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5.3 South Atlantic Inter-Ocean Exchanges

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5.3.1 Introduction

The exchanges of the South Atlantic with the Indian and Pacific Oceans are of critical importance for the global thermohaline circulation and its variability. The South Atlantic is the gateway by which the Atlantic meridional overturning circulation (MOC) communicates with the global ocean, exchanging properties and mass with the Indian and Pacific via the Southern Ocean and around South Africa. These inter-ocean links make possible the unique global reach of North Atlantic Deep Water (NADW) and of the compensating return flow within the ocean upper layers. The latitude of the passages connecting the South Atlantic to the Pacific and Indian Oceans as well as the sharply different nature of southeastern Pacific and southwestern Indian Ocean water masses, allow South Atlantic access of very different water types. As a result the South Atlantic involves nearly all the major climatically important water masses of the World Ocean (Antarctic Intermediate Water, Antarctic Bottom Water, NADW and Mode and thermocline waters). Cool, low salinity waters are introduced through the Drake Passage; warm, saline subtropical Indian Ocean waters enter at the Agulhas Retroflection (the cold and warm water routes, respectively). The resultant heat, freshwater and buoyancy budget of the South Atlantic is expected to be sensitive to the ratio of these two return flows. Which of the South Atlantic's neighbors dominates the inter-ocean exchange may to a large measure determine the meridional fluxes of the South Atlantic (Gordon, 1986, 2001; Weijer et al., 1999). Temporal variations in the ratio may be associated with climate variability as well as variations in the overturning circulation of the Atlantic Ocean. This explains why inter-ocean exchanges have been subject to much attention in recent years. Several review papers on the subject have appeared recently (Gordon, 2001; De Ruijter et al., 1999) and the reader is referred to those reviews for detailed descriptions of regional and global aspects of the topic. In this paper emphasis will be on recent results concerning exchanges between the subtropical South Atlantic and the Southern Ocean, the Pacific link via the Drake Passage and the subsequent transformations at the Brazil/Malvinas Confluence, and the Indian-Atlantic Ocean connection at the Agulhas Retroflection.

5.3.2 Exchanges between the South Atlantic and the Southern Ocean.

The real ocean conveyor flows around Antarctica, where the Antarctic Circumpolar Current (ACC) provides the major connection between the three oceans. Meridional fluxes of heat and freshwater, necessary to balance the air-sea buoyancy fluxes south of the ACC, are largely provided by mesoscale eddies (DeSzoeke and Levine, Bryden and Cunningham, 2001, Karsten and Marshall, 2001). Fresh water evaporating from the subtropical South Atlantic increases the surface salinity of the subtropical water. It is carried southward by the atmosphere and was observed to lead to a freshening of the surface layer of the ACC on its way eastward across the South Atlantic (Gordon and Piola, 1983). This fresh water is subsequently carried into the Pacific by the ACC and eventually has to return to the Atlantic via the Drake Passage and/or the Bering Strait.

Table 1: Solution fluxes from McDonagh and King (2002) on the sections corrected to zero net mass flux except the net freshwater flux that is calculated relative to a Bering Strait throughflow of 0.8 Sv at an average salinity of 32.5.

	A10 (30°S)	A11 (45°S)
Layer transports (Sv)		
Surface	7.1	9.7
Intermediate	7.3	6.0
Deep	-19.9	-21.0
Bottom	5.5	5.3
Heat (PW)		
Ekman	-0.03	0.21
Overturning	0.55	0.17
Gyre	-0.31	0.05
total heat	0.22±0.08	0.43±0.08
total salt (Sv psu)	-9.7	-2.9
Section average		
potential temperature (°C)	4.35	2.58
salinity	34.81	34.65
Net freshwater flux (Sv)	-0.5	-0.7

