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5.2 The South Atlantic contribution to the global thermohaline circulation

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5.2.1. Introduction

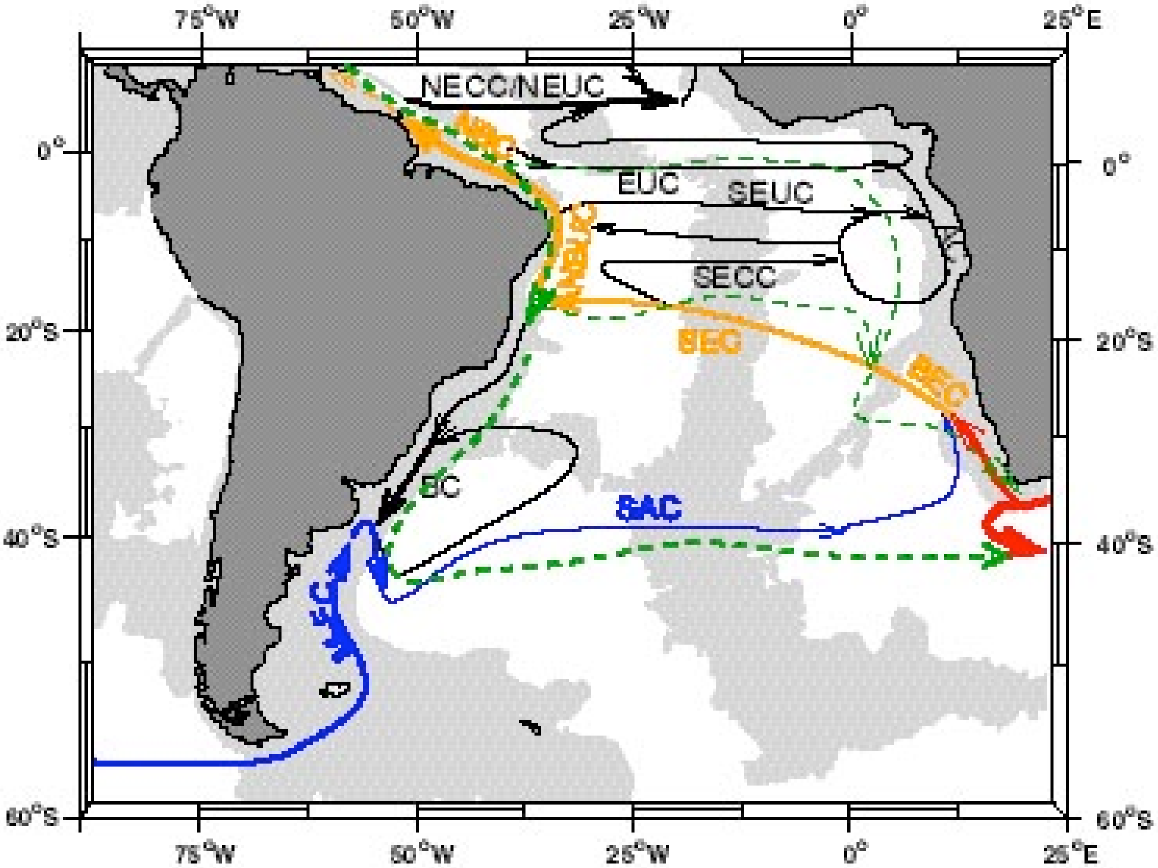

Figure 1: Schematic diagram of the meridional circulation elements in the South Atlantic. North Atlantic Deep Water (in green) flows southward primarily along the western boundary and also on the eastern basins and is exported to the Indian Ocean south of Africa. This flow is compensated by northward flows within the

thermocline and intermediate layers from Drake Passage (in blue) and as part of the Agulhas leakage (red), following the subtropical gyre and the North Brazil Current. Adapted from Peterson and Stramma (1991) and Stramma and England (1999).

