A description of the hydrography between

Cape Town and Antarctica

along the Goodhope Transect between

2004 - 2012

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Abstract

The Antarctic Circumpolar Current (ACC) within the Southern Ocean (SO) is the primary driver for global interoceanic exchanges. These exchanges form the foundation for the Meridional Overturning Circulation (MOC), a deep density driven circulation, which extends throughout the global oceans. The fronts of the ACC, consisting of several branches, separate zones of distinct water masses, thus identifying the location of the fronts and understanding their dynamics is of global importance. The GoodHope programme, is a repeat annual transect between South Africa and Antarctica, monitoring the exchanges within the Southeast Atlantic sector of the Southern Ocean. This is achieved through high resolution Expendable Bathythermograph (XBT) sampling. In this study XBT data over an eight year period (2004 – 2012) were investigated and analysed. One aim is to illustrate the variability of the fronts associated with the ACC using *in-situ* data from 21 transects during this eight year period. The Sub-tropical Front (STF) and Northern branch of the Sub-Antarctic Front (SAF-N) are seen to be the most variable with frontal latitudinal shifts ranging from 2-4° and 1-2° respectively. One cause of this high variability is the interaction of mesoscale features, particularly in the form of eddies and Agulhas rings. The southernmost fronts of the ACC, namely the Southern Antarctic Circumpolar front (sACCf), consisting of a Northern and Southern branch of the sACCf (sACCf-N and sACCf-S) and Southern Boundary (SBdy), also display high variability due to seasonality brought on by ice melt. The central fronts of the ACC, the Middle and Southern branches of the SAF (M-SAF and S-SAF) and Northern, Middle and Southern branches of the Polar Front (PF-N, PF-M and PF-S) remain throughout the eight year observations fairly constant, with shifts observed to be less than 1° of latitude. Grouping the GoodHope transects into austral summer periods, illustrates the di-pentadal nature of the STF, whereby the shifts are in response to mesoscale interactions. Comparing the mean position of the fronts and their position observed during a single winter cruise in July 2012, an overall Northward shift was observed with most of the fronts with significant shifts occurring in the SAF-N and PF-N. This is due to the outcrop of different water masses occurring further Southward and Northward respectively. A passing Agulhas ring or eddy which follows the southern Route and interacts with the STF, causes a deepening of the thermocline and so alters the location of the front due to the identification criteria being based on hydrographic variables. The shifts observed in the fronts are also accosted to the bathymetry whereby ridges and flat regions influence the variability. Understanding the variability of the ACC during this eight year period and the fronts therein broadens our knowledge of the ACC, and thus the MOC, through understanding of its dynamics and physical properties.

Literature Review

The Southern Ocean (SO) is the ocean region south of 35°S and makes up approximately a quarter of the global ocean surface area (Gille, 1994). It has been hypothesized (Rintoul & Bullister, 1999) to play an important role in the global climate as it connects the Atlantic, Indian and Pacific Oceans. This is due to the fact that the Southern Ocean has no continental barriers resulting in a circumpolar current. The inter-ocean exchanges within the Southern Ocean have broader implications on a global level since these waters spread gradually into other ocean basins (Gille, 2002; Speich, *et al*., 2008). As part of the Meridional Overturning Circulation (MOC) the return of the upper ocean water is important as it transports heat, salt and other properties between the various ocean basins (Sloyan & Rintoul, 2001). Through the convective overturning of the MOC, the transport within the ocean is linked to the global climate on decadal to centennial timescales (Speich, *et al.*, 2008).

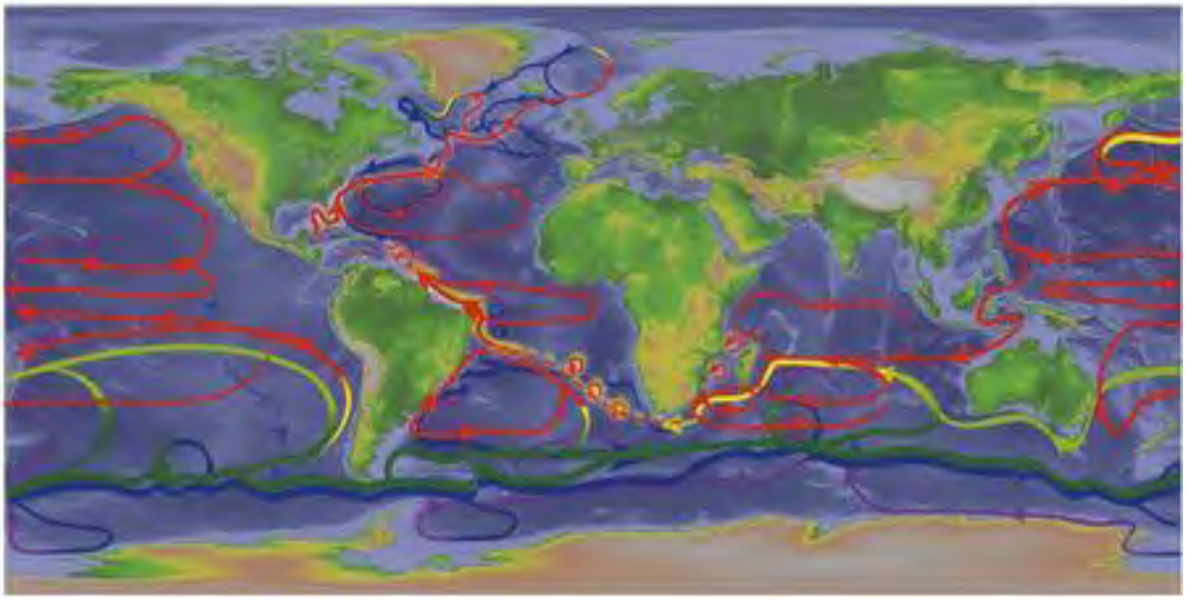

Figure 1: Schematic depicting the global Meridional Overturning Circulation. Red lines represent surface flows, yellow/ green represent intermediate flows and blue/ purple represent deep flows. (Base map by S.Speich adapted from Lumpkin & Speer, 2007 following Speich, et al., 2007)

Heat and salt from various water masses occurring in different ocean basins around the globe, are exchanged in the Southern Ocean. This exchange primarily occurs via the Antarctic Circumpolar Current (ACC), which runs unbroken around Antarctica. Due to its global climate impact, the ACC and the Southern Ocean proves to be an area of critical interest since global ocean temperatures have been shown to increase by 0.17°C since the 1950's (Gille, 2002; Gille, 2008). The same trend has been observed in the various sectors of the Southern Oceans, however detailed analysis of this heating remains unexamined as *in-situ* hydrographic observations, south of 30°S remain limited (Gille, 2002;

Gille, 2008). The greatest warming is highlighted within the ACC, where it is faster and more concentrated (Gille, 2002; Gille, 2008; Yasunaka & Kimoto, 2013), and the warming may have broader implications as the waters ventilated and heated in the Southern Ocean are spread globally. This in turn influences the storage capacity of soluble gases such as CO_2 as warmer waters hold less gas than colder waters (Gille, 2002). Hydrological and hydrographic observations are thus important as they aid the description and understanding of the processes, which occur within the Southern Ocean and across the ACC (Budillon & Rintoul, 2003; Aoki, *et al.*, 2003).

The Southern Ocean serves as an important storage system in terms of heat, freshwater, dissolved gases and plays a major role as a sink for both anthropogenic and naturally occurring CO_2 (Downes, *et al*., 2009; Swart, *et al*., 2012). Although it does not serve as a permanent CO_2 sink or source, it has the ability to retain CO_2 for long periods of time, such as decades to centuries (Metzl, *et al.*, 2006). It serves as an indicator for many anthropogenic tracers, and plays a major role in the global carbon cycle by the production and ventilation of various water masses (Speich, *et al.*, 2008). The Southern Ocean plays an important role with regards to water and heat exchange between the various ocean basins via the ACC. This in turn has an impact on the mean global climate (Yuan, *et al.*, 2004) through the carbon cycle and through its interactions with Antarctica.

i. The ACC and its associated fronts

The Southern Ocean and the fronts located within, play a major role in the global climate system and are of key importance to the Meridional Overturning Circulation (Graham, *et al.*, 2012). The ACC, a wind driven current, is not a homogenous eastward flowing current, but rather is comprised of multiple quasi permanent jets of enhanced flow (fronts) which are found to separate the ACC into separate zones of uniform water masses (Speich, *et al*., 2008; Swart, *et al*., 2012; Belkin & Gordon, 1996). A front is defined as a narrow region where a rapid change in water mass properties occurs. This rapid change is often related to horizontal property gradients and to a strong geostrophic flow. The thermocline is the most noticeable and common indicator of a front within the Southern Ocean and helps distinguish between various water masses and current systems within the upper layers of the ocean (Budillon & Rintoul, 2003). The fronts associated with the ACC, give a unique definition to physical, chemical and biological properties as well as their seasonal evolution with the deepening of the mixed layer and mixing of water masses (Sokolov & Rintoul, 2007). The fronts are also regions where upwelling and downwelling processes occur as different water masses either subduct or shoal due changes in density (this can be observed in Figure 8 presented further on in this study).

Seasonal changes in the Southern Ocean are of particular importance as they are related to the formation of water masses. These water masses, coupled with the flow within the Southern Ocean, ventilate the intermediate and deep layers of ocean basins (Rintoul, *et al.*, 1997). The winter months (July-Sept) serves as a ‘reset’ for the Southern Ocean via strong vertical mixing brought on by an increase in wind speed, which result in a deepening of the Mixed Layer Depth. In contrast summer months (December-February) are dominated by an increase in the stratification of the upper water column-resulting in high biological processes, such as photosynthesis and productivity (Metzl, *et al.*, 2006). *In-situ* hydrographic observations are scarce during winter due to the inclement weather conditions and logistical constraints, thus *in-situ* CTD data for the winter months is sparse (Swart, *et al.*, 2010).

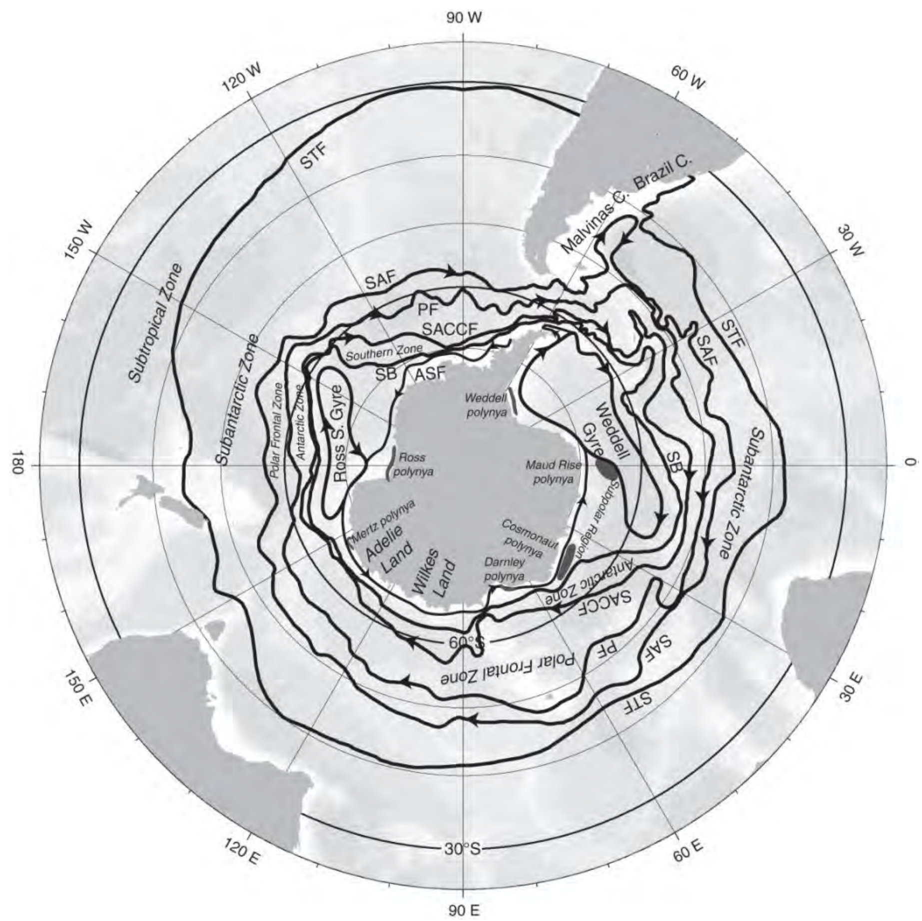

Figure 2: The Southern Ocean geography, principal fronts, and oceanographic zones. The Subtropical Front (STF) is the oceanographic northern boundary for the region. The eastward Antarctic Circumpolar Current (ACC) includes these fronts: Sub Antarctic Front (SAF), Polar Front (PF), Southern ACC Front (sACCf), Southern Boundary (SB). Front locations from Orsi, et al. (1995). The westward Antarctic Slope Front (ASF) (thin) follows the continental slope. Circulation of the ocean basins north of the SAF is not represented (reproduced from Talley, et al., 2011).