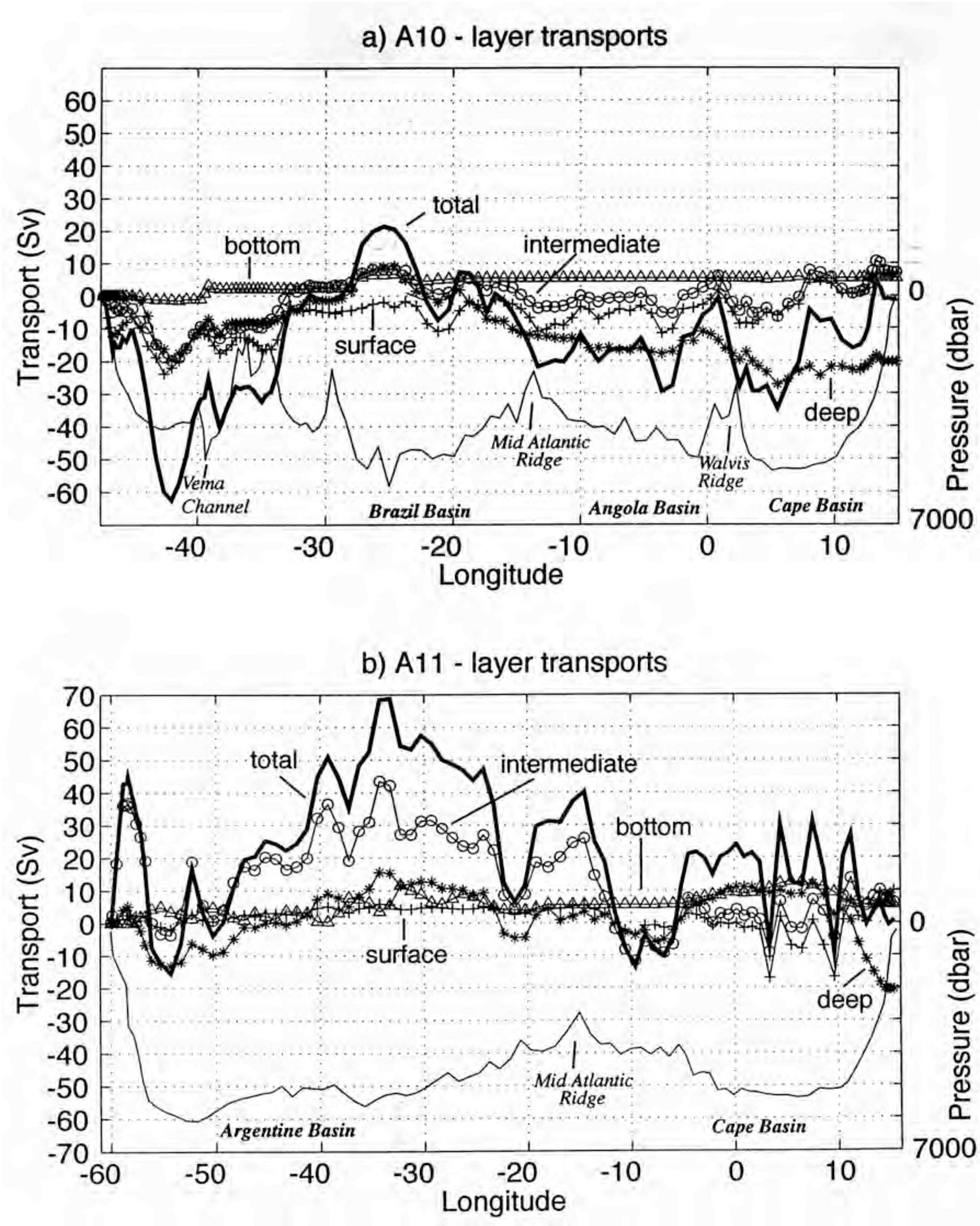

Figure 1: Transport in Sv (positive northwards) cumulated from the western end of the section for a) WOCE section A 10 and b) A 11. Transports of surface (+), intermediate (o), deep (□) and bottom (□) water are shown as well as the total transport in bold. The thin line shows the pressure of the bathymetry in each plot. (From McDonagh and King, 2002).

Several studies have concluded that the cold water route contributes significantly to the cross equatorial flow into the North Atlantic. England and Garçon (1994) estimated that about 6.5

Sv of these waters flow into the North Atlantic. Similar or larger cold water route contributions, based on inverse methods, water mass studies and models have also been estimated (eg. de las Heras and Schlitzer, 1999; Marchisiello et al., 1999; Sloyan and Rintoul, 2001b; You, 2002).

During WOCE (the World Ocean Circulation Experiment) two transatlantic hydrographic sections were occupied almost simultaneously: section A10 at 30°S and A11 eastward from South America to about 15°W at a nominal 45°S and from there closing on to South Africa. McDonagh and King (2002) analyzed these sections using an inverse model (constraining western boundary current transports and other elements of the circulation), providing the most recent estimate of the circulation and fluxes in this region. Their results confirm the, well known, fact that the South Atlantic carries heat equatorward (in contrast to the Pacific and Indian Oceans where it is poleward). At the A11 section the estimated northward heat flux is 0.43±0.08 PW while at 30°S it has decreased to 0.22±0.08 PW (1PW=1x10^{15}W). This implies a flux of heat from the ocean to the atmosphere in this latitude band of the South Atlantic of about 0.21 PW. Uncertainties in these heat flux estimates are dominated by uncertainty in the location and temperature of the flow near the surface (McDonagh and King, 2002).

The equatorward heat transport appears to be primarily a function of the large-scale meridional overturning circulation (Table 1); in the horizontal plane the wind-driven subtropical gyre transports heat poleward. Northward flows of warm surface, intermediate and bottom waters were balanced by 20 Sv of southward flowing North Atlantic Deep Water during the occupation of these WOCE-lines. Surface and intermediate waters (Figure 1 & Table 1) were returned to the South Atlantic at the A11 section from the Pacific via the Drake Passage and from the Indian Ocean via the Agulhas Retroflection.

The estimated net northward flux of intermediate water during this period is 6.0 Sv and comes entirely from the western part of the Atlantic subtropical gyre, i.e. west of 12°W (Fig. 1). East of 12°W the net flux of intermediate water was slightly negative (Fig. 1), suggesting that the intermediate water that is exported from the South Atlantic south of the Agulhas retroflection as part of the subtropical 'supergyre' (Gordon et al., 1992; De Ruijter, 1982) is partly transformed to surface water while looping through the western Indian Ocean. So, this result does not preclude a flux of intermediate water from the Indian to the Atlantic Ocean, as observed earlier (Gordon et al., 1992; Mc.Donagh et al., 1999) but it indicates that the Antarctic intermediate water residing within the Argentine Basin provides the primary balance at intermediate depths for Atlantic export of NADW. In addition there is northward flux of surface water is estimated at 9.7 Sv, returning to the Atlantic from the Indian Ocean.

Based on an analysis of data from a December 1988-January 1989 SAVE (South Atlantic Ventilation Experiment) cruise Gordon et al. (1992) concluded that during that period 15 Sv of the 25 Sv geostrophic transport of the Benguela Current was derived from the Indian Ocean and that 9 Sv (2 Sv warmer than 9°C and 7 Sv of lower thermocline and Intermediate Water) of that Indian Ocean water crossed the equator within the North Brazil Current.

