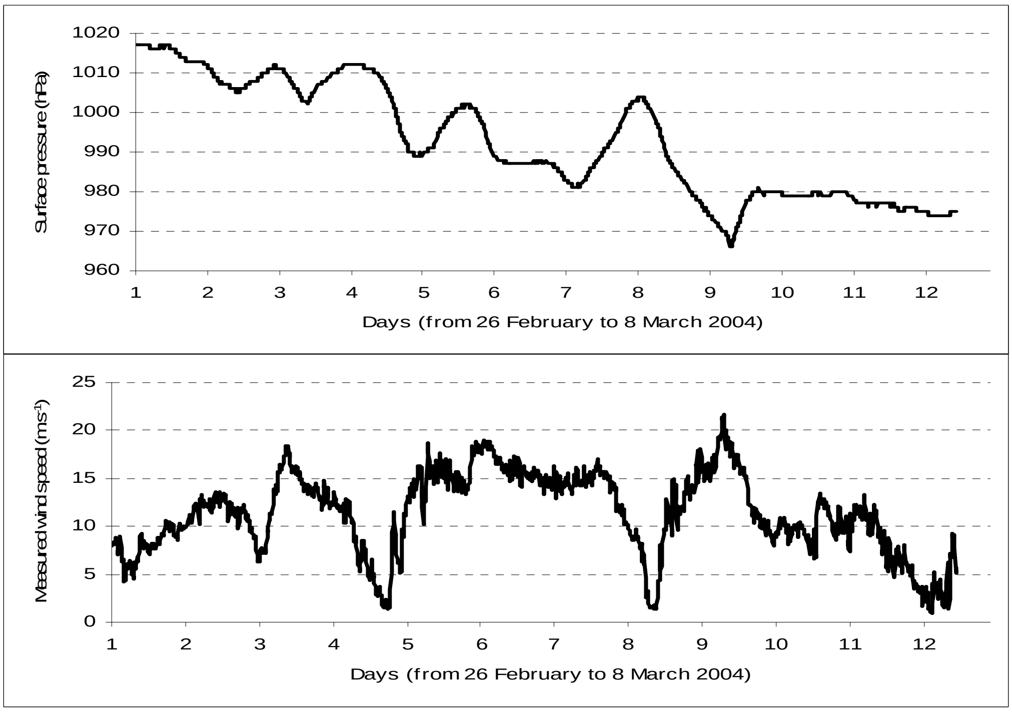
35°S
40°S
45°S
50°S
55°S
60°S
20°W
0°
20°E
40°E
10
10
10
6
6
6
2
2
2
2
Ocean Data View

Figure 2


30°S
40°S
50°S
60°S
10°W
0°
10°E
20°E
-15 -13 -11 -9 -7 -5 -3 -1 1 3 5 7 9
SHA(cm)
30°S
40°S
50°S
60°S
10°W
0°
10°E
20°
90
100
80
70
60
60
50
40
40
30



40˚S
50˚S
60˚S
70˚S
20˚W
0˚
20˚E
40˚E
Ocean Data View



Surface pressure (hPa)
1020
1010
1000
990
980
970
960
1
2
3
4
5
6
7
8
9
10
11
12
Days (from 26 February to 8 March 2004)
Measured wind speed (ms-1)
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
Days (from 26 February to 8 March 2004)

