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The South Atlantic and the Atlantic Meridional Overturning Circulation

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ABSTRACT

This article discusses the contribution of the South Atlantic circulation to the variability of the Meridional Overturning Circulation (MOC). The South Atlantic connects the North Atlantic to the Indian and Pacific oceans, being the conduit through which the southward outflow of North Atlantic Deep Water (NADW) is compensated by northward inflows of upper and intermediate waters. This circulation pattern, in which cold waters flow poleward and warm waters equatorward, generates a distinct heat flux that is directed from the poles towards the equator. Observations and models indicate that the South Atlantic is not just a passive conduit but that its circulation influences significantly the water mass structure of the Atlantic Meridional Overturning Circulation (AMOC). These transformations occur across the whole basin but are most intensified in regions of high mesoscale variability. Models and observations also show that the South Atlantic plays a significant role in the establishment of oceanic teleconnections. Anomalies generated in the Southern Ocean, for example, are transmitted through inter-ocean exchanges to the northern basins. These results highlight the need for sustained observations in the South Atlantic and Southern Ocean, which, in conjunction with modeling efforts, would improve the understanding of the processes necessary to formulate long-term climate predictions.

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1. Introduction

Two decades ago, discussions of greenhouse warming or the collapse of the global Meridional Overturning Circulation (MOC) were largely restricted to the academic elite. Nowadays, however, the same topics are the fodder of public debate. The general public's increased awareness of the physics of climate has been brought about partly by the mounting evidence that climate is indeed undergoing significant variability and change (e.g., data showing increases of global temperature and sea level rise during the last century), and partly by the predictions based upon model results about the consequences that such changes might have on societies (IPCC, 2007). It is not always easy to separate fact from fiction, but the paleo-climate record indeed suggests that past shutdowns of the MOC triggered ice ages with dramatic decreases of the temperatures in western Europe and beyond (IPCC, 2007; Speich et al., 2010).

The perceived fragility of the climate system has prompted a flurry of new studies whose conclusions are, if not alarming, at least worrisome. Hansen et al. (2001) reported a 20% reduction in the overflow of deep waters through the Greenland–Scotland Ridge that feeds the densest portion of the MOC cell. Häkkinen and Rhines (2004) showed that the subpolar gyre of the North Atlantic has slowed appreciably during the last decade and suggested that a weakening of the MOC is underway. Bryden et al. (2005) argued that the strength of the MOC has decreased by more than 30% over the last five decades. Although none of these studies is conclusive, as different models show different results and the findings of Bryden et al. are based on just five hydrographic snapshots; nevertheless the robustness of the conclusions deserves the attention of the scientific community.

Policymakers face the dilemma that although the changes suggested by the above studies could be the heralded response of the oceans to global warming, they could just as well be a natural mode of oceanic variability. To separate anthropogenic from natural effects we need to substantially improve the existing observational system and foster the development of more complex models of the climate system. At present there is only one quasi-comprehensive monitoring system of the AMOC in the northern North Atlantic: the RAPID/MOCHA array in conjunction with the observations of the warm, shallow limb in the Florida Current/Gulf Stream and of the Deep Western Boundary Current (DWBC) started in the early 1980s off Florida (Baringer and Larsen, 2001; Meinen et al. 2006)—provided the basin-wide integrated strength and vertical structure of the Atlantic Meridional Overturning Circulation (AMOC) at 26.5°N (Cunningham et al., 2007;

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Kanzow et al., 2007). Other attempts to monitor the same components are located in other parts of the North Atlantic (e.g., the Denmark Straits overflow); a small pilot effort recently started in the South Atlantic (Speich et al., 2010). These systems were designed to observe some of the important components of the AMOC that can, in turn, be used to verify and assimilate into models (Østerhus et al., 2005; Srokosz, 2004; Baringer and Garzoli, 2007).

Given the complexity and the worldwide impact of the AMOC, even if these systems succeed in giving us a warning of potentially important changes of the AMOC, the data collected by them are insufficient to determine the causality of such changes, and the existing systems are therefore unable to predict further evolution of such changes. To do so, a more comprehensive view that takes into account the changes in the other basins is needed as well. To interpret the climate-related changes occurring in the North Atlantic, for example, we need to understand the variability of its contiguous basin, the South Atlantic—not only because its heat and salt fluxes are essential for the formation of the North Atlantic deep waters, but also because of its natural link with all the other major oceans. For the purposes of this study, the South Atlantic is defined as the region between the tip of the Palmer Peninsula (60°S) and the northern limit of the subtropical gyre (15°S) to encompass the subpolar and subtropical regions.

Although the contribution of the South Atlantic to the AMOC was implicit in the early Meteor observations (Wüst, 1935), which show a mean South Atlantic meridional circulation that exports heat in the "wrong" direction (e.g., from the south pole to the equator), there is still great uncertainty on the absolute magnitude of the South Atlantic inter-ocean fluxes (see De Ruijter et al., 1999; Garzoli and Baringer, 2007). These uncertainties are compounded by the fact that the South Atlantic is not just a passive conduit for the transit of remotely formed water masses, but actively influences them through air–sea interactions, mixing, and subduction and advection processes. It is not sufficient, for example, to know the inflows at the Drake Passage and the Cape of Good Hope to determine the South Atlantic export of thermocline water to the North Atlantic. Indeed, it can be argued that, since the South Atlantic circulation depends on the inter-oceanic fluxes and those in turn depend on the South Atlantic circulation, any attempt to determine one independently of the other leads to an ill-posed problem.

In this article, an overview of the most outstanding characteristics of the South Atlantic circulation will be presented with emphasis on those aspects closely connected to the AMOC. The goal is to illustrate the role that the South Atlantic plays in the AMOC variability in order to highlight the importance of focusing some of the future research and monitoring efforts on the South Atlantic. Results of a numerical model and observations will be used to argue that the South Atlantic is not a passive ocean, that significant water mass transformations occur in the basin that affect the compensating flows that compose the AMOC, and that signals occurring in the adjacent oceans are transmitted through inter-ocean exchanges impacting its variability. An attempt will be made to demonstrate that, in addition to the already existent observations in the North Atlantic, monitoring the South Atlantic for inter-basin exchanges and the choke points that connect the basin with the Pacific and Indian oceans will improve our understanding of these phenomena, facilitate the search for predictors, and lead to improved climate prediction models.

2. Background

The mean meridional structure of the South Atlantic circulation involves a deep southward flow of cold and salty North Atlantic Deep Water (NADW) along the eastern coast of South America, and compensating northward flows of surface, central, and intermediate waters. The South Atlantic connects with the Pacific and Indian Oceans providing the gateway by which the AMOC connects with the rest of the globe. As such, a significant exchange of water masses imported from the adjacent basins is to be expected.