The Atlantic freshwater flux remains controversial. Wijffels et al., 1992 estimated 0.8 Sv flow through the Bering Strait and 0.7 Sv of net evaporation between there and 35°S in the

Atlantic. However, the recent inverse analyses at 45°S (McDonagh and King, 2002, Saunders and King, 1995 and Holfort and Siedler, 2001) consistently estimate that the freshwater flux southward through section A11 is between 0.55 Sv and 0.75 Sv, implying no net evaporation over the Atlantic north of that section.

5.3.3 Where and how to monitor the basin scale overturning fluxes?

There are a number of reasons for choosing the latitude of 30°S rather than 45°S (i.e. A11) for observing the net effect of the interocean exchanges between the South Atlantic and the Southern Ocean on the overturning fluxes: 1. 30°S crosses the subtropical gyre without excursion into the Southern Ocean; 2. the western boundary current at 30°S is clear of the confluence region of the Brazil and Malvinas/Falkland currents where transport estimates are difficult; 3. the flux of Antarctic Bottom Water across 30°S is constrained in the Vema and Hunter Channels and can be monitored; 4. to close onto the African continent a section at 45°S has to cut through the Cape Basin, where Agulhas Rings are injected into the South Atlantic (see below); in fact, to avoid intersection with the Agulhas Ring 'corridor' (evidenced also in Fig 1b) one would have to take an even more northerly section at about 26°S; 5. at 30°S transatlantic sections are zonal; 6. at 45°S there is significant zonal depth averaged temperature gradient which means that heat flux estimates are sensitive to small shifts in the horizontal gyre scale circulation.

In the inverse modelling studies mentioned earlier the detailed circulation patterns and hence the basin scale budgets are dominated by the a priori constraints on the solution, the most significant of these being the strength and properties of the western boundary currents such as the Brazil and Malvinas/Falklands Currents and Deep Western Boundary Current. Other constraints are also important, such as wind stress, air-sea buoyancy fluxes, Antarctic Bottom Water flux and the eastern boundary currents such as the Benguela. (For example in the inverse solutions of McDonagh and King (2002) the eastern side of the subtropical gyre circulations at A11 had a significantly different circulation from an earlier inverse solution of these data (Saunders and King, 1995). The depth-averaged differences in the Cape Basin circulation were greater than 40 Sv and accounted for the reduced equatorward heat flux estimates in the later section study. Improved observations of all these quantities will help to describe and quantify the basin scale exchanges. The large-scale baroclinic structure set up by the properties and distribution of the various water masses also contributes to uncertainty in the net fluxes. Making sufficient realizations of a transatlantic section at 30°S to reduce this error is probably impractical though monitoring the basin wide thermal shear by boundary density measurements (as demonstrated in a modelling study by Hirschi et al. (2002) for 26.5°N in the Atlantic) could be a practical option.

In the North Atlantic Jayne and Marotzke (2001) showed that the meridional overturning heat transport fluctuations were dominated by fluctuations in the velocity field. Continuous observations of the horizontal circulation and properties would likely constrain the estimates of the overturning and heat flux variability: profiling floats would partly provide such information, in particular in combination with well designed monitoring arrays across the western boundary current and across the Cape Basin (the latter to monitor the portion of the Agulhas leakage that takes part in the MOC).

5.3.4 The Pacific link with the Southwest Atlantic.

Volume transport through the Drake Passage.

The cold water flow from the Pacific Ocean into the South Atlantic is associated with the Antarctic Circumpolar Current (ACC) as it deflects northward downstream of Drake Passage. Since 1993 the UK has completed seven occupations of WOCE Southern Repeat section 1 across Drake Passage from Burdwood Bank to Elephant Island. Cunningham et al. (2001) analyzed these data to determine the transport and variability of the Antarctic Circumpolar Current in Drake Passage. The net through passage baroclinic transport relative to the deepest common level is 136.7±7.8 Sv and is carried principally by the two main jets of the ACC: the Subantarctic Front 53±10 Sv and the Polar Front 57±5.7 Sv. From the ISOS current meters, hydrography and bottom pressure measurements Whitworth III and Peterson (1985) determined the average total net transport through Drake Passage to be 134±11.2 Sv. Comparing the net and baroclinic transports suggests that the baroclinic field contains most of the net ACC transport through Drake Passage. This was shown in the work of Bryden and Pillsbury (1977), where the net transport contribution due to the velocity field at 2700 m was small, though variable. Rintoul et al. (2001) and Cunningham et al. (2001) reinterpreted the results of Whitworth III and Peterson (1985) to conclude that above 2500 m barotropic variability (±9.9 Sv) of the ACC is of the same order as the baroclinic variability (5.5 Sv): there is no reason to suppose that this variability would not be transferred to the Malvinas/Falkland Current. This has the important implication that monitoring of variability cannot be done purely by measuring pressure differences but must also include measurements of water mass variability.

Heat transport and divergence.

Transport or divergence of heat is a useful concept only where there is a net balance of volume. However, the volume-transport-weighted mean temperature across a boundary can be used to give an indication of the way a property is changing in some region.

Georgi and Toole, (1982) reported the volume-transport-weighted mean temperature for their analysis of two Drake Passage sections. This quantity is the total property transport divided by the total volume transport, and in the Georgi and Toole analysis has the value 2.52°C. They used the difference between this value and the equivalent value south of Africa (1.82 °C) to infer the heat lost by this sector of the ACC: essentially 0.7°C times 127 Sv (0.36 PW). The transport-weighted mean temperatures in °C for the six WOCE sections (Cunningham et al. (2001) ranged between 2.10 and 2.50. High values were for cruises, conducted in late Austral Spring, and the lower values were for early spring observations. In other words, the seasonal cycle, through heating of the surface layer where the velocities are greatest, introduces considerable changes in the heat transported through Drake Passage with a range of 0.4x137 Sv°C, or 0.22 PW. A study of heat gained or lost along the track of the ACC using mean temperatures at the choke points must therefore make very careful consideration of the seasonal signals in all the data used.