The export of about 15 to 20 Sv (1 Sv = 1×10^6 m^3 s^{-1}) of North Atlantic Deep Water through the South Atlantic to other ocean basins requires a compensating net northward flow through the South Atlantic and across the equator at other levels. Compensating northward flow is possible within the surface, intermediate and bottom water layers (Figure 1). Modifications of the water masses participating in the return flow within the South Atlantic can potentially lead to alterations of the thermohaline circulation and the associated meridional heat and freshwater fluxes. Diapycnal advection and mixing may be effective shortcircuits of the thermohaline circulation (THC). Similarly changes in the circulation may alter the meridional heat fluxes and impact the THC. An increased share of warm upper layer waters to the northward return flow would lead to increased net northward heat flux through the South Atlantic. The purpose of this note is to review the present knowledge on the meridional fluxes within the South Atlantic, to evaluate mechanisms within the South Atlantic that may impact on the THC.

5.2.2. Circulation and transports

South Atlantic and Indian Ocean thermocline water subducted at the southern edge of the subtropical gyres of the South Atlantic and South Indian Oceans are major contributors to the thermocline waters in the southwestern North Atlantic (Poole and Tomczak, 1999). Therefore, these water masses effectively participate in the net cross equatorward upper layer flow that balances the southward flux of NADW.

Denser waters contributing to the upper branch of the thermohaline circulation enter the Atlantic through Drake Passage and the Malvinas/Falkland Current (referred to as the cold water route) and the Agulhas Current and its retroflection (the warm water route). Based on a coarse resolution, just under 2°, numerical model England and Garçon (1994) estimated that the northward return flow was composed of 6.5 Sv from Drake Passage, 2.5 Sv of Indian Ocean thermocline water and 1.6 Sv of recirculated Indian Ocean Intermediate water. Recent analysis of water mass characteristics and volume transports suggests that Antarctic Intermediate Water (AAIW) is the major contributor to the upper layer return flow to the North Atlantic (de las Heras and Schlitzer, 1999; You, 2002). In contrast other studies suggest that warm surface and thermocline waters, presumably derived from the warm water route, are responsible for the cross-equatorial mass flux (eg. Macdonald and Wunsch, 1996; Holfort and Siedler, 2001; Donners and Drijfhout, 2003).

Within the South Atlantic various regions of enhanced mixing and modification of AAIW have been identified. Such enhanced property transfers are generally associated with small-scale mixing (Bianchi et al., 1993, 2002) and meso-scale eddies (Boebel et al., 1999a,b). Exchange between relatively cold-fresh AAIW derived from Drake Passage and AAIW recirculated within the South Atlantic subtropical gyre occurs in Brazil Malvinas Confluence (Piola and Gordon, 1989). Enhanced meridional exchange has also been associated with the Zapiola eddy in the southern Argentine Basin (Boebel et al., 1999a). AAIW from the Indian Ocean penetrates into the Atlantic from the Agulhas Current region and flows northwestward within the eastern limb of the Subtropical Gyre (Gordon, et al., 1992; Suga and Talley, 1995).

Water mass modification by vertical (diapycnal) mixing is significant throughout the South Atlantic (Sloyan and Rinotul, 2000) and there is evidence of intense mixing of the different varieties of AAIW in the subequatorial gyre (Suga and Talley, 1995).

Estimates of the relative contribution of each AAIW component and the meridional transports differ widely. You (2001) estimates a northward transport of AAIW across 10°S of about 4.3 Sv, with 2.7Sv entering the South Atlantic through Drake Passage and 1.6 Sv from the Indian Ocean. This transport is in good agreement with estimates based on lagrangian observations (eg. Boebel et al., 1999a). A recent analysis suggests that of 3.1 Sv of AAIW flowing northward across 25°S in the Atlantic 1.9 Sv are derived from Drake Passage, with and the remaining is derived from the Indian Ocean, Red Sea and the Indonesian Seas (You et al., 2003). However, some inverse calculations (de las Heras and Schlitzer, 1999) and numerical simulations (Marchisiello et al., 1998) lead to much larger net trans-equatorial flow of AAIW of 9 to 10.1 Sv. In the inversion the intermediate water flow is mostly derived from Drake Passage or locally formed within the South Atlantic basin. Other inverse solutions suggest that both the cold and warm water routes are important source waters for deep water formation in the north (Macdonald and Wunsch, 1996). This observation is in agreement with the findings of Poole and Tomczak (1999) who, based on water mass analysis, concluded that about half the thermocline waters in the Caribbean Sea are supplied from warm waters formed in the South Atlantic and Indian Oceans.

