University of Cape Town

Department of Oceanography

CHARACTERIZATION OF A WARM-CORED AGULHAS RING TRAVELLING SOUTH OF THE SUBTROPICAL FRONT

A minor dissertation presented in partial fulfilment of the requirements for the degree of Master of Science

by

Patrick Vianello

Supervisor: Dr Isabelle Ansorge

Co-supervisor: Dr Sebastiaan Swart

September 2010

PLAGIARISM DECLARATION

1. I know that plagiarism is wrong. Plagiarism is using another's work and to pretend that it is ones own.

2. I have used the American Psychological Association (APA) as the convention for citation and referencing. Each significant contribution to, and quotation in, this essay/report/project/… from the work, or works of other people has been attributed and has been cited and referenced.

3. This Masters Dissertation is my own work.

4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as his or her own work.

5. I acknowledge that copying someone else's assignment or essay, or part of it, is wrong, and declare that this is my own work

SIGNATURE: ___________________________

DATE: __________________

ABSTRACT

The south-eastern sector of the Atlantic Ocean near the South African coast is a region of high eddy activity in the form of Agulhas rings. These Agulhas rings play a vital role in the Indo-Atlantic inter-ocean exchange, and are critical for the global thermohaline circulation since these rings, spawned from the Agulhas retroflection, are typically of Indian Ocean origin. The pathway and behaviour of these Agulhas rings are affected by the underlying topography of the region with special reference to the Agulhas ridge and the Erica and Schmitt-Ott seamounts. This study investigates an Agulhas ring, which was identified during the Bonus-Goodhope cruise in February 2008. In addition to the hydrographic data obtained during this cruise, satellite data such as altimetry and Sea Surface Temperature (SST) are also employed to analyse and determine the origins of the feature, its development and life-span. The majority of Agulhas rings remain within the Subtropical domain, however during the 2008 Goodhope cruise a positive anomaly was observed south of the Subtropical Front in the Subantarctic zone. Studying these features which drift into the Subantarctic domain may be important in understanding the global heat and salt budget since these Agulhas rings have positive heat and salt anomalies with respect to the surrounding region. Overall, it can be concluded that the Subantarctic zone had a major impact on the core properties of the ring such as its mixed layer depth and that the underlying topography such as the Agulhas ridge had a major effect on the behaviour and life span of the ring.

ACKNOWLEDGEMENTS

I am extremely grateful to have had Dr Isabelle Ansorge as supervisor and Dr Sebastiaan Swart as co-supervisor during this project. If it was not for their advice and guidance over the past five months, this project would not have been possible. I would also like to acknowledge my two supervisors for their reviews on drafts of this project.

I would also like to acknowledge all those who took part in the Bonus-Goodhope cruise, which was completed in March 2008, without which, the hydrographic data would not be possible and hence the project would not have been possible.

Other datasets which were used in this study were downloaded (free of charge) via the internet. The altimetry data was available from AVISO (http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/index.html). Lastly, SST data was obtained from Remote Sensing Systems (http://www.remss.com/sst/microwave_oi_sst_browse.html).

Finally, I would like to acknowledge the University of Cape Town and the Post-Graduate Funding office for making this project possible as well as my family and friends for their constant support during the project.

Contents

1. LITERATURE REVIEW

1.1. Agulhas Current

Since Agulhas Rings originate from the retroflection region of the Agulhas Current, it is important to describe the characteristics of this western boundary current.

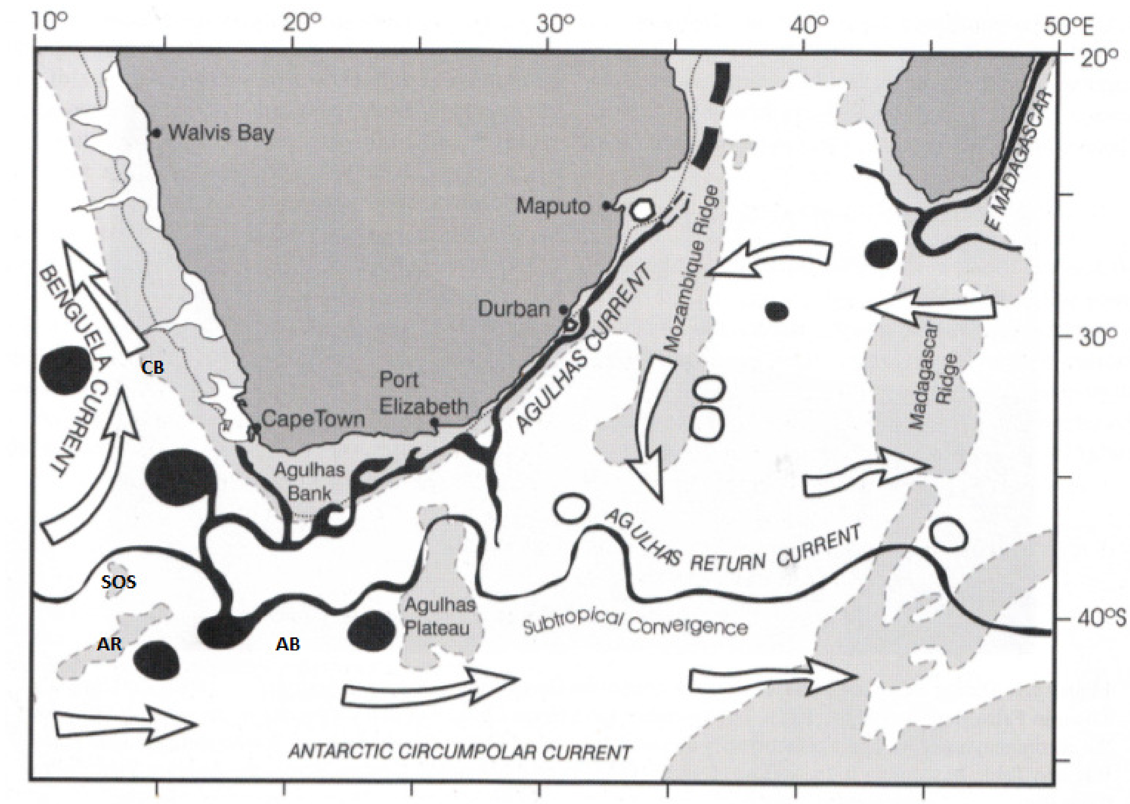


Figure 1.1 – Overview of the major currents surrounding Southern Africa (from Lutjeharms, 2006). Depths shallower than 3000 m are shaded. The edge of the continental shelf is marked by a dotted line. Intense currents are in black while the general background circulation has open arrows. Cyclonic eddies are denoted by open circles while the anti-cyclonic eddies are indicated by black circles. Included is the Agulhas Ridge (AR) and the Schmitt-Ott Seamount (SOS) while AB and CB represent the Agulhas Basin and Cape Basin respectively.

Flowing along the east coast of Southern Africa, the Agulhas Current is the western boundary current of the south-west Indian Ocean (Schouten et al. 2000). The Agulhas Current is characterised as a narrow, intense, fast-flowing current. On the basin scale of the Indian Ocean, the Agulhas Current is formed by the wind-driven subtropical gyre of the Indian Ocean. The sources feeding into this system are the East Madagascar Current, the Mozambique Current and a recirculation from the Agulhas Return Current (Stramma and Lutjeharms, 1997). However, the sources of the Agulhas Current are not fully understood but due to the oligotrophic nature of the current it is generally accepted that its sources are tropical and subtropical. The Agulhas transport increases from approximately 65 Sv at 32˚ S to 95 Sv in the proximity of the southern tip of Africa (Gordon et al. 1987). The current is approximately 100 km wide and has a mean velocity of approximately 0.6 m/s but reaches speeds in excess of 2.5 m/s (Lutjeharms, 2006). The Agulhas Current is typically subtropical with sea surface temperatures ranging between 27 ˚C in summer to 22 ˚C in winter and surface salinities ranging from 35.0 to 35.5 psu (Lutjeharms, 2006). The temperature of the Agulhas current is on average 6 ˚C higher than its surrounding waters (Lutjeharms, 2006).

1.2. Agulhas Leakage and Origins of Agulhas rings

The oceanic region south of Africa is a critical crossroad for the inter-ocean communication, where exchange of water, salt, heat, biota (animal and plant life) and human-induced (anthropogenic) tracers occurs between the subtropical South Indian Ocean, South Atlantic gyres and the cooler Southern Ocean Waters. The Agulhas leakage is the primary mechanism by which this transport takes place.

Numerical models have shown that the overturning circulation in the Atlantic Ocean is sensitive to the volume of heat and salt which is transported from the Indian Ocean (Lutjeharms, 2006). A modelling study by van Sebille and van Leeuwen, (2007) in which a two-layer model was used to study the translocation of Agulhas Rings and their associated energy into the North Atlantic Ocean proved that the rings temporarily increased the meridional overturning strength for approximately 1.5 years. An interesting result of this modelling study was that the Mid-Atlantic Ridge shortened the transfer time of the baroclinic energy (from 1300 days without the ridge to 10 days with the ridge in the model) while the transfer of barotropic energy was 10 days which was independent of the Mid-Atlantic Ridge. Hence the Mid-Atlantic Ridge is capable of converting barotropic energy to baroclinic energy (van Sebille and van Leeuwen, 2007). However, the presence of the Mid-Atlantic Ridge did not influence the response time of the overturning circulation (van Sebille and van Leeuwen, 2007). Since this overturning circulation in the Atlantic Ocean is a vital link in the global transport of heat from the tropics to the poles and consequently an important component of the global thermohaline circulation, the transportation of heat and salt from the Indian Ocean is critical (Lutjeharms, 2006). Most of this inter-ocean transfer takes place near the Agulhas Current Retroflection region through the spawning of large (>300 km) warm rings, which drift into the cooler South Atlantic and carry with them the warm, salty signature of the Indian subtropics (De Ruijter and Boudra, 1985). The mean position of the retroflection loop is approximately 20˚ E but is known to be highly variable (De Ruijter and Boudra, 1985). Recent investigations by Dencausse et al. (in press) have shown that the average position of the retroflection point is in a band between 18° – 20° E at 39.5° S. There are many occasions when the gradual westward movement of the retroflection loop ceases and it is during these events that Agulhas rings are shed (Schouten et al. 2000). There are various theories which propose mechanisms for these shedding events but a popular mechanism is associated with the meanders and increased instability in the Agulhas Current (Lutjeharms and Van Ballegooyen, 1988). As the Agulhas Current meanders, instabilities may form and these instabilities may interact with the Agulhas Return Current to form rings (Gordon, 1985; Duncomberae, 1991; Lutjeharms, 1996; De Ruijter et al. 1999; Lutjeharms, 2006). Over time, these rings gradually dissipate and "leak" their waters out into the Atlantic Ocean dispersing characteristics of the warm Indian Ocean into the cooler South Atlantic. However, the scarcity of direct observations in this region has greatly hampered the understanding of the physical environment, the variability of this exchange and its impact on the biota as well as the climate system of Southern Africa. Another theory of Agulhas ring formation is the intrusion of cold water from the south.

Occasionally cold denser Subantarctic Surface Water (SASW) extends northwards across the Subtropical Front (STF) literally “short circuiting “ the Agulhas Retroflection (Figure 1.2) and hence Agulhas rings may be formed (Lutjeharms and Fillis, 2003)

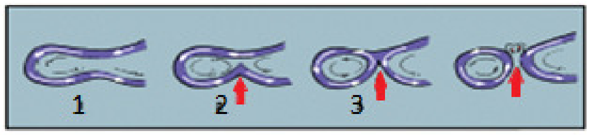


Figure 1.2 - sketch showing the intrusion of colder denser SASW, indicated by red arrows, and the influence of it on the Agulhas retroflection (from Lutjeharms, 2006).

To date, an abundance of information is available on the injection of Indian Ocean waters into the South Atlantic through ring shedding processes at the Agulhas Retroflection (Figure 1.1). The Agulhas rings, spawned at the Agulhas Retroflection, are anti-cyclonic in nature and consist of warm, salty Indian Ocean water. A typical characteristic of these Agulhas Rings is a very homogenous deep mixed layer with respect to the thermohaline properties, especially when these rings are subjected to intense convection. Figure 1.3 shows an Agulhas Ring (Astrid) which was surveyed during the MARE-1 cruise from 27 February to 19 March 2000. The ring was centred at approximately 37° 45' S and 18° 10' E (van Aken et al. 2003). The homogenous mixed layer can be seen to pressures of approximately 90 dbar in its centre by the depressed isotherms and isohalines.

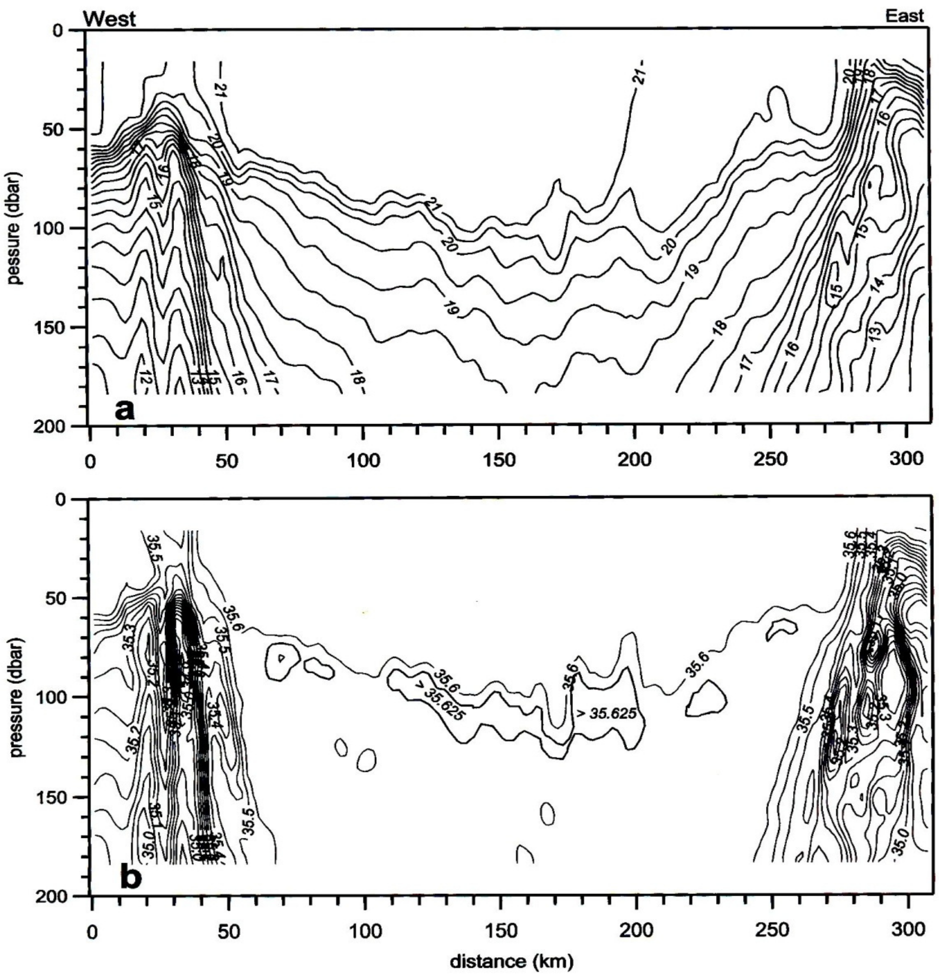


Figure 1.3 - Vertical distribution of temperature (a) and salinity (b) along the west-east section through ring Astrid (from van Aken et al., 2003). The horizontal resolution of the Scanfish survey at mid-depth amounts to 1.8 km. The isotherm distance in (a) is 0.5 ˚C; the isohaline distance in (b) is 0.05. In (b) an additional 35.625 isohaline has been drawn to mark the salinity maximum at the top of the thermocline (dashed line)

The total Agulhas leakage has been estimated to be about 15 Sv in the upper 1000 m, of which 10 – 13 Sv are due to Agulhas Rings (Richardson, 2007). From this, it is clear that Agulhas rings form a major part of Agulhas leakage with additional leakage via the advection of Agulhas filaments (Lutjeharms and Cooper, 1996; Gordon et al., 1992). However studies by Boebel et al., (2003) and Matano and Beier, (2003) have shown that cyclones also have an important role in the interocean exchange between the Indian and Atlantic Oceans although they are smaller than the anti-cyclonic Agulhas rings (van Sebille et al. 2010). Additionally, there may also be an interocean flux related to a continuous current seperate from the Agulhas leakage due to features which have detached from the Agulhas Current (van Sebille et al. 2010). The Good Hope Jet may be related to this interocean flux but the exact sources of this jet are not known (van Sebille et al. 2010). Part of the origins of this jet are most likely from the South Atlantic Ocean subtropical gyre but there may also be a connection from the Indian Ocean where the inshore part of the Agulhas Current may feed into the Good Hope Jet (van Sebille et al. 2010). However, further studies would need to be conducted in order to quantify this type of interocean flux.

Agulhas Rings are an important source of heat and salt for the South Atlantic Ocean and a key link in the global thermohaline circulation (Gordon, 1986). Agulhas rings are the most energetic of their kind in the world ocean (Olson and Evans, 1986). Rough estimates of the volume transport of each ring are approximately 0.5 – 1.5 Sv, dependent on ring size (Schouten et al. 2000). When propagating through the South Atlantic, Agulhas rings generally have positive Sea Surface Temperature (SST) anomalies compared to the surrounding waters but these anomaly signatures disappear fairly rapidly due to the strong air-sea fluxes in the region (Olson et al. 1992). Due to this, Sea Surface Height (SSH) data from satellite altimetry are used to track Agulhas rings as the SSH anomaly signature disappears more gradually than the SST anomaly associated with Agulhas Rings.

There are varying opinions on the number of rings shed per year but Goni et al. (1997) estimated approximately 3-6 rings shed per year, while a statistical study undertaken by Dencausse et al. (in press) during the period of 1992 – 2006, estimated approximately seven rings shed per year and Molinari et al. (2002) estimated 4-7 rings shed per year. The average drift velocities of these rings are approximately 5-15 km/day but they can slow down and even stall when encountering topographic obstacles (Byrne et al. 1995; Dencausse et al. in press).