5.3.5 The Brazil-Malvinas confluence.

The Subantarctic Front, located near 56-57°S at Drake Passage, loops northward reaching 38°S in the western Argentine Basin to form the Malvinas/Falkland Current (MFC). Estimates of the volume transport of the MFC range between 40 and 70Sv, the barotropic component accounting for about 75 to 85% of the transport (eg. Saunders and King, 1995a; Peterson et al., 1996; Vivier and Provost, 1999, see also Fig.1b). MFC variations have been found to be associated to anomalies in the wind stress curl north of 60°S and to baroclinic waves propagating along the shelf break of South America (Vivier et al., 2001, see also Garzoli and Giuliv, 1994). In contrast with transport variations at the eastern boundary of the South Atlantic, it has been suggested that even large fluctuations of MFC transport have a moderate effect on the meridional heat flux across 40°S (Saunders and King, 1995b). However this conclusion does not consider possible temperature changes within the core of the western boundary current (see also the above discussion on the a priori constraints imposed on inverse models).

Near 38°S the MFC collides with the southward flowing Brazil Current forming the Brazil/Malvinas Confluence (BMC). That region is characterized by high mesoscale eddy energy and thermohaline finestructure activity. The BMC undergoes large meridional fluctuations (Olson et al., 1988), presumably caused by wind induced transport fluctuations of the Brazil Current (Matano et al., 1993) and wind fluctuations further south (Garzoli and Giulivi, 1994). A substantial, not yet quantified, amount of MFC water describes a sharp cyclonic loop, returning southward to about 50°S, near the Falkland Escarpment.

In the upper layers the MFC carries the densest variety of Subantarctic Mode Waters (SAMW, sigma theta < 27.15) from the southeast Pacific, and the denser Antarctic Intermediate Water (AAIW, sigma theta > 27.25). These waters are responsible for the remarkably low salinity water observed in the western South Atlantic (generally referred to as AAIW). The lighter variety (SAMW) is exposed to the winter atmosphere within the MFC and its southward return, therefore local modifications by sea-air interactions are possible (Piola and Gordon, 1989; Talley, 1996; Stramma and England, 1999; Sloyan and Rintoul, 2001b). The region between the MFC and its return is frequently occupied by waters found south of the Subantarctic Front in the ACC, but there is no evidence of interaction with waters from the Subtropical domain.

The inverse calculations suggests that within the Atlantic sector of the Southern Ocean about 8 Sv of Antarctic Surface Water are converted into lower SAMW by sea-air interaction (Sloyan and Rintoul, 2001b). Most of this conversion takes place in the SW Atlantic. The same study concludes that an additional 6 Sv of warm-salty thermocline water is converted to upper SAMW by sea-air interaction between the Argentine Basin and the mid ocean ridge at 20°W.

At the BMC and its seaward extension there is evidence of subduction and intense mixing of the cold fresh varieties of Drake Passage intermediate waters with the AAIW recirculated in the South Atlantic subtropical gyre, which enters the region as part of the Brazil Current (see also Fig 1a). There is also evidence of subduction of relatively fresh intermediate waters along the South Atlantic Current. A substantial amount (50%) of South Atlantic water is estimated to contribute to the northward flowing Benguela Current in the eastern South Atlantic (Garzoli and Gordon, 1996). This appears to be the main path of northward flow of Atlantic waters at subtropical latitudes (Sloyan and Rintoul, 2001b).

The above results suggest that the inflow of SAMW and AAIW and the modifications of these water masses within the southwest Atlantic are key elements of the thermohaline circulation. The possible effects of the large variations of the mass transport of the MFC as well as variability in the wind stress and sea-air heat and freshwater fluxes within the western South Atlantic are unknown. However, these changes are likely to impact on the thermohaline characteristics of the SAMW/AAIW layers and ultimately on the properties of the northward flux of these waters further downstream in the Subtropical and Tropical South Atlantic.

Further down in the water column the MFC carries varieties of Circumpolar Deep Water (CDW) and Antarctic Bottom Water (AABW). The northward flow of deep waters (~40 Sv) occurs in a narrow band along the western boundary and most of these waters appear to return southward with the Malvinas Return Current (Sloyan and Rintoul, 2001a). The thermohaline characteristics of the deep water within the Malvinas Return Current show clear penetrations of NADW well south of the Brazil/Malvinas Confluence. Arhan et al., (2002) have detected diluted NADW flowing over the Falkland Plareau. There is evidence of intense lateral (isopycnal) mixing between varieties of CDW and NADW within the Argentine Basin, notably along the western boundary current (Georgi, 1981), and associated to energetic eddies in the Georgia Basin (Arhan et al., 2002). Further east the core of NADW becomes progressively less salty due to vertical mixing. Thus, the Southwest Atlantic is the region of intense mixing, where NADW first comes in contact with the deep waters from the ACC.

Clearly, an intelligent monitoring system has to be designed for this highly variable region of intense exchange and mixing. A long term monitoring array should also be maintained across the Drake Passage to observe the varying Pacific to Atlantic fluxes.