Based on inverse solutions for the global circulation, the transport of NADW across the equator is around 12 to 15 Sv. The net northward upper layer flow derived from hydrographic data being only slightly higher (18Sv, Wienders et al., 2000). Inversions also suggest that, as it flows southward through the South Atlantic, NADW transport is increased by about 50% by contributions of AAIW from above and “Antarctic Bottom Water” (_^{n} > 28.11 kg m^{-3}) from below (Ganachaud and Wunsch, 2000). These South Atlantic dianeutral transfers are significant short-circuits in the global meridional overturning that require further investigation. Global thermohaline and Chlorofluorocarbon analyses also suggest that south of 30°S about 10 Sv of abyssal water upwell through the _^{n} = 28.11 kg m^{-3} neutral surface (Orsi et. al., 1999). A substantial part of this transfer in the Atlantic sector occurs within the Argentine Basin. This study also shows that a branch of water less dense than __ = 28.28 kg m^{-3} flows northward into the Brazil Basin, thus contributing to balance the flow of NADW across 30°S. There is also evidence of strong mixing between NADW and Circumpolar Deep Water (CDW) in the Argentine Basin (Georgi, 1981). In addition, eddy stirring may play a key role in the meridional exchange of NADW-CDW across the ACC within the western Gerogia Basin (Arhan et al. 2002). Estimates of the abyssal contribution to the northward flow across 30°S in the Atlantic range between 6 Sv (_^{n} > 28.11 kg m^{-3}, Ganachaud and Wunsch, 2000) and 3 Sv (de las Heras and Schlitzer, 1999).

A Lagrangian analysis based on the output of the OCCAM circulation model provides new insight on the role of the warm water route in the upper limb of the thermohaline circulation in the South Atlantic (Donners and Drijfhout, 2003). The technique quantifies the contribution of different water mass pathways. This study suggests that most of the Atlantic upper layer cross-equatorial flow (15.5 Sv) originates in the Indian Ocean, within the upper 1200m of the Agulhas leakage (Figure 2). The Lagrangian analysis is not incompatible with previous section integrated inverse solutions, which suggest a major contribution from the cold water route (eg. Sloyan and Rintoul, 2001). The apparent inconsistency is mostly due to relatively large recirculations, which are not properly resolved in the section integrated fluxes. However, the inferred sources of South Atlantic upper layer return flow are important since they strongly impact on the estimated meridional heat flux.