1.3. Theories of Ring Formation

Oceanic rings form from strong ocean currents which become unstable (Olson, 1991). This hydrodynamic instability occurs when the strength of the ocean currents exceed the capability of the geostrophic balance to support a steady flow (Pedlosky, 1979). The hydrodynamic instability in the major western boundary currents and even the Antarctic Circumpolar Current (ACC) manifests itself in the form of meanders which, with time, grow. Sometimes, as these meanders grow, parts of the fluid current get closed off and the current becomes linear and stable once again (Olson, 1991). During this closing off process, rings with water mass properties of the original current are created.

Another theory in which rings are formed is when rings are created adjacent to the western boundary current during the boundary current separation process (Olson, 1991). This is related to when the western boundary current leaves the ocean adjacent to the coastline and enters the ocean interior. This process of ring formation was first described with reference to the East Australian Current (Nilsson et al. 1977; Nilsson and Cresswell, 1981). The theory of this ring formation process states that it is possible that within the mechanics of the boundary current separation, meanders tend to grow which in turn create eddies (Hurlburt and Thompson, 1980; Ou and De Ruijter, 1986; Campos and Olson, 1999). The Agulhas current is interesting in that it is possible that Agulhas rings may be formed from either one of the above processes (Veronis, 1973; Ou and De Ruijter, 1986).

1.4. Water masses associated with Agulhas rings

Very young rings which have recently spawned from the Agulhas Retroflection have water properties very similar to the actual Agulhas current (Gordon et al. 1987). The surface waters contain large amounts of South Indian Subtropical Surface Water but there are also small quantities of Indian Tropical Surface Water (Gordon et al. 1987). At lower depths, particularly in the thermocline, South Indian Central Water dominates and there are also traces of Subtropical Mode Water (STMW). In the intermediate and deep waters associated with the Agulhas current and hence the Agulhas rings, Antarctic Intermediate Water, Red Sea Water and Indian Deep Water is present (Arhan et al. 1999). The South Indian ocean intermediate water is more saline than the South Atlantic Intermediate water because of the penetration of high salinity Red Sea Water (Piola and Georgi, 1982). Although there are traces of intermediate water of Indian ocean origin in Agulhas rings (Lutjeharms, 1996), inter-ocean fluxes associated with these rings have generally been calculated to include only the surface and thermocline waters (McDonagh et al. 1999). It must be noted that once the Agulhas rings have spawned off from the Agulhas Retroflection, mixing takes place within the ambient water masses and these water mass properties from the Indian ocean are gradually diluted as the rings propagate through the Atlantic ocean.

1.5. Splitting theory of Oceanic Rings

The anomaly to be investigated will be known as Anomaly A for ease of reference. Since it will be shown that Anomaly A splits many times during its lifetime, it is important to be familiar with some theories associated with oceanic ring splitting. Arguably, the most important mechanism responsible for the majority of ring splits is the influence of bottom topography. With reference to anti-cyclonic eddies, when they encounter a ridge or seamount, there exists a possibility of significant erosion and the ring may split with the expulsion of potential vorticity filaments from the core of the original ring (Herbette et al.

2003). As the ring approaches the bathymetric obstacle, there is advection of deep water across the isobaths of the topographic feature which can create bottom eddies (cyclonic and anti-cyclonic) which in turn causes erosion to the original ring and has the potential to deform or split the original ring (Herbette et al. 2003). However, the erosion may not be strong enough to split the ring and hence the bathymetry may only influence the path taken because the deep cyclone recently formed near the bathymetric obstacle may form a dipole with the original anti-cyclonic ring and this interaction will push the arrangement away from the topography (Herbette et al. 2003).

There are other mechanisms which may be responsible for the splitting of rings. In particular, for rings which split more than once in their lifetime, after a ring splits it may become unstable and this instability may induce another splitting event later on (Schouten et al. 2000).

1.6. Behaviour and pathways of Agulhas Rings

The behaviour of Agulhas Rings in the south-eastern Cape basin is complex. The south-eastern Cape basin, often known as the 'Cape Cauldron' is turbulent in nature and there is intense water mass mixing in this region (Boebel et al. 2003). Examples of the turbulent characteristic of this region include the interactions between anti-cyclonic Agulhas rings and cyclonic rings. It is in this Cape basin region where the Agulhas rings undergo significant decay (Schouten et al. 2000; Schmid et al. 2003). Bathymetric obstacles such as ridges and seamounts can influence the behaviour of rings such as ring paths, air-sea exchanges, splitting and the decay rate. Once Agulhas rings are formed and detached from the Agulhas Retroflection, they generally follow either one of three routes. These three routes have been described in detail by Dencausse et al. (in press) and are called the Northern, Central and Southern Routes (Figure 1.4).

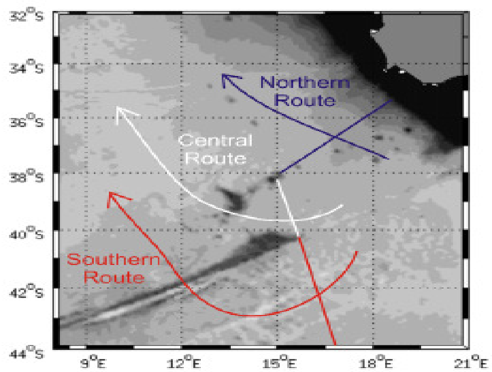


Figure 1.4 - three routes taken by Agulhas Rings , (from Dencausse et al. in press).

Figure 1.5 shows the Sea Level Anomaly in the Southern Ocean south of Africa for the period October 1998 to July 2009. The significant anomalies represented here all cover the 3 routes described by Dencausse et al. (in press). This map of Sea Level Anomaly depicts the turbulent activity of this region (caused by the Agulhas Current, Agulhas Retroflection, cyclones and anti-cyclones (Agulhas Rings).

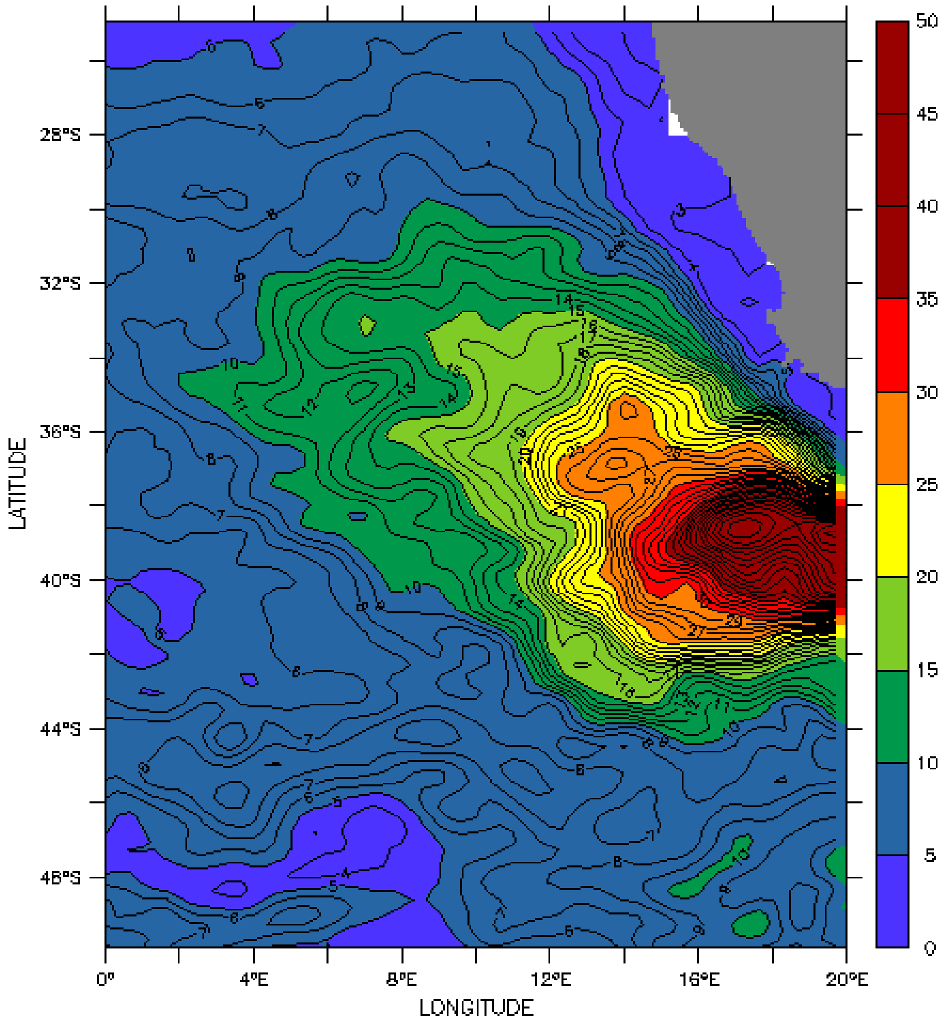


Figure 1.5 – Map of Sea Level Anomalies (cm) in the Southern ocean, south of Africa averaged over the period from October 1998 to July 2009 (from Aviso, 2009).

The three routes are defined according to the paths they take with reference to particular topographic features such as the Erica seamount and the north-eastern part of the Agulhas Ridge (Dencausse et al. in press). The speed and direction of the rings depend on the internal dynamics of the ring, the surrounding flow around the ring and the ring's interaction with bottom topography (McDonagh et al. 1999). The bottom topography, with special reference to the Erica and Schmitt-Ott seamounts and the Agulhas Ridge, plays a major role in determining the behaviour (route) of the rings, potentially impeding their westward drift and may cause the rings to split with the resulting rings diverging northwards and southwards respectively (Dencausse et al. in press). The orientation of the Agulhas

Retroflection at the time of the ring shedding event can also influence the route direction of the ring.

The Northern Route: This route is defined as any ring which drifts north of the Erica seamount (Dencausse et al. in press). It is relatively easy for rings to exit the Agulhas Basin through this route without splitting, as they are not extensively affected by bottom topography (Dencausse et al. in press). Although minimal splitting occurs in the Agulhas basin in this route, once these rings enter the Cape Basin, they seem to be very prone to splitting (Dencausse et al. in press). Possible reasons for this are the rings interactions with the continental slope and interactions with south-westward moving cyclones in this region (Boebel et al. 2003; Morrow et al. 2004).

The Central Route: This route is defined as any ring which drifts between the Erica seamount and the northern part of the Agulhas Ridge and is the most common route for the path of Agulhas rings (Dencausse et al. in press). The rings which take this route are very prone to splitting due to vigorous interaction with the surrounding bathymetry (Agulhas Ridge and the Erica and Schmitt-Ott seamounts), which causes the rings to become unstable (Dencausse et al. in press).

The Southern Route: The rings which adopt the central route rarely cross the Subtropical Front (STF) into colder Subantarctic waters but most of the rings which adopt the southern route do cross the climatological STF (Dencausse et al. in press). The Southern Route is defined as any ring which drifts south of the Agulhas Ridge. As these rings drift into colder Subantarctic waters, they undergo some hydrological modifications by mixing at their edges and high air-sea fluxes (Dencausse et al. in press). Due to this, they contribute differently to the inter-ocean exchanges as opposed to the other two routes (Dencausse et al. in press). The most noticeable property of these eddies after drifting through the Subantarctic waters are their high homogeneous cores with respect to their thermohaline properties (Dencausse et al. in press). The reason for this is that the high rates of air-sea fluxes lead to deep convection and cooling (Arhan et al. 1999; Gladyshev et al. 2008). An interesting characteristic of this route is that many of the rings stall near the Agulhas Ridge before either dissipating completely or crossing the Agulhas Ridge (Dencausse et al. in press). It has been estimated that approximately 50% of the Southern Route rings manage to cross the Agulhas Ridge but this is probably an underestimate since many of these rings lose their surface signal through capping of warmer waters (Herbette et al. 2004). The rings which adopt this route have the longest mean life-time, possibly because while these rings are stalling in the Agulhas Basin, they do not encounter the intense turbulent activity of the Cape Basin (Dencausse et al. in press). It is important to note that although the majority of Agulhas Rings remain within the Subtropical Zone (STZ), a few enter the Subantarctic domain before returning north-westwards. In a study by Dencausse et al. (in press) in which 186 ring trajectories were counted between October 14th 1992 and January 3rd 2007, 80.1 % or 149 trajectories remained in the Subtropical domain and 19.9 % or 37 trajectories drifted into the Subantarctic domain before continuing north-westward back into the Subtropical domain.

1.7. Overview of the Southern ocean

Since Agulhas rings propagate through the South Atlantic Ocean as well as the Southern Ocean, it is important to be familiar with this domain.

Agulhas rings propagate in two of the three regions described by Gladyshev et al. (2008):

- The Subtropical domain north of approximately 40˚ S. (The Subtropical front (STF) forms the domain's southern limit).
- The eastward flowing Antarctic Circumpolar Current (ACC), in which the STF (40˚ S) forms the domain's northern limit while the Southern Boundary of the ACC (Sbdy),56˚ S, forms the domain's southern limit.

However, the second domain in which the ACC flows, can be subdivided into three sub-zones, namely the Subantarctic zone, Polar Frontal zone and the Antarctic zone (Tomczak and Godfrey, 2005). The Agulhas rings which drift into the second region described by Gladyshev et al. (2008) only propagate through the Subantarctic zone and for this reason only the Subantarctic zone will be discussed in this study.

There are distinct differences in water mass properties, especially at the surface, between the Subtropical domain and the Subantarctic zone. At the surface in the Subantarctic domain, there exists Subantarctic Surface Water (SASW) which lies above the salinity minimum of the lower Antarctic Intermediate Water (AAIW), (Whitworth and Nowlin, 1987). SASW is greatly influenced by the subtropical gyres to the north and by air-sea exchanges (Whitworth and Nowlin, 1987). The STF marks the northern limit of the SASW and the southern limit of the warmer and more saline Subtropical Surface Water (STSW) located within the Subtropical domain (Burls and Reason, 2006). There is convergence between the SASW and the STSW at the STF and due to differences in density between the two water masses, SASW subducts below the subtropical surface waters (Burls and Reason, 2006).

The ACC is a unique current in that it flows uninterrupted around Antarctica and connects each of the ocean basins (Gordon, 1986; Speich et al. 2001; Swart et al. 2008). This current is the primary means of water, heat and salt transport between the Atlantic, Pacific and Indian oceans and these exchanges are critical for the global Meridional Overturning Circulation (MOC), (Speich et al. 2001; Swart et al. 2008). There are five fronts associated with the ACC and are identified by distinct meridional differences in the upper ocean water properties such as temperature and salinity (Orsi et al. 1995). The five fronts from north to south (Figure 1.6) are as follows, Subtropical Front (STF), Subantarctic Front (SAF), Antarctic Polar Front (APF), Southern ACC Front (SACCF) and the Southern Boundary of the ACC (SBdy), (Sokolov and Rintoul, 2009).

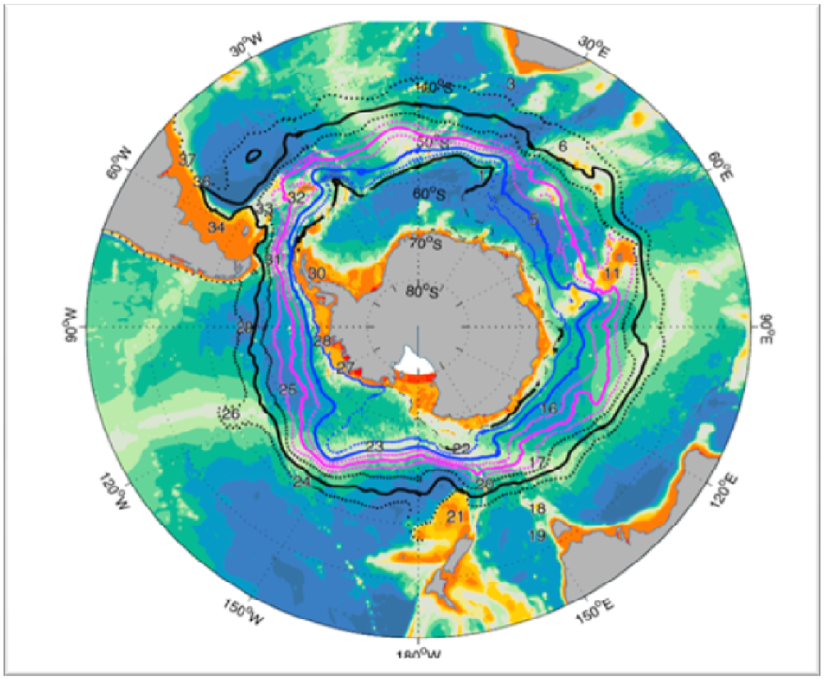


Figure 1.6 – The Southern Ocean fronts are colour coded from south to north as follows: SBdy (Southern Boundary of the ACC), black; SACCF (Southern ACC front) (-S and -N), blue; APF (Antarctic Polar Front) (-S, -M, and -N), magenta; SAF (Subantarctic Front) (-S, -M, and -N), black; STF (Subtropical Front) (-S, -M, and -N), blue. The middle branches of the fronts are shown by solid lines, while the northern and southern branches (where applicable) are show by dotted lines. In the case of the SACCF, the northern branch is shown by solid line and the southern branch is shown by dotted line. The 2000 m bathymetric contour is shown by thin black line (from Sokolov and Rintoul, 2009).

The main focus of this investigation is on the STF as this is the front in which anomaly A crosses. All of the fronts in the Southern Ocean display variability but the STF has the highest variability out of all the Southern Ocean fronts at the Greenwich meridian (Swart et al. 2008; Swart and Speich, 2010). The position of the STF also varies with longitude and the mean position of the STF in the South-East Atlantic is approximately 37˚ S while the mean position in the region south of the Agulhas Retroflection (10˚ – 20˚ E) is approximately 42˚ S (Lutjeharms, 2006). Reasons for the southward shift include the impact of the Agulhas current and Agulhas retroflection on the STF (Lutjeharms, 2006). For the purposes of this ring case study, we will consider the position of this front (calculated from hydrographic data obtained during the Bonus-Goodhope cruise) to be approximately 42˚ 20' 00". The STF marks the boundary between warmer, saltier waters of the subtropics to the north and the cooler, fresher waters of the Subantarctic zone.