Identification of fronts associated with the ACC

As fronts separate different water masses into zones whereby, the change in water mass properties allow for its easy identification. As a result, when using data from a hydrographic transect, the ACC is identified using hydrographic criteria (Sokolov & Rintoul, 2007; Faure, *et al.*, 2011). The identification of the fronts differs because of the varying criteria adopted by researchers. This is largely determined by data availability and thus different results are reported in the literature (see Table 1). Recent studies such as, Sokolov and Rintoul (2009), have revised the criteria upon which to identify fronts and have thus, shifted from using hydrographic measurements, which use subsurface properties, to using surface signatures, such as Sea Surface Height (SSH) and Sea Surface Temperature (SST) gradients calculated from remotely sensed satellite data (Graham, *et al.*, 2012). The comparison of the gradients from satellite data and *in-situ* subsurface temperature data are well matched, however due to the *in-situ* data being more highly resolved than the satellite data (spatially), smaller scale features are evident and distinct (Swart, *et al*., 2012; Sokolov & Rintoul, 2009). The Sub Tropical Front (STF), Sub Antarctic Front (SAF), Antarctic Polar Front, sometimes known as the Polar Front (PF), Southern Antarctic Circumpolar Front (sACCf) and Southern Boundary (SBdy) make up the oceanic fronts seen between South Africa and Antarctica. The study and description of these frontal systems and hydrographic sections have improved due to the use of Expendable Bathythermographs (XBT's), CTD's and satellite observation (Swart, *et al*., 2008; Swart, *et al*., 2010). Beside the main fronts identified in the SO, Sokolov and Rintoul (2009) infer that these fronts can be distinguished into multiple robust, persistent branches which are also circumpolar. These have been classified as SAF-N, SAF-M, SAF-S; PF-N, PF-M, PF-S; sACCf-N, sACCf-S & SBdy, where -N, -M and -S are shortened for Northern, Middle and Southern respectively (Sokolov & Rintoul, 2007; Sokolov & Rintoul, 2009).

These fronts (and branches) are identified as follows:

Table 1: Criteria for the identification of the frontal systems south of Africa (adapted from Sokolov and Rintoul 2009)

Front	**Indicator**	**WOCE (^{0}C)**
SAF – N	θ at p = 400 dbar	6.32 ± 0.71
SAF – M	θ at p = 400 dbar	4.06 ± 0.34
SAF – S	θ at p = 400 dbar	2.65 ± 0.21
PF – N	θ at p = 200 dbar	1.99 ± 0.23
PF – M	θ in θ_{max}	2.15 ± 0.03
	θ in θ_{min}	1.22 ± 0.30
PF – S	θ in θ_{max}	2.01 ± 0.06
	θ in θ_{min}	0.48 ± 0.37
sACCf – N	θ in θ_{max}	1.87 ± 0.12
	θ in θ_{min}	-0.29 ± 0.33
sACCf – S	θ in θ_{max}	1.59 ± 0.19
	θ in θ_{min}	-0.71 ± 0.34
SBdy	θ in θ_{min}	-1.11 ± 0.09

Description of the ACC Fronts

Subtropical Front

The Subtropical Front (STF) marks the boundary between warm, salty subtropical surface water and cooler, fresher Sub Antarctic 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 STF have shown that in the South Atlantic the its mean position lies at 41˚40'S (Lutjeharms and Valentine, 1984). Previous studies in the South-east Atlantic sector of the Southern Ocean (Smythe-Wright, *et al.*, 1998) have identified two separate fronts associated with the Northern (NSTF) and Southern boundaries (SSTF) of the STF. These observations have been made from over 10 datasets extending across the South Atlantic from the Brazil Current at 42˚W to the Agulhas - Benguela region at 11˚E. Surface temperature and salinity definitions given by Belkin and Gordon (1996) cover the range 14.0 –16.9˚C, 34.87 – 35.58 for the NSTF and 10.3 – 15.1˚C, 34.30 – 35.18 for the SSTF. The changes in temperature and salinity are nearly density-compensating, so that the density gradient across the STF is weak.

Sub-Antarctic Front

In contrast to the STF, the vertical shear associated with the main fronts of the ACC - the Sub Antarctic Front (SAF) and Antarctic Polar Front (PF) - typically extends throughout the water column. The Sub Antarctic 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 STF, which is clearly characterised by a sharp and consistent gradient in both surface and subsurface expressions, making identification extremely easy (Whitworth and Nowlin, 1987), 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. North of the SAF the salinity minimum of the AAIW is pronounced; south of the SAF the salinity minimum is weak or absent. The SAF is predominantly a subsurface front and can be defined by the most vertically orientated isotherm within a temperature gradient lying between 3˚C and 5˚C, while its surface expression extends between 8˚C and 4˚C. Lutjeharms and Valentine (1984) have identified the SAF as having a mean position of 46˚23'S south of Africa. Using the criteria described by Belkin and Gordon (1996) 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. Recent investigations (Swart, *et al.*, 2010) have shown that in the South Atlantic, the SAF is often found as a broad frontal band extending over 250km (43˚38'S - 47˚17'S) and with a number of narrow reversals. This observation is in agreement with Holliday and Read (1998) 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 (1984) and Wexler (1959) have ascribed these inversions to either wind-induced upwelling or the poleward shedding of eddies.

Antarctic Polar Front

The PF marks the northern limit of the Antarctic zone and the subsurface expression of the PF is historically identified by the northern limit of the 2˚C temperature minimum at a depth of 200m (Belkin and Gordon, 1996). In some instances this is not coincident with the surface expression of the PF (Lutjeharms and Valentine, 1984) and instead the surface expression can be identified by the maximum temperature gradient between 6˚C and 2˚C. The PF 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 creating a distinct subsurface T_{min}. Temperatures for Winter Water range from -1.8 – 6°C at the PF and salinity from 33.4 - 34.2.

Southern Antarctic Circumpolar Front (sACCf)

Orsi *et al.* (1995) 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 PF. 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 ~65˚S. 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). Two branches of the sACCf, marked by a high salinity gradient 33.80 – 33.63 at 63.4ºS and 33.78 - 33.09 at 64.7˚S between 0.9 –0.7˚C, were observed by Holliday and Read (1997) in the South East Atlantic from their RRS Discovery dataset. South of Australia 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 63˚48'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 0˚C forming a reliable indicator of the position of the sACCf

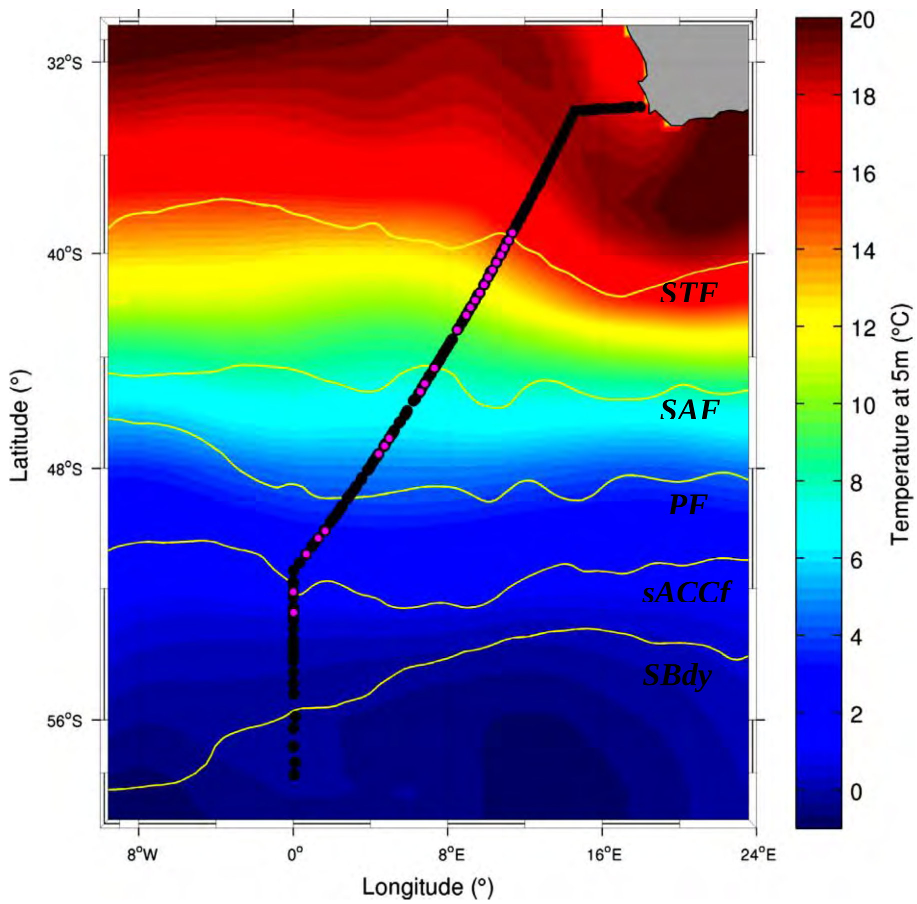

Figure 3: Schematic showing the five fronts located within the Southern Ocean along the GoodHope transect. From north to south, they are: STF, SAF, PF, sACCf and SBdy. [Image extracted from Hutchinson, et al. (2013)].

ii. Mesocale features and the ACC

Mesoscale turbulence which may arise as result of wind forcing, baroclinic/ barotropic instability, and topographic interactions have influence on the variability of the ocean currents. The turbulence, often generate eddies which is one of many significant contributors in the transport of momentum, heat and nutrients (Glorioso, *et al.*, 2005). The variability of the fronts, which occurs mainly through these submesoscale to mesoscale activities, is known to enhance the biomass of phytoplankton through the introduction of nutrients from other water masses (Glorioso, *et al.*, 2005; Swart, *et al*., 2012). Although the GoodHope transect does not intersect the Agulhas Current or the Agulhas Return Current, the impact/influence of the mesoscale features which spin off from these currents can be identified across the fronts and within the different front zones (Faure, *et al.*, 2011). The rings which shed off the Agulhas Current Retroflection are believed to be the strongest observed in the ocean. These rings are of crucial importance in the Indo-Atlantic exchange with the predominant properties being temperature and salinity, however eddies may alter various hydrographic properties, such as salinity, oxygen and nutrients (Hallberg & Gnanadesikan, 2006; Arhan, *et al*., 2011). The ring shedding events are known to have a great effect on the local biology and primary production (Glorioso, *et al.*, 2005). This occurs through altering the ambient temperature, salinity and nutrients by the introduction of new water masses into the ocean basin environment. Concurrent with this are both the upwelling and downwelling processes which occur within the mesoscale features which also affect the local environment. These interactions would influence temperature, salinity, nutrients and other variables either increasing or decreasing it dependant on the water mass properties.