The warm and salty water that spreads in the North Atlantic is cooled primarily by evaporation, which sinks to the deep ocean and forms the North Atlantic Deep Water (NADW) (e.g., Gordon, 1986). Export of NADW to other ocean basins is compensated for by a net northward flow through the South Atlantic and across the equator of surface, intermediate, and bottom water layers (Broecker, 1991; Schmitz, 1995; Speich et al., 2002). The compensating northward flow is a mixture of warm and salty surface and central waters, and cooler fresher Atlantic Intermediate Water (AAIW) (Fig. 1). The surface water is characterized by high salinity and is formed in the tropics/subtropics transition region by subduction between 12° and 15°S (Tomczak and Godfrey, 1994). Central water is commonly subducted into the thermocline, and its formation in the South Atlantic occurs at the confluence of the Brazil and Malvinas currents (Gordon, 1989; Vivier and Provost, 1999) in the southwestern Atlantic with characteristics of Subtropical Mode Water at 16–18 °C. Also in the Southwestern Atlantic, the AAIW originates from a surface region of the circumpolar layer, in particular north of the Drake Passage (Talley, 1996) and in the Malvinas Current, a loop of the circumpolar current entering the South Atlantic. In the eastern side of the basin, AAIW from the Indian Ocean enters the South Atlantic via the Agulhas leakage.

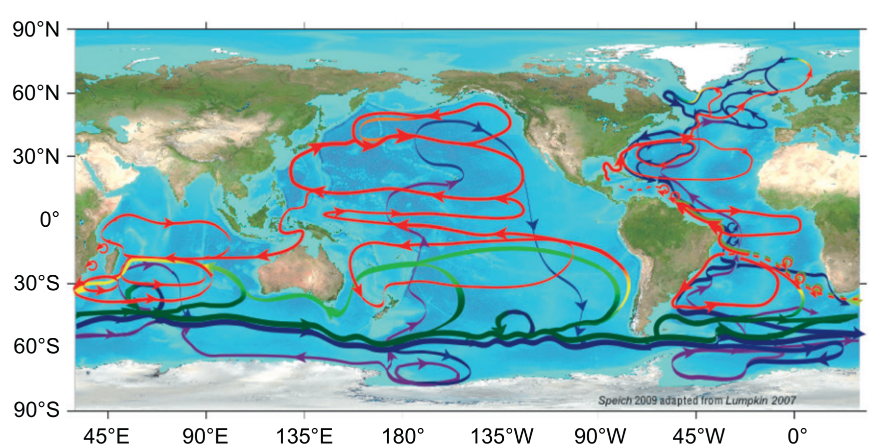

Fig. 1. Schematic of the world ocean Meridional Overturning Circulation. Red is surface flow, blue and purple are deep flows, and yellow and green represent transitions between depths (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.
(Base map by S. Speich adapted from Lumpkin and Speer, 2007 by following Speich et al. 2007.)

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This South Atlantic circulation pattern, in which warm waters flow towards the equator and cold waters flow towards the pole, results in an equatorward heat flux. This net northward flow of properties is expected to be sensitive to the relative contributions of the components of the returning flows originating in each one of the connecting oceans.

The South Atlantic is the only basin extending to high latitudes in which the heat transport is equatorward. Although this distinct heat flux was recognized by the middle of the last century (Model, 1950), the sources for the upper waters are still in dispute. A portion of the South Atlantic upper waters is produced locally (see Stramma and England, 1999, and references therein), but most of the South Atlantic upper waters are thought to originate in the Pacific and Indian oceans. At issue are not only the relative importance of these sources but also the mechanisms of entrainment. Gordon (1986) proposed the warm path hypothesis, which postulates that the South Atlantic receives most of its upper waters from the Indian Ocean as eddies and filaments released at the retroflection of the Agulhas Current and driven to the northwest by the Benguela and the Benguela Current extension. Rintoul (1991) proposed an alternative source, the cold path, by which AAIW injected from the Pacific through the Drake Passage is converted to surface water through air–sea interactions to become the main supply of South Atlantic upper waters. To reconcile the differences between these theories, Gordon et al. (1992) proposed a modification of the original warm path route by which the AAIW carried eastward by the South Atlantic Current is entrained into the Indian Ocean and recirculated by the Agulhas Current (Fig. 1).

It has been nearly two decades since the publication of Gordon's and Rintoul's influential articles, but there is still no consensus on the origins of the South Atlantic northward mass outflow (De Ruijter et al., 1999). Some of the studies that followed supported the cold-path theory (England et al., 1994; Macdonald, 1996; de las Heras and Schlitzer, 1999; Marchisiello et al., 1998; Sloyan and Rintoul, 2001; Nof and Gorder, 1999; You, 2002), other studies supported the warm-path theory (Holfort and Siedler, 2001; Weijer et al., 2002; Donners and Drijfhout, 2004; Speich et al., 2002), and still others postulated that both paths are important (Matano and Philander, 1993; Macdonald and Wunsch, 1996; Poole and Tomczak, 1999). Donners and Drijfhout (2004) contested the studies supporting the cold-path hypothesis on the ground that their conclusions were biased by the method of analysis. Using the results of a global, eddy-permitting model, they argued that the results of inverse calculations are hindered by a lack of spatial resolution. They showed that if the model results are analyzed within an Eulerian framework they also seem to suggest the dominance of the cold-path over the warm-path theories. However, if the model results are analyzed with a Lagrangian technique, which follows the trajectories of specific water masses, they show the dominance of the warm path over the cold path. Although these arguments are far from being conclusive, they clearly illustrate that the weakest link of existing estimates of the South Atlantic water mass balance is our lack of knowledge of the South Atlantic circulation itself. The uncertainty about the South Atlantic circulation also manifests itself in the estimates of the meridional heat transport, which vary from negative to positive values (e.g., Macdonald et al., 2001). This broad spread in the estimates reflects deficiencies in both the data available and in the methodology used for the calculation.

Since climate change studies assess the variability of the different components of the Earth system, it seems particularly worrisome that the gaps in our understanding of the South Atlantic variability are much larger than those of its mean circulation. There are numerous studies on the mesoscale variability of the South Atlantic most energetic regions such as the Brazil/Malvinas Confluence (e.g., Olson et al., 1988; Gordon and Greengrove, 1986; Garzoli, 1993; Matano et al., 1993) and the Agulhas retroflection (e.g., Lutjeharms and Gordon, 1987; Boebel et al., 2003), but very few on the low-frequency variability of the large-scale circulation. Venegas et al. (1997,1998) and Palastanga et al. (2002) investigated the low-frequency variability of the South Atlantic's sea surface temperature (SST) from approximately 40 years of climatological data. They identified three low-frequency modes of variability with periods of about 14, 6, and 4 years that, according to their analyses, are associated with variations of sea-level pressure. Sterl and Hazeleger (2003) and Haarsma et al. (2005) added that these modes are generated by anomalous winds through turbulent heat fluxes, Ekman transport, and wind-induced mixing.

Although these studies are valuable contributions to our understanding of the climate variability over South America and Africa, it has been argued that SST anomalies do not necessarily reflect the variability of the oceanic circulation below the mixed layer. Witter and Gordon (1999) published an observational study of the low-frequency variability of the South Atlantic's thermocline circulation. Using 4 years of altimeter data they identified two dominant modes of sea surface height (SSH) variability. The first mode has a maximum in the eastern portion of the basin and indicated that the anti-cyclonic circulation in the subtropical gyre weakened from 1994 to 1996 and strengthened thereafter. They also observed a similar temporal signature in the zonal winds, suggesting a coupling between the oceanic and the atmospheric variability. The second mode was associated with interannual variations in the Brazil/Malvinas Confluence.