2. INTRODUCTION

The ocean region south of Africa plays a unique role in providing a source for the equatorward flux of heat in the South Atlantic. However, it has been suggested (Speich et al., 2001; 2002) 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 anti-cyclonic ring shedding processes at the Agulhas Retroflection region (Lutjeharms and Van Ballegooyen, 1988) and by filaments of Agulhas Current water (Lutjeharms and Cooper, 1996). Recent modelling studies on the global ocean circulation suggest that Indo-Atlantic inter-ocean exchanges through the Agulhas Current system are far more important for the thermohaline circulation than the direct input of water through the Drake Passage (Speich et al., 2001; 2002). Estimates in the percentage of mode and intermediate waters entering the Atlantic through Agulhas leakage are highly variable and can be as much as 50% (Gordon et al., 1992). In addition, the nature of this pathway appears to vary (Dencausse, in press) between a northern, central and southern route. In order to gain more understanding of the role of this key component on the global ocean circulation, more understanding of the pathway in which Indian Ocean waters are injected into the Atlantic Ocean via Agulhas Rings is important.

In March 2008, the Bonus-Goodhope cruise was completed. 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. A key component of this programme is the implementation of a high-density hydrographic line between Cape Town and Antarctica (Ansorge et al. 2005). An outcome of this transect is that it overlaps the pathway of Agulhas rings which, once shed from the Agulhas Retroflection, may travel into the South Atlantic via the “southern route” (Swart et al, 2008; Gladyshev et al., 2008; Dencausse et al., in press; Swart and Speich, 2010). Thus, the Goodhope programme is able to provide additional information in determining the nature and scale of the injection of Indian Ocean water into the south-eastern Atlantic via the Agulhas Retroflection. A number of key objectives of the Goodhope programme (Ansorge et al., 2005) are:

- To improve understanding of Indo-Atlantic inter-ocean exchanges and impact on global thermohaline circulation and thus on global climate change.
- Understand the influence these exchanges have on climate variability over Southern Africa.
- Study air-sea exchanges and their role on the global heat budget with emphasis on intense exchanges within the Agulhas Retroflection region.

The Bonus-Goodhope cruise was multidisciplinary in that it included biogeochemical sampling along with the physical oceanography sampling (CTD and XBT's). This was additional to the normal Goodhope programme which only incorporates physical oceanography sampling. During the first week of the survey, altimetry identified a positive anomaly south of the Subtropical Front (STF) at approximately 43˚ S along the Goodhope transect. The occurrence of subtropical warm and salty water (temperatures ~ 13.95 ˚C and salinities ~ 35.16) so far south provided an opportunity to study in detail the character and behaviour of a possible Agulhas Ring located within the Subantarctic zone. Altimetry data following this survey could be used to track the pathway of this feature and explore the role prominent bathymetry would have on the anomaly's movement.

This study aims to analyse the nature of this feature as well as its life-span and to determine whether its source is the Agulhas retroflection region.

The following objectives will be attempted in this study:

- Confirming the identity of the anomalous feature observed during the 2008 survey. Establishing the identity of the feature is essential as the study will contribute information about the feature.
- The lifetime of these particular features.
  Knowing how long these features exist and when the most significant decay occurs is critical to see the length of time they have an effect on the surrounding region and could be essential in estimating the effect they have on the climatology of the region which could be a factor in the climate variability of Southern Africa.
- The paths these features take when travelling through both the Subtropical region as well as the Subantarctic zone.
  Determining the path of these features helps to determine the effect these features have on the particular zone it travels through such as the modification of the thermohaline properties caused by these features.
- Influence of underlying topography on the path and speed of these features.
  Understanding the role of the topography on these features can help to better predict the behaviour of future similar features and hence estimate the effect these features have on the surrounding region.
- Core properties of these features such as temperature, salinity and density while drifting through the Subantarctic zone and determining the Mixed Layer Depth (MLD) within them as this will help in understanding the role this route has on Indo-Atlantic exchanges.

The structure of this thesis is as follows: Chapter three presents the dataset which was used in this study as well as methods which were employed in analysing the data. Chapter four investigates the core properties of the feature from hydrographic data at the time of sampling as well as determining the position of this feature. Chapter five investigates the evolution of the eddy with respect to its path and decay from remotely sensed data. The surface geostrophic velocities obtained from remote sensing data are also compared to geostrophic velocities calculated from hydrographic data before some concluding remarks in chapter six.

3. DATA AND METHODS

3.1. Data

A range of datasets were utilized in the analysis of the anomaly observed along the Bonus-Goodhope 2008 transect. These datasets are described in the following sections:

3.1.1. Hydrographic Data

To effectively measure oceanic changes with respect to its thermohaline properties, in particular across regions of inter-basin exchange, high-density observations need to be undertaken. Repeat XBT and CTD sections across "chokepoint" regions provide measurements of changes in the upper ocean heat content and temperatures on both seasonal and inter-annual time scales. The Bonus-Goodhope survey was undertaken between 8th February – 24th March 2008 onboard the RV Marion Dufresne. This survey consisted of a single section across the Antarctic Circumpolar Current between South Africa and Antarctica. A total of 79 full-depth CTD stations and 132 XBT stations were undertaken to observe the structure of the ACC (Goodhope Postcruise Report, 2008). At each CTD station, vertical profiles of salinity, temperature and density were obtained to a maximum depth of 5000 m. Sippican Deep Blue XBT's were deployed to a maximum depth of 1000 m. Figure 3.1 shows the cruise track undertaken during the Bonus-Goodhope survey.

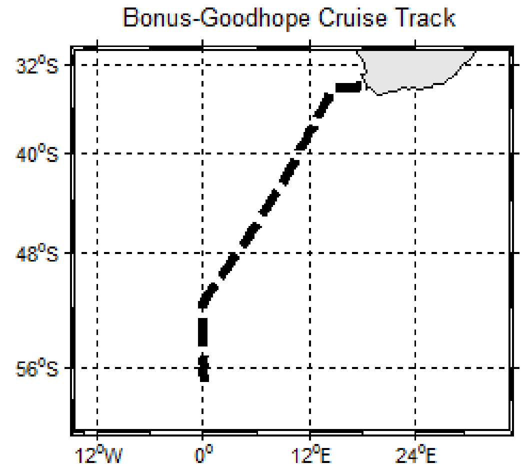


Figure 3.1. Cruise track undertaken during the Bonus-Goodhope survey conducted between February – March 2008.

3.1.2. Satellite Remote Sensing Data

Having the advantage of studying vast regions in a relatively short time, remotely sensed ocean parameters offer a quasi-synoptic view of the sea surface. This is ideal for studying both the short and long term variability of the oceans. For the purpose of this study, two remote sensing products were used, namely, satellite altimetry and sea surface temperature.

Altimetry: Satellite altimetry uses active sensors, emitting pulses and measuring the time taken for the reflection to reach each sensor. Two main types of altimetry products are available, near-real time (NRT) and delayed time (DT). Furthermore, data can be obtained either from a single satellite or merged multi-altimeter missions. Merged data significantly reduces error in mapping (Le Traon et al., 1998) and DT products are more precise than NRT products (SSALTO/DUACS, 2006). Merged products have been shown to give more realistic estimates of sea surface height, geostrophic velocity and energy than single-mission products (Ducet et al., 2000). For the purpose of this study Upd – Updated series, Delayed Time Maps of Absolute Dynamic Topography (MADT) obtained from the Archiving, Validation and Interpretation of Satellite Oceanographic data base (AVISO) were used.

MADT data is simply the Sea Level Anomaly (SLA) added to the Mean Dynamic Topography (MDT). MADT data was utilized in order to track the anomaly from its formation close to the Agulhas Retroflection until it "disappeared" from the altimetry signal. MADT data was used in preference to the SLA data since the MADT data was able to pick up the mean currents associated with the Agulhas current and Agulhas Retroflection current more accurately and hence the time and region of formation of the anomaly could be more accurately obtained since it was suspected that the anomaly formed at the Agulhas Retroflection. AVISO surface geostrophic velocities were also obtained across the anomaly. Specific anomalies such as Agulhas rings can be tracked manually by identifying such features at regular space and time intervals. The wide ground track observations of the TOPEX/Poseidon mission south of South Africa (Gründlingh, 1995) have led to discontinuity in the eddy tracking process, resulting in extensive extrapolation to establish continuity in eddy course. However, the probability of anomalies "disappearing" or "reappearing" while drifting across satellite tracks are greatly lessened by the combination of dual satellite crossovers of TOPEX/Poseidon and Jason-1 with the closely spaced ground tracks of ERS-2. Consequently one can be more confident of the continuity in the passage of either cyclonic or anti-cyclonic anomalies from one period to another (Ansorge and Lutjeharms, 2003). For the purposes of this study the life time of the anomaly was considered to be from the date of formation until the signal disappeared approximately 18 months later.

Sea Surface Temperature (SST): Sea Surface Temperatures (SST's) were obtained from Microwave Infra-red optimum interpolated (MWIR OI) SST radiometer data. This data was obtained from Remote Sensing Systems (Remote Sensing Systems, 2009). MWIR OI SST radiometer data is essentially a blended SST product which incorporates infra-red (IR) data as well as microwave data (MW). Using this blended product enables researchers to take advantage of the high spatial resolution of IR data. Microwave data is incorporated due to its ability to penetrate through cloud layers . This data is a daily gridded product with a resolution of approximately 0.09˚ (9 km) and spans the entire planet (90˚N to 90˚S). OI (Optimum Interpolation) is a method which uses the statistical properties of irregularly spaced data to interpolate the data onto a regular grid (Remote Sensing Systems, 2009). For the purposes of this study, a weekly averaged SST data set was created from the raw daily SST data in order to keep consistent with the MADT data which was a weekly averaged product.

3.2. Methods

3.2.1. Hydrographic Data

The CTD and XBT temperature data were combined to create a higher resolution product in the upper 1000 metres across the anomaly region. In some cases CTD data required additional "calibration" due to increase spiking and hysteresis during the upcast. In addition, due to the multidisciplinary nature of the Bonus-Goodhope survey, several stations were repeated for biogeochemical purposes and these were omitted from the data used in this study. The combination of CTD and XBT data at 10 Nm intervals is ideal in resolving the physical-chemical character of mesoscale features. The edges of the ring were identified from increased temperature gradients and were determined by maxima in the temperature gradients in the region of the feature (maximum temperature gradients were approximately 2 ˚C/˚Lat). The in-situ data was also used to calculate the geostrophic velocities along the Bonus Goodhope transect. The geostrophic velocities were calculated using the following equation:

$$v = dH / (f \times L)$$

where dH is the difference in dynamic height between two stations separated by distance L,
f is the Coriolis Parameter and
v is the geostrophic velocity

Figure 3.2 shows the XBT and CTD stations in the region of the anomaly. The edges of the anomaly indicated were obtained via the maximum temperature gradients.

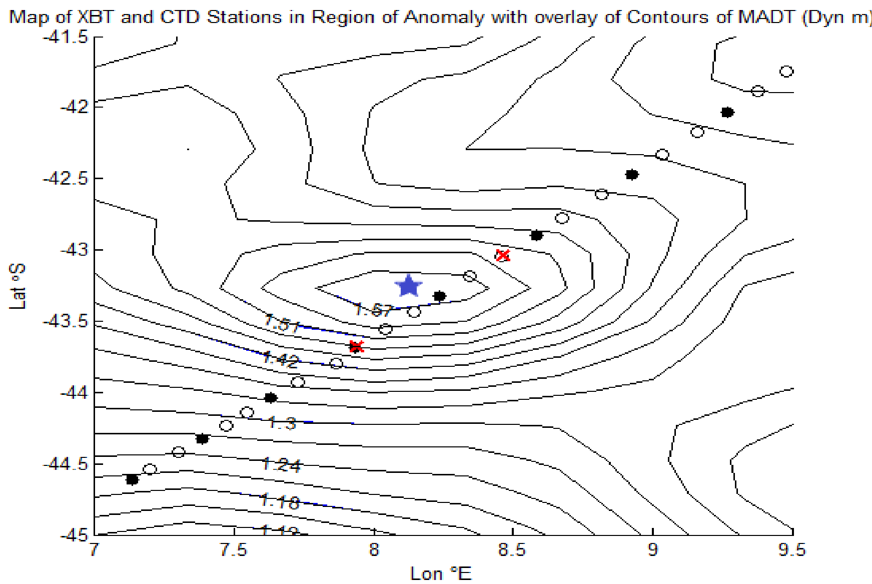


Figure 3.2. XBT and CTD stations in region of anomaly. Red crosses indicate edges of anomaly A, blue star indicates anomaly A's core, solid circles indicate CTD stations while empty circles indicate XBT stations.

The core properties of anomaly A such as temperature, salinity and density can be determined from the *in-situ* data. Unfortunately due to the nature of the Goodhope transect only a single line across the feature was occupied and not intensive, repeat sections as with other anomaly studies in the Southern Ocean (Ansorge et al., 2005; Swart et al., 2008). Hence a 3D image of the anomaly cannot be obtained. Due to the lack of intensive *in-situ* data, an exact amount of heat and salt injected into the ACC can also not be determined. Another shortcoming with only having data from a single transect is that the evolution of these core properties throughout the lifetime of the ring cannot be determined. The *in-situ* data provides confidence of the physical-chemical nature of this anomaly – this in turn enables the anomaly to be identified clearly from satellite imagery and the feature studied from its generation to its dissipation.

3.2.2. Satellite Remote Sensing Data

Altimetry: Anti-cyclonic rings in the ocean can be identified from MADT data as positive anomalies with respect to the surrounding waters. A positive anomaly (possibly an Agulhas ring) was tracked manually by identifying the core of the feature (the maximum MADT in the region of the anomaly). The anomaly was first identified from *in-situ* hydrographic data. It was then back-tracked using the MADT signal to determine its exact source. It was assumed that the anomaly represented an Agulhas Ring, which had moved southwards from the Agulhas Retroflection region into the Subantarctic Zone. In addition, a second aim of the study is to determine the life span of this feature and thus using the same dataset the anomaly was tracked forward in time until the MADT signal for the eddy was lost. The total time in which the signal of the feature was present on the altimetry maps and thus could be accurately tracked was 18 months. However, minor discrepancies may exist since the altimetry signature for the anomaly may become unrecognisable before the actual dissipation of the ring (processes such as air-sea interaction, merging into a larger ring or capping of warmer surface waters). Using altimetry, the pathway taken by the anomaly will be tracked in detail. Since bathymetric information of the underlying sea floor in this region is available, the influence prominent topography has on the anomaly's speed and path will be followed.

Sea Surface Temperature (SST): MWIR OI SST radiometer data was used to track the variation in SST across this anomaly from its formation date until it was unrecognisable on the altimetry data. Tracking was undertaken by relaying the co-ordinates obtained from the altimetry tracking analysis. The interaction between Subtropical and Subantarctic surface water masses plus increased air-sea interaction may result in the surface temperature signal diminishing and thus it is common for anomalies in this region to lose their SST signal early on. Hence the anomaly would not be identifiable from SST radiometer data for the same length of time as with altimetry data. However, in this case study, the anomaly was identified from SST data for the entire duration of its life span.

3.3. Data Analysis and Visualisation

The data in this study was analysed using the computer programming language MATLAB. MATLAB is a high-level, general purpose, scientific programming language that provides an environment for data manipulations and graphical representations. With its ability to perform calculations with maximal numerical precision and versatility, simple scripts and functions can be written to perform routine procedures on matrix data. Advance algorithms are available enabling data analysis and visualisation of outputs. MATLAB was used extensively throughout this study and was used to analyse raw data obtained from the hydrographic observations as well as from the satellite remote sensing database.

3.4. General Remarks

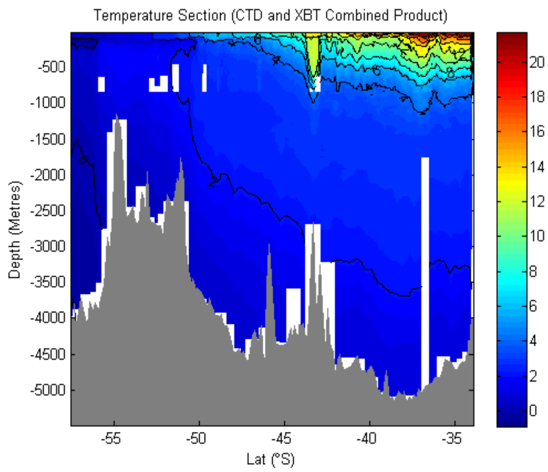
This study uses a combination of *in-situ* and remotely sensed datasets in order to determine the nature, source, trajectory and life span of a positive anomaly observed during the 2008 Bonus-Goodhope survey. It was anticipated from the datasets that the anomaly encountered was in fact an Agulhas Ring spawned from the Agulhas Retroflection area and following the “southern route” as established by (Dencausse et al. in press). The aim of this study is therefore to establish the nature of this feature and to determine whether it is such a ring and to determine the effect topography has on its path and life-span.

4. OBSERVATIONS OF ANOMALY A FROM IN-SITU DATA

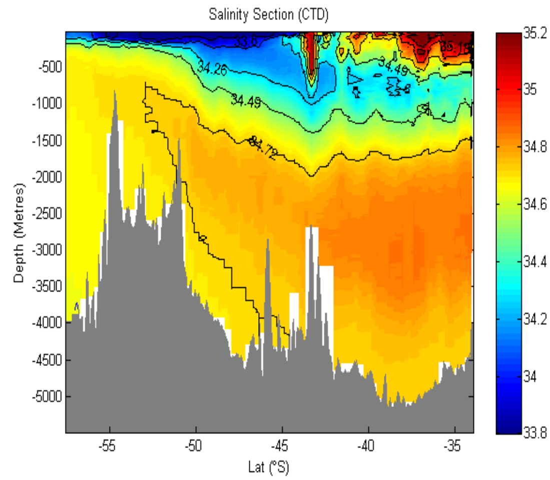
This chapter investigates anomaly A with respect to the *in-situ* data obtained during the Bonus-Goodhope cruise, which was completed in March 2008. The main objective of this chapter is to identify the anomaly and determine whether it was indeed a warm-core ring. In identifying what the anomaly is, the findings in this study could be useful in analyzing future anomalies of a similar nature. Establishing the water masses contained within the feature will help to establish its origin as well as identifying what the anomaly is.