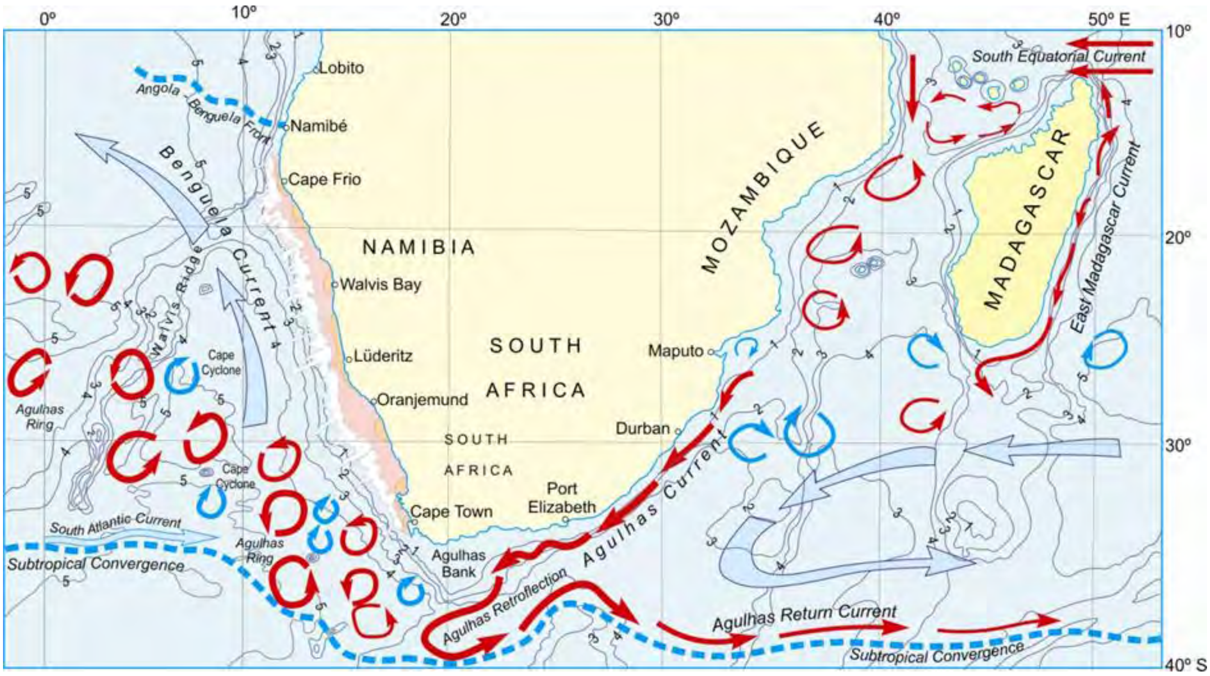

Figure 4: An illustration of the flow of the Agulhas Current and the Agulhas Return Current with the shedding of Agulhas Rings into the Atlantic Ocean at the Agulhas Retroflection. The dashed blue line in the south represents the STF and the Angola-Benguela Front in the North (Ansorge and Lutjeharms 2007).

Agulhas rings follow one of three routes in the Cape Basin, namely the Northern route, northeast of the Erica sea mount; the Central route, which passes between the Erica seamount and the Agulhas ridge and the Southern route whereby the rings pass further south into the SAZ. Although the central route is the predominant eddy pathway, a significant percentage of eddies and Agulhas rings pass through the Southern Route (Dencausse, *et al.*, 2010). The southernmost trajectories of the rings could influence the position of the STF as it is generally found on the southern flank of the rings (Dencausse, *et al.*, 2010). Agulhas rings are often accompanied by a cyclonic eddy in the region (Baker-Yeboah, *et al*. 2010). The anticyclones exchange heat through air-sea interaction and through lateral near-surface exchanges with the surrounding waters which eventually leads to cooling of the core and deep convection (Dencausse, *et al.*, 2010).

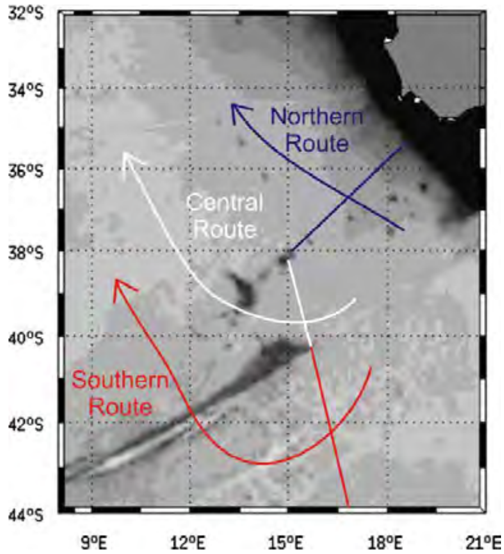

Figure 5: A depiction of the three projected routes of eddies.[Extracted from Dencausse, et. al. (2010).]

The STF, south of Africa, is largely influenced by intense mesoscale features as Agulhas rings are shown to alter the position and permeability of the STF (Dencausse, *et al.*, 2010; Swart, *et al*., 2012). These eddy features may extend as far as the SAZ, depending on their size, translational velocity and intensity. The rings that cross the STF are usually not tracked further south than 38°S, as it is hypothesized that these rings subduct below the warmer tropical surface water (Dencausse, *et al.*, 2010). The mesoscale features are primarily accountable for the variability of and within the SAZ (Arhan, *et al*., 2011; Swart, *et al*., 2012). Eddies entrained into the SAZ play an important role in the heat budget south of Africa. Within the SAZ, Sub Tropical mode water is formed from the waters from ensuing eddies which interact with the atmosphere through the winds and overlying cold air. The result of this is significant heat loss to the atmosphere. The mesoscale activities which occur south of the STF result in diffusion of Sub Tropical Water into the SAZ and thus- alters the properties of the surrounding water. The warming of the SAZ prevents the formation of surface mixed layers. The deep mixed layer is incumbent of the SAZ (Faure, *et al.*, 2011). On average, 2.7 rings per year are shed off and enter the SAZ through their south-westerly movement passage(Arhan, *et al*., 2011; Swart, *et al*., 2012).

The previous literature lays the foundation for the forthcoming study and the analysis and interpretation of the data and results will help broaden and expand the existing knowledge about the ACC, Southern Ocean, MOC and the global climate and global oceans.

Introduction

The Antarctic Circumpolar Current forms an important link in the global thermohaline overturning circulation. Modifications in the temperature and 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 Africa has been an observational goal for many years. Such observations have been conducted during the World Ocean Circulation Experiment (WOCE) in the 1990s in which repeat transects across the ACC were restricted to 3 chokepoints. Intense and periodic monitoring across the Drake Passage and south of Tasmania have continued since WOCE, however a regular monitoring line between South Africa and Antarctica commenced only in 2004. Despite several publications (Ansorge, *et al.*, 2004, Swart *et al.*, 2008, 2009 and Billany, *et al.*, 2010) our understanding of the seasonal signal of the ACC on the physical, biological and biogeochemical characteristic of the ACC remains limited.

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 continue with 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.

The GoodHope Programme

The GoodHope transect (or National Oceanic and Atmospheric Administration (NOAA) AX25 transect) was established in 2004 as an observational project with international collaborations between six countries (namely France, South Africa, United States, Germany, Russia and Spain) and 11 institutions (Ansorge, *et al*., 2005 ; Speich, *et al*., 2008). This transect was developed to monitor the waters south of Africa in terms of their physical structure, dynamics, and volume flux. Understanding the exchange occurring between ocean basins, in particular the Indo-Atlantic exchanges is crucial with regards to heat and salt exchange between the various ocean basins. As a result, much attention is given to two latitudinal bands: 35°S and 40°S, between South Africa and the Subtropical Front, where eddies and Agulhas rings are observed to cross the GoodHope transect, and ~40°S-55°S, the mean position of the ACC (Speich, *et al*., 2008; Swart, *et al*., 2008; Ansorge, *et al*., 2005).

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 Africa, where the inter-basin exchanges occur. The advantages of the GoodHope programme are four-fold:

(1) It runs approximately along with the TOPEX/POSEIDON – JASON 1 altimeter ground-tracks and continues to serve as a validation of altimetry-derived sea height anomaly data;

(2) The southern fraction of this line (south of 50˚S) 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 transect also overlapped until 2008 the region 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 and most important the leakage between the Indian and Atlantic Oceans via Agulhas Rings.

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

The GoodHope transect is advantageous as it is run concurrently with existing programmes. These include: the TOPEX/POSEIDION JASON 1 satellite ground tracks, a mooring array (seen south of 50°S, deployed by the Alfred Wegener Institute for Polar and Marine Research, during the WECCON project), the USA–ASTTEX programme pressure inverted echo sounders, (and the XBT transect AX25) (Ansorge, *et al.*, 2005).

More recently the Southern Ocean Carbon-Climate Observatory (SOCCO) and Southern Ocean Observing System (SOOS) programmes have been initiated, with the GOODHOPE transect being one of the key monitoring methods for the SO. SOCCO and SOOS have allowed for intensive physical and biogeochemical sampling to transpire in the hope of better understanding the link between the climate and the carbon cycle. This is achieved through the use of *in-situ* data (gathered from XBTs, surface and underwater gliders, Argo floats, moorings and surface drifters) coupled with numerical models and remotely sensed observations, implemented to answer and clarify key questions related to the physical and biogeochemical links in the Southern Ocean and thus the global ocean. On average, two GoodHope transects are carried out each year with subsurface and biological sampling taking place (Swart, *et al.*, 2012).

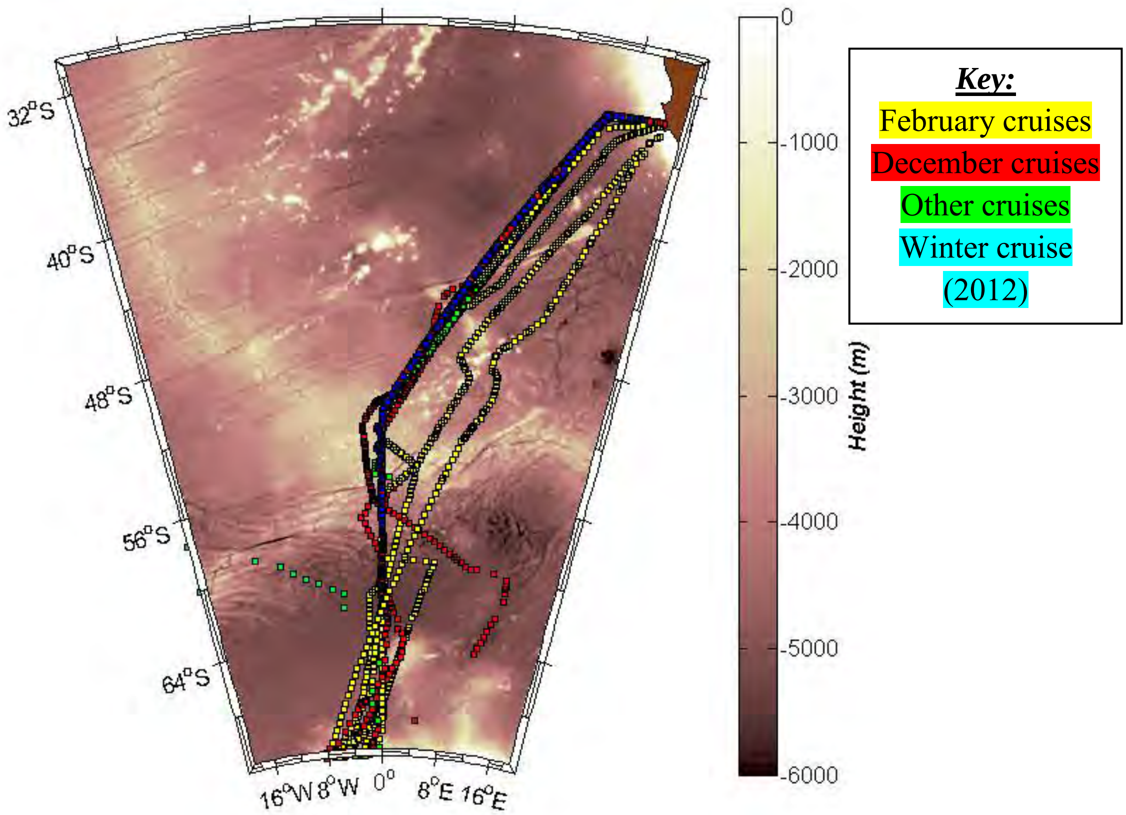

Figure 6: A map showing all the cruises along the GoodHope transect from 2004 – 2012.The bathymetry used is a subset from the ETOPO2 dataset.

