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SUBDUCTION OF SOUTH ATLANTIC SUBTROPICAL MODE WATERS

Guilherme Nogueira Mill[1] and Afonso de Moraes Paiva[2]

ABSTRACT. The formation of the Subtropical Mode Waters (STMW) in the South Atlantic, part of the South Atlantic Central Water (SACW), by the subduction process, transferring mixed layer fluid into the permanent thermocline, is investigated using results of numerical simulations with the HYbrid Coordinate Ocean Model (HYCOM). Subduction rates were estimated by the kinematic method, adding the lateral induction of fluid through the sloping base of winter mixed layer with the vertical velocities at the base of winter mixed layer. Subduction rates above 100 m/year were found over the South Atlantic Subtropical Front, with maximum rates larger than 200 m/year in three distinct regions. The subduction pattern is dominated by the contribution of lateral induction, specially over the Subtropical Front, with rates significantly larger than the maximum rate of Ekman pumping. Different STMW were identified, associated with maximum layers thickness in isopycnals representative of upper and middle portion of SACW. The regions of maximum subduction rates were associated with the formation of the STMW.

Keywords: mixed layer, ventilation, SACW, permanent thermocline, lateral induction.

RESUMO. A formação de Águas Modais Subtropicais (AMS) no Atlântico Sul, que fazem parte da Água Central do Atlântico Sul (ACAS), transferindo fluido da camada de mistura para a termoclina permantente pelo processo de subducção, foi estudada a partir dos resultados de simulações numéricas com um modelo oceânico de coordenadas híbridas (HYCOM – Hybrid Coordinate Ocean Model). A subducção foi calculada pelo método cinemático, somando as contribuições da indução lateral de fluido através da base da camada de mistura e as velocidades verticais na base da camada de mistura de inverno. Foram encontradas taxas de subducção superiores a 100 m/ano ao longo da Frente Subtropical do Atlântico Sul, com três núcleos distintos de máxima subducção atingindo mais de 200 m/ano. A indução lateral mostrou-se o processo dominante na subducção, especialmente ao longo da frente, com taxas significativamente superiores ao bombeamento de Ekman. Foram identificadas diferentes AMS associadas às máximas espessuras de camadas representativas das porções média e superior da Água Central do Atlântico Sul (ACAS). As regiões de máximas taxas de subducção estão associadas à formação das AMS.

Palavras-chave: camada de mistura, ventilação, ACAS, termoclina permanente, indução lateral.

Universidade Federal do Rio de Janeiro, Programa de Engenharia Oceânica, COPPE – Centro de Tecnologia, Bloco C, sala 209, Cidade Universitária, Ilha do Fundão, 21941-914 Rio de Janeiro, RJ, Brazil. Phone/Fax: +55(21) 2562-8755 – E-mails: guilhermemill@gmail.com; mpaiva@oceanica.ufrj.br

INTRODUCTION

The South Atlantic Central Water – SACW – is formed in the Subtropical Front and it is transported by the South Atlantic Subtropical Gyre. It presents a nearly linear distribution in a typical T-S diagram. The temperatures vary between 5-6 and 18-20°C and salinity varies between 34.6 and 36 (Sverdrup et al., 1942; Miranda, 1985). However, the SACW presents in fact a modal structure that can be seen in a volumetric T-S, which is the result of a formation of large volumes of water, vertically homogeneous with specific properties called Subtropical Mode Waters (STMW). Mode waters are fundamental to understand the formation of the ocean permanent thermocline and also for climatic studies as they reflect the interannual anomalies, or even larger period anomalies, in the atmospheric forcing during the formation process (Paiva & Chassignet, 2002).

Central waters are formed by the combination of horizontal and vertical fluxes from the base of the mixed layer – ML which ventilate the thermocline and this process is called subduction (Cushman-Roisin, 1987). During winter, the heat loss through the air-sea interface leads to buoyance loss of the surface waters, increasing density and producing deep convection. In the end of the season, the homogenized water is transferred definitely from the ML to the subsurface layers originating the STMWs, which present typical properties related to the winter ML.

STMWs occur in all the oceans, and many studies have been developed in order to describe their spatial distribution and to understand the associated formation processes, especially in the northern hemisphere. For example, the 18°C water which is formed in the internal border of the Gulf Stream in a region of intense heat loss to the atmosphere and which covers a large extension in the North Atlantic ocean, is probably the best described mode water in literature (e.g., Schroeder et al., 1959; Worthington, 1959; Talley & Raymer, 1982; Jenkins, 1987; New et al., 1995; Klein & Hogg, 1996; Paiva & Chassignet, 2002; Peng et al., 2006). In spite of the relative stability of the main properties of this mode water, observational data indicate that interannual thickness and temperature anomalies can be intense, being associated to anomalous atmospheric forcing (Talley & Raymer, 1982; Talley, 1996; Hanawa & Talley, 2001; Paiva & Chassignet, 2002). On the other hand, in the North Pacific ocean, a colder mode water is formed in the Kuroshio extention, with temperature of 16°C and salinity of 34.8, which is called North Pacific Mode Water (Talley, 1988; Suga & Hanawa, 1995). Having a large zonal extension, the Pacific ocean presents other two SMWs: the central subtropical mode water, with temperature varying from 9 to 12°C and the eastern subtropical mode water, with temperature varying from 12 to 22°C (Hanawa & Talley, 2001).