A recent study analyzed the variability of the South Atlantic subtropical gyre using satellite derived SSH and SST anomalies and concluded that the interior of the gyre has expanded by $\sim$40% of its total area. They also found that the mean dynamic height of the gyre had increased 3 cm per decade and hypothesized that this increase may be due to increased heat storage of the upper layer. Lumpkin and Garzoli (in press), through the analysis of a combination of surface drifters and altimetry, found a southward shift of $0.86 \pm 0.06^{\circ}$ per decade in the confluence latitude of the Brazil and Malvinas Currents. A comparable trend is found in the latitude of the maximum wind stress curl averaged across the South Atlantic basin. This variation appears to be inversely related to long-term variations in SST anomaly in the Agulhas–Benguela pathway of the eastern South Atlantic subtropical basin. The time series of the bifurcation of the South Equatorial Current shows a trend of $-0.23 \pm 0.06^{\circ}$ per decade with an asymmetric growth of the subtropical gyre.

In summary, the South Atlantic is the main pathway of the compensating flows needed to maintain mass balance due to the export of NADW. This compensation is accompanied by a distinct northward heat transport. The strategic location of the South Atlantic raises the question of whether this basin is just a passive conduit for the passage of remotely formed water masses or whether its internal dynamics influences the AMOC. To address this question in the following sections, the variability of the South Atlantic heat transport (Section 3) and its relation to internal dynamics (Section 4) and inter-ocean exchanges (Section 5) will be discussed.

For the purposes of this article we will discuss the results of the Parallel Ocean Circulation Model (POCM-4C), which is a global eddy-permitting numerical simulation that has been extensively compared with observations (e.g., Tokmakian and Challenor, 1999; Baringer and Garzoli, 2007). To illustrate the realism of this simulation, in Fig. 2 we compare the mean circulation patterns derived by from this model with those inferred from the observations by Stramma and England (1999). The circulation patterns inferred from model and observations are remarkably similar. The left panel shows the observations and the right panel shows the model for the surface (top), intermediate (middle), and deep (lower) layers, respectively. In the case of both model and observations, the Agulhas Current intrudes in the southeast portion of the basin and retroflects at about 20°E. The Benguela Current and the Benguela

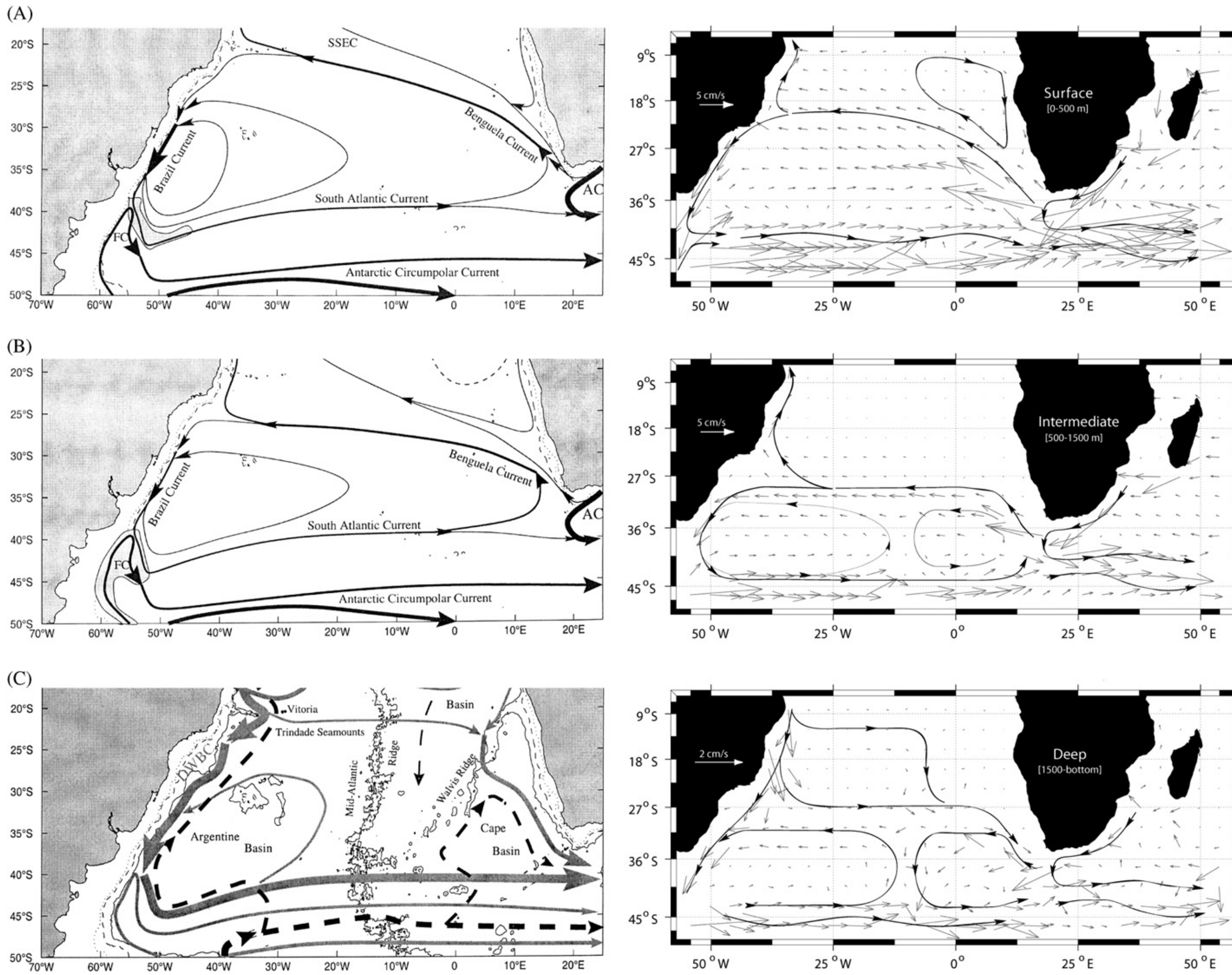

Fig. 2. Left panel: . Schematic representation of the large-scale SACW (top), AAIW (middle), and North Atlantic Deep Water circulation (bottom). Right panel: Climatological depth-averaged velocities from the Parallel Ocean Circulation Model (POCM-4C) at: (A) surface (0–500 m), (B) intermediate (500–1500 m), and (C) deep (1500 to bottom) levels. The horizontal velocities were binned in 41 × 41 boxes. The superimposed schematics show the path of the major water masses.
The left panel is adapted from Stramma and England (1999).

Current extension form the eastern boundary current of the South Atlantic subtropical gyre (Peterson and Stramma, 1991; Richardson and Garzoli, 2003). The bifurcation of the South Equatorial Current is observed at about 18°S and the confluence of the Brazil and Malvinas at approximately 38°S, both in the model and the observations. The southern edge of the subtropical gyre is also located at 45°S in both cases. The AAIW (middle panel) shows a shift of the upper boundary of the gyre to the south and a recirculation cell in the western basin. The DWBC flows southward along the continental shelf of South America, breaks down into eddies at approximately 18°S (Schott et al., 2005), and reconstitutes again south of 27°S.