5.3.6 The exchanges between the Indian and South Atlantic Oceans.

The South Atlantic, South Indian and Southern Ocean waters intermingle in the Cape Basin region, one of the most turbulent spots of the world ocean. In the canonical description of the global conveyor belt the South Atlantic's subtropical gyre draws heat and salt from this region and exports them to the tropics. Although this entrainment in the upper layers is largely ascribed to the shedding of large rings and eddies from the Agulhas Current, the major western boundary current of the South Indian Ocean, it is unclear how these mesoscale, transient fluxes are ultimately integrated into the global thermohaline circulation. The exchanges in the opposite direction, taking place in the lower layers, are largely inferred from water type dilutions (e.g. You et al., 2003; Van Aken et al., 2003) and modelling (e.g. Matano and Beier, 2003).

Modelling of the Atlantic meridional overturning circulation has demonstrated (Weijer et al., 2001, 2003) that the insertion of the warm and salty waters from the South Indian Ocean has a stimulating and stabilizing impact on the thermohaline overturning cycle of the Atlantic as a whole. Furthermore, ocean modelling simulations of the southern hemisphere suggest

(Speich et al., 2002) that the wind-driven circulation is connected in a subtropical super-gyre that results in an efficient conveyer of upper layer waters between all three oceans, north of the ACC. This implies that monitoring the exchanges around South Africa will have far wider implications than the local circulation only.

The Agulhas Retroflection.

The major and most studied part of the interocean exchange south of Africa is the shedding of rings at the Agulhas retroflection (De Ruijter et al., 1999). A secondary, but much smaller, source is the leakage due to Agulhas filaments (Lutjeharms and Cooper, 1996). Direct leakage of Agulhas water at different levels is probably also a component of the interocean exchange, but this part is very poorly quantified due to the dominance of the rings in the region. There is evidence that variations of the Benguela Current transport are due to a variable Agulhas leakage (Garzoli et al., 1996).

At its westward termination the Agulhas Current carries out an abrupt retroflection with the majority of its water subsequently flowing eastward as the Agulhas Return Current (Gordon et al., 1987; Lutjeharms and Ansorge, 2002). To what extent the Aguhas Return Current is an extension of the South Atlantic Current (Stramma and Peterson, 1990) is not known, but water that recirculates as part of the above-mentioned subtropical super-gyre will pass into the Indian Ocean directly south of the retroflection (De Ruijter, 1982; Gordon et al.,1992). The retroflection loop lies between 10° and 21° E and regularly occludes (Lutjeharms and Gordon, 1987), forming an Agulhas ring that subsequently moves off into the South Atlantic. This process of ring shedding is controlled from upstream through the downstream movement of large, solitary meanders, Natal Pulses (Van Leeuwen et al., 2000). These, in turn, seem to be related to inherent circulation variability of the larger Indian Ocean as described below.

On occasion the Agulhas Current may undergo an early retroflection and the throughflow to the retroflection may cease for a number of months (De Ruijter et al., 2003; Lutjeharms et al., in preparation).

Heat flux and dissipation of Agulhas rings.

Agulhas rings may have diameters of up to 500 km, but the more general, average diameter for these features is 320 km. They extend to the ocean floor and have azimuthal speeds between 0.3 and 1.5 m/s (e.g. Van Aken et al., 2003). On having been shed, they move off into the South Atlantic at rates of about 4-8 km/day. Rings have been tracked across the greater part of the South Atlantic Ocean subtropical gyre (Byrne et al., 1995; Schouten et al., 2000). In a recent review Boebel et al. (2003) estimated that only half of the Agulhas eddies that populate the Cape Basin cross the Walvis Ridge and propagate to the west. Although revealing, this value is likely to underestimate the anisotropic distribution of the eddy variability in the southeastern Atlantic as satellite altimeter data indicate differences of eddy variability across the Walvis Ridge of approximately an order of magnitude (Fig. 2). Altimeter based descriptions (Schouten et al., 2000) have also indicated that, on average, Agulhas rings loose at least 50% of their energy in the Cape Basin within the first half year after their shedding, i.e. between their point of origin and the Walvis Ridge (Fig. 3). A large part seems to dissipate - to an extent that they are no longer identifiable as entities in the altimeter signal- in the same region. This implies that most of the energy, excessive salt and heat carried by Agulhas rings is not evenly distributed across the South Atlantic gyre, but is inserted into the water masses in this far-south-western corner of the ocean basin. It may subsequently be advected northwestward within the Benguela Current, the South Equatorial Current and across the equator. This makes monitoring of the evolution of these features as closely as possible to their point of origin essential.