The hydrographic data collected along the Bonus-Goodhope survey indicated a positive temperature and salinity anomaly at approximately 43˚ S and extended to over 1200m in depth. Figures 4.1 (a) – (d) suggest from the highly depressed isotherms and isohalines that the anomaly is indicative of a warm and salty feature lying within much cooler waters with a core temperature of 13.9 ˚C and salinity of 35.16. Furthermore, hydrographic data reveals that the anomaly had moved southwards across the climatological STF at 40˚ 30' 00" S and that the anomaly was located in the Subantarctic zone. This is interesting as the ACC flows through the Subantarctic zone and hence these type of anomalies may play an important vehicle in the transfer of heat and/or salt within the Meridional Overturning Circulation. There is evidence of the STF from the hydrographic data because of the strong temperature and salinity gradient and the strong frontal band. The core position of the STF from (Orsi et al., 1995) is defined by the potential temperature at 100 m (10˚C < θ_{100m} < 12˚C) and by the maximum salinity gradient (between 34.6 and 35.0) within this temperature band and hence from this definition, the hydrographic data indicates the position of the STF to be 42˚ 20' 00" S. This position will be the core position of the STF in this study. The *in-situ* data shows that the anomalous properties of anomaly A were present as far down as 2000 m (by the depressed isotherms and isohalines).

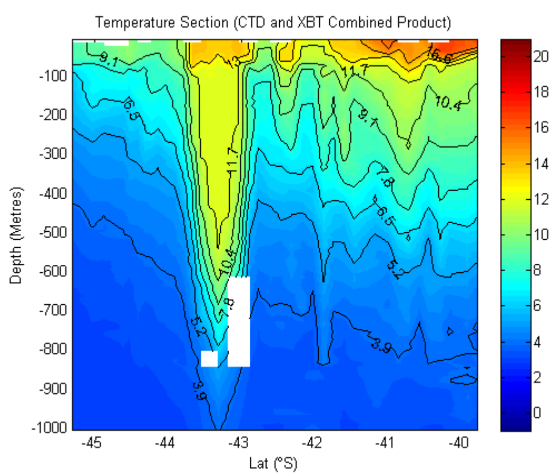
(a)


Temperature Section (CTD and XBT Combined Product)
Depth (Metres)
Lat (°S)

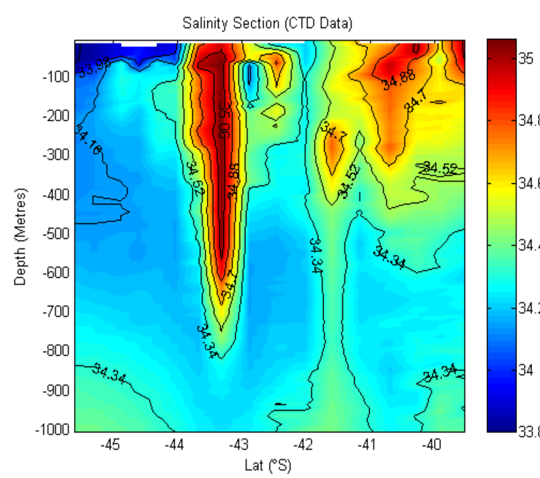
(b)


Salinity Section (CTD)
Depth (Metres)
Lat (°S)

(c)


Temperature Section (CTD and XBT Combined Product)
Depth (Metres)
Lat (°S)

(d)


Salinity Section (CTD Data)
Depth (Metres)
Lat (°S)

(e) (f)

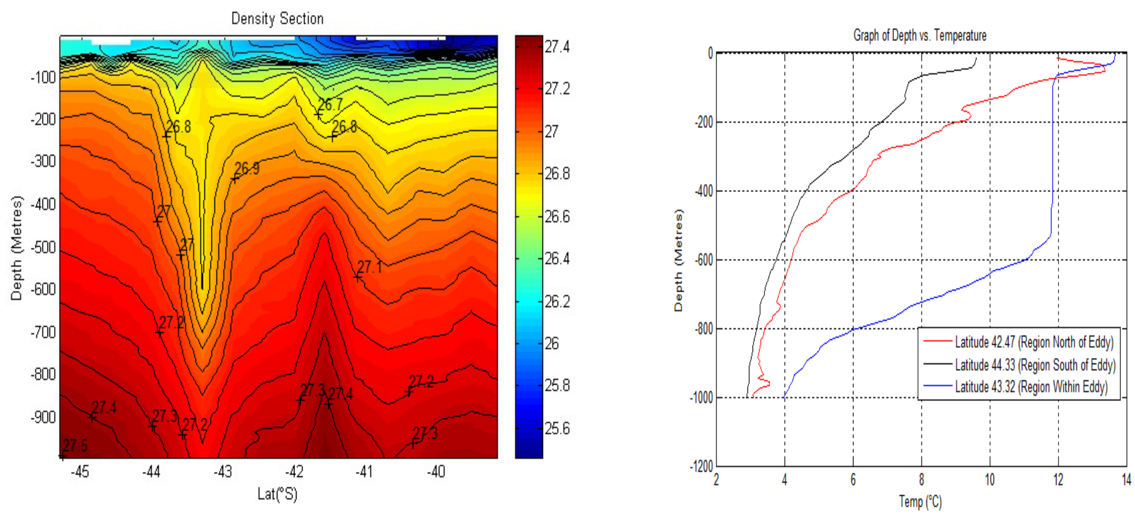


Figure 4.1 (a) Temperature section along the Bonus-Goodhope transect (contour intervals 2 ˚C). (b) Salinity section along the Bonus-Goodhope transect (contour intervals 0.23). (c) Temperature section zoomed into anomaly A (contour intervals 1.3 ˚C). (d) Salinity section zoomed into anomaly A (contour intervals 0.18). (e) Density section zoomed into anomaly A (contour intervals 0.1). (f) Graph of Depth vs. Temperature for three stations in region of feature.

In Figure 4.1(e) the isopycnals show a clear ring signal. The isopycnals in the region of the anomaly are depressed below 200m (specifically the 27.2, 27.12, 27.04, 26.96, 26.88 and 26.8 kgm^{-3} isopycnals). The density section shows that the waters within the ring are less dense than the surrounding waters (the sigma-t values within the anomaly were approximately 26.8 kgm^{-3} while in the surrounding waters at a depth of 500m, the sigma-t values were approximately 27.16 kg.m^{-3}.

Another interesting observation from the temperature and salinity profiles is the extent of the subsurface mixed layer depth (MLD) within the core of this feature. Figure 4.1(f) shows a near constant temperature of approximately 12 ˚C between 90m and 550m in the region of the core of the anomaly (a strong thermostad) whilst in the region just north and south of the anomaly, the temperature decreases at nearly a constant rate with depth (in the region south of the anomaly the temperatures decrease from approximately 7.5 ˚C at 90m to 4 ˚C at 550m and in the region north of the anomaly the temperatures decrease from approximately 12 ˚C at 90m to 4.5 ˚C at 550m). The deep MLD within the core provides further support that the anomaly had undergone strong convection (high air-sea fluxes) and most likely occurred principally while it was in the Subantarctic zone (Gladyshev et al., 2008). The homogeneity may also partly be the result that the feature had its origins in the Agulhas Current since, during the winter, the mixed layer within the Agulhas current can exceed 75m in depth (Lutjeharms, 2006).

4.1. Identification of Water Masses within the Anomaly

In order to identify the possible source of the anomaly, water masses associated within this feature were identified from T-S plots. In total (Figure 4.2(a)), five stations were plotted north of the anomaly and five stations were plotted south of the anomaly while a single station was plotted within the anomaly (this station was the best station to capture the thermohaline properties of the anomaly since it was close to the core of the anomaly). From the T-S diagram, the temperatures and salinities for the station within the ring were typically subtropical and generally greater than all the stations south of the anomaly (highest temperatures and salinities within the anomaly were approximately 14 ˚C and 35.16 respectively while the highest temperatures and salinities for the stations south of the anomaly were approximately 6 ˚C and 34.8 respectively). The plots for the stations north of the anomaly resemble the plot for the station within the anomaly closer than the plots for the stations south of the anomaly (since the stations north of the anomaly were in the Subtropical zone while the stations south of the anomaly were in the Subantarctic zone). An interesting observation regarding the thermohaline properties for the anomaly was that the anomaly’s maximum salinity (35.16) was greater than all the salinities for the other ten stations (maximum salinity within these ten stations was 35.09) while the maximum temperature within the anomaly was greater than all the stations south of the anomaly but lower than the maximum temperature for the stations north of the anomaly. From this it was clear that the anomaly was losing its temperature signatures faster than its salinity signatures. A possible reason for this rapid decay of the anomalous temperature signature was due to increased air-sea interaction as the anomaly had moved further south into the Subantarctic zone. The convection which occurred would have changed the SST over the anomaly but the salinity would not be affected by convection (salinity is a conservative property while temperature is not). It must be noted that although from the T-S diagram the maximum temperature in the stations north of the anomaly was greater than the maximum temperature within the anomaly, the temperatures at greater depths were generally higher within the anomaly than the temperatures at depths for the stations north of the anomaly while the surface signatures were vice versa. These surface signatures further prove that strong air-sea interaction through convective mixing was occurring within the core of the anomaly.

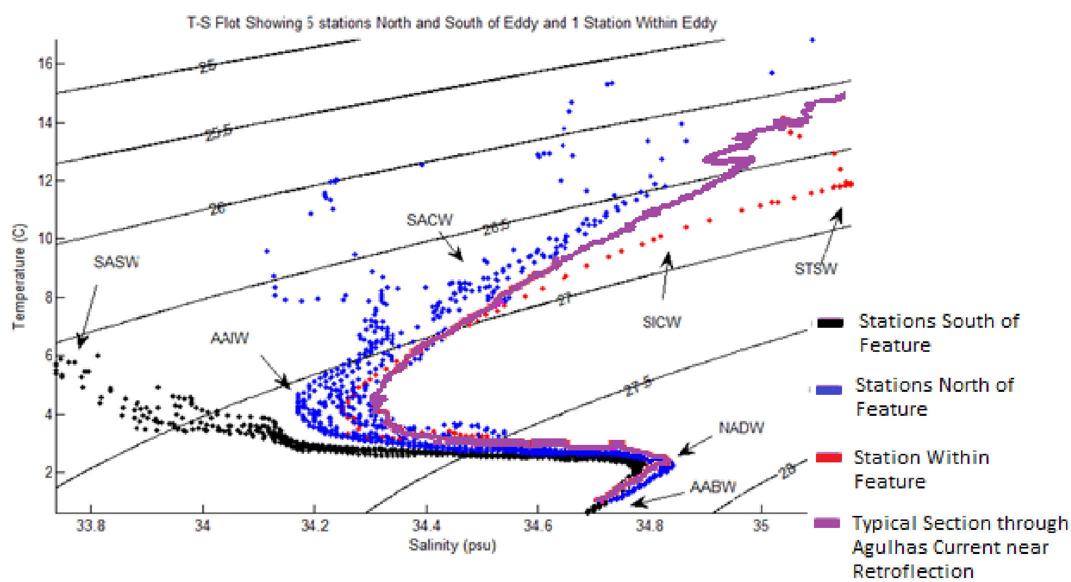


Figure 4.2 (a) Temperature-Salinity (T-S) plot showing Stations within the region of anomaly A

Water masses within the ocean can be identified from certain salinity and temperature ranges. Table 4.1 shows the water mass type and the corresponding temperature and salinity ranges. The temperature and salinity ranges from Emery, (2001) may seem large but it must be noted that these ranges are not confined to the region of interest (SE Atlantic and SW Indian Oceans) but over the entire Atlantic and Indian Oceans. Figure 4.2(b) shows the T-S plots for three stations in the vicinity of anomaly A in the SE Atlantic Ocean while additionally, there is a T-S plot of a typical station within the Agulhas Current near the Retroflection. Antarctic Bottom Water (AABW - temperature ~ 1.5 ˚C and salinity ~ 34.7) was present in all of the stations except for the station within the anomaly. At the time of sampling the feature with the CTD, the feature was above a bathymetric obstacle and hence the depth was approximately 2700m at this point and AABW fills all the basins within the Atlantic Ocean below 4000m depth (Tomczak and Godfrey, 2005).

Water masses identified within the anomaly were North Atlantic Deep Water (NADW), Antarctic Intermediate Water (AAIW), South Indian Central Water (SICW) and Subtropical Surface Water (STSW). The AAIW signature within the anomaly was not very different to the AAIW signature north of the feature (temperature ~ 4 ˚C and salinity ~ 34.3) while the AAIW within the typical Agulhas Current section near the Agulhas Retroflection also had salinities of approximately 34.3 and a temperature of approximately 4 ˚C. It must be noted however that there may be slightly higher salinities within the Agulhas Current at other stations for AAIW due to processes such as mixing with high salinity Red Sea Water (temperature range 5 – 14 °C and salinity 34.8 – 35.4 (from Emery., 2001). However, since many stations within the Agulhas Current (especially near the Retroflection) show salinities (for AAIW) similar to AAIW for waters within the Subtropical zone in the Atlantic Ocean, it was difficult to determine whether the waters within the anomaly at depths of approximately 800m–1500m had Indian Ocean origins. However, the salinity for AAIW within the anomaly (34.3) was still greater than the salinity for the AAIW signature of its surrounding waters within the Subantarctic zone (34.2), indicating an injection of more saline waters into this region and hence the ACC. There was a presence of South Indian Central Water (SICW) in the station within the anomaly and this had properties very similar to the SICW in the typical station within the Agulhas Current (temperature ~ 10 ˚C and salinity ~ 34.8). At similar depths within the station north of the feature there was a presence of SACW (South Atlantic Central Water) with temperatures and salinities approximately 10 ˚C and 34.6 respectively. The presence of more saline SICW within the feature than its surrounding waters (SACW) is an indicator that this feature had its origins in the Indian Ocean since this SICW had similar thermohaline properties to SICW within the Agulhas Current. The feature also had signatures of Subtropical Surface Water (STSW) with salinities of approximately 35.2 and temperatures of approximately 13 ˚C. This STSW is identified on the T-S diagram by a shallow sub-surface salinity maximum (Lutjeharms, 2006). This is due to precipitation which induces freshening of surface waters. STSW has salinity signatures > 35.5 and hence the high salinities within the anomaly (35.2) had most likely been diluted at the time of sampling. Although these salinity signatures had most likely been diluted (most likely due to mixing), they were still higher than all the sampled stations within the Atlantic and hence this is another indicator that this feature had its origins within the Indian Ocean. The station to the south of the feature (within the Subantarctic zone) had a signature of Subantarctic Surface Water (SASW, temperature ~ 7.5 ˚C and salinity ~ 34.2).

Table 4.1 Water masses and their typical temperature and salinity ranges (from Emery, 2001)

Water Mass	Temperature Range (°C)	Salinity Range
Antarctic Bottom Water (AABW)	-0.9 – 1.7	34.64 – 34.72
North Atlantic Deep Water (NADW)	1.5 – 4	34.8 – 35.0
Antarctic Intermediate Water (AAIW)	2 – 6	33.8 – 34.8
South Atlantic Central Water (SACW)	5 – 18	34.3 – 35.8
South Indian Central Water (SICW)	8 – 25	34.6 – 35.8
Subantarctic Surface Water (SASW)	3.2 - 15	34 – 35.5
Subtropical Surface Water (STSW)	-	> 35.5

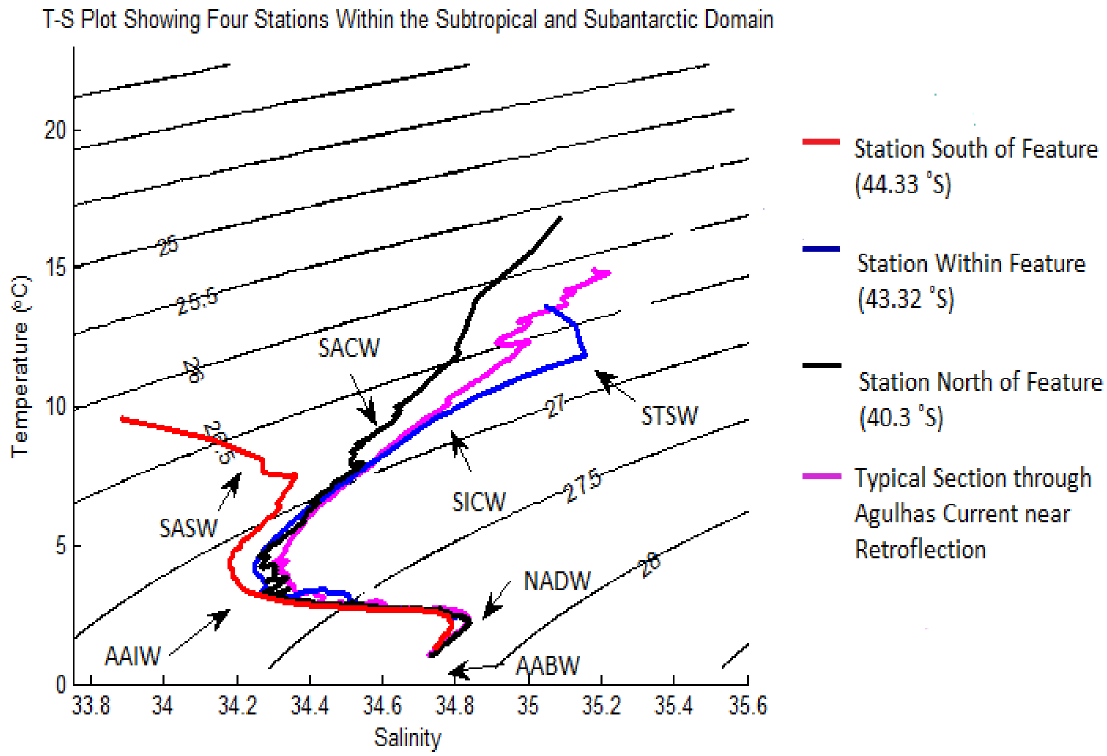


Figure 4.2 (b) Temperature-Salinity (T-S) plot showing three stations in the region of the anomaly and a typical station (in pink) within the Agulhas Current.