3. The South Atlantic's heat transport

During WOCE, two zonal hydrographic sections confirmed that there is a net northward heat flux associated with the AMOC (e.g., Ganachaud and Wunsch, 2003). Estimates of this heat flux in the North Atlantic range from 0.9 to 1.6 PW. The South Atlantic estimates are more uncertain than those in the North Atlantic. Within the subtropical region, the northward heat flux estimates range from negative values (−0.23 PW, de las Heras and Schlitzer, 1999) to almost 1 PW (0.94 PW, direct method, Saunders and King, 1995; 0.88 PW, inverse model, Fu, 1981) where 1 PW$=10^{15}$ Watts. Differences in the estimates derived from observations may be a consequence of the different methods used to calculate the heat transport and the different database used. Heat transport differences between the models may be a consequence of the models' ability to reproduce the pathways of the intermediate water and to represent the variability of the boundary currents. However, large heat transport variability may be a real feature of the South Atlantic circulation due in part to the large mesoscale variability, particularly at the boundaries. Both margins are characterized as highly energetic and variable regions, and therefore, natural variability cannot be ruled out. In order to understand the validity of the northward heat transport estimates, it is important to understand the mesoscale variability of the boundary currents. Having a clear understanding of the mesoscale variability is also valid for monitoring the AMOC. Observations will be highly resolved in time and then used to filter out the mesoscale variability so that components that are only from the mesoscale are not attributed to AMOC. However, mesoscale variability may be also due to real changes in the AMOC. For example there is evidence that as Agulhas leakage diminishes, ring shedding also diminishes (Biastoch et al., 2009). This would be a case where the mesoscale variability may be due to real changes in AMOC.

In a recent publication (Baringer and Garzoli, 2007), the product of the POCM model was analyzed to obtain the meridional heat transport across 30° and 35°S. Results from the POCM analysis (Fig. 3) yielded a mean heat transport at 30°S equal to 0.55 ± 0.24 PW, and 0.6 ± 0.27 PW at 35°S. These results are in good agreement with observations at 35°S of 0.54 ± 0.11 PW (Garzoli and Baringer, 2007). The time series of POCM heat transport are shown in Fig. 3, top panel. The series show seasonal and interannual variability and a marked annual cycle. The existence of this annual cycle is not consistent with the observations to date. According to Garzoli and Baringer (2007), the Ekman component of the heat transport has a marked annual cycle that is opposite in phase from the geostrophic component of the heat transport. As a result, the total heat transport, which is defined as the sum of its components, shows a seasonal signal of smaller amplitude.

There is a close relationship between the South Atlantic heat transport and the strength of the AMOC. Analysis of hydrographic data collected along nominally 35°S (Dong et al., 2009) indicates that the northward heat transport variability is significantly correlated with the AMOC, where a 1 Sv (1 Sv $=10^6$ m^3/s) increase in the AMOC would yield a 0.05 ± 0.01 PW increase in the meridional heat transport. Barreiro et al. (2008) analyzed the products of two models (ECBILT-CLIO and GFDL-CM2.1) and obtained a correlation of 0.7 between the heat transport across 30°S and the AMOC intensity in the basin.

Changes in the heat transport across 30°S are also noticed in the circulation of the eastern boundary. Numerical experiments show that a freshening in the North Atlantic induces a surface warming in the Benguela upwelling region (e.g., Stouffer et al., 2006). This can be understood as a consequence of the deepening of the local thermocline due to a decreased equator-to-subtropics surface density gradient that affects the surface wind-driven circulation (Fedorov et al., 2007; Barreiro et al., 2008). These modeling results indicate that the coastal upwelling region in the southeastern Atlantic may be another key region for future indirect monitoring of the changes in the Atlantic Ocean heat transport.

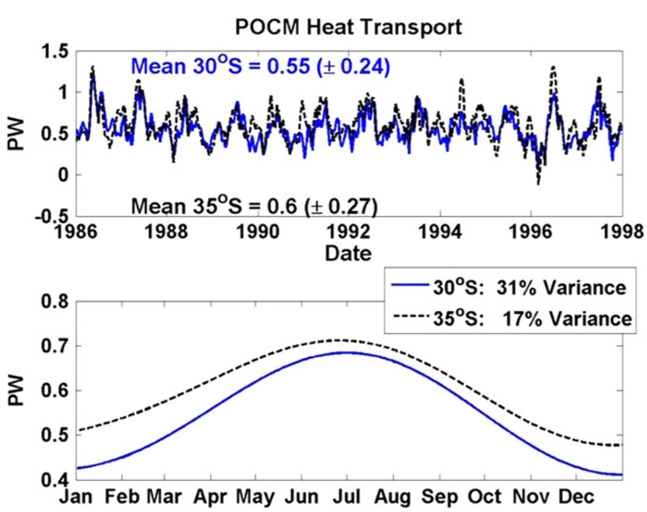

Fig. 3. Time series of the total heat transport (top panel) at 30°S (solid) and 35°S (dashed) obtained from the POCM velocity and temperature fields. In parentheses after the mean value of the series is the standard deviation. The lower panel is the climatological annual cycle of the heat transport (1986–1998) computed from the full-time series at 30°S (represents 31% of the RMS variance) and at 35°S (represents 17% of the RMS variance).
From Baringer and Garzoli (2007).

4. The South Atlantic water mass transformations

The South Atlantic contains two of the most energetic regions of the world ocean: the confluence of the Malvinas and Brazil Currents on the western side of the basin, and the retroflection of the Agulhas Current in the eastern side (Legeckis and Gordon, 1982; Garnier et al., 2002). The encounter of the warm and saltier southward-flowing Brazil Current with the cold and fresh northward-flowing Malvinas Current (a branch of the Antarctic Circumpolar Current) was first denominated the Confluence by Gordon and Greengrove (1986). The location of the Confluence varies in time and space due to the internal dynamics of the system and the seasonal variations of the wind stress forcing (Olson et al., 1988; Gordon and Greengrove, 1986; Garzoli, 1993; Matano et al., 1993). In addition to the annual cycle, anomalous northward penetrations of the Malvinas Current have been attributed to changes in the winds at the Drake Passage (Garzoli and Giulivi, 1994). In the south of Africa, the Agulhas Current enters the Atlantic, retroflects and, in the process sheds large energetic rings that carry Indian Ocean waters into the Atlantic (e.g., Duncombe Rae et al., 1996; Goni et al., 1997; Speich et al., 2002; Lutjeharms, 1996; Garzoli et al., 1999). The large variability in these boundary regions not only reflects internal ocean dynamics but also energetic inter-ocean exchanges with the South Pacific and South Indian oceans. Also to be considered is that the Antarctic Circumpolar Current, one of the stronger currents of the globe, constitutes the South Atlantic southern boundary. It is therefore to be expected that the South Atlantic acts as a strong source of mixing and water mass transformation for the compensating flows.