Since its implementation in 2004, the GoodHope transect has contributed significantly to understanding the dynamics and mechanisms of the Southern Ocean through increased data measurements through regularly sampled transects (Speich, *et al.*, 2008). To date, over 21 transects have been completed. The success of the GoodHope project depends largely on repeated high resolution XBT sampling, full hydrology measurements, and regular deployment of Argo floats, which continuously measure temperature and salinity in the upper 2000m. The time-length for data measurements with use of the Argo floats, is largely dependent on the lifespan of the battery inside the float and may sometimes be prematurely disabled due to damage by sea ice or ships.

Two chokepoints in the SO, namely the Drake Passage and South of Australia, have been intensely sampled since 1990 (Speich, *et al.*, 2008), however the third chokepoint, between Africa and Antarctica has only been monitored since 2004 despite this region being vital to inter-ocean exchanges and its contribution to the MOCs structure and stability. The region south of Africa is unique as it is the conduit for distribution of North Atlantic Deep Water (NADW) to the global ocean and is a major driver in the Indo-Atlantic, and the Pacific, due to the exchanges of salt and heat (Speich, *et al.*, 2008)

Southern Ocean observations are limited in time due to the harsh conditions of the region. From the sparse data, it is possible to predict and establish the surface and subsurface seasonal variability for the large-scale circulation, however determining larger scales of variability (temporal and spatial) are challenging. Due to the sparseness of the sampling, it is difficult to obtain a baseline for the climatology of the Southern Ocean (Lyman, *et al.*, 2010) however continuous observations along the GoodHope transect will allow for the investigation into the structure and variability of the fronts seen in the Southern Ocean, South of Africa and so model and evaluate the Southern Ocean and the processes therein.

This work, presents the first descriptive study of all the GoodHope transects occupied since 2004. By analysing high resolution *in-situ* XBT data obtained from 21 different cruises undertaken along this transect, the variability in the position of the ACC and its associated fronts between cruises is investigated and compare it to a similar study undertaken by Billany, *et al* (2010). The GoodHope transect undertaken in July 2012 is unique in that it represents the first and only winter transect undertaken along this line, thus a comparison is investigated between the position of the ACC during summer versus the winter months. From this we identify the seasonal change which occurs within the Southern Ocean using a snapshot of the oceanic state during the winter of 2012. Lastly we investigate the variability of the ACC fronts between cruises, and investigate possible factors which influence this variability. Two factors are considered and analysed, namely:

(i) The interference and influence of mesoscale features, such as eddies and Agulhas Rings on the position of the ACC and its fronts, and
(ii) The influence topography has on the position of ACC along the GoodHope transect.

The interference and effect the mesoscale features have on the ACC, is analysed with the use of satellite data, namely daily sea surface height anomaly data. The effect of the topography is assessed by investigating the bathymetry at specific regions, along the GoodHope transect. We consider these factors individually and so the variability of the ACC in the central southeast Atlantic is partially resolved.

Data and Methods

Given the various factors highlighted in the previous sections, special attention needs to be given to the data and methodology when considering the GoodHope programme and transects. This is observed through the analysis of each individual transect and through the analysis of the XBT bias and whether it has a notable impact on the positions of the front.

In-situ XBT data

The GoodHope transect (AX25) is a high resolution XBT transect, with XBT with deployments implemented since February 2004 to July 2012. Most of the GoodHope transects undertaken are completed during austral summer (December – January). Rough seas and sea ice have prevented dedicated cruises during winter months during the eight year period (2004 to 2012) of the analysis presented here. This seasonal bias in sampling is illustrated in Figure 7.

During this period from 2004 - 2012, a total of 21 high resolution XBT (Sippician Deep Blue) transects were undertaken. On average, two GoodHope transects are undertaken in February or December, with an average of 158 XBTs deployed at 25km interval during each transect. The data collected was quality controlled at NOAA/AOML and further inspected before any analysis or investigation transpired. The data from the cruise undertaken in January 2012 was discarded, as this cruise did not follow the typical GoodHope transect along the Greenwich Meridian and only 19 XBTs were deployed. (The data for the various cruises were and can be obtained from http://www.aoml.noaa.gov/phod/hdenxbt/ax_home.php?ax=25)

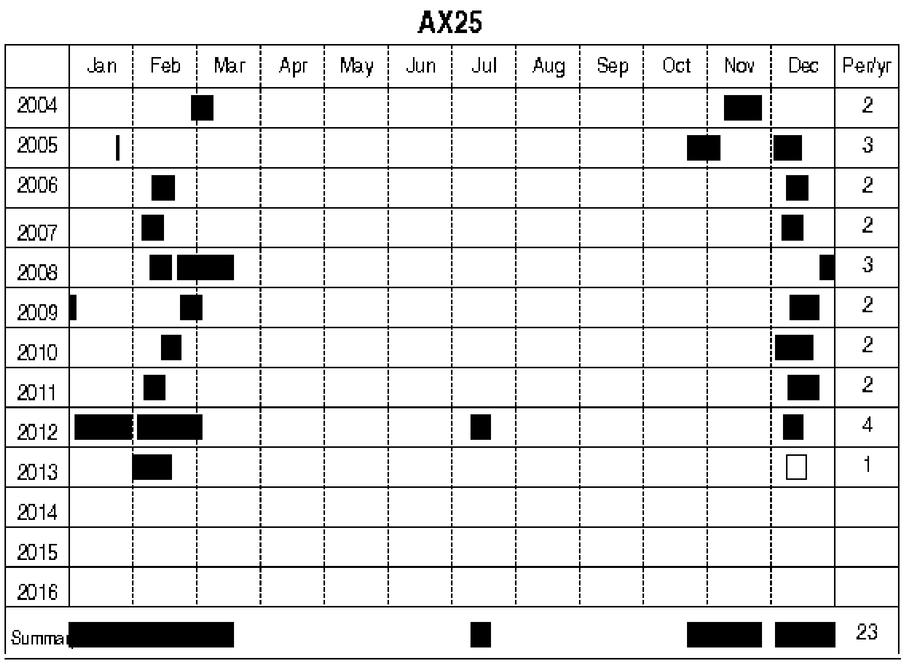

Figure 7: A list of cruises undertaken along the GoodHope transect. (Image adapted and extracted from www.noaa.com)

Front Identification and XBT bias

The various fronts were identified from temperature sections of each GoodHope transects using the criteria set out in Table 1. As the positions of the fronts are determined from temperature sections, the XBT bias has to be taken into account. This bias is shown to produce an offset with certain oceanic properties (Hutchinson, *et al*., 2013; Gouretski & Koltermann, 2007; Lyman, *et al*., 2010), such as ocean heat flux and ocean heat content. The impact of the bias on the position of the various fronts in the ACC does not result in a significant change in the position of the front (<0.01°).

Remotely Sensed (Altimetry) Data

The altimetry data for identifying the eddy assessed in the case study was accessed through NOAA's National Operational Model Archive & Distribution System's (NOMADS) Live Access Server (LAS). The data used was obtained from NOAAs optimum interpolated SST (AVHRR + AMSR) at a resolution of 0.25°/27.7km. The anomalous temperature for the region 30°S - 45°S, 10°W - 20°E was investigated as this region is prone to high mesoscale activity generally occurring in the form of Agulhas Rings which originate from the Agulhas Current Retroflection. The current NOMADS LAS has been updated by NOAA and so data can be accessed through the National Virtual Ocean Data System (NOVDS) http://ferret.pmel.noaa.gov/las/ , Physical Oceanography Distributive Active Archive Centre (Physical Oceanography DAAC) LAS http://thredds.jpl.nasa.gov/las/ or the National Oceanographic Data Centre (NODC) LAS http://data.nodc.noaa.gov/las/

Bathymetry Data: ETOPO 2

The topography of the GoodHope transect in section 2.2 is constructed using the ETOPO2 dataset with 2 by 2° resolution across both the land and sea. The data for the ETOPO2 dataset is composed chiefly from satellite observations and ship echo sounding measurements available for public access at http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO2/ETOPO2v2-2006/

All the data (XBT and altimetry), analysis and construction of figures were investigated and composed using Matlab R2011b, version 7.13.0.564, with the exception of Figure 11 (July 2012 transect) which was produced using Ocean Data View (ODV) version 4.4.4.

With the following methodology and datasets, eight years of high resolution XBT data, we are able to resolve the variability of the ACC and in so doing, investigate the effect mesoscale events and topography have on position of the ACC. The high resolution and length of the dataset achieved during the first decade of GoodHope measurements enable the core objectives of this study to be confidently achieved namely:

(i) The interference and influence mesoscale features, such as eddies and Agulhas Rings have on the position of the ACC and its fronts and

(ii) The influence topography has on the position of the ACC along the GoodHope transect

Results and Discussion

1. Frontal Shifts over the last decade

The ACC is the primary driver for the exchange of water, heat and salt between the Indian, Atlantic and Pacific Oceans. This exchange is a key element in the MOC, which has an impact on the global climate. Since the ACC is an important component, of the global ocean understanding its special extent and structure is crucial to understanding the ACC (Swart, *et al*., 2008; Orsi, *et al*., 1995). Due to its influence on the global climate and MOC, the position of the ACC and its fronts are of key importance. The frontal zones are regions of water mass formation and therefore a shift in the region may have an impact on the water mass production and in turn the exchange of heat. Using the hydrographic data from 21 separate transects along the GoodHope transect, the question of whether there is an annual shift in the position of the fronts of the ACC is posed?

1.1) Comparison of frontal positions from individual cruises

Key Question 1 – The interference and influence mesoscale features, such as eddies and Agulhas Rings have on the position of the ACC and its fronts

Using the criteria outlined by Sokolov and Rintoul, (2009) (Table 1), the fronts for individual transects were identified and graphed (Figure 8). As Sokolov and Rintoul, (2009) do not define criteria for the STF, the conventional identification of 10°C at 200m extrapolated from Belkin and Gordon's (1996) study in the South-east Atlantic was used to identify and locate the front. The frontal positions are represented in the figure below.