4.2. Geostrophic Velocities

The strength of the anomaly as well as its vertical extent can be clearly defined by the geostrophic velocity profiles. The geostrophic velocities were computed using Matlab and were derived from the hydrographic data (temperature and salinity). Only the geostrophic velocities down to approximately 2500m could be calculated as CTD readings at certain stations failed at lower depths and the underlying topography also restricted the calculation of the geostrophic velocities at lower depths. Figure 4.3 shows the anomaly was present at around 43˚ S and the core can be identified by the near zero geostrophic velocities (The zero geostrophic velocity contour was located at 43° 06' 00" S). From figure 4.3, the isovels (lines of constant velocity) clearly show anomaly A. The isovels are tightly spaced in the regions between the maximum ring velocities on either side of the anomaly and the core of the anomaly. These tightly spaced isovels show a rapid drop off of anomaly velocity towards the core. The section of geostrophic velocities in the region of the anomaly shows that the anomaly is anti-cyclonic in nature. The maximum geostrophic velocities observed in the anomaly were approximately 28 cm/s located on the southern edge of the anomaly. These high velocities continued down to approximately 800m before gradually decreasing to surrounding conditions at approximately 2400m. The maximum geostrophic velocities observed on the northern edge of the ring were approximately 22 cm/s and these high velocities continued down to approximately 250m before gradually decreasing to surrounding conditions at approximately 1900m. These geostrophic velocities are a slight underestimate due to the reference level used (2500 dbar).

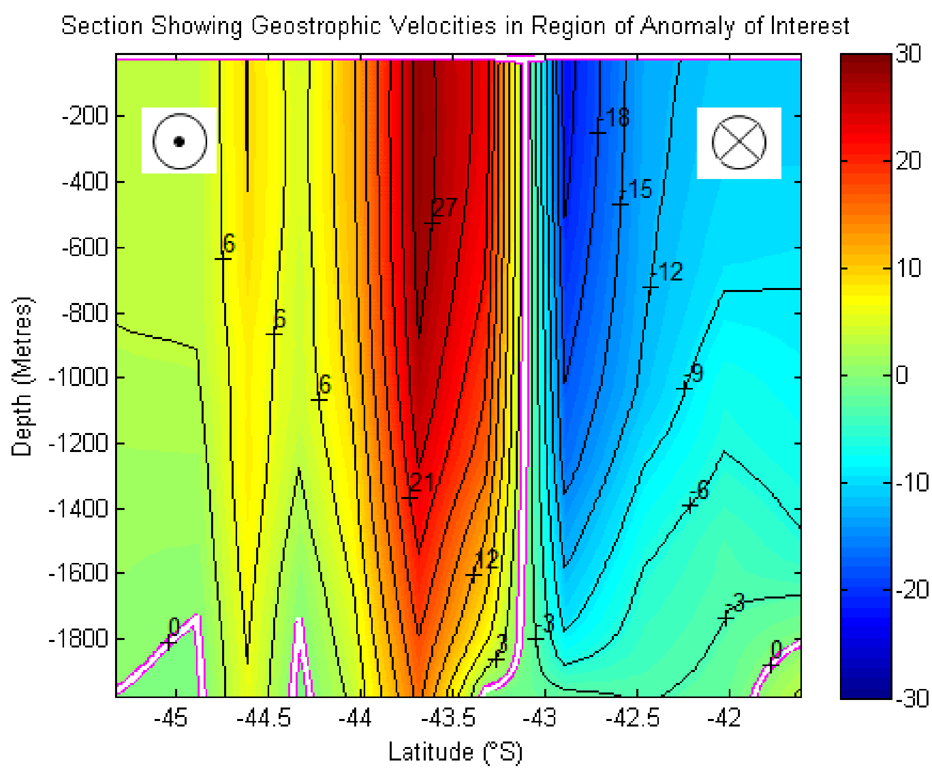


Figure 4.3 Geostrophic velocity section (cm/s) across Anomaly A calculated from CTD data during the Bonus-Goodhope cruise (Contour intervals 3 cm/s). The White Contour indicates the zero velocity contour.

4.3. Obtaining position of the anomaly's Core

Since the anomaly was tracked using altimetry data, the position of the core of this anomaly, when the CTD and XBT measurements were taken on 27 February 2008, needed to be obtained in order to identify the feature from the altimetry data on that date. Since the anomaly had higher temperatures compared to the surrounding waters, a temperature gradient across the ring could be used to identify the positions of the edges of the anomaly (the edges of the anomaly can be identified from the maximum temperature gradients). From figure 4.4 the maximum temperature gradients were 0.018 °C/Km (1.94 ˚C/˚Lat) and -0.02 °C/Km (-2.28 ˚C/˚Lat) located at approximately 43° 40' 48" S and 43˚ 02' 24" S respectively. For simplicity, it was assumed that the core of the anomaly was half way between the two edges. From this the core of the feature was located at 43˚ 21' 36" S. This agrees well with the zero geostrophic velocity contour in figure 4.3 where it was located at approximately 43° 06' 00" S. The discrepancy is due to the assumption that the anomaly was perfectly cylindrical in the calculation using temperature gradients.

The average temperature gradient was obtained between depths of 200m and 750m. The upper 200m were ignored in the calculation of the temperature gradient since surface processes could lead to inaccuracies (wave mixing etc.)

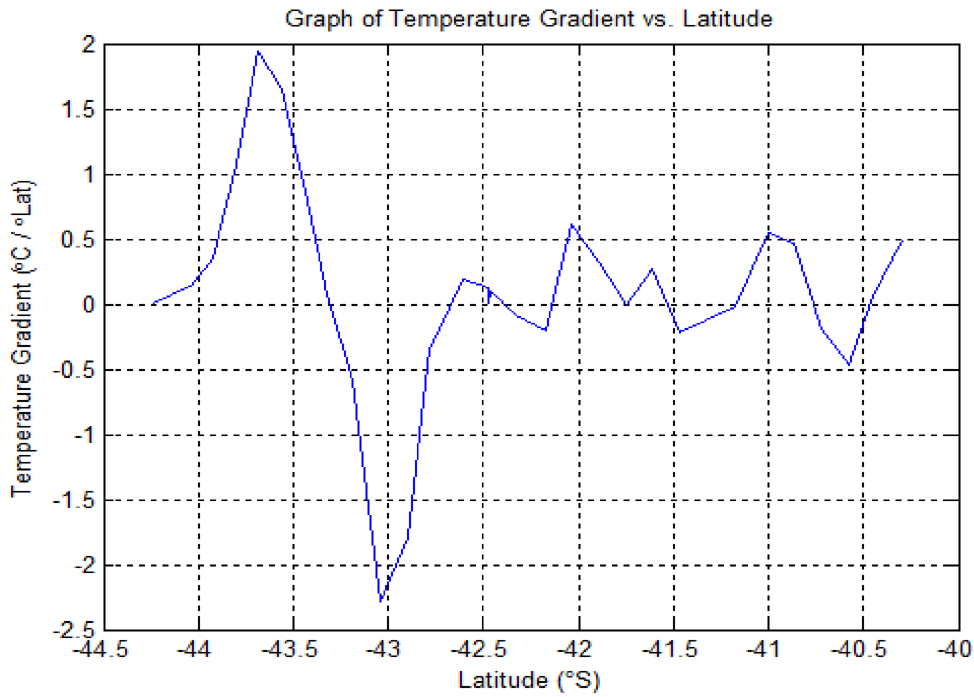


Figure 4.4. Graph showing the temperature gradient with change in latitude.

4.4. Summary

Detailed analysis of XBT and CTD data confirm that this anomaly was warm-cored with higher temperatures and salinities (13.95 °C and 35.16) than the surrounding waters. There was evidence that, at the time of sampling, the feature had undergone strong convection due to the deep mixed layer depth associated with the core and its southern position (cooler conditions within this region as opposed to the Subtropical region). Various water masses were identified within this feature and correlate with water masses found in the Indian Ocean (South Indian Central Water). The geostrophic velocities confirmed that the feature had a strong anti-cyclonic motion which is typical of warm-cored rings (Lutjeharms, 2006). Since this anomaly consisted of warmer and saltier waters than its surroundings and it had a strong anti-cyclonic motion with water masses typical of Indian Ocean origin, it was most likely an Agulhas Ring which had spun off from the Agulhas Retroflection. It was not surprising that the anomaly (first identified on the Bonus-Goodhope cruise in 2008) which was located within the Subantarctic zone turned out to be a warm-cored ring (most likely an Agulhas Ring) since previous studies (Dencausse et al. in press) have shown that a few Agulhas Rings indeed travel through the Subantarctic zone for a part of their lifetime along the “Southern Route” definition described by Dencausse et al. (in press). The next chapter will determine where and when this feature was formed and will hopefully confirm that it had its origins near the Agulhas Retroflection which will prove that the ring was indeed an Agulhas Ring. At the time of sampling, the feature was located within the Subantarctic zone (43.36˚S) and hence this Ring was most likely travelling through the “Southern Route” described by Dencausse et al. (in press). This trajectory will be confirmed in the following chapter.

.

5. OBSERVATIONS OF RING FROM SATELLITE DATA

It was determined from the previous chapter that anomaly A was a warm-cored anti-cyclonic ring which was most likely spawned from the Agulhas Retroflection with positive temperature and salinity anomalies. The previous chapter confirmed that this was an anti-cyclonic ring which was located within the Subantarctic zone (43˚ 21' 36" S) and it had water masses of Indian Ocean origin trapped within it. Due to this, the anomaly was most likely an Agulhas Ring which spun off from the Agulhas Retroflection. This chapter will determine the origins of this ring (whether it did indeed spin off from the Agulhas Retroflection) and hence determine whether this ring was indeed an Agulhas Ring. In addition, this section will look at the pathway and lifetime of the anomaly as well as the influence of the underlying topography on it (especially the Agulhas Ridge). In addition to using satellite altimetry (MADT data) to study the behaviour of the anomaly, MWIR OI SST data is also used to analyze the feature. Ring A was identified on the maps of MADT by using the position of the anomaly obtained from the hydrographic data.

5.1. Evolution of the Ring

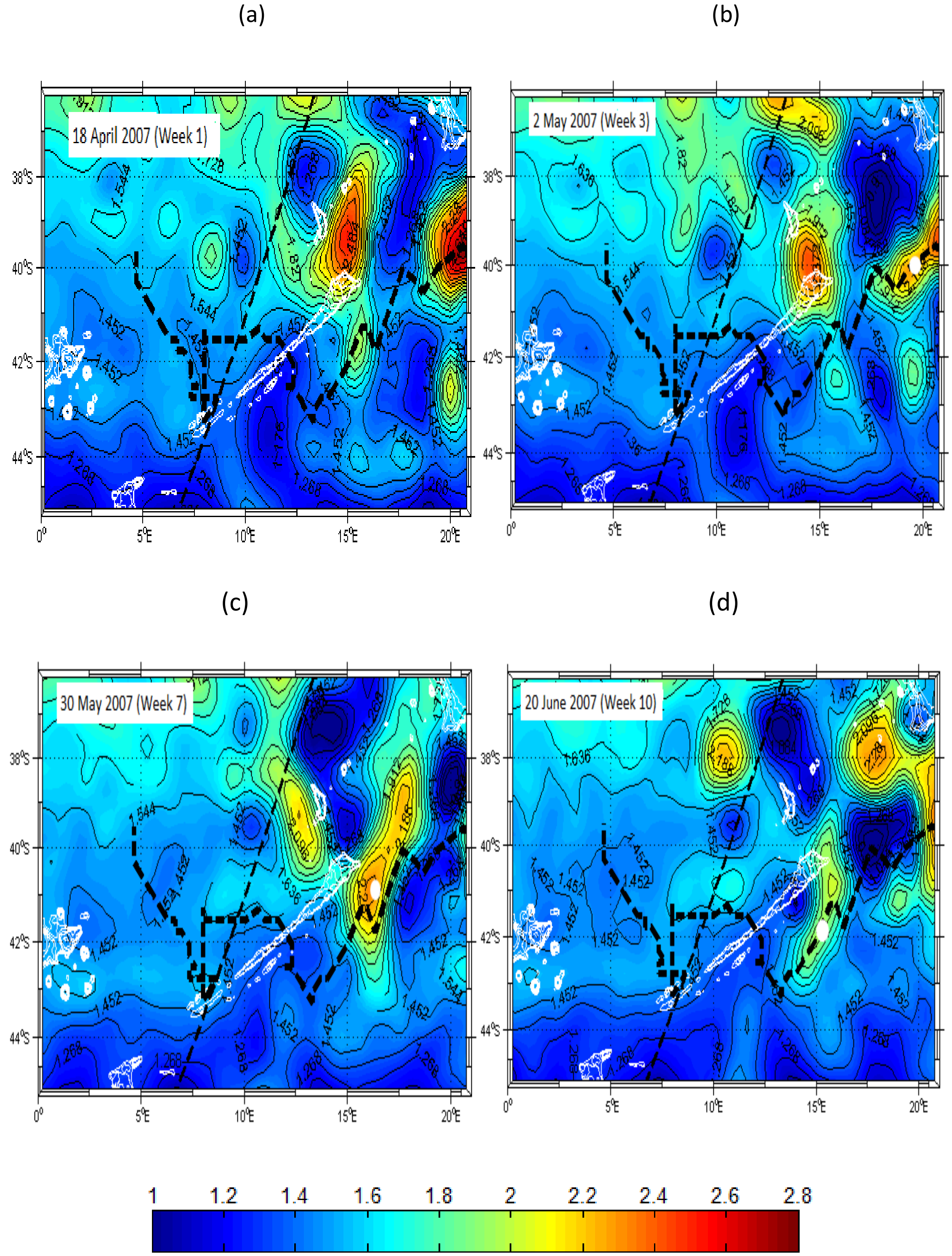
The anomalous sea surface height signal associated with ring A was able to be tracked from 18 April 2007 when it began its separation from the Agulhas Retroflection until 17 September 2008 (when the MADT signal for the ring was too weak to accurately pin point the location), approximately 1 ½ years later. This meant that the ring had a lifetime of at least 1 ½ years or probably longer as the loss of the MADT signal was most likely not at the same time as the complete dissipation of the ring (even though at this time, it was suspected that a larger, more “intense” ring merged with ring A). Figure 5.1 and Figure 5.2 depict the evolution of ring A from its formation date until its apparent dissipation using maps of MADT data. Included in these figures are the Bonus-Goodhope line and the overall path of the ring during its lifespan.

The region of the Agulhas Retroflection at the time of formation of the ring was estimated to be at 39˚ 46' 47" S and 20˚ 40' 12" E while the location of the ring when the MADT signal for the ring was lost was at 39˚ 31' 23" S and 04˚ 40' 00" E, suggesting that there was not much variation in the latitude from the beginning and the end but in the period between, the ring shifted as far south as 43˚ 16' 19" S. This observed region of the Agulhas Retroflection complies with (Lutjeharms and Van Ballegooyen, 1988) which states that the average position of the Agulhas Retroflection can be found between 10˚ - 20˚E. Hence ring A drifted south of the Subtropical Front (STF) into the Subantarctic zone and was travelling through the “Southern Route” definition described by Dencausse et al. (in press) in which the rings drift south of the Agulhas Ridge into the Subantarctic zone. These “Southern Route” rings also undergo intense hydrologic modifications through mixing and air-sea exchanges and ring A, which was sampled while in the Subantarctic zone, had also undergone hydrologic modifications as the ring had a homogenous core with respect to the thermohaline properties. Many of the “Southern Route” rings described by Dencausse et al. (in press) also re-enter the Subtropical zone and drift north-westwards. This chapter will also determine whether ring A re-enters the Subtropical zone before dissipation.

The evolution of ring A is described in two sections. The first section is from from its formation (18 April 2007) until it was sampled on the Bonus-Goodhope cruise on 27 February 2008. The second section is from the sampling date until its apparent dissipation on 17 September 2008. The MADT data which was used to track the ring was a weekly averaged product and the dates given in the following sections are in the middle of these respective weeks.

5.1.1. Pre-Cruise Description

The MADT during week 1 (18 April 2007) within the Agulhas Retroflection had a maximum of 2.76 Dyn m and during week 3 (2 May 2007) there was a presence of the actual separation and formation of the ring (MADT was 2.28 Dyn m) since the altimetry data began to show a feature distinct from the Agulhas Retroflection. By week 5 (16 May 2007) the separation from the Agulhas Retroflection was complete and during this week the maximum MADT within the ring was 2.41 Dyn m. During week 7 (30 May 2007) there were signs of a splitting event within ring A since the altimetry signal showed two distinct maxima in the region of ring (MADT of these two maxima were both approximately 2.31 Dyn m). By week 8 (6 June 2007), the split was complete and it is an interesting region with respect to the bathymetry as this region is just to the east of the northern part of the Agulhas Ridge which separates the Cape Basin from the Agulhas Basin. The subdivisions moved in opposite directions with the one moving in a northerly direction while the other one (ring A) started to move in a southerly direction. During this time the MADT of ring A was 2.39 Dyn m. This splitting event was very similar to a splitting event described in (Dencausse et al. in press) - where the two components of the split ring also moved in a northerly and southerly direction respectively. This provided further evidence of the role of the northern tip of the Agulhas ridge which impacts on the dynamics of rings within this particular region. By week 10 (20 June 2007) there was evidence of another splitting event in the southern subdivision of the original ring and the split was complete by week 12 (4 July 2007). It was at around this time, week 12, that the ring was drifting into the Subantarctic zone south of the STF (During this week the position of the ring was approximately 42˚ 47' 05" S and 14˚ 00' 00" E while the position of the STF was approximately 42˚ 20' 00" S from hydrographic data). After week 12, the ring continued to drift but at a slower velocity and remained in the Subantarctic zone for a while (approximately five months before re-entering the Subtropical domain). As can be seen in Figure 5.5(a) and Figure 5.5(b) there is a rapid decay of the Agulhas ring for the first couple of weeks of its lifetime. The dynamic height drop off is fairly rapid for the first 10 weeks (MADT decreased from 2.76 Dyn m to 1.96 dyn m) while the SST drop off was fairly rapid for the first 20 weeks (decreased from 20.35 ˚C to 13.35 ˚C). Both of these rapid drop-offs can most likely be attributed to the modification of the ring's thermohaline properties by mixing and air-sea exchanges (the ring cools). The extended period of the SST rapid drop-off after week 10 (20 June 2007) until week 20 (29 August 2007) was likely due to the ring drifting into the Subantarctic zone and warm-cored rings in this region undergo intense air-sea exchanges (during this time the Dynamic Height continues to drop but not as rapidly as during the first 10 weeks). These intense air-sea exchanges will decrease the SST of warm-cored rings rapidly with time. A possible reason why the dynamic height didn't decrease rapidly from week 10 until week 20 may be that the deep convection which resulted from the intense air-sea exchanges may have been more delayed and occurred over a longer time period than the rapid SST drop-off (the thermohaline properties throughout the ring modified less rapidly than the decrease in SST and hence the dynamic height drop off was more gradual). During this time (week 10 to week 20) the MADT decreased from 1.96 Dyn m to 1.82 Dyn m.