The complexity of the South Atlantic's water mass structure reflects its connections to the neighboring basins. The SACW (South Atlantic Central Waters) found in the subtropical gyre are produced locally (e.g., Stramma and England, 1999). The AAIW has two sources: it originates from a surface region at the Brazil–Malvinas Confluence north of the Drake Passage, and it also receives an injection of water from the Indian Ocean as part of the Agulhas/Benguela current system. The sources of the Benguela Current (Garzoli and Gordon, 1996) include Indian and South Atlantic subtropical thermocline water: saline, low-oxygen tropical Atlantic water, and cooler, fresher subantarctic water. In the area between the continental shelf and the Walvis Ridge it was found that 50% is derived from the central Atlantic (which from geometry may be chiefly South Atlantic water), 25% comes from the Indian Ocean (which may be chiefly Agulhas water), and the remaining 25% may be a blend of Agulhas and tropical Atlantic water (Garzoli and Gordon, 1996). Schmid and Garzoli (2009) analyzed hydrographic and trajectory data collected with Argo floats. The analysis shows interesting new results on the spreading of the AAIW in the Atlantic, which among others show indications for a southward spreading of AAIW from the equator to the eastern boundary.

A complex vertical structure of water masses is also observed in the southwestern Atlantic due to the poleward penetration of subtropical waters associated with the Brazil Current and the equatorward penetration of subantarctic waters associated with the Malvinas Current. These various water masses contribute even more to this very complex dynamical confluence zone. At the surface, the Brazil Current carries subtropical water and the Malvinas Current subantarcric Surface Water. After the two currents collide, although there is some mixing, the most robust structure is the thermohaline front that separates the water masses. Below the first 1000 km, there is AAIW flowing equatorward and there is also evidence of westward flowing Weddell Sea deep water at the very bottom of the Brazil–Malvinas Confluence zone (Cunningham and Barker, 1996). Between the AAIW and the Weddel Sea deep water there are three different water masses flowing poleward: North Atlantic Deep Water, Lower Circumpolar Deep Water, and Upper

Circumpolar Deep Water (Piola and Gordon, 1989; Talley, 2003; Stramma and England, 1999; Sloyan and Rintoul, 2001).

As an example of the different water masses in the South Atlantic, the trajectory of an Argo float deployed in the South Pacific west of the Drake Passage cruising the Atlantic towards the Indian Ocean is shown in Fig. 4. The float, parked at a nominal depth of 1000 m, surfaces every 10 days collecting hydrographic data during its mission that is transmitted to the Argo data centers in real time. The float was deployed in October 2005, and by April 2010 it is approaching the Indian Ocean. The hydrographic data collected by float shows the changes of the water mass distributions along the way. The profiles are color coded to show these transitions. The float followed the Antarctic Circumpolar Current, loops into the Malvinas Current, and flows east from the confluence region (Fig. 4A). The time depth distribution of the salinity field is shown in Fig. 4B, and the vertical profiles in Fig. 4C. The T/S diagrams (Fig. 4D) show the transition between the water masses as the float moves towards the east. The subantarctic mode water (in blue) sinks at the confluence to form the AAIW. The isopycnal 27.0 and 27.5 mark the transition between the SACW and the AAIW.

In a comprehensive inverse study of water mass transformations, Sloyan and Rintoul (2001) combined hydrographic data collected south of 12°S. They concluded that within the Atlantic sector of the Southern Ocean there is a transformation of Antarctic surface water into lower South Atlantic Mode Water (SAMW).

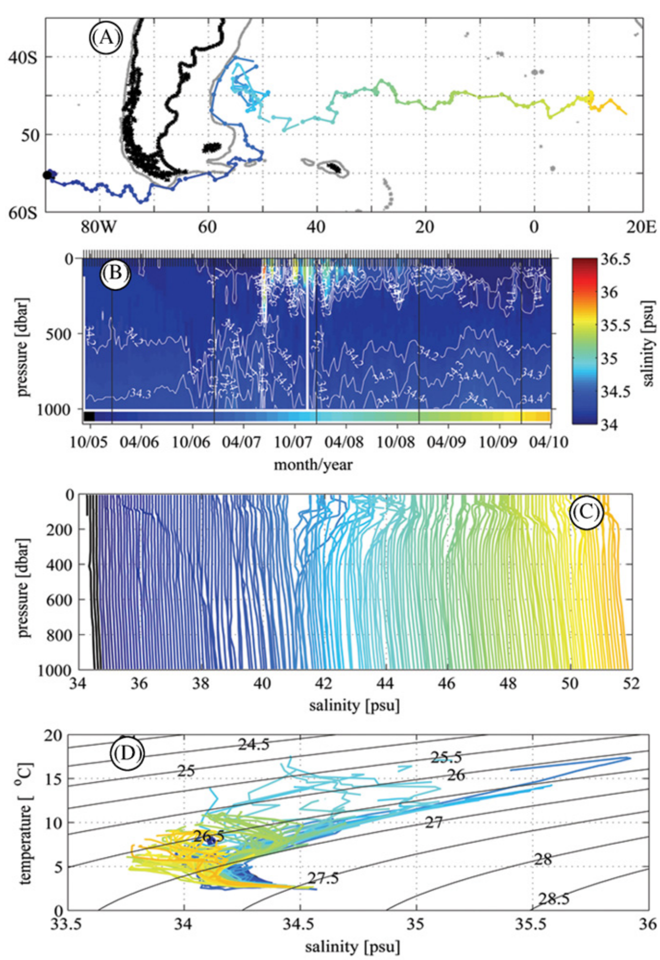

Fig. 4. Trajectory of Argo float WMO 3900427 deployed in October 2005, which transitioned from the South Pacific to the South Atlantic while drifting across different water masses. In April 2010 the float is approaching the Indian Ocean. The top panel (A) shows the trajectory of the float. The salinity section is shown in panel (B). Individual vertical profiles of salinity are shown in panel (C). The T/S diagrams are shown in panel (D).

This conversion occurs in the southwestern Atlantic near the confluence region and it is attributed to air–sea interaction. Another significant water mass transformation (about 6 Sv) occurs further north between the Argentine basin and the mid-Atlantic ridge at approximately 20°W. Here thermocline water is transformed to upper SAMW by air–sea interaction. At the eastern side of the basin, the South Atlantic Current meets with the westward injection of Indian Ocean waters carried by the Agulhas Current, leading to water mass exchanges through the Agulhas leakage, and the retroflection and the rings shed during the process. These mesoscale interactions have an impact on the AMOC through the transformation and subduction of SAMW and AAIW (Hazeleger and Drijfhout, 2000; Schmid et al., 2003).

Several attempts have been made during the last few years to estimate the South Atlantic's water mass transformations using state-of-the-art eddy-permitting numerical simulations. Donners et al. (2005) observed that in the South Atlantic portion of Ocean Circulation and Climate Advanced Modeling (OCCAM, Webb et al., 1997), intermediate waters are imported from the Pacific and light surface waters are imported from the Indian Ocean. In return, SACW and denser water masses are exported to the Indian Ocean. It was observed that while surface water abducts in the South Atlantic, all other water masses experience a net subduction. The subducted AAIW and SAMW reemerge mainly in the Antarctic Circumpolar Current farther downstream, while lighter waters reemerge in the eastern tropical Atlantic. Thus most of the northward export of South Atlantic waters is constrained to the surface waters.