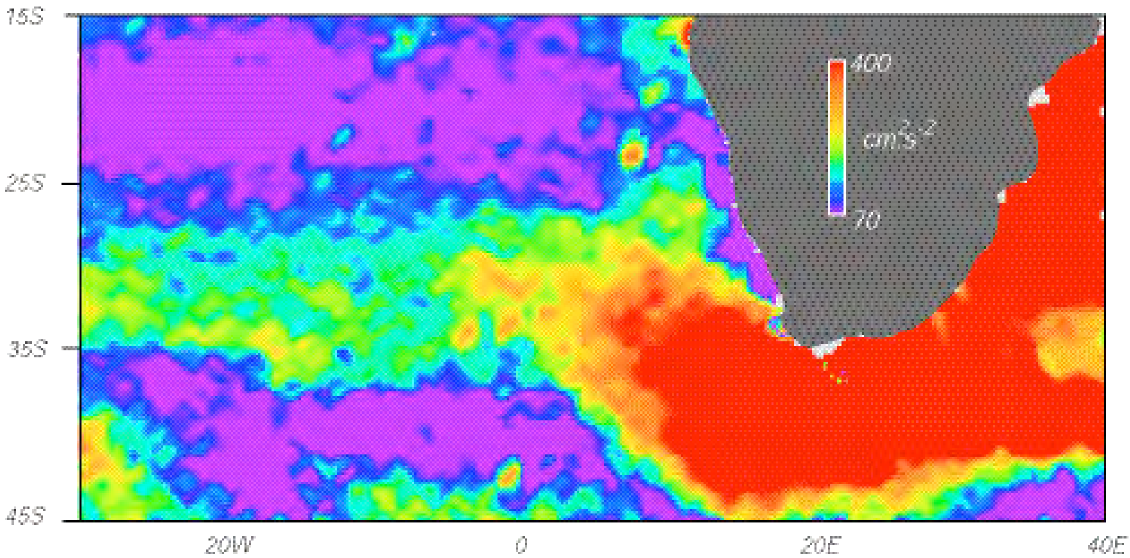

Figure 2: RMS variability of sea surface height in the southeastern Atlantic computed from 10 years of T/P altimeter data, clearly revealing the main paths of Agulhas Rings and the sharp decay of eddy variability away from the Cape Basin.

One of the reasons for the sharp decay of eddy variability away from the Cape Basin seems to be related to the dynamical structure of the rings and eddies and their interactions with each other, the mean circulation and the bottom topography. The most recent analyses of the Cape Basin variability show the co-existence of cyclonic and anticyclonic vortices. While the existence of anticyclones has been known for quite some time (e.g., De Ruijter et al., 1999 and references therein) the cyclonic structures have been largely ignored until quite recently. One of the reasons is that the surface signature of cyclones, in the region where most of the observations have been taken, is substantially smaller than that of the anticyclones. Cyclones, however, seem to outnumber anticyclones by a 3 to 2 ratio (Boebel et al., 2003). The analysis of numerical model simulations indicate that anticyclones and cyclones tend to form dipole-like structures that resemble the Heton model of Hogg and Stommel (1985), with an anticyclone intensified at the surface and a cyclone intensified at the bottom (Matano and Beier, 2003). In the simulations the propagation of both cyclones and anticyclones is strongly affected by the bottom topography. The Walvis Ridge and the Vema Seamount block the passage of bottom-intensified cyclones and changes the trajectories of the upper-intensified anticyclones. From the anticyclones that are able to escape the basin the deep compensation generated by the ridge generates substantial losses of energy.

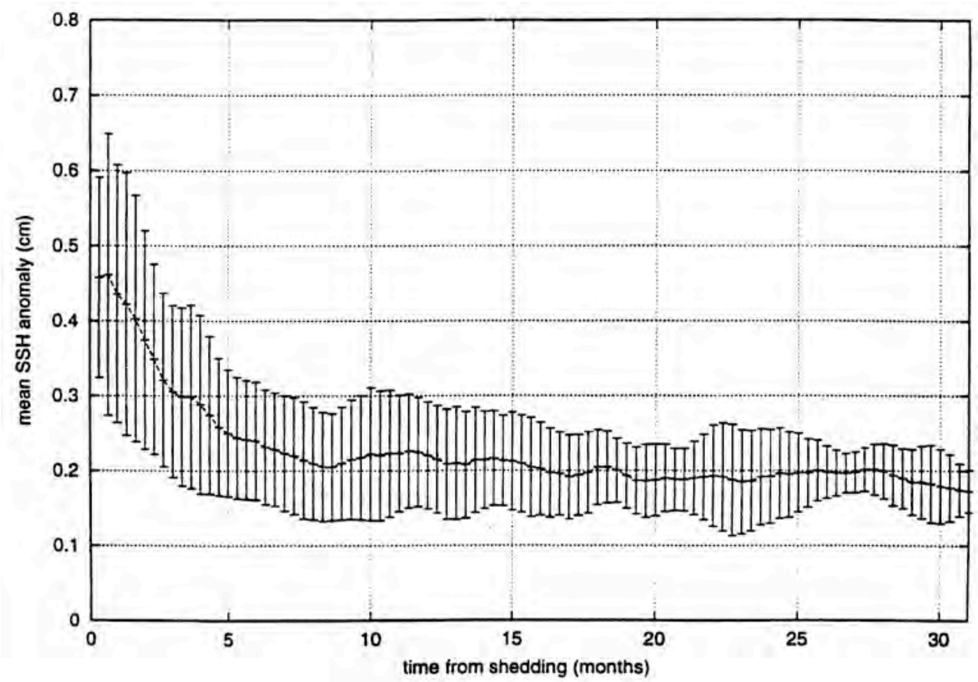

Figure 3: Mean sea surface height variability (and bars of 1 standard deviation) of an ensemble of 11 Agulhas Rings as a function of their age, showing very strong decay in the Cape Basin in the first 5 months of their lifetime.

Rings and eddies that do cross the Walvis Ridge follow a mostly westward path towards the western boundary and although their ultimate fate is unknown it seems reasonable to surmise that mixing processes within the subtropical gyre can transfer a portion of their properties to the global conveyor belt.