(a)
(b)
18 April 2007 (Week 1)
2 May 2007 (Week 3)
(c)
(d)
30 May 2007 (Week 7)
20 June 2007 (Week 10)
38°S
40°S
42°S
44°S
0°
5°E
10°E
15°E
20°E
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8

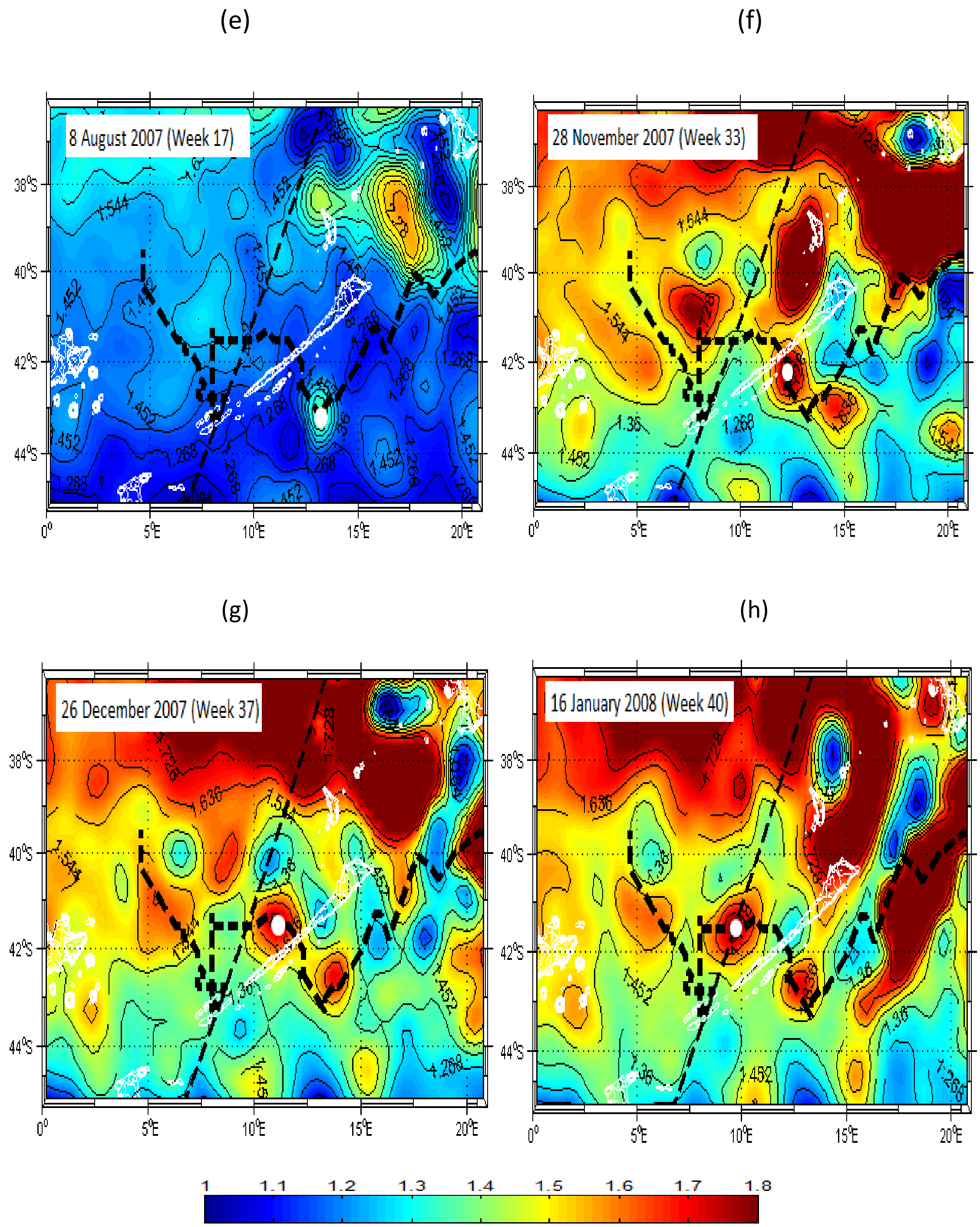


Figure 5.1 Maps of MADT data depicting the evolution of ring A from its formation date until sampling of the feature during the Bonus-Goodhope cruise (Contour interval 0.09 Dyn m). Ring A is identified on these maps by a white circle and the straight black dotted line depicts the Goodhope line while the other dotted line depicts the path of Ring A. (Note: colourbar changed after Week 17 so feature can be clearly seen).

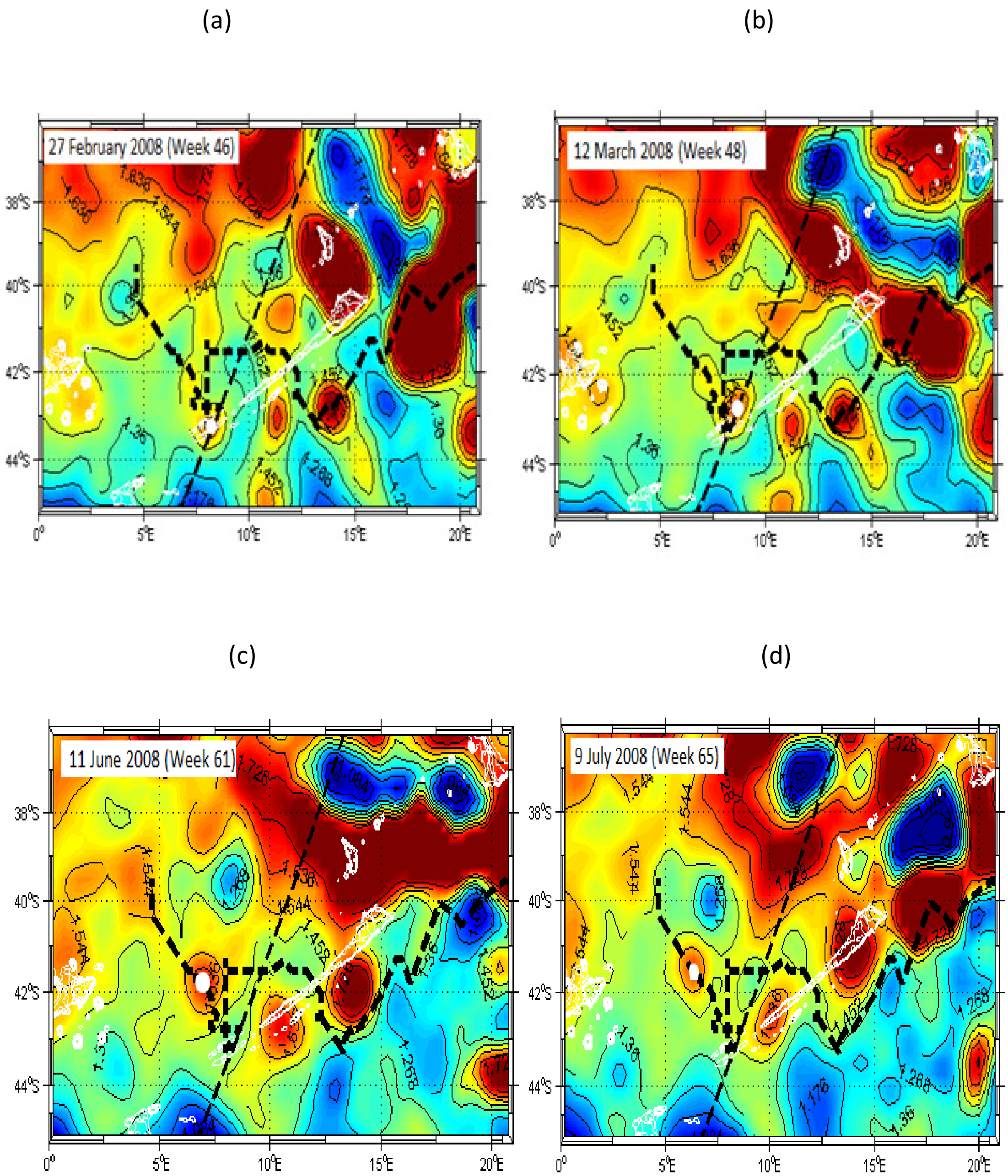
From week 17 (8 August 2007) until week 33 (28 November 2007), approximately four months, the feature stalled and did not make any significant movements. During this time the MADT gradually dropped from 1.83 Dyn m to 1.80 Dyn m and the SST dropped from 13.8 ˚C to 11.8 ˚C. This drop-off of SST was an indication that convection was occurring while the ring stalled in the Subantarctic zone. This stalling region was in the vicinity of the central part of the Agulhas Ridge and one could be fairly confident that this ridge had a major influence on the stalling event of this ring. During this time the ring was exposed to the conditions of the Subantarctic zone and the water mass properties most likely changed by mixing and air-sea interactions (although there was no proof of this since there were no in-situ measurements around this region at that time). There was most likely a lot of convection occurring during this time which further homogenised the core properties of the ring. During weeks 34-37 (5 December 2007 – 26 December 2007) the ring crossed the Agulhas Ridge near its central part where there is a fracture zone and the ocean depth (~ 2700 m) is deeper than the surrounding parts of the Agulhas Ridge (~ 2200 m). Also during this time the ring crossed over the STF back into the Subtropical domain (At around week 34 the position of ring A was approximately 42˚ 02' 47" S and 12˚ 20' 00" E). Figure 5.3 shows the bathymetry in the region of the Agulhas Ridge as well as the path of ring A while crossing the Agulhas Ridge. From figure 5.5(a) and figure 5.5(b) during weeks 34-37 (5 December 2007 – 26 December 2007) there was a net drop-off of dynamic height (1.78 – 1.75 Dyn m) but a net increase in SST (12.3 – 13.1 ˚C). It was during this time that the ring crossed back into the Subtropical domain. Hence the SST increase was most likely due to mixing of the surface waters between the ring and the surrounding environment (The SST within the ring at this time was cooler than the SST of the surrounding environment although it must be noted that the temperatures at deeper levels were still likely higher within the ring than the surrounding environment). The SST of the ring was only cooler than the surrounding environment in the Subtropical domain at this time because it had just come from the Subantarctic zone where intense air-sea exchanges caused a rapid drop-off in SST.

It was interesting to note that another ring after ring A also stalled in this region near the ridge but after stalling, it drifted in a SW direction before crossing the ridge. From approximately week 40 (16 January 2008) until week 43 (6 February 2008) there was an increase in SST (13.5 – 14.1 ˚C) but a decrease in dynamic height (1.8 – 1.65 Dyn m). This could have been an indication of warmer surface waters capping the ring at upper levels and hence the dynamic height signal of the ring may have been hindered due to this capping. It was also during week 40 (16 January 2008) that the ring crossed the Goodhope line.

Ring A then crossed the Goodhope line during week 40 (16 January 2008). At around week 43 (6 February 2008) there were signs that the ring was going to split yet again. This was a small separation and the separation was complete by week 46 (27 February 2008). During this separation period, the ring once again drifted over the STF into the Subantarctic zone (The first evidence that ring A re-entered the Subantarctic zone was during week 45 where its position was approximately 43˚ 16' 19" S and 8˚ 00' 00" E). It was during week 46 that the ring was sampled using CTD's and XBT's on the Bonus-Goodhope cruise and full vertical profiles of temperature and salinity for the ring were obtained. During this sampling time the MADT and SST was 1.6 Dyn m and 13.6 ˚C respectively.

5.1.2. Post-Cruise Description

After ring A was sampled during the Bonus-Goodhope cruise, the ring once again crossed the Goodhope line during week 48 (12 March 2008) and from this week until approximately week 58 (21 May 2008) the ring stalled once again (2 ½ months) and also "intensified" (MADT increased from 1.62 - 1.69 Dyn m while the SST decreased from 12.32 - 11.16 Dyn m. It must be noted that although during this time the dynamic height increased, it did not necessarily mean that the thermohaline properties (temperature and salinity) increased much, if at all (the temperature and salinity actually most likely decreased as it was subjected to the conditions of the Subantarctic zone). It was interesting to note that during this stalling event, the ring was once again in the Subantarctic zone although it "intensified" during that time. The intensification in the dynamic height was most likely due to a STF ring feeding into the flow of the feature, the STF ring merged with ring A, (Swart and Speich, 2010). STF rings are formed because the eastward flowing ACC current interacts with the mid-oceanic ridge. The reasons behind this second stalling event were not as clear as the first stalling event earlier in the vicinity of the Agulhas ridge but possible reasons were that the ring was interacting with the STF ring as well as another ring to the north of it (which it merged with later on) and that the ring had just crossed the Agulhas Ridge and lost some of its inertia. During weeks 57 – 61 (14 May 2008 – 11 June 2008) there was a merging process between the ring and another anti-cyclonic ring north of it (during this time the ring began to move north and re-entered the Subtropical domain). The stalling process could have ended when ring A formed an eddy dipole with a surrounding cyclonic ring. After this merging process, the ring continued on its northward track through to approximately week 72 (27 August 2008) and during this time the dipole remained intact. From around week 68-75 (30 July 2008 – 17 September 2008) it was suspected that the ring became entrained into a larger anti-cyclonic ring because the MADT signal from ring A was too weak to identify by week 75 and there was a larger anti-cyclonic ring nearby (During this time the MADT decreased from 1.58 – 1.43 Dyn m). It was also suspected that the cyclonic ring which formed the dipole with the original ring (ring A) formed a new dipole with the larger anti-cyclonic ring.


(a)
(b)
27 February 2008 (Week 46)
12 March 2008 (Week 48)
(c)
(d)
11 June 2008 (Week 61)
9 July 2008 (Week 65)
38°S
40°S
42°S
44°S
0°
5°E
10°E
15°E
20°E

(e) (f)

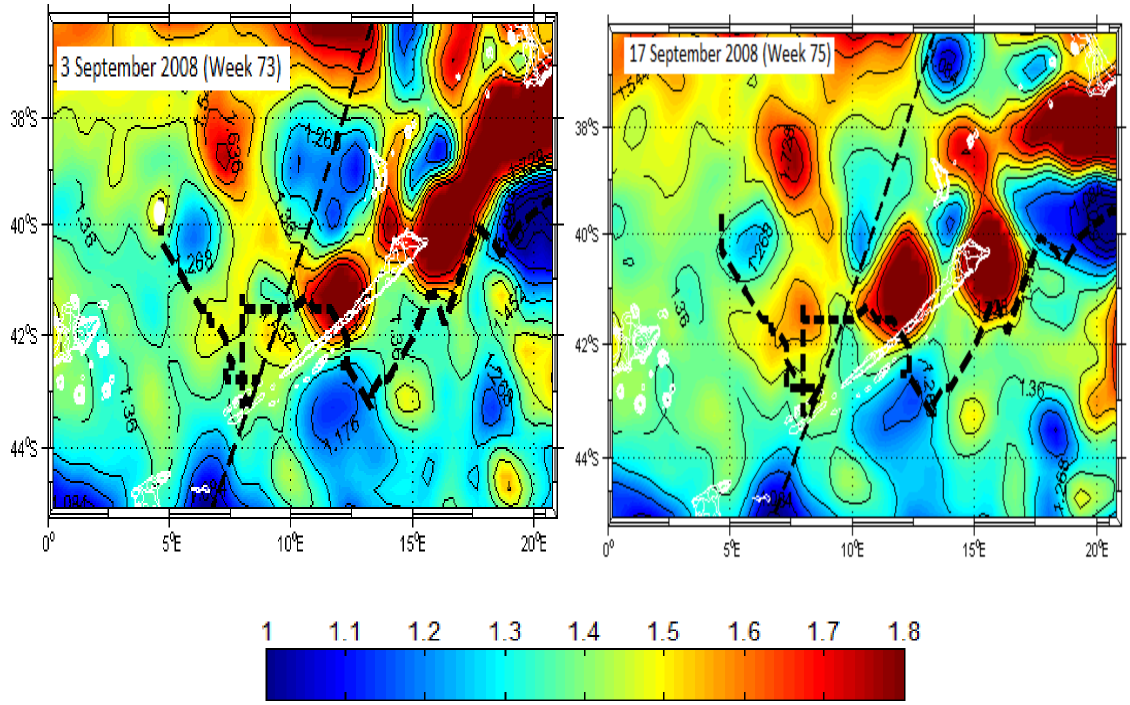


Figure 5.2 Maps of MADT data depicting the evolution of ring A from the sampling of the feature during the Bonus-Goodhope cruise until its apparent dissipation (Contour interval 0.09 Dyn m). Ring A is identified on these maps by a white circle and the straight black dotted line depicts the Goodhope line while the other dotted line depicts the path of Ring A.