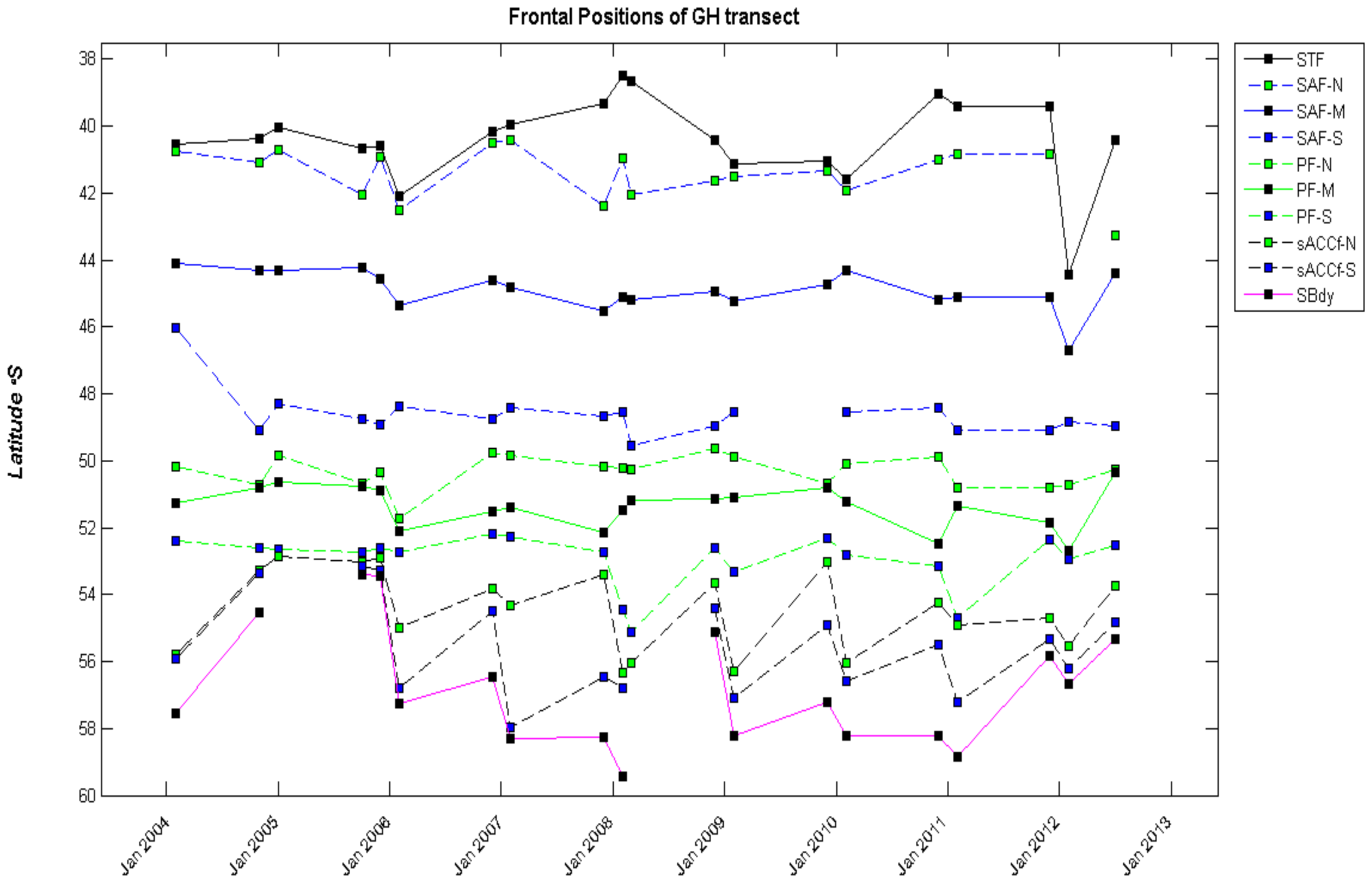

Figure 8: Latitudinal positions of the frontal systems from each individual transect and the respective branches of the ACC identified for that transect. The black squares (on a solid line) represent the main or middle branch of the front whereas the green and blue squares (on a dashed line) represent the northern and southern branches respectively. The black line represents the STF, blue lines - SAF, green lines – PF, grey lines – sACCf and cyan line – SBdy.

Variability of the ACC fronts observed during the GoodHope Cruises

The STF and the SAF-N in figure show the largest and most irregular variability observed with latitudinal shifts ranging from 2-4º and 1-2° respectively. A high standard deviation of the mean of 1.36° is observed for the STF, where the mean position of the STF is 40.38°S. The mean position for the SAF-N is located at 41.30°S ±0.65°. This is due to the frequent mesoscale activity, such as eddies and Agulhas Rings, which alter the frontal positions as these mesoscale features advect through the region either Northward or Southward (Dencausse, *et al.*, 2010). The ring shedding events are thought to have a great effect on the local biology and primary production as the rings may alter the local temperature, salinity and nutrients and more importantly the Mixed Layer Depth (MLD) (Billany, *et al.*, 2010 ; Swart, *et al.*, 2012).

Mesoscale events may enter the SAZ and occasionally alter the position of the SAF-N and possibly the SAF-M. The SAF-M (mean position 44.92°S ±0.61°), SAF-S (mean position 48.59°S ±0.72°) and

PF-N, M, S (mean positions 50.32°S ±0.51°, 51.41°S ±0.59°, 52.98°S ±0.84° respectively) display little variability with no notable perturbations with mean standard deviations in latitudinal position ranging from 0.5° to 0.7°. This is in agreement with Billany, *et al*, (2010) where the largest variability is observed north of the SAZ and less pronounced variability occurring within the SAF and PF. The southernmost fronts, namely the sACCf and SBdy, show large variability, possibly due to seasonal sea ice melting. This variability is confirmed with mean standard deviations of 1.25°, 1.48° and 1.84° are seen for the sACCf-N (mean position 54.48°S), sACCf-S (mean position 55.61°S) and SBdy (mean position 56.88°S) respectively. The melting of sea ice inputs colder fresher water into the Antarctic zone, which thus alters the temperature and salinity of the surrounding waters. This input leads to the formation of Winter Water mass which is defined as the subsurface temperature minimum water which is overlaid by warmer, fresher, well mixed surface layer water (Park, *et al.*, 1998). As a result of this input, a shift in the position of the front was observed. The shift in frontal position of the sACCf and SBdy (shown in Figure 8) occurs mainly over the summer months between December and February. During this period, the seasonal melting of sea ice around the Antarctic continent occurs which adds cold fresher water into the Southern Ocean.

Due to the paucity of GoodHope transects and the lack of sampling throughout the year, individual transects are grouped into austral summers (December, January, February) in order to construct a mean inter-annual comparison of the frontal positions. Although Argo would provide supplementary data, XBT's provide higher resolution data as they are more regularly sampled, thus smaller features are easily identified. The grouped summers are examined in order to obtain a better understanding of the variability of each front and allows for a more deductive approach in observing the variability annually.

1.2) Comparison of Summer frontal positions

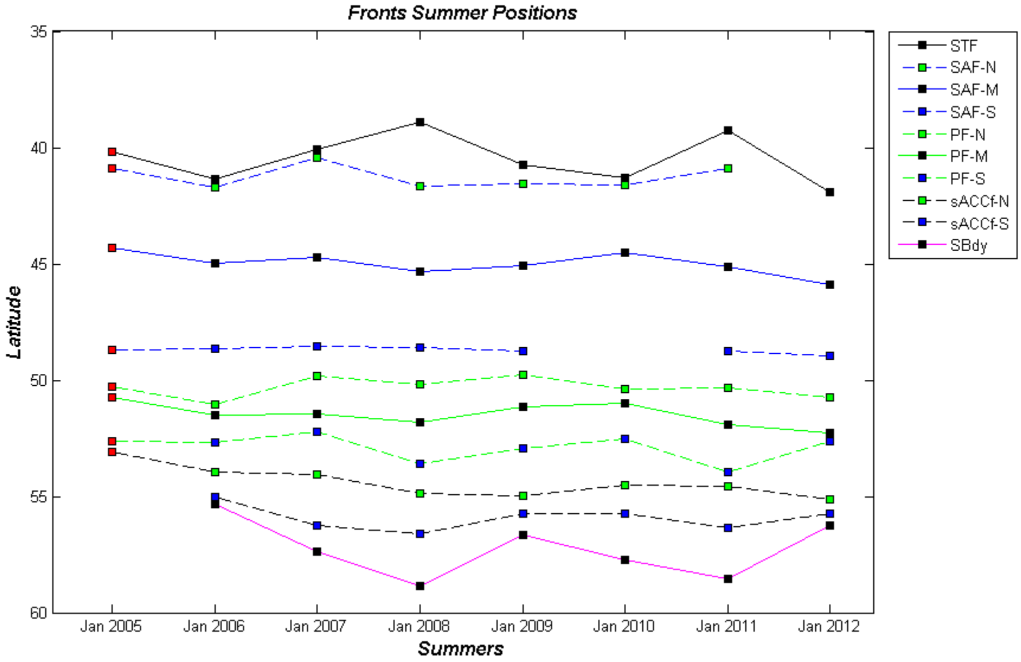

Figure 9: Graph showing the summer frontal positions. Red dots represent summer 2005 taken from (November 2004 and January 2005); all other dots are grouped from austral summer (December to February)

Grouping the GoodHope transects into one austral summer season, allows for a more deductive year-to-year approach in identifying the variability which occurs in the fronts. Once again, the STF is the most variable of all the fronts, with shifts ranging between 2 – 4° however a slight di-pentadal nature is observed. This result suggests that there may be some larger scale pattern/event which may affect the position of the STF. Billany, *et al*. (2010), it is inferred that the phasing of the Semi-annual oscillation (SAO) may impact on the seasonal shift in the position of the fronts. A similar di-pentadal pattern is observed within the SAF-N and the SAF-M, however, it is not as pronounced as that observed in the STF. The SAF-N is observed to partially follow the STF with a slight lag in the position. This is also observed in the SAF-M whereby there could be a slight lead of the STF. Although the magnitude of the variability is not as high as that of the STF, the positional shift observed follows that of the STF and SAF-N. The SAF-S displays very little variability over the seven year time period (seven summers) with no notable shifts in the position. The PF-N, M and S display moderate summer variability with an irregular pattern. The variability of the PF-N shows no distinct pattern with a high Southward shift in the front in the summer of 2006. The PF-M position had a slight di-pentadal pattern, however the time period is too short to draw any conclusive patterns which may exist. The same is observed with the PF-S whereby a slight pattern can be seen, however the timeframe does not allow for any conclusive patterns. The sACCf-N displays an irregular pattern with a Southward shift over a five year time period (from Summer 2005 to Summer 2009) with a relatively smaller shift observed in a three year period (Summer 2009 and Summer 2012). The sACCf-S was observed to follow the highly variable pattern of the SBdy. This may be due to the magnitude of sea ice formation from one year to the next.

Although there is variability within the SAF, PF and sACCf, the magnitude and range of the variability is not as great as that of the STF and the SBdy (Billany, *et al.*, 2010). As the focus of this work is not the ice formation and melting dynamics, the variability of the SBdy is not discussed in detail within this study. To correlate summer variability with the variability of the STF from individual cruises, an overlay graph was created. The choice for focussing on the STF is two-fold: it has the largest variability of all the ACC fronts observed and it is affected by mesoscale features, which will be highlighted further later on in this manuscript.