A number of other factors also play an important role in the modifications of Agulhas rings once shed. The anomalous surface temperatures of fresh Agulhas rings and the reigning atmospheric conditions in the general region lead to enormous heat and fresh water losses from these features (Walker and Mey, 1988) of up to 1000 W/m^2 on occasion (Rouault and Lutjeharms, 2000). This leads to substantial mixing and convective overturning in the upper layers of these features (Olson et al., 1992) and thus to changes to their water mass characteristics. Recent studies have demonstrated that Agulhas rings may spend substantial periods in the south-western corner of the Cape Basin (Schouten et al., 2000), with water being exchanged between them at intermediate depths (Boebel et al., 2003a) and between them and recently discovered Agulhas cyclones (Lutjeharms et al., 2003). Clearly, this *Cape Cauldron* is a region of intense mesoscale turbulence and mixing which complicates considerably the estimation and monitoring of the exchange between the South Indian and the South Atlantic Ocean.

The anomalous heat flux brought about by a newly spawned Agulhas ring relative to its new South Atlantic environment was estimated to be 7.5×10^{-3} PW and the salt flux due to one ring about 4×10^{5} kg/s (Van Ballegooyen et al., 1994). However, the ranges of these variables as estimated from different research projects are very large, sometimes because authors use different reference temperatures (De Ruijter et al., 1999; Gordon, 2001). McDonagh and King

(2002) analysed the impact of two Agulhas rings that were sampled in the Cape Basin on the A11 hydrographic section. They estimated that together the two eddies contributed 0.08±0.14 PW northward heat flux. This recent estimate of northward heat flux due to Agulhas rings is much larger than that estimated by Van Ballegooyen et al. (1994). Using the work of Byrne et al. (1995) McDonagh and King (2002) estimate that half of the Agulhas rings crossing A11 remain intact north of that section, and each ring injects about 0.025 PW of heat into this region. Clearly, these are huge quantities for mesoscale eddies in the ocean, both facilitating and hindering their accurate monitoring.

The heat flux from the Indian to the Atlantic Ocean for an Agulhas leakage of 15 SV if balanced by water that leaves the Atlantic within the upper 1500m (i.e. via the supergyre) is 0.3 PW. If balance is made with the colder NADW then the flux will be 0.8 PW (Gordon, 2001). The estimated total injection of Indian Ocean water into the Atlantic by the rings is from 5 to 10 Sv.

5.3.7 Upstream control from the Indian Ocean

It has been demonstrated recently from satellite altimeter data that the shedding of Agulhas rings is a much more regular process then previously thought, at a frequency of 4 to 5 cycles per year (Schouten et al., 2002a). Eddies from the Mozambique Channel (De Ruijter et al., 2002) and from the East Madagascar Current (De Ruijter et al., 2003) reach the retroflection at that frequency and trigger the shedding of the Rings. The intermittency found in ring shedding statistics in earlier studies is probably related to processes such as instabilities and ring splitting occurring between the actual pinching off and the first unambiguous observation of a separate ring from the altimeter signal.

From altimeter data Schouten et al. (2002b) have presented evidence for an oceanic teleconnection between wind variations over the equatorial Indian Ocean and the regular shedding of Agulhas Rings at a lag of about two years. The equatorial signal seems to be carried across the Indian Ocean by a succession of Kelvin and Rossby waves that eventually seem to control the timing and frequency of the eddy formation around Madagascar and subsequent Agulhas Ring formation. Two observed ‘gaps’ in ring formation over the past decade, one in 1996 (Goni et al., 1997) the other one between January and September 2000 (Quartly and Srokosz, 2002), could be traced back to the equatorial anomalies asociated with the 1994 and 1997/1998 Indian Ocean Dipole/El Niño events, respectively. So, interannual and longer time scale variations in the interocean exchange around South Africa may be linked to the strength and variability of the equatorial climate modes of the Indian Ocean.

5.3.8 Monitoring.

A number of possibilities exist for the monitoring of the oceanic exchanges that take place south of Africa. The first is to observe and identify Agulhas ring shedding from satellite remote sensing. If the surface thermal expressions of Agulhas rings can be directly related to the average heat and salt content of such features (Lutjeharms and Van Ballegooyen, 1988), observations from satellite of the thermal signature of rings would give a first order estimate of the heat and salt flux brought about by these features. However, these features rapidly loose their distinctive surface temperatures due to exchanges with the atmosphere thus making them indistinguishable from the general background environment. The use of satellite altimetry overcomes this liability. Agulhas rings have one of the strongest sea surface height signals in the world. This makes them eminently observable with altimetry. It has been shown that the sea surface height and the dynamical signal of rings based on hydrographic observations are closely related (Goñi et al., 1997). However, altimetry signals of smaller rings may be lost between suborbital tracks and it has been shown that rings may break up and dissipate (Schouten et al., 2000) or subsequently coalesce (Boebel et al., 2003a). This makes the tracking of rings to monitor the heat and salt flux they represent difficult. The best current option would be to monitor Agulhas rings with altimetry while making simultaneous current or hydrographic observations. This has been achieved (Garzoli and Goni, 2000; Van Aken et al., 2003) with a high degree of success. Two monitoring projects using this combination of observations are currently planned.