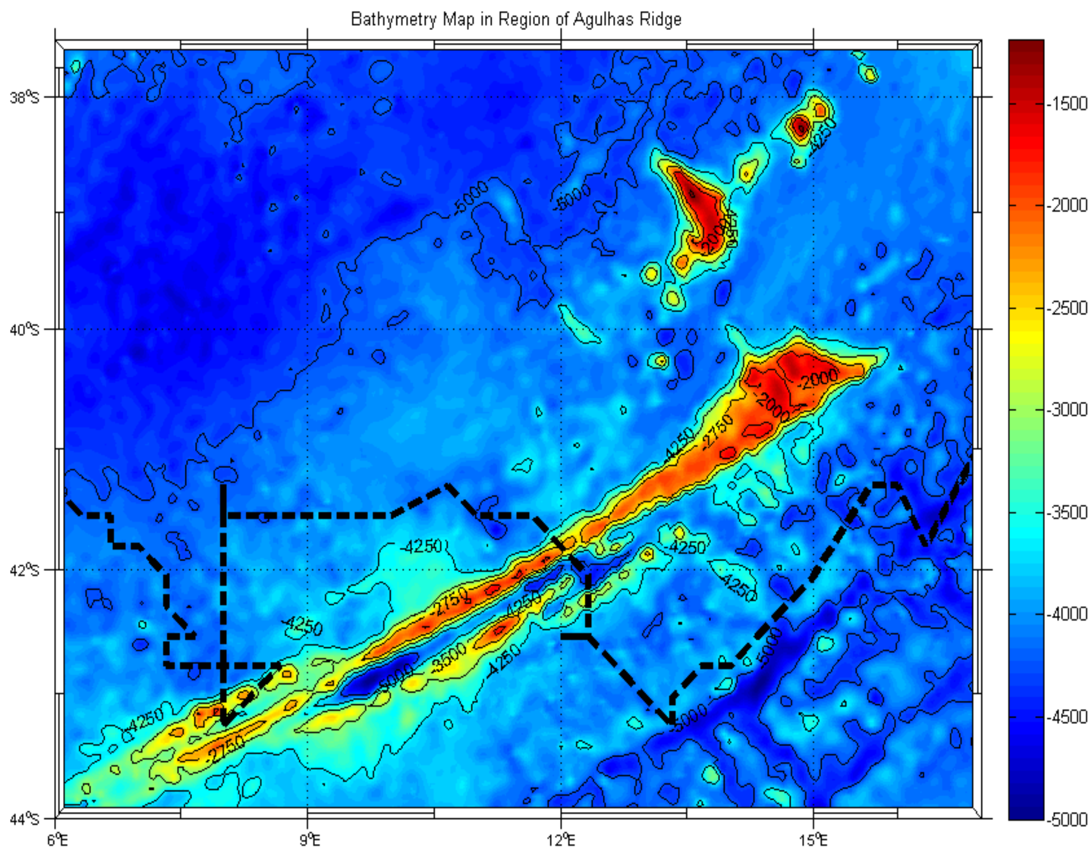


Figure 5.3 The bathymetry in the region of the Agulhas Ridge as well as the path of ring A taken in crossing the Agulhas Ridge.

Figure 5.4 shows the SST anomaly of ring A on specific dates. On 8 August 2007 (week 17) the maximum SST was approximately 13.8 ˚C, on 26 December 2007 (week 37) the maximum SST was approximately 13 ˚C while on 12 March 2008 (week 48) the maximum SST was approximately 12.3 ˚C. The SST anomaly was strong on 8 August 2007 (positive anomaly) as the ring had just drifted into the Subantarctic zone. After this date, the ring underwent intense air-sea exchanges as shown by the rapid decrease in SST in figure 5.5(b) since the positive SST anomaly was subjected to the conditions of the Subantarctic zone. On 26 December 2007 the ring displayed a negative SST anomaly with respect to the surrounding region. The most likely reason for this was that the ring had just drifted back into the Subtropical domain and underwent significant air-sea exchanges while in the

Subantarctic zone. Although on this date, there was no hydrological data, the subsurface properties most likely still had a positive temperature anomaly with respect to its surroundings as well as positive salinity anomaly. The SST anomaly of the ring was still significant on 12 March 2008 (positive SST anomaly) although it had eroded significantly by this stage. The positive SST anomaly was evident due to its presence in the Subantarctic zone once again.

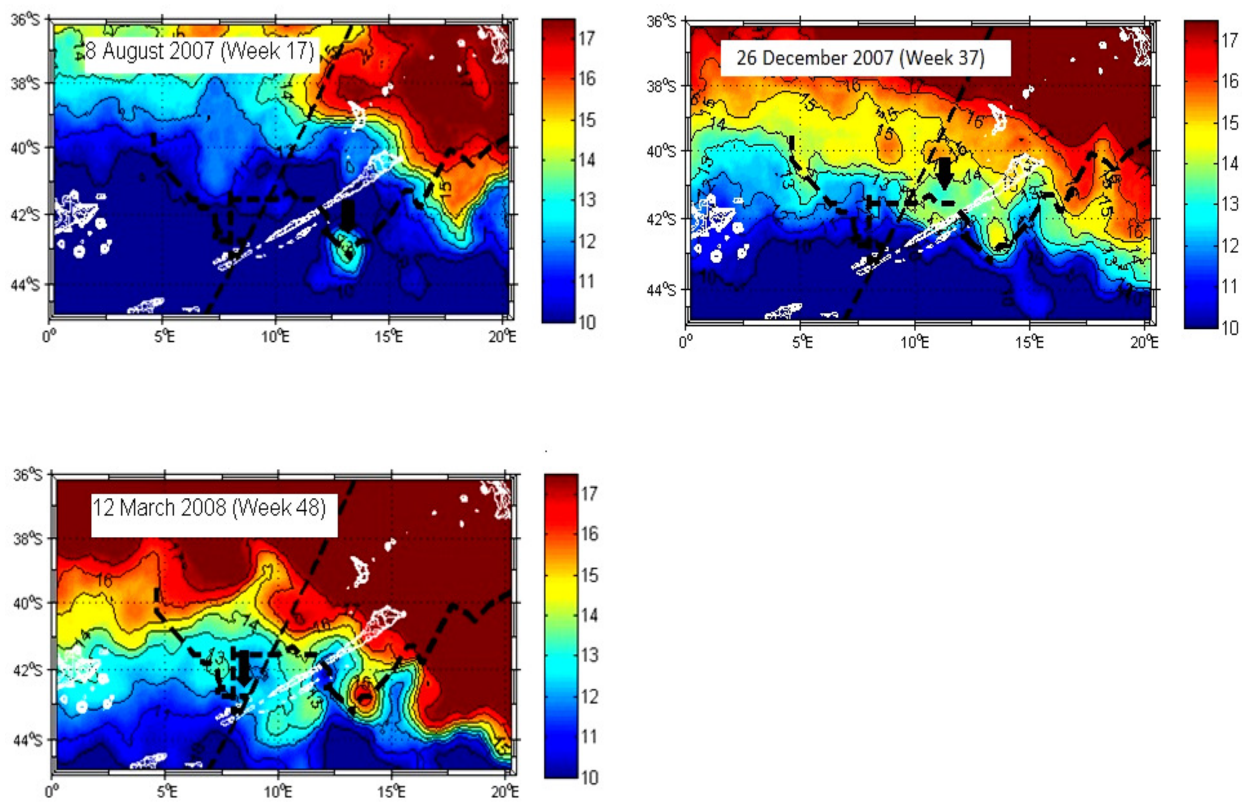


Figure 5.4 Maps of SST showing the SST anomaly of Ring A.

A linear approximation was performed on the dynamic height evolution of the ring (Figure 5.5 (a)) to obtain a rough estimation of its decay rate. The first ten weeks were omitted from this approximation since the rate of dynamic height drop-off was far greater during this time than the average drop-off after week ten until the apparent dissipation of the ring at around week 75. However, from this linear approximation it cannot really be estimated at which time the ring completely dissipated since the dynamic height (in ambient conditions in the absence of any rings) in the region of this ring's path was not really known. The linear approximation of the relationship between dynamic height and Time was statistically significant at the 5% confidence level and the relationship is strong (R^2 = 0.804).

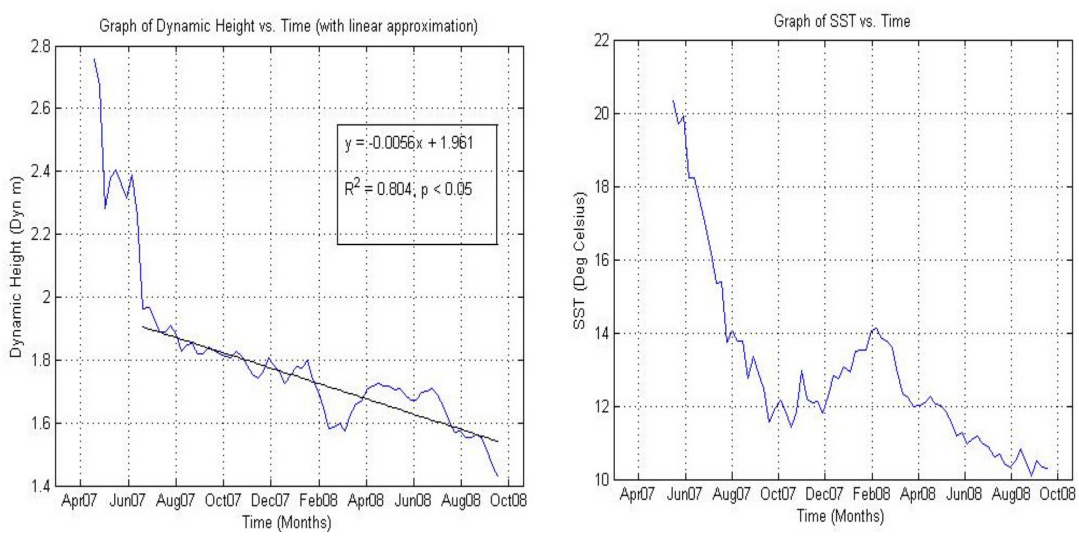


Figure 5.5 (a) Graph of dynamic height vs. time with linear approximation. (b) Graph of SST vs. Time.

5.2 Surface Geostrophic Velocities

Surface geostrophic velocities were obtained from satellite altimetry on two dates, 16 January 2008 and 27 February 2008 (correlating to the date of CTD and XBT deployments over ring). Figure 5.6(a) and Figure 5.6(b) show the total magnitude of the surface geostrophic velocities in the region of ring A as well as the direction of these velocities indicated by arrows. Included in these figures is an overlay of contours of MADT. The maximum surface geostrophic velocity within the ring observed on 16 January 2008 was

50.56 cm/s on the northern side (41˚ 02' 55" S , 9˚ 20' 00" E) whilst the surface geostrophic velocities on the southern side were approximately 42.55 cm/s (41˚ 47' 54" S, 10˚ 40' 12" E). The maximum surface geostrophic velocity within the ring observed on 27 February 2008 was 43.72 cm/s on the southern side (43˚ 45' 20" S, 8˚ 00' 00" E) whilst the surface geostrophic velocities on the northern side were approximately 33.27 cm/s (43˚ 01' 44" S, 8˚ 20' 00" E). The position of the geostrophic velocities calculated from hydrographic measurements agreed well with the position of the geostrophic velocities obtained from satellite altimetry on 27 February 2008 however, the magnitude of the surface geostrophic velocities differed between the hydrographic measurements and the satellite altimetry. The main reason for this was that the geostrophic velocities calculated from hydrographic measurements were underestimated due to the reference level (2500 dbar) used to calculate the velocities (this is the level assumed where there was no motion) being too shallow and actual velocities below this reference level were not captured. The maximum surface geostrophic velocities calculated from hydrography on 27 February 2008 were on the northern side and southern side of the ring, 22.17 cm/s and 28.21 cm/s respectively. Thus the geostrophic velocities calculated from the hydrographic observations captured 66% of the total geostrophic velocities on the northern side and 65 % on the southern side of the ring. This is very similar and hence there was likely no bias in the calculated values across the ring. Both of the geostrophic velocities, from satellite altimetry and hydrographic observations, indicated a strong anti-cyclonic motion of ring A.

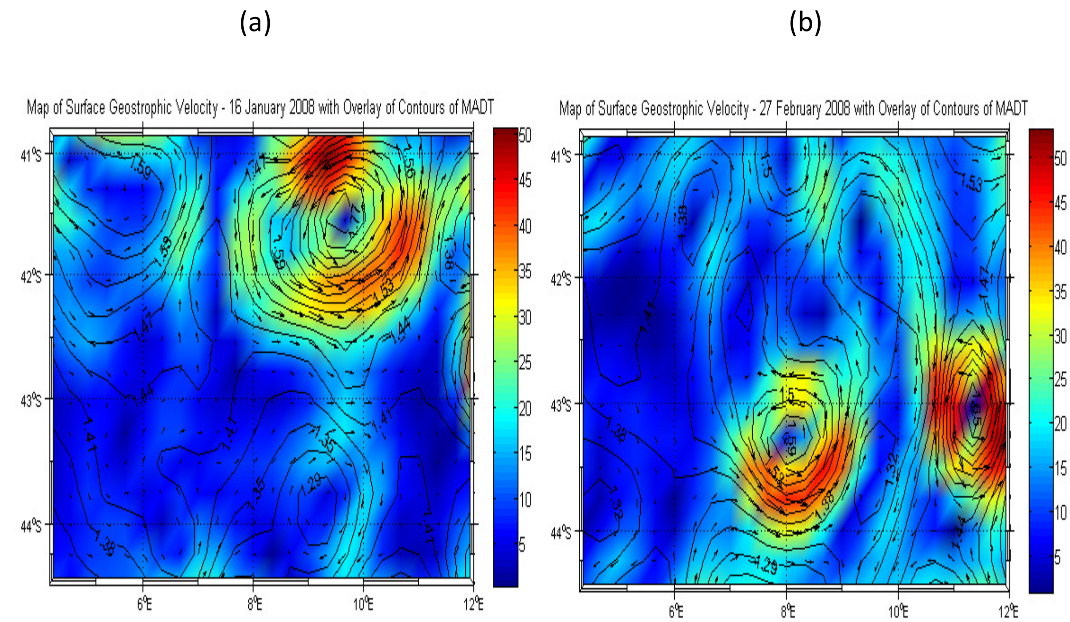


Figure 5.6 Maps of surface geostrophic velocity (cm/s) on 16 January 2008 (a) and 27 February 2008 (b)

5.3. Summary

In the previous chapter it was determined that the ring A was located within the Subantarctic zone and that it contained waters of Indian Ocean origin. This showed that ring A was most likely an Agulhas Ring which spun off from the Agulhas Retroflection. In this chapter, using satellite altimetry (MADT data) and SST data, it was further corroborated that ring A was indeed shed from the Agulhas Retroflection approximately 10 months prior to the Bonus-Goodhope cruise. Since this ring contained waters of Indian Ocean origin (special reference to the positive temperature and salinities anomalies within the ring), its anti-cyclonic motion and that it was shed from the Agulhas Retroflection, it can be assumed that ring A was indeed an Agulhas Ring.

Satellite altimetry showed that the Agulhas Ring had a lifetime of approximately 1 ½ years and travelled the “Southern Route” described by Dencausse et al. (in press) since it travelled south of the Agulhas Ridge into the Subantarctic zone before it crossed the Agulhas Ridge and continued in a north-westward direction. Before the Agulhas ring crossed the Agulhas Ridge it stalled in the Subantarctic zone for approximately four months where it most likely underwent significant convection and mixing since it was exposed to the conditions of the Subantarctic zone. Evidence of this was that the MADT and SST signals dropped during this period and during the time of sampling onboard the Bonus-Goodhope cruise (after this stalling event), the Agulhas Ring showed high homogeneity within its core with respect to its thermohaline properties. The underlying topography (especially the Agulhas Ridge) affected the translational speed of the Agulhas Ring (the ring stalled and slowed down in the vicinity of these topographical barriers) as well as causing splitting events. The most significant splitting event most likely affected by the underlying topography was when the ring sub-divided just to the east of the extreme northern part of the Agulhas Ridge. This splitting event led to two rings drifting northward and southward respectively. Ring A travelled southward, after this splitting event. The underlying topography also affected the path of the Agulhas Ring as when it crossed the Agulhas Ridge, it crossed through the fracture zone where the oceanic depth was greatest. The most rapid period of decay was within the first 10 weeks (shown by the rapid drop-off of MADT) and was likely due to the waters of high salinities and temperatures within the Agulhas Ring being exposed to the colder and fresher waters of the South-East Atlantic Ocean.

6. DISCUSSION AND CONCLUSION

During the Bonus-Goodhope cruise in February 2008, an anomalous patch of warm and salty water extending approximately 90 km in diameter and 2000 m in depth was observed in the Subantarctic zone at approximately 43˚ S on 27 February 2008. A key aim of this study was to determine exactly what this feature was and to determine when the most significant decay of this feature occurred. Other key questions which were examined were determining the lifetime of this Agulhas Ring, the path this ring followed and what effect the underlying topography had on the path and speed of the Agulhas Ring. Hydrographic data obtained from the Bonus-Goodhope, Satellite altimetry and SST radiometer data were used to answer these questions. Hydrographic data was used to investigate the core properties of the feature such as temperature, salinity and the extent of the MLD within the feature. The maximum MADT signal of this anomaly was approximately 2.76 Dyn m which was at the beginning of its lifetime when the anomaly was shed from the Agulhas Retroflection during April 2007. Hydrographic observations and satellite altimetry both agreed with the position of the core of the feature. The most significant decay with respect to Dynamic height drop-off and SST drop-off occurred toward the beginning of the ring's lifetime (first 10 weeks with respect to the Dynamic height and the first 20 weeks with respect to the SST). During these first 10 weeks, Agulhas Ring A remained within the Subtropical zone (During week 1 its position was 39˚ 46' 47" S and 20˚ 40' 12" E while during week 10 its position was 42˚ 02' 47" S and 15˚ 00' 00" E) and the MADT dropped from 2.76 Dyn m to 1.96 Dyn m. At around week 12, Agulhas ring A drifted into the Subantarctic zone and it was for this reason that the rapid SST drop-off continued until week 20 (the ring was subjected to intense air-sea exchanges). At week 20 the rings position was approximately 43˚ 01' 44" S and 13° 00' 00" E. From week 1 until week 20 the SST signature dropped from 20.34 ˚C to 13.35 ˚C. The MADT signal did not drop significantly from week 10 – week 20 (possibly because the deep convection which resulted from the intense air-sea exchanges may have been more delayed and occurred over a longer time period than the rapid SST drop-off). Surface geostrophic velocities obtained from satellite altimetry as well as geostrophic velocities calculated from hydrography showed a distinct anti-clockwise rotation which is typical of warm-cored rings.

The surface geostrophic velocities obtained on 16 January 2008 and 27 February 2008 showed the decay of the Agulhas ring between the two dates since the geostrophic velocities were greater on 16 January 2008. The maximum surface geostrophic velocity within the Agulhas Ring on 16 January 2008 was 50.56 cm/s while the maximum surface velocity within the ring on 27 February 2008 was 43.72 cm/s. During this same period of time the maximum SST within the ring dropped from 13.52 to 12.9 while the MADT dropped from 1.8 Dyn m to 1.6 Dyn m. The drop in SST can also be attributed to the fact that during this time period, the Agulhas Ring drifted into the Subantarctic zone and hence it was subjected to the harsh conditions of this zone.