Schouten and Matano (2003) investigated the formation of mode waters and intermediate waters in the Southern Ocean from POCM. The model reproduces the MOC in the world ocean. The zonally integrated Meridional Overturning stream function in neutral coordinates for the Atlantic south of 20°S is shown in Fig. 5 (left panel). The dashed lines indicate what part of the overturning occurs within the mixed layer. In the Southern Ocean, most of the overturning is confined to the mixed layer and associated with seasonal variability. In the same study, Schouten and Matano (2003) calculated the model transports in isopycnal layers across 30°S. The transports can be interpreted as diapycnal transformations within the basins. In the Atlantic (Fig. 5 right panel), a Meridional Overturning Circulation of 17 Sv is observed. Results show that eddy fluxes of heat and buoyancy play an important role in the formation of the intermediate waters by transferring water from the southern parts of the subtropical gyres into the ACC and vice versa. The effects of eddy fluxes are strongly concentrated in the Cape Basin and the Brazil–Malvinas Confluence in the Atlantic Ocean.

Although the analysis of Schouten and Matano (2003) highlighted the contribution of the South Atlantic circulation to the overall water mass balance, its focus was not the South Atlantic but the Southern Ocean. To advance these matters we evaluated the water mass transformation within the Sotuth Atlantic basin using the results of the same model. The volume transports in neutral density layers are computed and the mean convergence or divergence within a given density range is equivalent to the removal or formation of water due to diapycnal processes. Density changes in the upper 1000 m are below 0.1 kg/m^3 for most of the southern hemisphere. As diapycnal transformations are found to modify water masses at far higher rates, possible model drifts are neglected and steady state is assumed. The isopycnal transports in $4^\circ \times 4^\circ$ boxes between 70°S and 20°N are then computed. The convergence or divergence of the transport in a given isopycnal layer can be interpreted as diapycnal removal or formation. Volume divergences in $4^\circ \times 4^\circ$ horizontal boxes and in discrete sigma levels were first computed. These boxes were then grouped in seven distinct regions (Fig. 6, upper panel). Results are shown in Fig. 6, lower panel. The model results show significant water mass conversions within the South Atlantic, particularly in regions of

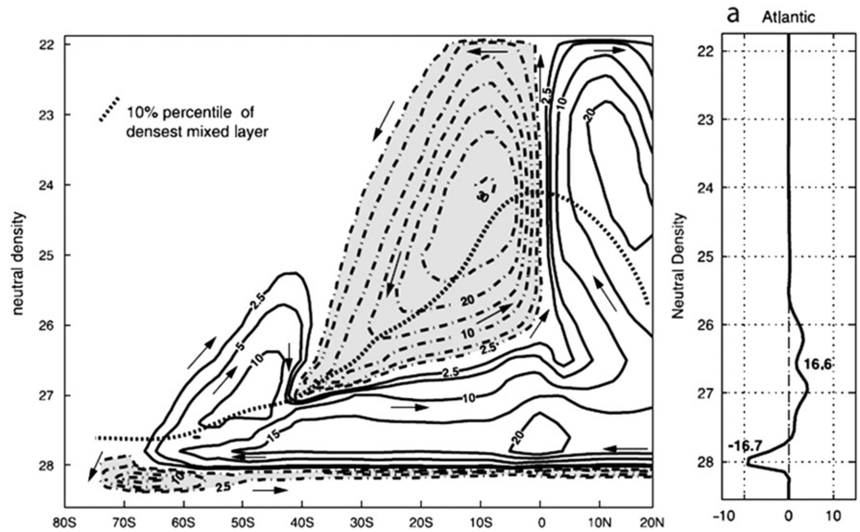

Fig. 5. Left panel: zonally integrated Meridional Overturning in neutral density coordinate. To indicate the position of the mixed layer, maximum surface layer density in the monthly mean field is evaluated. The dotted line shows the 10% percentile along latitude circles and can be considered a lower bound of the maximum mixed layer density at each latitude. Right panel: model transports in isopycnal layers into the Atlantic through 30°S. The units on the horizontal axis correspond to convergence within 0.1 neutral density ranges.
Adapted from Schouten and Matano (2006).

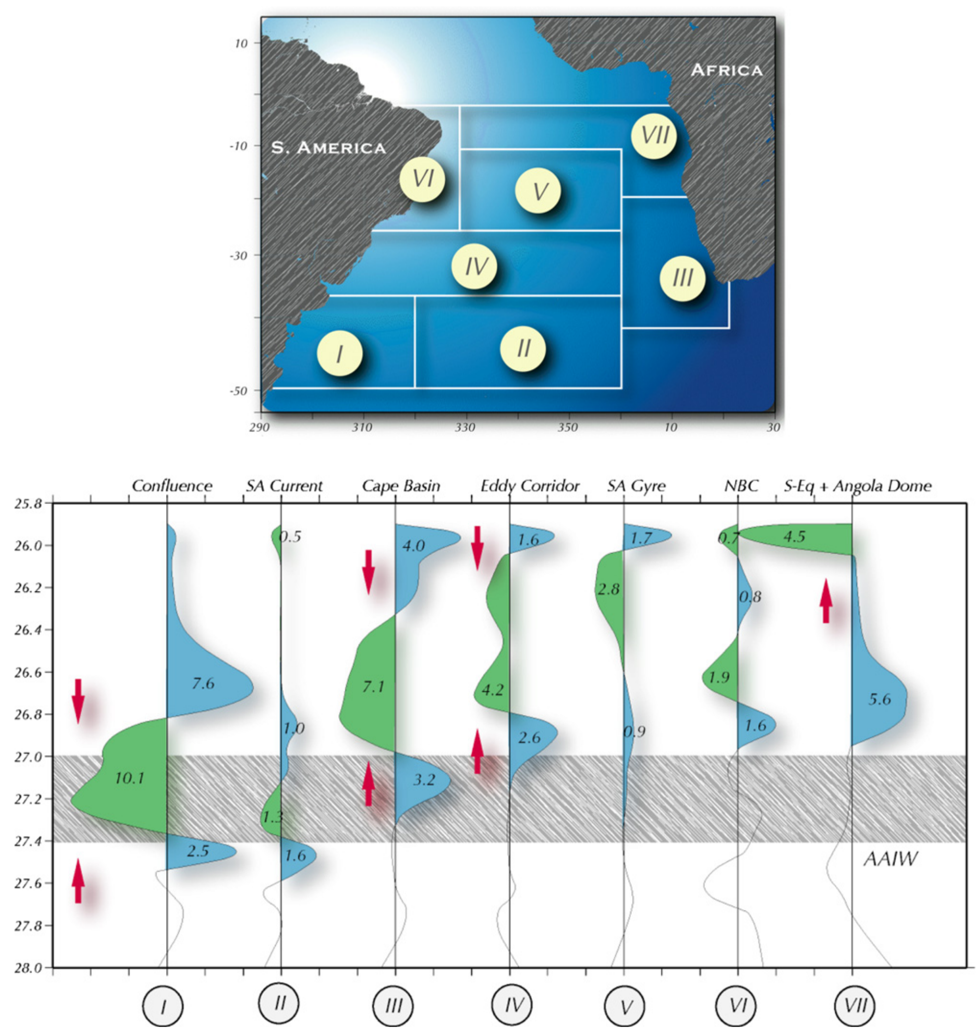

Fig. 6. Water mass transformation in the South Atlantic computed from the product of the POCM model. Top: location of the seven boxes where volume divergences at discrete sigma levels were computed. Bottom: sign and magnitude of the water mass transformations.