Figure 4

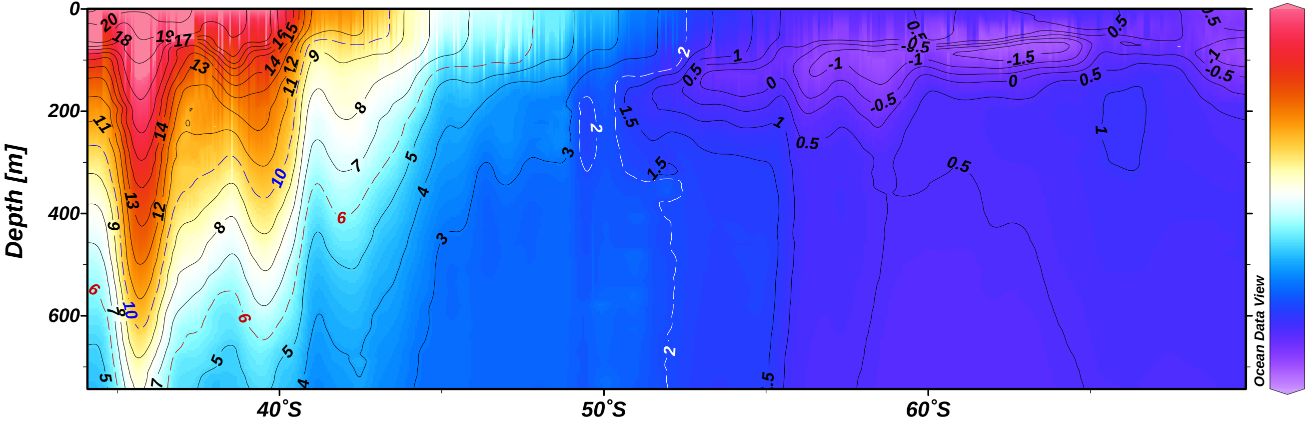
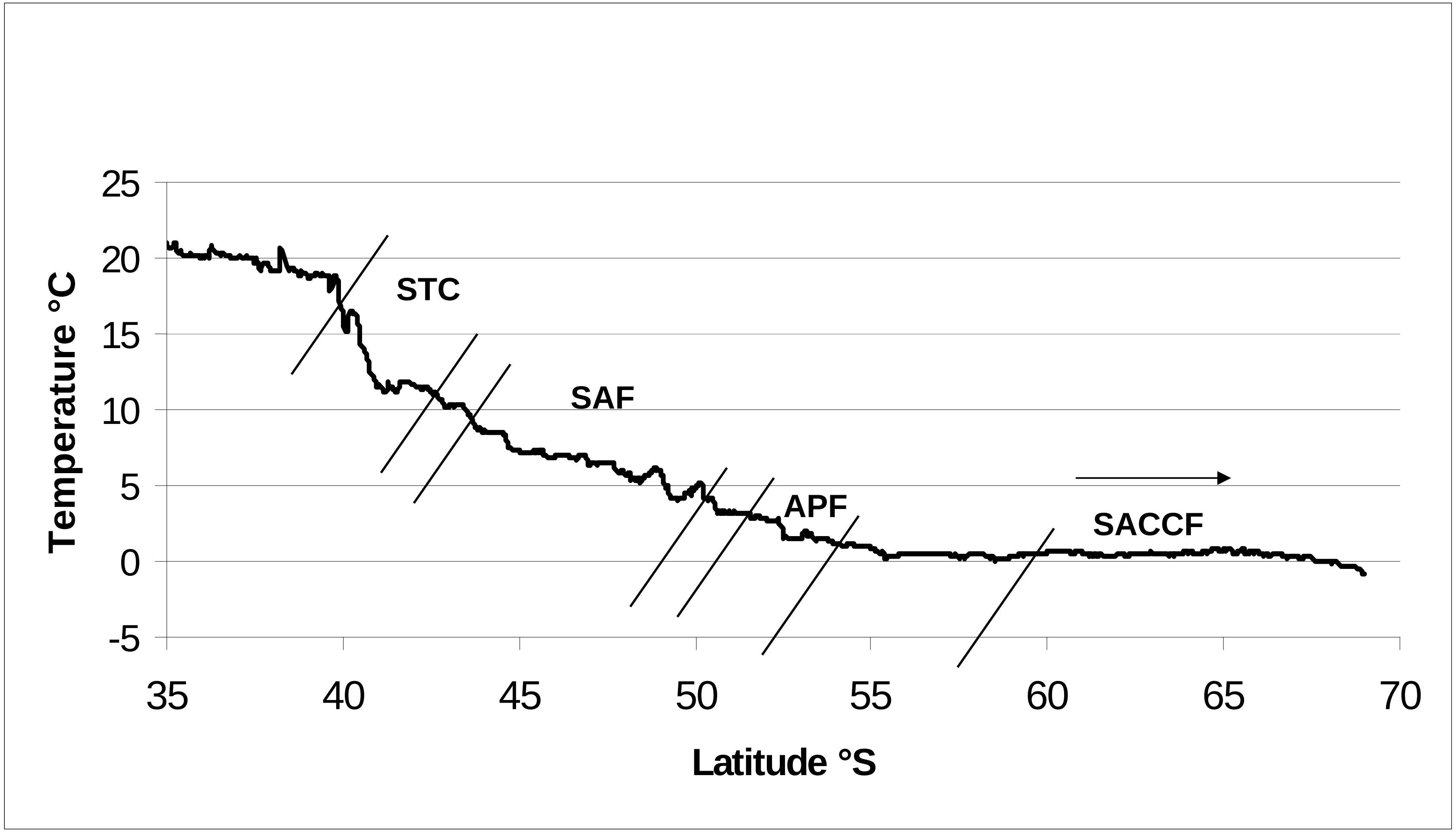
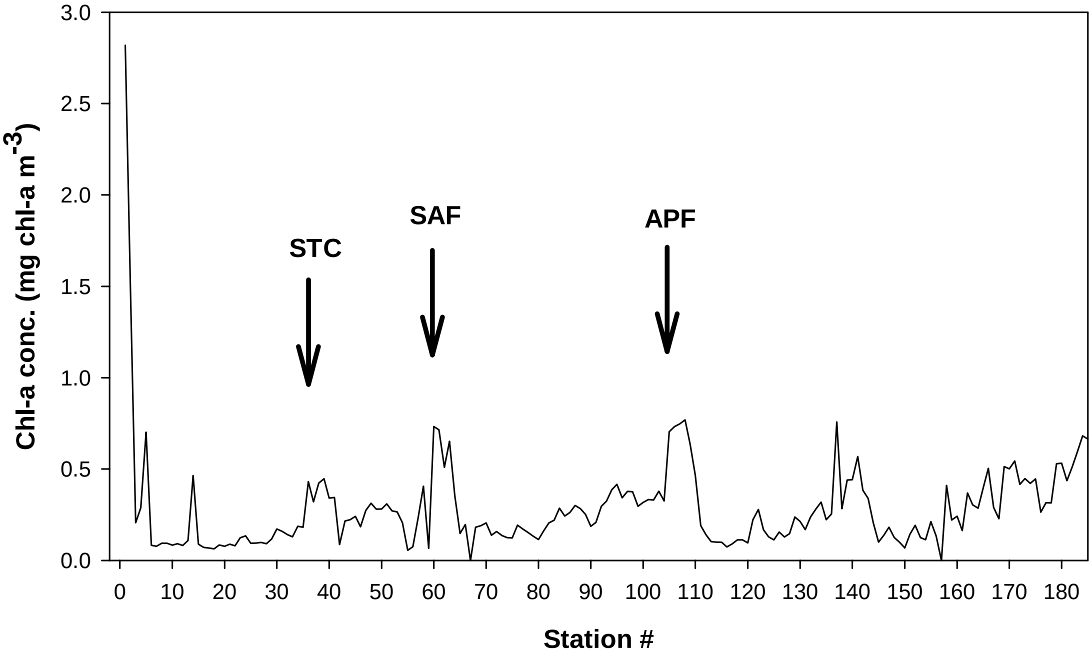

Depth [m]
0
200
400
600
40˚S
50˚S
60˚S
15
10
5
0
Ocean Data View

Figure 6



Temperature °C
25
20
15
10
5
0
-5
35
40
45
50
55
60
65
70
Latitude °S
STC
SAF
APF
SACCF



3.0
2.5
2.0
1.5
1.0
0.5
0.0
Chl-a conc. (mg chl-a m-3)
STC
SAF
APF
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Station #

Figure 7