The CTD results show that the hydrographic structure extended down to approximately 2000 m, which indicated that the underlying topography such as the Agulhas Ridge may have influenced its behaviour. Results from the satellite altimetry confirmed that the Agulhas Ridge did indeed influence the behaviour of the Agulhas ring with respect to its translational speed and path. The ring spent a significant amount of time (approximately 4 months) stalling in the proximity of the Agulhas Ridge before crossing it. The properties observed from hydrography confirmed that there were water masses of Indian Ocean origin trapped within the Agulhas ring. Water masses which were identified from the Indian Ocean within the ring included Subtropical Surface Water (STSW) of Indian Ocean origin and South Indian Central Water (SICW). The geostrophic velocities calculated from hydrography on 27 February 2008 and the velocities obtained from satellite altimetry on 16 January 2008 and 27 February 2008 indicated a strong anti-cyclonic motion which is typical of warm-cored rings. Since anomaly A contained waters of Indian Ocean origin, it was shed from the Agulhas Retroflection and it had a strong anti-cyclonic motion (typical of warm-cored rings), this anomaly is indeed an Agulhas Ring.

Maps of MADT indicated that the Agulhas Ring had an approximate lifetime of 18 months (April 2007 – September 2008) with splitting and merging events throughout this time. In September 2008, it was unlikely that the Agulhas Ring completely dissipated even though the altimetric signature was lost. Merging with a larger ring was suspected to have occurred at around this time. Possible reasons for the loss of the altimetric signal (other than complete dissipation of the Agulhas Ring) include capping of surface waters with warmer water and a merging process with a larger ring. The Agulhas Ring initially moved south of the Agulhas Ridge into the Subantarctic zone before moving north across the STF and crossing over the Agulhas Ridge over a fracture zone (ocean depth ~ 2700m while the surrounding parts of the Agulhas Ridge had depths of approximately 2200m). Once it crossed over the Agulhas Ridge, the ring once again crossed over the STF before moving in a North-Westerly direction. The trajectory of this ring was hence travelling the "southern route" described by (Dencausse et al. in press) since it travelled south of the Agulhas Ridge into the Subantarctic zone. The "Southern Route" described by Dencausse et al. (in press) also describes these rings moving in a North-Westerly direction once crossing the Agulhas Ridge and Agulhas Ring A did indeed move in a North-Westerly direction once crossing over the Agulhas Ridge. Rings travelling through the "Southern Route" also undergo intense hydrologic modifications (Dencausse et al. in press) and Agulhas Ring A had evidence of this from the deep Mixed Layer Depth (MLD) associated with the core (a strong thermostad of 12 ˚C between 90m and 550m)

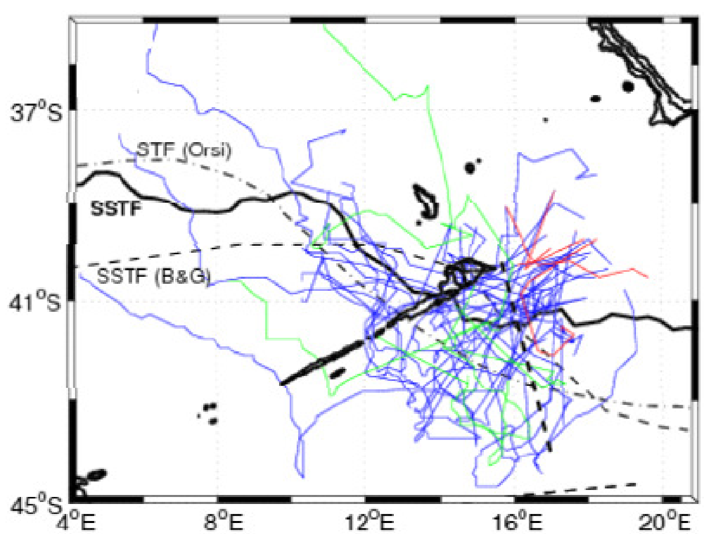


Figure 6.1. The trajectories of rings along the "Southern route" from (Dencausse et al. in press)

Figure 6.1. shows the trajectories of past Agulhas Rings travelling through the “Southern Route” description in which they veer into the Subantarctic zone before moving in a North-Westerly direction. It must be noted that of the three routes described by Dencausse et al. (in press), Agulhas Rings adopt this “Southern Route” the least compared to the other two routes (Northern and Central Route). Dencausse et al. in press studied the trajectory of Agulhas Rings between October 1992 and December 2006 and found that 27.7% of the rings (31 Agulhas Rings) crossed through the “Northern Route”, 49.1% (55 Agulhas Rings) crossed through the “Central Route” while 23.3% (26 Agulhas Rings) crossed through the “Southern Route”.

This case study was therefore important in understanding the dynamics of these rings travelling south of the Agulhas Ridge with respect to their trajectory and modification of the core properties while in the Subantarctic zone. Shortcomings though of this case study were that the sampling of the feature during the Bonus-Goodhope cruise involved only a single transect over the feature and hence the core properties could not extensively be studied. Additionally, there were no other samplings of the feature at other parts of its lifetime as there were no other cruise samplings and profile floats sampling the Agulhas Ring. More can be studied on these particular Agulhas Rings which travel the “Southern Route” through the Subantarctic zone such as the heat and salt anomalies within these rings (if there were to be extensive sampling of the ring through cruise samplings and/or profile floats or model data). Looking at the heat/salt content of these Agulhas Rings may be important for further understanding of the global heat and salt budget as these rings travel into the Subantarctic zone and encounter the ACC which travels uninterrupted around the globe.

7. REFERENCES

Ansorge, I.J., & Lutjeharms, J.R.E. (2003). Eddies originating at the South-West Indian Ridge. *Journal of Marine Systems, 39*, 1-18.

Ansorge, I.J., Speich, S., Lutjeharms, J.R.E., Göni, G.J., de Rautenbach, C.J.W., Froneman, P.W., Rouault, M., & Garzoli, S. (2005). Monitoring the oceanic flow between Africa and Antarctica: Report of the first GoodHope cruise. *South African Journal of Science, 101*, 29-35.

Arhan, M., Mercier, H., & Lutjeharms, J.R.E. (1999). The disparate evolution of three Agulhas rings in the south Atlantic Ocean. *Journal of Geophysical Research, 104*, 20987-21005.

Aviso. (2009). *Sea Surface Height Products.* Retrieved from http://www.aviso.oceanobs.com/

Boebel, O., Lutjeharms, J., Schmid, C., Zenk, W., Rossby, T., & Barron, C. (2003). The Cape Cauldron: A regime of turbulent inter-ocean exchange. *Deep-sea Research, Part II, 50*(1), 57-86. doi:10.1016/SO967-0645(02)00379-X

Burls, N.J., & Reason, C.J.C. (2006). Sea surface temperature fronts in the midlatitude South Atlantic revealed by using microwave satellite data. *Journal of Geophysical Research, 111*, C08001. doi:10.1029/2005JC003133

Byrne, D. A., Gordon, A.L., & Haxby, W.F. (1995). Agulhas Eddies: A synoptic view using Geosat ERM data. *Journal of Physical Oceanography, 25*, 902-917.

Campos, E.J.D., & Olson, D.B. (1999). Stationary Rossby waves in western boundary current extensions. *Journal of Physical Oceanography, 21,* 1202-1224.

De Ruijter, W.P.M., & Boudra, D.B. (1985). The wind-driven circulation in the South Atlantic-Indian Ocean. I. Numerical experiments in a one-layer. *Deep-Sea Research Part A, 32*, 557-574.

De Ruijter, W.P.M., Biastoch, A., Drijfhout, S.S., Lutjeharms, J.R.E., Matano, R.P., Pichevin, T., van Leeuwen, P.J., & Weijter, W. (1999). Indian-Atlantic inter-ocean exchange: dynamics, estimation and impact. *Journal of Geophysical Research, 104*, 20885-20911.

Dencausse, G., Arhan, M., & Speich, S. (in press). Routes of Agulhas rings in the southeastern Cape Basin. *Deep-Sea Research, Part I.*

Ducet, N., Le Traon, P.Y., & Reverdin, G. (2000). Global high-resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and 2. *Journal of Geophysical Research, 105*, 19477-19498.

Duncombe Rae, C.M. (1991). Agulhas retroflection rings in the South Atlantic Ocean: An overview. *South African Journal of Marine Science, 11*, 327-344.

Emery, W.J. (2001). Water types and water masses. In J.H. Steele, S.A. Thorpe & K.K. Turekian (Eds.), *Encyclopedia of ocean sciences* (pp. 3179-3187). San Diego, CA: Academic Press.

Gladyshev, S., Arhan, M., Sokov, A., & Speich, S. (2008). A hydrographic section from South Africa to the southern limit of the Antarctic Circumpolar Current at the Greenwich meridian. *Deep Sea Research Part I, 55*, 1284-1303.

Goni, G.J., Garzoli, S.L., Roubicek, A.J., Olson, D.B., & Brown, O.B. (1997). Agulhas ring dynamics from TOPEX/POSEIDON satellite altimeter data. *Journal of Marine Research, 55*, 861-883.

Hydrographic report of the Bonus-Goodhope cruise (Goodhope Postcruise Rep. No. UCT 1-2008). Cape Town, South Africa: University of Cape Town, Department of Oceanogrpahy.

Gordon, A. L. (1985). Indian-Atlantic transfer of thermocline water at the Agulhas retroflection. *Science, 227*(4690), 1030-1033.

Gordon, A. L. (1986). Inter-Ocean Exchange of Thermocline Water. *Journal of Geophysical Research, 91*, 5037- 5046.

Gordon, A.L., Lutjeharms, J.R.E., & Grundlingh, M.L. (1987). Stratification and circulation at the Agulhas retroflection. *Deep Sea Research Part A, 34*, 565-599.

Gordon, A.L., Weiss, R.F., Smethie, W.M., & Warner, M.J. (1992). Thermocline and intermediate water communication between the South Atlantic and Indian Ocean. *Journal of Geophysical Research, 97*, 7223-7240.

Gründlingh, M.L. (1995). Tracking eddies in the southeast Atlantic and southwest Indian Oceans with TOPEX/Poseidon. *Journal of Geophysical Research, 100*, 24977-24986.

Herbette, S., Morel, Y., & Arhan, M. (2003). Erosion of a surface vortex by a seamount. *Journal of Physical Oceanography, 33*, 1664-1679.

Herbette, S., Morel, Y., & Arhan, M. (2004). Subduction of a surface vortex under an outcropping front. *Journal of Physical Oceanography, 34*, 1610-1627.

Hurlburt, H.E., & Thompson, J.D. (1980). A numerical study of loop current intrusions and eddy shedding. *Journal of Physical Oceanography, 10*, 1611-1651.

Le Traon, P.Y., Nadal, F., & Ducet, N. (1998). An improved mapping method of multisatellite altimeter data. *Journal of Atmospheric and Oceanic Technology, 15*, 522-534.

Lutjeharms, J.R.E. (1996). The exchange of water between the South Indian and the South Atlantic Oceans. In G. Wefer, W.H. Berger, G. Siedler & D. Webb (Eds.), *The South Atlantic: Present and past circulation* (pp. 125-162). Berlin, Germany: Springer-Verlag.

Lutjeharms, J.R.E. (2006). *The Agulhas Current.* Berlin, Germany: Springer-Verlag.

Lutjeharms, J.R.E., & Cooper, J. (1996). Interbasin leakage through Agulhas Current filaments. *Deep-Sea Research Part 1, 43*(2), 213-238.

Lutjeharms, J.R.E., & Fillis, C.S. (2003). Intrusions of Subantarctic water across the subtropical convergence south of Africa. *South African Journal of Science, 99*, 173-176.

Lutjeharms, J.R.E., & van Ballegooyen, R.C. (1988). The retroflection of the Agulhas Current. *Journal of Physical Oceanography, 18*, 1570-1583.

Matano, R. P., & Beier, E.J. (2003). A kinematic analysis of the Indian/Atlantic inter-ocean exchange. *Deep-Sea Research Part 2, 50*, 229-250.

McDonagh, E.L., Heywood, K.J., & Meredith, M.P. (1999). On the structure, paths, and fluxes associated with Agulhas rings. *Journal of Geophysical Research, 104*(C9), 21007-21020.

Molinari, R. L., Lusic, R., Garzoli, S.L., Baringer, M.O. & Goni, G. (2002). Benchmarks for Atlantic Ocean circulation. *CLIVAR Exchanges, No. 25, International CLIVAR Project Office, Southampton, United Kingdom,* 6-9. Retrieved from http://www.aoml.noaa.gov/phod/benchmarks/

Morrow, R., Birol, F., Griffin, D., & Sudre, J. (2004). Divergent pathways of cyclonic and anti-cyclonic ocean eddies. *Journal of Geophysical Research*. *Lett., 31,* L24311. doi:10.1029/2004GL020974

Nilsson, C.S., Andrews, J.C., & Scully-Power, P. (1977). Observations of eddy formation off East Australia. *Journal of Physical Oceanography, 7*, 659-669.

Nilsson, C.S., & Cresswell, G.R. (1981). The formation and evolution of East Australian Current warm-core eddies. *Progress in Oceanography, 9*, 133-183.

Olson, D.B., & Evans, R.H. (1986). Rings of the Agulhas Current. *Deep Sea Research Part A, 33*, 27-42.

Olson, D.B., Fine, R., & Gordon, A.L. (1992). Convective modification of water masses in the Agulhas*. Deep Sea Research Part A, 39*, S163-S181.

Olson, D.B. (1991). Rings in the ocean. *Annual Review of Earth and Planetary Sciences, 19*, 283- 311.

Orsi, A.H., Whitworth III, T., & Nowlin Jr., W.D. (1995). On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep-Sea Research Part I, 45*, 641-673.

Ou, H.W., & De Ruijter, W.P. (1986). Separation of an inertial boundary current from a curved coastline. *Journal of Physical Oceanography, 16*, 280-289.

Pedlosky, J. (1979). *Geophysical fluid dynamics*. New York: Springer-Verlag.

Piola, A.R., & Georgi, D.T. (1982). Circumpolar properties of Antarctic intermediate water and Subantarctic mode water. *Deep-Sea Research Part A, 29*, 687-711.

Remote Sensing Systems. (2009). *Microwave (MW) + InfraRed (IR) OI Sea Surface Temperature (SST)*. Retrieved from http://www.remss.com/sst/microwave_oi_sst_browse.html

Richardson, P.L. (2007). Agulhas leakage into the Atlantic estimated with subsurface floats and surface drifters. *Deep-Sea Research Part I , 54*, 1361-1389.

Schmid, C., Boebel, O., Zenk, W., Lutjeharms, J.R.E., Garzoli, S.L., Richardson, P.L., & Barron, C. (2003). Early evolution of an Agulhas Ring. *Deep-Sea Research II*, this issue (PII: SO967-0645(02)00382-X)

Schouten, M.W., de Ruijter, W.P.M., & van Leeuwen, P.J. (2000). Tranlsation, decay and splitting of Agulhas rings in the southeastern Atlantic Ocean. *Journal of Geophysical Research, 105 (C9*), 21913-21925.

Sokolov, S., & Rintoul, S.R. (2009). Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 1. Mean circumpolar paths. *Journal of Geophysical Research, 114*, C11018, doi:10.1029/2008JC005108, 2009.

Speich, S., Blanke, B., & Madec, G. (2001). Warm and cold water paths of a GCM thermohaline conveyor belt. *Geophysical Research Letters, 28*, 311–314.

Speich, S., Blanke, B., de Vries, P., Drijfhout, S., Döös, K., Ganachaud, A., & Marsh, R. (2002). Tasman leakage: A new route in the global ocean conveyor belt. *Geophysical Research Letters, 29(*1416). doi:10.1029/2001GL014586

SSALTO/DUACS user handbook. (M)SLA and (M)ADT near-real time and delayed time products. Version 1rev5. Ref: CLS-DOS-NT-06.034. Retrieved from http://www.aviso.oceanobs.com/

Stramma, L., & Lutjeharms, J.R.E. (1997). The flow field of the subtropical gyre in the South Indian Ocean into the Southeast Atlantic Ocean: A case study. *Journal of Geophysical Research, 99*, 14053-14070.

Swart, S., & Speich, S. (2010). A satellite altimetry based Gravest Empirical Mode South of Africa: Part II: 1992 – 2008 Heat, Salt and Mass Transport variability and changes. *Journal of Geophysical Research*, *115*, C03003. doi: 10.1029/2009JC005300.

Swart, S., Speich, S., Ansorge, I.J., Goni, G.J., Gladyshev, S., & Lutjeharms, J.R.E. (2008). Transport and variability of the Antarctic Circumpolar Current south of Africa. *Journal of Geophysical Research, 113*(C9), C09014-C09026. doi: 10. 1029/2007JC004223.

Tomczak, M., & Godfrey, J. (2005). *Regional oceanography: An introduction.* Retrieved from http://www.egs.uct.ac.za/webmirror/regoc/pdfversion.html

van Aken, H. M., van Veldhoven, A.K., Veth, C., de Ruijter, W.P.M., van Leeuwen, P.J., Drijfhout, S.S., Whittle, C.P., & Rouault, M. (2003). Observations of a young Agulhas ring, Astrid, during MARE in March 2000. *Deep-Sea Research Part I, 50*, 167-195.

van Sebille, E., & van Leeuwen, P.J. (2007). Fast Northward Energy Transfer in the Atlantic due to Agulhas Rings. *Journal of Physical Oceanography, 37*, 2305-2315.

van Sebille, E., van Leeuwen, P.J., Biastoch, A., & de Ruijter, W.P.M. (2010). On the fast decay of Agulhas rings*. Journal of Geophysical Research,* 115, C03010. doi:10.1029/2009JC005585.

Veronis, G. (1973). Model of world ocean circulation: I. Wind-driven, two layer. *Journal of Marine Research, 31*, 228-288.

Whitworth, T. III, & Nowlin Jr., W.D. (1987). Water masses and currents of the Southern Ocean at the Greenwich Meridian. *Journal of Geophysical Research, 92*(C6), 6462-6476.