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intense mesoscale variability such as the southwestern Atlantic and the Cape Basin. The signs and magnitude of the conversions indicated by the model are in good agreement with those suggested by the observations, showing a conversion from surface and deep waters into intermediate waters in the southwestern Atlantic and from intermediate into surface waters in the Cape Basin region (Sloyan and Rintoul, 2001; Piola et al., 2000). Near the tropics there is a net conversion of intermediate into surface waters. As it was shown in the previous section, a heat balance of POCM reveals that the passage of these water masses at 30S generates a northward heat flux of 0.55 PW, a value very close to the 0.50 PW recently estimated from observations by Garzoli and Baringer (2007). The model balances are also consistent with the canonical circulation schemes derived from observations (e.g., Gordon et al., 1992) and they highlight two important characteristics of the South Atlantic circulation, namely that there is an active water mass transformation within the South Atlantic basin, and that a large portion of this transformation occurs in the highly energetic boundary regions.

The previous results indicate that the Brazil/Malvinas Confluence and the Cape Basin region are not only the main gateways for the entrainment of thermocline waters from neighboring oceans, but also for their modification. Considering the high levels of variability of these regions, it is expected that the intense mixing associated with this variability will affect the regional water mass structure. Little is known about the dynamical mechanisms that control the variability of these intensely energetic boundary regions. For example, it is unknown whether or not the Confluence variability is influenced by the ACC variability, or if the shedding of Agulhas rings is modulated by the low frequency variability of the South Indian Ocean. Such topics are not only relevant to our understanding of the local dynamics, but also to the mechanisms that regulate the inflow and outflows through these choke points of the global thermohaline circulation. In what follows we will expand the discussion on the questions posed by the models on these two regions in particular, and for the open basin in general.

5. South Atlantic inter-ocean exchanges

The South Atlantic inter-ocean exchanges are a weighty element of the AMOC; without them, the dense waters produced in the North Atlantic would not be able to spread to the Indian and Pacific basins and the lighter waters produced therein would not be able to reach the North Atlantic. The South Atlantic not only facilitates the inter-ocean exchanges, but it may also set preferential paths of communication. Although the strength of the AMOC is determined by convection in the North Atlantic, this convection is highly sensitive to the properties of the returning flow, specifically to whether it is dominated by contributions from the Indian or the Pacific oceans. Thus, convection in the North Atlantic is, to a large extent, dependent on what type of water mass the South Atlantic exports. If the inflows from the Indian and Pacific Oceans had similar water mass characteristics, then the mechanisms controlling the South Atlantic circulation (and its inter-ocean exchanges) would be largely irrelevant to the AMOC variability. The crux of the problem, however, is that the Indian and the Pacific water masses have marked differences. Changes in the ratio of entrainment from these distinct sources have profound implications for the stability and variability of the AMOC (e.g., Weijer et al., 2002; Biastoch et al., 2009). Paleoceanographic data indicates that the transition from the last glacial conditions and the resumption of the AMOC were correlated with a strengthening of the inflow from the Indian Ocean, suggesting a crucial role of the Agulhas leakage in glacial terminations and the resulting resumption of the AMOC (Peeters et al., 2004). Since most of the South Atlantic inter-ocean exchange is mediated by highly energetic western boundary currents, the question of what controls the variability of the inter-ocean exchanges can therefore be rephrased in terms of what controls the variability of its western boundary currents. In particular, the major western boundary currents, the Malvinas Current, which connects the South Atlantic to the Pacific Ocean, and the Agulhas leakage, which connects the South Atlantic to the Indian Ocean.

The contribution of the Malvinas Current to the AMOC is twofold: first it injects the relatively fresh and cold intermediate waters into the South Atlantic that are ultimately drawn into the North Atlantic, and second, it contributes to the observed water mass transformations in the Argentinean Basin (see Section 4). The links between the variability of the Malvinas Current and the atmospheric and oceanic circulation in the Southern Ocean are not well established, but all evidence suggests that low-frequency variations in the Malvinas Current transport are connected to variations of the Antarctic Circumpolar Current transport in the Drake Passage, wind stress forcing in the circumpolar region, and the propagation of eddies from the South Pacific Basin (Garzoli and Giulivi, 1994; Vivier et al., 2001; Fetter and Matano, 2008; Spadone and Provost, 2009). Analysis of the POCM model (Fetter and Matano, 2008) showed that the observed low correlation between the transport variations of the Antarctic Circumpolar Current and the Malvinas Current is masked by higher frequency variability. They also showed that as part of this high variability there are anomalies that propagate to the interior and that affect the transports at the boundaries of the South Atlantic.

Following Fetter and Matano, (2008), the POCM product was analyzed together with wind stress products and sea surface height anomalies from AVISO altimetry (http://www.aviso.oceanobs.com/). A principal estimator patterns (PEP) analysis (e.g., Davis, 1977; Fetter and Matano, 2008) was conducted between SSH anomalies and the wind stress curl. Results of the analysis are shown in Fig. 7.

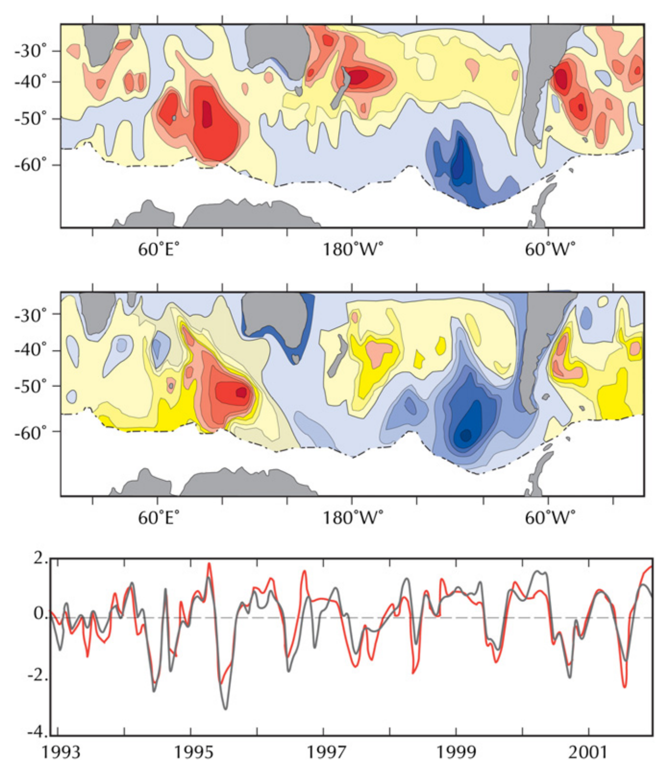

Fig. 7. Results of the principal estimator patterns between SSH and wind stress curl. Top: SSH anomalies, Middle: wind stress anomalies, and Bottom: time dependence of the principal mode. Blue is from the POCM and black is from the AVISO data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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The top panel shows the amplitude of the SSH anomaly as derived from the Aviso product, and the middle panel those of the wind curl as derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) winds. The lower panel shows the time series of the first PEP estimator of model product and the AVISO data. There is a strong coherence between the two series, reinforcing the validity of the model to perform the analysis. Interesting to note is that the maximum amplitude in SSH observed at the Brazil–Malvinas Confluence, approximately centered at 300°W and 40°S (Fig. 7, top panel), is out of phase with a maximum of the curl of the wind stress in the South Pacific centered at around 250°W and is in phase with the anomalies south of Australia at 80°W. This is an indicator of a strong correlation of the variability of the winds in the Southern Ocean and the variability of the western boundary currents in the South Atlantic. There is not enough evidence to assess the impact of the Malvinas Current variability on the AMOC. However, as it was shown in the previous section, model results and observations indicate that it contributes to water mass transformation in the Argentinean Basin (e.g., Fig. 5). Only a relatively small portion of the Malvinas Current waters is entrained in the subtropical gyre and funneled to the North Atlantic. This mostly occurs in the Agulhas Retroflection region where a portion of the South Atlantic Current diverts north to feed the Benguela Current.