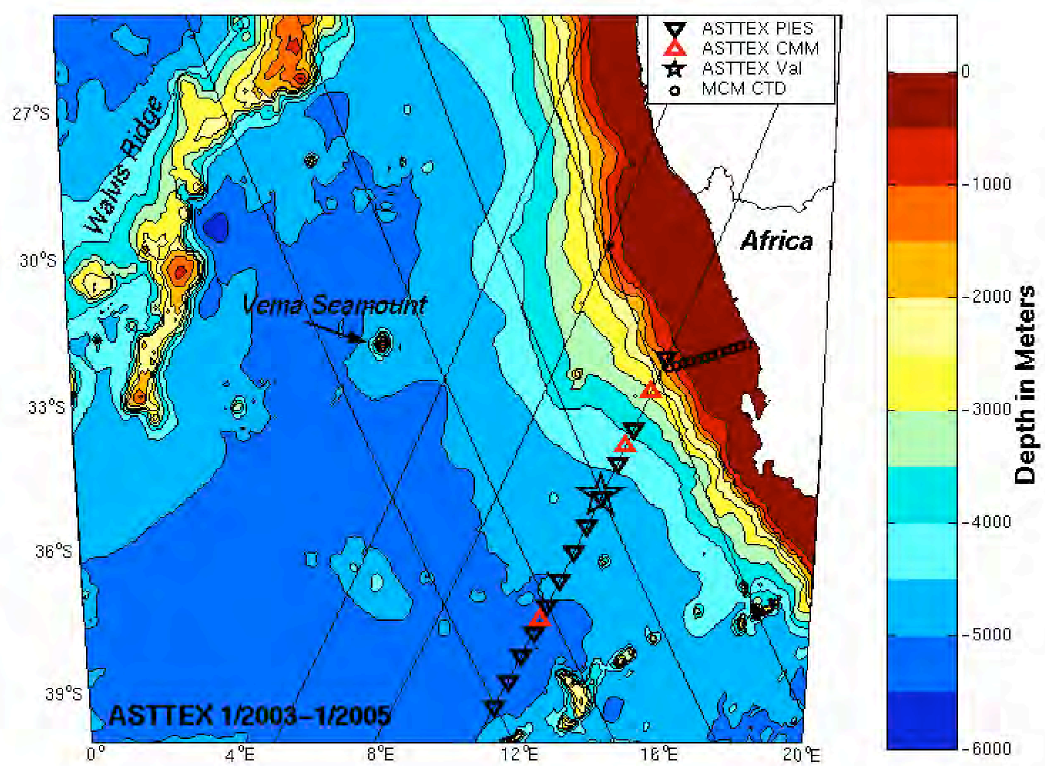

Figure 4: The ASTTEX array southwest of Africa (from the web site: http://www.gyre.umeoce.maine.edu/ASTTEX).

The first, ASTTEX (see http://www.gyre.umeoce.maine.edu/ASTTEX), will place a line of inverted echosounders on a TOPEX/Poseidon suborbital track to the southwest of Africa (Fig. 4). By all estimates this will effectively monitor Agulhas leakage and the movement of rings into the South Atlantic for the years 2003 - 2005. A further, international proposal, GoodHope will attempt to cover this line with hydrographic observations at least twice a year. The line will then extend along the SR2 line of WOCE to the Antarctic continent to monitor changes in the Antarctic Circumpolar Current south of Africa. It therefore seems that for the immediate future, this part of the interocean exchange will be monitored sufficiently, but for a time period limited to only a few years. Other components of the system will not be covered in the same way.

The inflow and variability of the South Atlantic Current (Stramma and Peterson, 1990) to the region south of Africa is poorly known. Exactly how much of this water is absorbed into the equatorward drift of the Benguela Current and how much continues on to join the Agulhas Return Current (Boebel et al., 2003b) carrying water into the South Indian should be established. Considering the temporal variability of the currents in this region, it is relatively safe to assume that the flux carried by the South Atlantic Current would be highly variable. To date there are no plans to monitor this.

It may be crucial to an understanding of the thermohaline circulation of the Atlantic Ocean to establish how much heat and salt are injected by Agulhas rings in the Cape Basin and how much is carried into the subtropical gyre of the South Atlantic. It might be considerably more difficult to design a monitoring array to establish these fluxes unequivocally. A pilot project, MARE (Mixing of Agulhas Rings Experiment), to try to establish the amount of heat and salt injected into the Benguela by an Agulhas Ring has recently finished its observational phase (e.g. Van Aken et al., 2003). One ring has been surveyed three times at half-yearly intervals, but the analysis appears to be severely hampered by the mesoscale turbulence features mentioned above. Combining these in situ observations with satellite altimetry data into a data-assimilation system is presently underway and this 'tuned' system will then be used to design a long term monitoring system for the interocean exchanges in this highly variable region of the South Atlantic.

5.3.9 Discussion.

Both the Brazil-Malvinas confluence in the southwest Atlantic and the Cape Basin in the southeast Atlantic are hot spots of variability and mesoscale turbulence of the World Ocean. This is to an important degree controlled by the varying inter-ocean fluxes through the Drake Passage and around South Africa, respectively, together with fluctuations of the South Atlantic subtropical gyre (Gordon, 2003). Waters of Pacific, Indian, Atlantic and Southern Ocean origin collide and blend in these regions. Moreover, very large buoyancy fluxes across the ocean-atmosphere interface lead to intense vertical mixing, convection and subduction in these regions. Eventually, the transformed water masses feed the Benguela Current and subsequently the upper equatorward limb of the meridional overturning circulation of the Atlantic. Their temperature and salinity characteristics, in particular also their vertical profiles, are controls on the buoyancy budget and overturning of the Atlantic. Variability in these characteristics results from both the varying ratio between the input of cool and relatively fresh Pacific waters around South America and that of warm and salty Indian Ocean waters around South Africa and from the varying intensity of the water mass transformation processes in the southwest Atlantic and the Cape Basin. Modelling studies have shown that Agulhas leakage tends to stimulate and stabilize the northern sinking mode of the Atlantic overturning circulation (Weijer et al.,2002, 2003). Bering Strait (or other northern) fresh water fluxes oppose and destabilize it. In the present day situation the stabilizing southern ocean fluxes dominate, but with reduced (or no) Indian Ocean input the northern overturning is expected to be much closer to a switch to a different mode, with associated climate fluctuations.