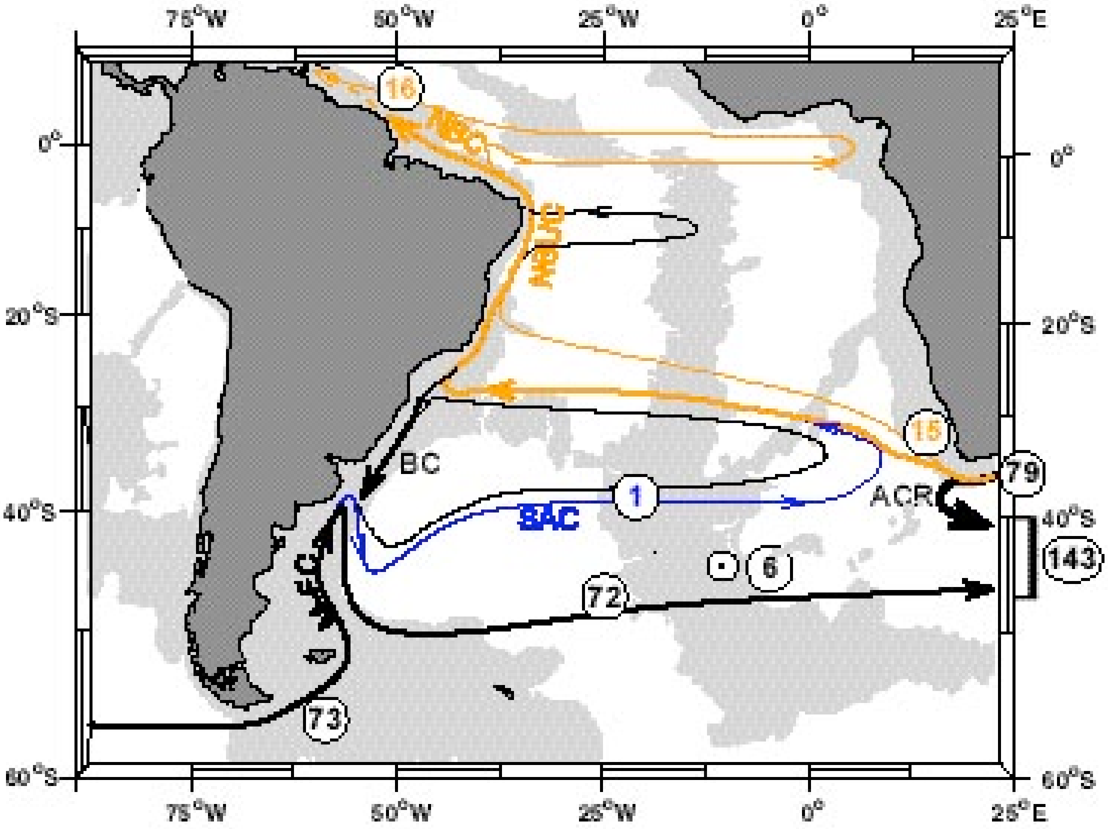

Figure 2: Schematic diagram of the upper layer limb of the Atlantic meridional circulation derived from the lagrangian analysis of Donners and Drijfhout (2003). The blue line represents the flow from the Pacific Ocean and the orange line the Agulhas leakage. The black arrows represent other parts of the upper layer circulation. Numbers within circles are volume transports (Sv). The symbol ⊙ represents upwelling from through the base of the intermediate waters. The shaded areas are shallower than 4000m.

5.2.3. The meridional heat flux

The thermohaline properties of the water masses contributing to the northward return flow in the Atlantic, together with NADW characteristics, determine the ocean's meridional heat and freshwater fluxes. Variations of the thermohaline properties, which are directly related to the different pathways and water masses, must lead to variability of the meridional fluxes. Since variations in the thermohaline properties of NADW are relatively small, we expect that meridional flux variability will be dominated by changes in the composition of the water masses within the upper limb of the THC. For instance, an increased share of warm upper layer waters derived from the Indian Ocean to the northward return must lead to increased net northward heat flux through the South Atlantic. Estimates of the South Atlantic meridional heat flux near 30°S are given in Table 1. To some extent the wide range in these estimates arise from misrepresentations of the eddy heat fluxes (eg Bennett, 1978). In Bennett's direct estimates the large range is due to different parameterizations of the width of the western boundary current. In fact, a realistic width (~100 km) leads to the lower heat flux estimates of order 0.2 PW.

Table 1. Estimates of South Atlantic meridional heat flux near 30°S

Latitude (°S)	*Heat Flux (PW)*	*Method / Source*
32	0.66-0.88	Inverse / Fu (1981)
30	0.69	Sea-air fluxes / Hastenrath (1982)
32	0.16-0.68	Direct / Bennett (1978)
32.5	0.63	Numerical model (OCCAM) / Donners
32	0.4	Direct / Bryan (1962)
30	0.39	Sea-air fluxes / Bunker (1980)
30	0.38	Sea-air fluxes / Hsiung (1985)
30	0.3	Inverse / Macdonald & Wunsch (1996) and Ganachaud & Wunsch (2000)
30	0.29	Numerical model / Marchesiello et al. (1998)
30	0.26	Numerical model / Matano (personal comm., 2003)
32	0.24	Inverse / Rintoul (1991)
30	0.22	Direct / McDonogh and King (2002)
30	0.19	Numerical model / Matano & Philander (1993)
30	- 0.23	Inverse / de las Heras & Schlitzer (1999)