1.3) Variability of the STF

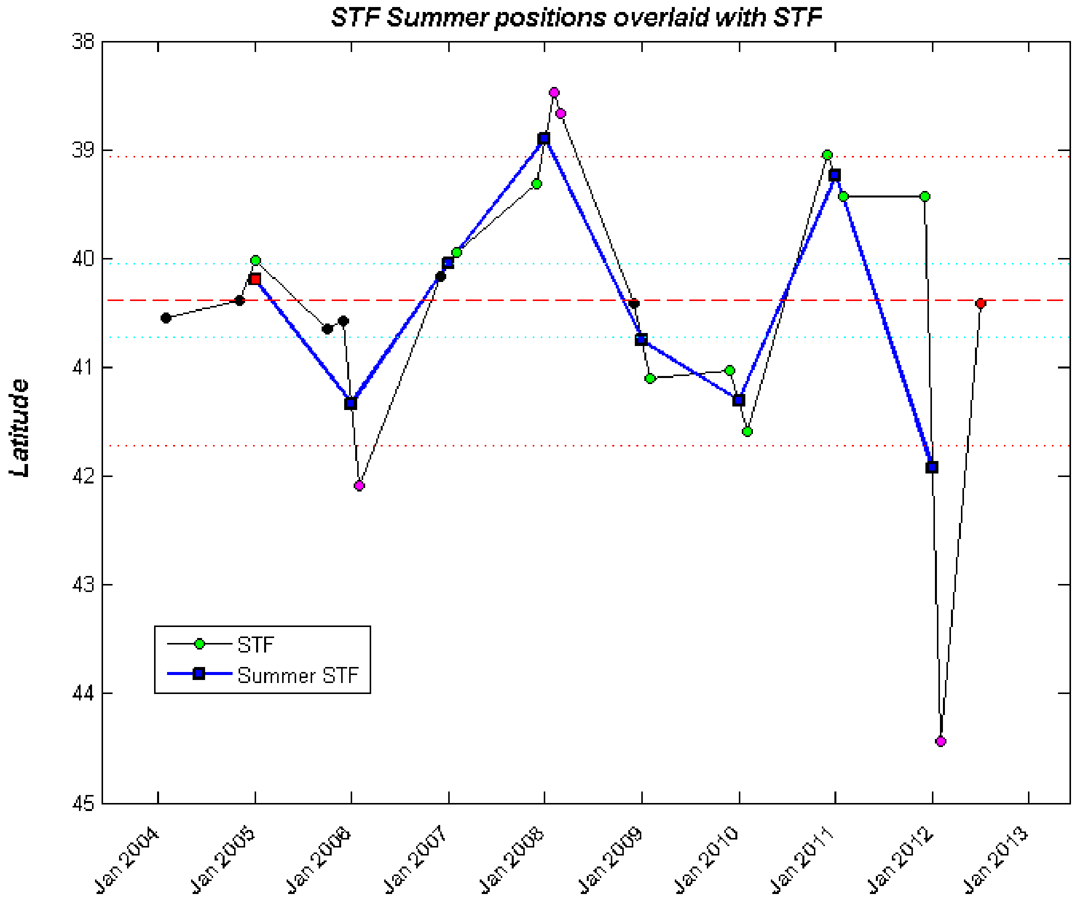

Figure 10: A graph showing the STF mean summer positions (blue line) derived from and overlaid onto the STF observed positions for individual transects (black line). The dashed red line represents the mean position of the STF, the dotted red lines represents one std. deviation from the mean and the dotted cyan line represents 0.25 of a std. deviation within which specific cruises (black dots) were selected to create a composite. Anomalous transects are shown in magenta. July 2013 (winter cruise) is represented as a red dot and Summer 2005 (November 2004 & February 2005) is represented as a red square.

From Figure 8, the frontal position derived from individual transects, no distinct pattern is observed in the STF, however, when overlaid with the summer positions, it is evident that a pattern becomes more distinct (see Figure 10).

Figure 10 indicates that the shift in the summer position of the STF is observed from the various cruises where anomalies within the frontal position have occurred. These anomalous shifts are thought to be a result of mesoscale activity and influence of Agulhas rings and eddies. These Agulhas rings, shed off from the Agulhas Current and Agulhas Retroflection, distort the thermal structure of the upper layer of the ocean. This, in turn, impacts the identification of the frontal position, when identified from both satellite and *in-situ* data, as it affects the temperature, sea surface height (SSH). Further investigation on the effect of the mesoscale on the thermal structure of the upper ocean is presented in the following chapter.

1.4) Winter Comparison of front positions

The GoodHope transect in July 2012 is unique in that it represents the first winter transect undertaken along this monitoring line. The lack of data is due to the rough sea state, stormy conditions and severe sea ice formation occurring within the Southern Ocean making it challenging for winter sampling. The July 2012 GoodHope transect, thus, presents a snapshot of the winter conditions of the SO. This is of particular importance as winter serves as a 'reset' for several hydrographic variables such as nutrients and chlorophyll. The mixed layer is deepened as more mixing occurs due to weather/wind induced turbulence. The data obtained during this winter period is of importance as it presents the first high resolution temperature of the upper 1000m and is crucial for improved input of models and satellite calibration.

Table 2: Table showing the mean frontal position of the various fronts of the ACC, the winter frontal positions and the magnitude and direction of the shift observed.

Front	***Mean Position (°S)***	***Mean Standard Deviation***	***Winter Position (°S)***	***Directional Shift***
STF	40.38	1.36°	40.42	0.036° South
SAF-N	41.29	0.65°	43.25	1.954° South
SAF-M	44.91	0.61°	44.4	0.519° North
SAF-S	48.59	0.72°	48.94	0.346° South
PF-N	50.32	0.51°	50.27	0.058° North
PF-M	51.41	0.59°	50.33	1.083° North
PF-S	52.97	0.85°	52.52	0.458° North
sACCf-N	54.48	1.25°	53.73	0.751° North
sACCf-S	55.61	1.48°	54.81	0.8° North
SBdy	56.87	1.84°	55.33	1.549° North

During winter, an overall Northward shift is observed in most of the fronts with the magnitude of the frontal shift ranging between 0.05° and 1.5°. The only fronts to experience a Southward shift are the STF, SAF-N and SAF-S with the largest of these shifts occurring in the SAF-N where the Southward shift is seen to be almost 2° in latitude. This is also the only significant shift observed within all the frontal shifts where its Southward shift exceeds that of the standard deviation. A possible reason for this is that the outcrop of the Sub-Antarctic Mode Water (SAMW) may have occurred slightly further south than usual. A similar scenario is observed in the PF-M where the significant Northward shift of 1.083° could be attributed to the outcrop of Antarctic Intermediate Water occurring further north than usual. This was observed in the temperature/salinity section of the July 2012 transect (see figure 11).

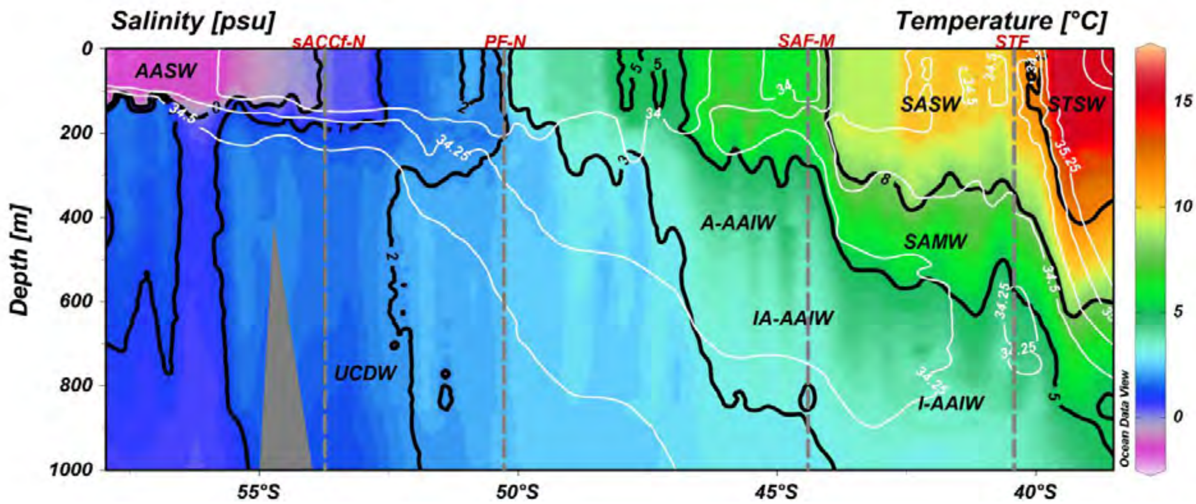

Figure 11: Temperature section of the July 2012 transect with the water masses identified. Overlaid onto it are haloclines (solid white and black dashed line (34.6)), isotherms (solid black) and dashed grey lines indicating the frontal positions. The water masses read as follows: Subtropical Surface Water (STSW),Sub Antarctic Surface Water (SASW), Sub Antarctic Mode Water (SAMW), Antarctic Intermediate Water (AAIW), Upper Circumpolar Deep Water (UCDW), and Antarctic Surface Water (AASW). I-, A- & IA-AAIW: Indian, Atlantic & Indo-Atlantic Antarctic Intermediate Water.

Although some of the shifts are > 0.5° in latitude, they are smaller than those observed in the other two chokepoints within the Southern Ocean (between Tasmania and Antarctica and in the Drake Passage) ranging between 1°-2° (Budillon & Rintoul, 2003). Most of these Northward shifts in the fronts are proposed to be seasonal as they migrate with the movement of the Inter Tropical Convergence Zone (ITCZ). This seasonal shift occurs predominantly during the winter months and returns to its initial position during the summer months. The STF and the SAF-N are prone to the Southward shift as the winter cruise passed directly through a warm core eddy which may have shifted the position of these fronts (Wu, *et al.*, 2007 ; Anderson, *et al.*, 2009).

2. Links to Mesoscale Variability and Topography:

Key Question 2: The influence topography has on the position of the ACC fronts along the GoodHope transect

Historically, the understanding of variability in the strength and position of the ACC fronts within the Southern Ocean was limited due to scarce *in-situ* data. To some extent, this has been partially overcome with the development of remote sensing and observations (SST and SSH) which can be used to identify the frontal systems in the Southern Ocean. (Graham, *et al.*, 2012). Mesoscale activity affects the location of the front positions when identified with *in-situ* measurements and remotely sensed data (Faure, *et al*., 2011; Swart, *et al*., 2012; Dencausse, *et al*., 2010). This is of key interest as many numerical models have difficulty in resolving the front (chiefly the STF) due to influence of frequent mesoscale features. For remotely sensed instrumentation, the position of the front is identified using measurements of SSH by calculating the SSH gradients at various points. The passing mesoscale features have key signatures of raised or depressed SSH and alter the gradients, when crossing fronts,. Consequently, this affects the identification of the front and makes it difficult to locate the true position of the front should there have been no mesoscale interference.

Similarly, mesoscale features have unique temperature and salinity profiles which affect the identification of the front from *in-situ* data. This is because the criteria for the identification of the front from *in-situ* data - is based upon key hydrographic variables, namely temperature and salinity. The northern extent of the ACC is subject to high variability due to passing mesoscale features such as Agulhas rings and eddies (Swart, *et al*., 2012). Of all the fronts, the STF is predominantly the most affected by the passing of mesoscale features, and so the question of how the STF is influenced by these passing mesoscale features is posed. By looking at various case studies of specific cruises undertaken along the GoodHope transect, the question of how Agulhas rings affect the STF is resolved.

2.1) How is the thermal structure of the upper ocean (1000m) altered with the passing of an Agulhas Ring?

Agulhas rings are shown to alter the position and permeability of the STF as these criteria are temperature driven (Swart, *et al*., 2012). Because of its position, the STF modulates the salinity and temperature of water from the Agulhas leakage and therefore enhances the formation of NADW (Graham, *et al*., 2012). The rings that are shed off the Agulhas Current, as a result of the variability of the Agulhas retroflection, make it difficult to identify the STF because of the effect the ring has on the ambient temperature. These rings have a major influence on the MOC through its impact on the global heat and salt budget (Swart, *et al*., 2008; Beal, *et al*., 2011).

In order to obtain a better understanding of how the mesoscale features affect the position of the STF, two individual cruises. The first cruise track (February 2006) intersects a mesoscale feature whereas the second cruise (December 2008) does not. As a result, the STF located from the first cruise is further south than to the STF located from the second cruise.