Due to its direct connection to the subtropical gyre there are more studies on the Agulhas Current impact on the AMOC. Donners and Drijfhout (2004) estimated that 90% of the upper branch of the AMOC is derived from the inflow of Indian Ocean water into the South Atlantic. Biastoch et al. (2009) argued that the Agulhas leakage is a source of decadal AMOC variability. According to this hypothesis, low-frequency signals induced by the Agulhas are carried across the South Atlantic by Rossby waves and into the North Atlantic along the American continental slope. The resulting signal in the AMOC transport gradually diminishes from south to north, but has an amplitude in the tropical Atlantic of comparable magnitude to the effect of subarctic deep water. Biastoch et al. (2009) also show that the transport of Indian Ocean waters into the South Atlantic via the Agulhas leakage has increased during the past decades in response to the change in wind forcing. Studies based on paleo data and simplified models (Weijer et al., 2002; Peeters et al., 2004) concluded that a shutdown of the Agulhas Current influences the deep water formation in the North Atlantic with obvious consequences for the AMOC. In a recent publication, Haarsma et al. (2005) used a coupled ocean–atmosphere model to investigate the impact of the Agulhas leakage on the Atlantic circulation. The experiments performed mimic the closure of the warm-water path in favor of the cold-water path. Their results reinforce the role of the Agulhas leakage on the AMOC; the modified water characteristics due to the shutdown of the Agulhas leakage remain unaffected when crossing the equatorial region and therefore are capable of affecting the deep water formation in the North Atlantic.

Goni et al. (1997) observed that there is a close correlation between the transport of the Agulhas Current and the shedding of rings. Altimeter data analysis indicates that the Agulhas rings are modulated by the flow through the Madagascar Current and the Mozambique Channel. Analysis of altimeter data showed significant interannual variations in the rate of Agulhas ring shedding (Goni et al., 1997; Quartly and Srokosz, 2002). These studies lead to the conclusion that low-frequency (interannual and longer) variations in the inter-ocean exchange around South Africa are linked to large-scale modes of climate variability.

Although there are far more studies on the impact of the Agulhas Current on the AMOC, observations indicate that at least half of the northward upper ocean flux transported by the Benguela Current is from subpolar origin, i.e., it is ultimately derived from the Malvinas Current. In fact, Garzoli et al. (1997) noted that although the annual mean value of the Benguela Current transport (~13 Sv) changes less than 20% from year to year, there are marked interannual transitions in the sources from which it drains its waters, i.e., the South Atlantic Current or the Agulhas Current. This observation raises the question of whether years of strong South Atlantic inflow can be characterized as cold-path years while those of strong Agulhas inflow can be characterized as warm-path years. The nature of the mechanisms that would regulate the dominance of one path over the other is unknown. Whether changes in the sources of the Benguela transport can really affect the inter-hemispheric exchange is another unknown question.

6. Summary and discussion

Observations and models consistently indicate that the South Atlantic is not just a passive conduit for the passage of water masses formed in other regions of the world ocean but instead actively participates in their transformation. They occur across the entire basin, but are intensified in regions of high mesoscale variability, particularly at the Brazil/Malvinas Confluence and the Agulhas Retroflection region. It has also been argued that the South Atlantic circulation may set preferential paths for inter-ocean exchanges. Observations show interannual variations in the sources that feed the Benguela Current and hence in the northward cross-equatorial fluxes. It has also been shown that processes occurring in the Southern Ocean and the adjacent basins alter this variability. There are dynamical processes that link the South Atlantic to the other basins and that mediate the observed water mass transformations. In spite of this mounting evidence on the contribution of the South Atlantic to the AMOC, it is obvious that still there are more questions about this portion of the AMOC than answers. To advance our understanding of the AMOC and its climatic implications it is imperative to expand the existing observing systems towards other important regions, particularly those like the South Atlantic containing strategic choke points of the AMOC. This will allow us not only to document climatically important phenomena, but also to improve our capacity to forecast them. Ongoing and new observations should have three major foci: (1) regions where topography significantly alters the deep circulation; (2) choke points where deep water is exchanged between the major ocean basins (e.g., the Drake Passage); and (3) deep strong flows where the major water masses are carried significant distances within basins. A South Atlantic monitoring system should measure the meridional heat transport and its variability along a zonal line across the basin. Observations at the boundaries should provide information on the DWBC passages and intensity. The upper limb of the AMOC, carrying AAIW at mid-latitudes, the role of the Agulhas rings, and leakage in these transfers should be further investigated. To advance our understanding of the AMOC pathways it is necessary to determine the influence of the bottom topography on the mean circulation. For example, it is necessary to establish how the mid-Atlantic Ridge affects the water mass transformation and meridional fluxes. What happens at the bifurcation of the South Equatorial Current where the DWBC breaks into eddies? How is it reconstituted again at mid-latitudes as observations show both at the eastern and western boundaries? Different deep-water masses separated by topographic features can mix and exchange properties. The highest priority sites in the Atlantic are the Weddell Sea, the Vema Channel, and the Romanche Fracture Zone sill in the South Atlantic, and in the Samoan Passage, Denmark Straits, and Cape Farewell in the North Atlantic.

Our capacity to establish efficient monitoring systems can be greatly improved by dedicated modeling studies of the South Atlantic circulation and its connection to the neighboring basins. High-resolution models could help to determine the optimal location and minimum requirements for a monitoring system

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designed to measure components of the AMOC in the South Atlantic Ocean. The failure of some state-of-the-art global eddy-resolving models to resolve critical aspects of the AMOC such as the path of the Agulhas rings highlights our need to focus our attention on this climate-relevant region. If, as observed, a numerical model fails to reproduce the correct path of the Agulhas eddies, it will produce the wrong meridional heat and salt fluxes, and hence will distort the structure of the AMOC. As we strive to move from coarse-resolution to high-resolution climate models, these issues need the pressing attention of the modeling community. Equally alarming is the observed failure of these models to reproduce the formation of the Zapiola Anticyclone in the Argentinean Basin. The evidence presented herein indicates that this is an active region for water mass formation. Models that fail to reproduce this particular feature, however, are likely to grossly underestimate this important component of the South Atlantic circulation.

The limitations of this paper, which pose more scientific questions than answers, point toward the need for sustain observations in the South Atlantic and Southern Oceans in conjunction with modeling efforts that will help to increase our understanding of the most important processes and allow us to formulate meaningful climate predictions.

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