The analysis of de las Heras and Schlitzer (1999) suggests that the southward flow of NADW is balanced primarily by Atlantic AAIW, but their standard solution exhibits poleward heat flux at 30°S. In agreement with Gordon (1986), their inversions show that increased Agulhas leakage, mostly of Indian Ocean AAIW, results when the solution is forced to achieve positive heat fluxes in the South Atlantic. When forced to produce the largest meridional heat fluxes estimated for the Atlantic across 30°S (e.g. ~ 0.69 PW, Hastenrath, 1982), the northward flux is composed of 5.5 Sv of warm waters and 9.9 Sv of AAIW. This latter solution produces mass and heat fluxes similar to OCCAM´s (Donners and Drijfhout, 2003), but, compared to observations, also leads to an unrealistic upper layer temperature drift over large areas of the subtropical South Atlantic.

5.2.4. Variability - Winds

The above studies are not suitable to shed light on the possible effects of the wind over the South Atlantic on the thermohaline circulation. However, a basin scale numerical model (eg Marchisiello et al., 1998) produces a variable, wind dependent, northward flow across the South Atlantic at intermediate levels. In the model, the contributions of upper layer waters and AAIW to the northward flow vary in response to seasonal variations of the mid-latitude wind. Contributions of each flow component are 6 and 7.5 Sv in winter to 4.5 and 9.6 Sv in summer, respectively. The model derived seasonal flow variability leads to an increased basin-wide meridional heat flux in summer. Variability of the mid-latitude winds over the

South Atlantic must produce variations in the strength of the subtropical gyre circulation and possibly impacts on the trans-equatorial transfer of upper layer water into the North Atlantic. The region of interest is the bifurcation of the South Equatorial Current near South America, and whether changes in the gyre strength may impact the transport and water mass properties of the North Brazil Current. Because the strongest northward flows appear to be associated to the highly variable North Brazil Current, direct evidence of these changes is not available. Moreover, substantial discrepancies in the surface wind produced by different sources (eg. NCEP, ECMWF) may lead to large uncertainties in the associated upper layer flow patterns and fluxes derived from numerical models (see Oke et al., 2003).

Numerical simulations have shown that variations in the heat and freshwater fluxes associated with the Indian to Atlantic transfer can induce relatively large changes in the strength of the meridional circulation (Weijer et al., 2002). In the model, heat and freshwater anomalies produce changes in the zonally averaged meridional pressure gradient and the circulation changes primarily occur along the western boundaries.

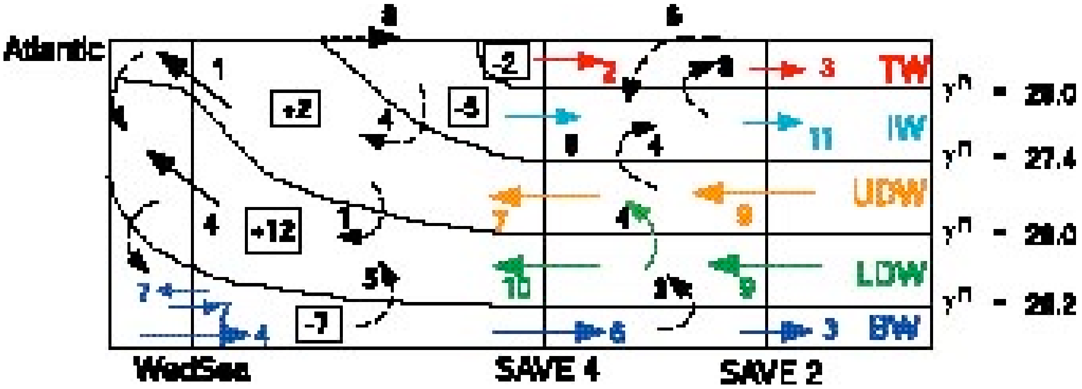

Figure 3: Schematic representation of the South Atlantic meridional circulation (Sv) in selected neutral surface intervals (TW: Tropical Water, IW: Intermediate Water, UDW; Upper Deep Water, LDW: Lower Deep Water, and BW: Bottom Water). Epineutral fluxes are represented by solid arrows, dianeutral fluxes by dashed arrows. The near surface dotted arrows from UDW to IW at the outcrop of $\_^n$ = 27.4 and from TW to IW, represent dianeutral fluxes due to sea-air interaction. Adapted from Sloyan and Rintoul (2001).