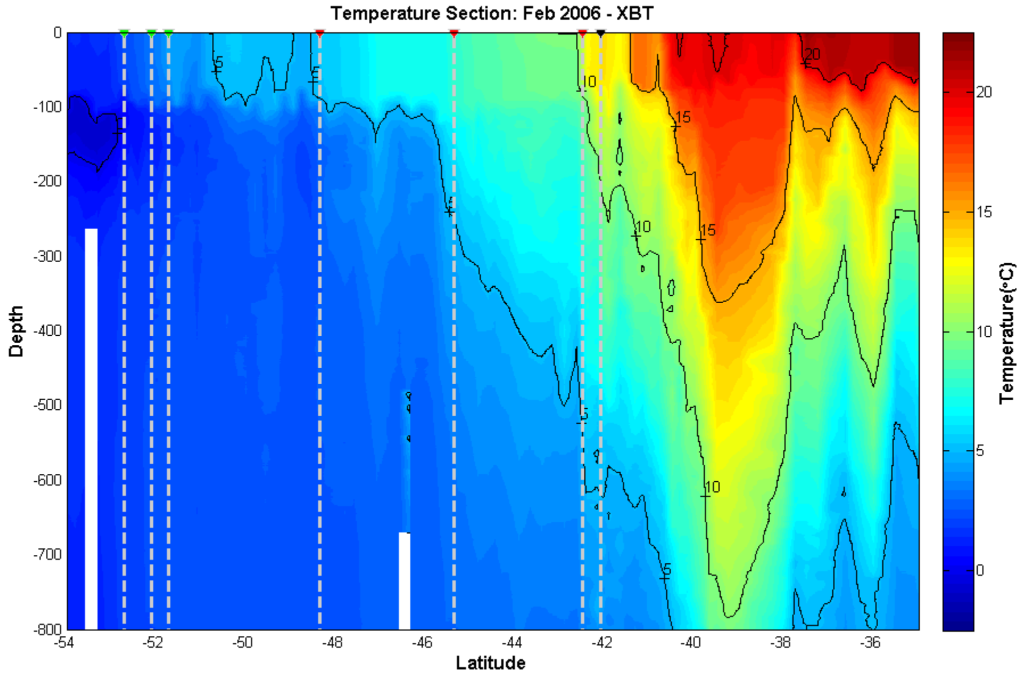

Figure 12: Temperature section along the GoodHope transect in February 2006 passing through an Agulhas ring (39°S). Coloured arrowheads from right to left on top represent the position of the fronts (black – STF; red –SAF-N,M,S; green – PF-N,M,S) as defined in Table 1.

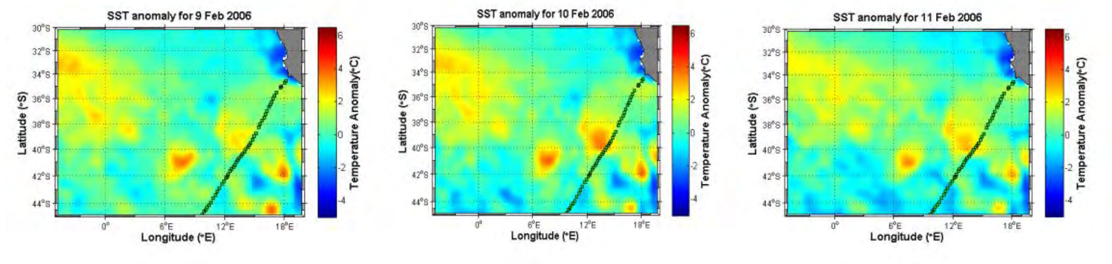

Figure 13(a)(b) and (c): Sea surface temperature anomaly (annual) South-west of Cape Town overlaid with the cruise track for 3 days in February 2006.

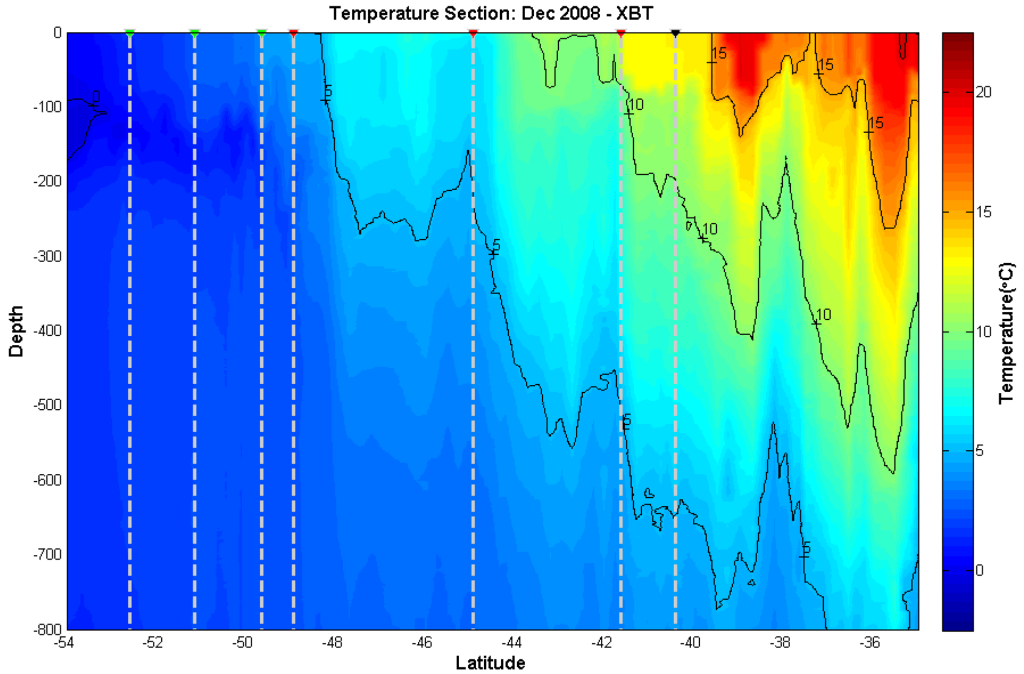

Figure 14: Temperature section along the GoodHope transect in December 2008 which does not pass through an Agulhas ring. Coloured arrowheads from right to left on top represent the position of the fronts (black – STF; red –SAF-N,M,S; green – PF-N,M,S)

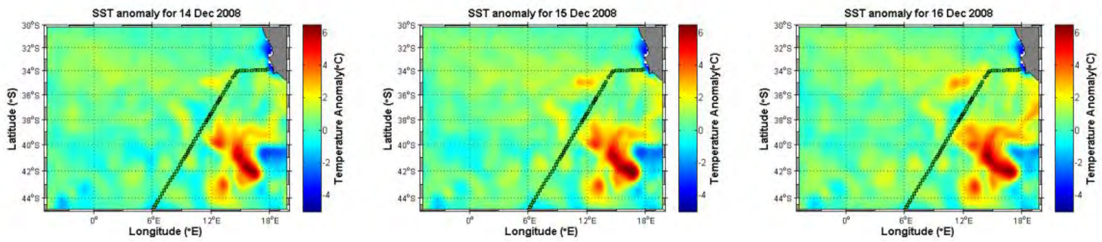

Figure 15(a)(b) and (c): Sea surface temperature anomaly (annual) South-west of Cape Town overlaid with the cruise track for 3 days in December 2008.

Figure 12 demonstrates how the 10°C isotherm is deepened by up to 300m when compared to Figure 14. This is as a result of the cruise undertaken in February 2006 intersecting an Agulhas ring whereas the cruise undertaken in December 2008 veers past an Agulhas ring. This is confirmed by SST anomaly data (Figures 13a, b and c; Figures 15a, b and c) whereby a clear picture is observed of the cruise tracks intersecting the Agulhas ring and where it does not. A key characteristic of the passing mesoscale feature is the deepening of the isotherm. This characteristic, results in the STF being placed further South than at the mean position of 40.384°S.

A temperature difference section between two cruises allows one to identify the thermal impact that an eddy has on the upper ocean thermal structure. Figure 16 illustrates this by a simple difference between the two cruises.

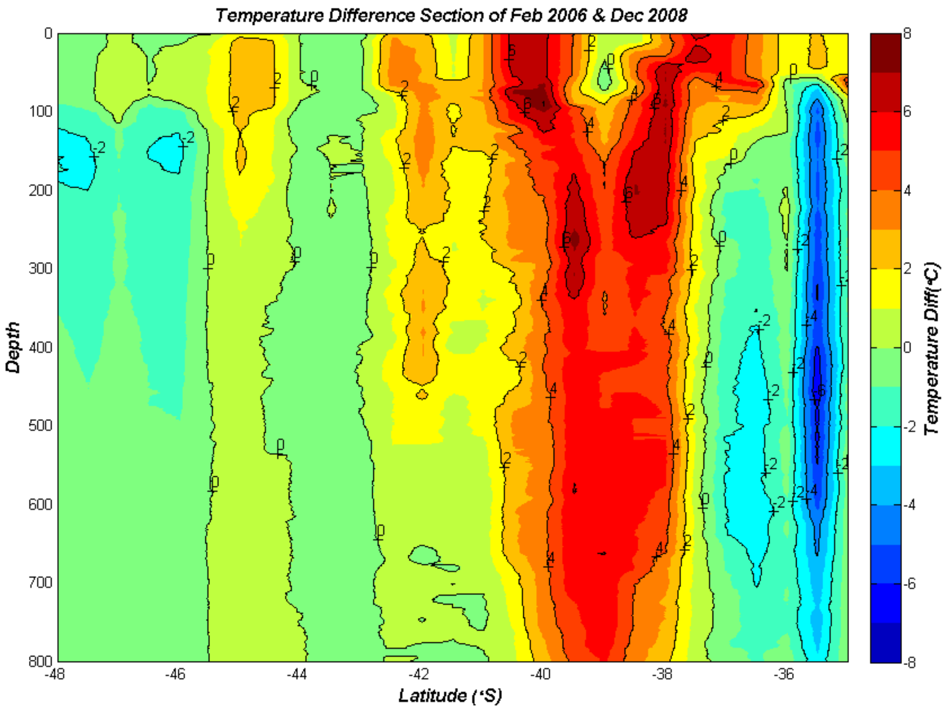

Figure 16: The temperature difference section of February 2006 and December 2008.

From this figure at the location it is evident that the eddy alters the temperature profile of the ocean by up to 6°C where the eddy was intersected. This profile also highlights the barotropic nature of the ring as the 2°C and 4°C isothermal difference is observed to extend down to 900m. This difference is characteristic of Indian Ocean Water which is warmer than the waters from the South Atlantic (Swart, *et al.*, 2010). This is in accordance with Arhan, *et al.* (2011) who deduces that eddies trap Sub Tropical water down to 900m and the water below being from the northern part of SAZ or local water. This water is trapped by eddies which flow Southward from the Agulhas Current.

The shift in the STF is a process that is not completely understood as many factors contribute to this shift. The variability of the STF is, thus, partially attributed to the passing of mesoscale features because these features alter the thermal structure of the water column. This is observed by the passing of Agulhas rings and eddies which alter the local temperature and is seen to shift the position of the STF, as the criteria for the identification for the STF from *in-situ* data is temperature dependant. Although mesoscale variability is one of the major contributors to the shift of the STF, it is only but one factor to consider.

The GoodHope programme monitors the exchanges between the Indian and Atlantic so as to better understand the processes involved in the exchanges. The GoodHope transect, thus, provides regular information on the volume transport of the exchanges (Arhan, *et al.*, 2011)

2.2) Is frontal variability linked to topography?

Along the GoodHope transect, two major oceanic ridges are crossed, the Mid Atlantic Ridge, located near 54°S, and the Agulhas Ridge, located at 43°S. These ridges are traversed by all of the GoodHope transects and thus the link of variability in the position of the front (the STF and SAF-N) to topography can be posed?

A recent paper by Graham, *et al.* (2012) poses the question whether the fronts within the Southern Ocean are controlled by winds or topography. Their results are that topography plays a vital role in the position of the fronts as the fronts are observed to be barotropic in nature. Abyssal Regions with flat topography are observed to have lower variability than regions with steep topographic ridges. Within these flatter regions, the wind is, thus, the primary controller of the shift in the front. This paper predominantly focuses on the Pacific sector of the SO, however the implications of the results are applicable to all sectors of the SO. This is observed by the confirmation that flat regions of the Southern Ocean experience smaller shift in the position of the front via the low variability seen in the SAF and PF (Figure 8) of the central southeast sector of the SO. This is because this sector of the Southern Ocean is seen to not have many topographic features (Figure 6).

In this study, the same has been observed for the STF and SAF-N whereby these two fronts are located near the Agulhas ridge at 43°S and which may be attributed to the shift in the front. This is illustrated by the temperature difference observed in the combined February 2008 and March 2008 transects against the mean frontal position composite. In both the February and March 2008 transects, the STF was observed to be 1.3° further south than with any of the other transects.