Numerical and theoretical studies suggest that if eddy fluxes are neglected, the thermohaline circulation is a function of the strong southern winds (i.e., the winds along the section connecting the tip of South America with the tip of South Africa, Nof, in preparation). Furthermore, even though this transport is determined by the wind, it is not the Ekman transport itself that ends in the North Atlantic as NADW. Rather, it is a broad flow of surface and intermediate water along the eastern part of the basin, which flows northward, crosses the equator and then become NADW. Previous studies have suggested a strong dependence of NADW formation to zonal Southern Hemisphere winds (e.g. Toggweiler and Samuels, 1993, 1995). However, model studies show that thermohaline forcing in the northern North Atlantic alone can generate about 75% of NADW.

5.2.5. Water mass conversions within the Subtropical South Atlantic

Sinking of North Atlantic Deep Water in the northern North Atlantic must be balanced by upwelling in other regions of the World Ocean. Because direct observation of vertical velocities is not possible, in the past uniform upwelling has sometimes been assumed (e.g. Stommel and Arons, 1960). Estimates of vertical or cross-isopycnal fluxes can be derived indirectly from observations or from numerical simulations. Inverse box models have been used to estimate the area averaged cross isopycnal or dianeutral fluxes. Sloyan and Rintoul (2000) explicitly included the diapycnal fluxes of mass, heat and salt in the set of unknowns of their inversion for the Southern Ocean. Their results indicate significant water mass transformations within the subtropical South Atlantic. These fluxes would explain the changes in the thermohaline characteristics of each water mass within the basin. However, the effects of isopycnal mixing can also lead to similar water mass transformations.

In the region bounded by the Save 2 and Save 4 hydrographic sections the inversion of Sloyan and Rintoul leads to an upward (towards less dense water) mass flux of NADW/CDW of about 6 Sv, into the densest intermediate water layer. The heat and salt fluxes through this interface are also upward. The upward (up-gradient) heat flux is a result of advective heat fluxes being larger than the (downward) diffusive heat flux. A small upward mass flux and downward heat and salt fluxes are estimated through the intermediate water - thermocline interface, mostly dominated by downward diffusion. The layers most affected by these diapycnal fluxes correspond to Subantarctic Mode Water (e.g. the less dense intermediate water). Sloyan and Rintoul speculate that the diapycnal fluxes most likely occur in regions of intense mixing and eddy variability, such as the Brazil/Malvinas Confluence in the western South Atlantic. As a result of the heat and salt fluxes, downstream modifications of the thermohaline properties of the water mass cores are observed.

Ongoing analysis of eddy permitting global numerical simulations based on POCM (Matano et al., 2003) suggest that in the southwest Atlantic there is a conversion of NADW and surface water to intermediate water. This result is qualitatively in agreement with the increased northward transport (3 Sv) of intermediate waters derived by the inversion of Sloyan and Rintoul (2000, 2001). The inversion also suggest that about 6 Sv of warm-salty upper layer water are converted to intermediate water by sea-air exchange and suggest that these modifications most likely occur in the Argentine Basin (Sloyan and Rintoul, 2001).

The POCM analysis also shows that surface (sigma-theta < 26.2) and intermediate waters (sigma theta > 26.7) are converted to subsurface waters within the Cape Basin, while further north, in the subtropical gyre, the conversion is mostly from subsurface water to surface waters (sigma theta < 26). The model suggests that the regions of largest water mass conversions are the Cape Basin and the western South Atlantic, which are those of highest mesoscale variability within the South Atlantic Ocean.

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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