To create a mean frontal position composite, specific cruises were selected (represented as black dots in Figure 10). These specific cruises were selected as they were within 0.25 of a std. deviation from the mean (represented as dotted cyan line and dotted red line in Figure 8 respectively). Although the July 2012 transect (red dot in Figure 10) falls within the 0.25 std. deviation region, it is not included in the construction of the mean frontal position composite as this is the first and only early winter transect undertaken along the GoodHope transect.

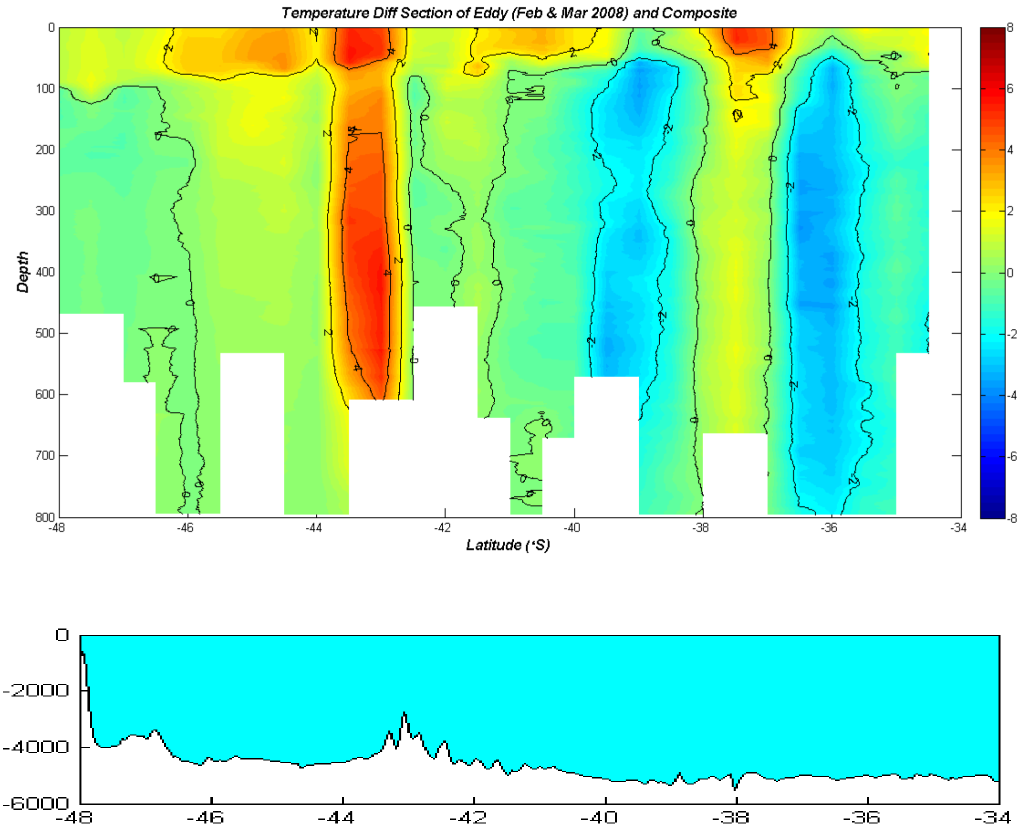

Figure 17(a) and (b): 17(a) represents the temperature difference between the combined February 2008 and March 2008 transects and the mean frontal position composite. 17(b) highlights the bathymetry along the 8.85°E longitude. The Agulhas Ridge can be seen at 43°S.

Figure 17(a) illustrates the difference observed when passing through an Agulhas ring at the Agulhas ridge. The difference in temperature (about 4°C) is attributed to an Agulhas Ring which is shed off and stalled at the Agulhas ridge (seen in Figure 17(b)). This stalling is due to the Agulhas ring interacting with the topography because of its barotropic nature. The same Agulhas ring was sampled by both the February and March 2008 transects. When Agulhas rings reach the ridge, they stall for some time and undergo cooling, though this cooling does not impact their life span. Because of the cooling that occurs when rings are stalled at the Agulhas ridge, the rings lose their SSH anomaly signature as the core of the ring is cooled (Dencausse, *et al.*, 2010). As a result of the Agulhas ring being stalled by the ridge, a Southward shift of approximately 1.3° is observed in the STF. This was also noted by Swart, *et al,* (2012) whereby the same shift was observed. The implication of this is that topography plays a considerable role in the position and variability of the STF, moreover on the fronts of the ACC, within the central southeast sector of the Southern Ocean.

Conclusion

The Southern Ocean (SO), south of 40°S, plays a major role in the heat and salt budget across the globe which in turn drives the Meridional Overturning Circulation, a deep density driven current, which extends around the globe (Gille, 2002). It forms the platform for inter ocean exchanges through its interconnectivity of the various oceans (Speich, *et al.*, 2008).

The ACC is the primary driver for the inter-basin exchanges (Speich, *et al.*, 2008). It follows on that the ACC is the global link to all the major oceans in that specific deep water masses from the North enter the circumpolar current, and mix with the Antarctic shelf water, thus, changing its properties (Orsi, *et al.*, 1995). The understanding of the fronts and their variability is of importance as our knowledge of the ACC and its dynamics is poor (Swart, *et al.*, 2012).

The central southeast Atlantic sector of the Southern Ocean primarily consists of Indo-Atlantic exchanges which occur via Agulhas Rings which originate from the variability of Agulhas retroflection. The GoodHope transect, created and implemented in 2004, provides a monitoring transect to observe, monitor and investigate the processes which occur within the central southeast Atlantic sector of Southern Ocean (Swart, *et al.*, 2012). Topographically, the area between the South Africa and Antarctica is one of the 3 major 'choke-points' in the Southern Ocean as it runs through the Southwest Indian Mid-Oceanic Ridge and has been less investigated than the other two chokepoints until the implementation of the GoodHope transect (Holliday & Read, 1998). Several groups and programmes, such as SOCCO and SOOS, continue to undertake transects along the GoodHope transect to improve the quantity and quality of sampling within the Southern Ocean and thereby understand the processes which occur therein (Arhan, *et al.*, 2011).

Key Question 1 – The interference and influence mesoscale features, such as eddies and Agulhas Rings have on the position of the ACC and its fronts

By identifying the positions of the fronts of the ACC from *in-situ* XBT data and comparing the results, the variability within each of the fronts can be observed. The largest variability was observed in the southernmost fronts, namely the sACCf and SBdy, and northernmost fronts, namely the STF and the SAF-N. The central fronts displayed low variability displaying a shift ranging about 1°. The southernmost fronts displayed high variability due to the seasonal change of the surrounding environment, more specifically the melting of sea ice which alters the temperature and buoyancy of the surrounding waters. The northernmost fronts display high variability due to frequent mesoscale activity, such as eddies and Agulhas rings, which occur as a result of variability of the Agulhas retroflection, however no distinct pattern can be observed due to the sparseness of the data and lack of scientific cruises. Further observations are thus required for a more in-depth analysis of the variability. Grouping the GoodHope transects into austral summers, allows for a more regular pattern to be observed than by observing the individual cruises.

The results obtained in this study confirm those reported by Billany, *et al,* (2012) whereby the variability of the northern and southern fronts of the ACC (STF, sACCf and SBdy) are highly variable whereas the mid fronts of the ACC remain fairly consistent (SAF and PF). This is confirmed through the high standard deviations from the mean for the southern and northern fronts and low standard deviations middle fronts.

By grouping the GoodHope transects undertaken between 2004 and 2012 into summers, a distinct pattern can be observed in the STF, SAF and the SBdy. The STF displays a di-pentadal nature whereby a six year pattern is observed in the shift of the front. This is observed in the SAF-N as well, however, it is not as pronounced as the shift in the STF. The SBdys annual shift may be attributed to the magnitude of sea ice melting from year to year where more ice may be formed in some years and less in others.

When overlaying the summer frontal positions and the frontal position from each transect undertaken, it is evident that the shift in summer positions can be associated to the cruises where the cruise track completed for that transect intersected an eddy or Agulhas ring. This affect the position of the front as the criteria for identifying the front is dependent upon key hydrographic variables, namely temperature and salinity.

The July 2012 GoodHope transect presents a snapshot of the winter conditions in the SO. Most of the fronts are observed to shift Northwards with only the STF, SAF-N and SAF-S shifting Southwards, this was due to the transect intersecting an Agulhas ring thus altering the position of the fronts. Of all the frontal shifts, only two are of significance, the SAF-N and the PF-M whereby a shift of 1.95°S and 1.08°N are observed respectively. This is due to the outcrop of different water masses, namely Sub-Antarctic Mode Water and Antarctic Intermediate Water occurring further Southward and Northward respectively. Overall the Northward shift of all the fronts may be due to the seasonal migration in the latitude of the ITCZ where the climatic zone shifts slightly Northward during the winter months and the winds which drive the ACC shifts as well (Wu, *et al.*, 2007 ; Anderson, *et al.*, 2009). Although a comparison is investigated between winter and the mean position, it is only a ‘snapshot’ over the time period. The July 2012 winter transect is only a single cruise and therefore limited with sampling and knowledge of the winter scenario. More cruises (transects) are required to expand our existing data and knowledge about the conditions of the Southern Ocean during winter.

Although there is a shift in the location of the fronts, the question of how Agulhas rings affect the position of the STF is investigated here by carrying out a case study comparison of two cruises (one undertaken in February 2008, which passed through an eddy; and another one undertaken in

December 2008 which did not pass through an eddy) and observing the how the upper ocean thermal structure changes by the passing eddy. In this comparison, it becomes evident the impact the Agulhas ring has on identifying the STF. Passing through the ring deepens the thermocline due to the core of the eddy being warmer than the surrounding. These Agulhas rings are of importance to the Indo-Atlantic exchanges and, in turn, the global heat and salt budget.

Key Question 2: The influence topography has on the position of the ACC fronts along the GoodHope transect

Even though mesoscale features affect the position of the northern fronts of the ACC, it is only one factor to consider when considering the variability. The GoodHope transect encompasses two major oceanic ridges, namely the Agulhas ridge and the Mid-Atlantic ridge which also contribute to the variability observed in the position of the northern fronts of the ACC. This occurs via the Agulhas ridge stalling Agulhas rings which follow the Southern Route. This stalling does not affect the lifespan of the Agulhas ring although affects the position of the northern ACC fronts, especially the STF by deepening the isotherm which defines the frontal position. The low variability of the SAF and PF is an indicator that there is a very small adjustment in the position of the front over the flat topographic region. This result confirms the results of Graham, *et al,* (2012) observed in the Pacific Ocean and its application to the central southeast sector of the SO.

A better understanding is needed in order to fully characterize and evaluate all the processes and dynamics which occur in the SO. From this study, two key limitations are identified: the length of timeframe and, the sparseness of data. Although short term patterns can be identified, the period of the timeframe does not allow for any long term modes of variability to be identified. Thus, a longer time series would allow for a more defined investigation and more conclusive results as to the variability of the fronts. Because observations are sparse, our understanding of the ACC, MOC and Southern Ocean remain rudimentary. This is predominantly observed in the lack of cruises undertaken during winter in the Southern Ocean. Argo has greatly improved sampling within the Southern Ocean where its greatest impact comes from increases in both the temporal and spatial sampling which would not usually occur due to the harsh and inclement conditions (Lyman, *et al.*, 2010). Considering Argo float data to identify the fronts would be of great significance however, the limitations of robotic systems may influence the amount of data collected. These include lifespan, maintenance and both hardware and software malfunctions. Despite these, further studies lead toward a comparison between Argo float data and XBT data and the identification of the fronts from either set of data from the identification criteria being based largely upon hydrographic variables. This is possible as both Argo floats and XBT's measure temperature through vertical profiling, thus the two datasets would allow for a comparison of the location of the fronts when identified using the same criterion from either dataset. This would also allow for a more in depth seasonal study as Argo floats are autonomous and sample all year round.

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