In the South Pacific ocean, a mode water formed between Fiji and New Zealand, with temperatures varying between 15 and 19°C and salinity of 35.5, presents a smaller thickness when compared to the 18°C North Atlantic water and to the 16°C North Pacific water (Roemmich & Cornuelle, 1992). In the eastern boundary a mode water variety called South Pacific Eastern Mode Water by Tsuchiya & Talley (1996), with temperatures between 13 and 20°C and salinity between 34.3 and 35.5, circulates to northeast and eventually joins to the South Equatorial Current.

In the Indian ocean, between 28°E and 45°E, a mode water is formed with temperature of 17°C and salinity of 35.6 (Olson et al., 1992), while further east, between 37°S-42°S and 60°E-80°E, Tsubouchi et al. (2010) describe a mode water with 12.8°C for temperature and 35.1 for salinity. Some studies indicate that there is a mode water leakage from the Indian ocean to the South Atlantic basin, modifying the properties of the eastern Atlantic thermocline (Gordon, 1985; Sprintall & Tomczak, 1993). In part this leakage would be carried out by the Agulhas retroflection rings (Gordon & Haxby, 1990; Byrne et al., 1995; Garzoli et al., 1999; Richardson, 2007).

In the South Atlantic ocean, the first STMW description was presented by McCartney (1977), who identified a mode water with temperatures between 12 and 13.5°C in the Subtropical Front. Tsuchiya et al. (1994) described two STMWs, a lighter one located to the north of 36°S, with temperatures between 13-13.5°C for temperature, and another one located to the south of 36°S, with temperature around 11.6°C for temperature. Based on *WOCE (World Ocean Circulation Experiment)* hydrographic data, Provost et al. (1999) identified three different mode waters in the South Atlantic ocean, in the upper and middle portion of the thermocline, with temperatures from 16 to 18°C, from 14 to 16°C and from 12 to 14°C. Félix et al. (2005) and Mill et al. (2014) question the existence of the warmer mode that would represent in fact a fossil portion of the mixed layer during the summer restratification, identifying the 14 to 16°C water as the dominant mode of the western South Atlantic.

Observational *in situ* data and air-sea fluxes (Schmitt et al., 1989; Speer & Tziperman, 1992; Marshall et al., 1993; Qiu & Huang, 1995; Weller et al., 2004), and numerical model results (Williams, 1991; New et al., 1995; Spall, 1995; Williams et al., 1995; Hazeleger & Drijfhout, 2000; Peng et al., 2006) have been used to calculate subduction rates in the northern hemisphere. Observational studies have been extended to the south hemisphere with caution, as the observational bases are established on sparse data with questionable representativity. Karstensen & Quadfasel (2002), focusing on the South Hemisphere, calculated the surface water transformation by heat and mass fluxes and annual mean transferences of water volumes to the thermocline from the geostrophic velocity fields. The authors verified the annual transference of 21 Sv from the mixed layer to the thermocline in the South Atlantic ocean in which about 50% are concentrated in the region of the Brazil-Malvinas Confluence. On the other hand, De Miranda et al. (1999), based on results of a high resolution numeric model, suggest that the STMW formation in the South Atlantic ocean occurs distributed along all the Subtropical Front.

The present work is a contribution to the study of the subduction and of the mode water formation in the South Atlantic ocean, based on the results of a numerical simulation carried out using the HYCOM – HYbrid Coordinate Ocean Model (Bleck, 2002) ocean model. The purpose is to characterize the subduction pattern in the South Atlantic Ocean and its relation to the STMW formation. Subduction rates are calculated evaluating the different contribution of the two main formation processes: horizontal fluxes and vertical fluxes through the base of the mixed layer. To our knowledge, this is the first study published in Brazil specifically about subduction and STMW formation – therefore, the next section presents a detailed review of the subduction process and of the calculation of subduction rates. The configuration and forcing of the numerical simulation are then described. Results are presented and discussed in terms of the importance of the South Atlantic ocean as a region of significant water mass transformations, and of the dominance of horizontal geostrophic fluxes over Ekman pumping for defining the characteristics of the main thermocline. Finally, the conclusions of this work are presented.

KINEMATIC CALCULATION OF SUBDUCTION

There are two main approaches for calculating subduction rates. The first is based on the analysis of the heat and mass fluxes between the ocean and the atmosphere and on the calculation of the density fluxes through the sea-air interface (Speer & Tziperman, 1992; Speer et al., 1995). The second, called kinematic method (Marshall et al., 1993; New et al., 1995), is based on the analysis of circulation in the upper ocean layers and it can be carried out in a Lagrangian or Eulerian reference frame. The last one was used in this study and will be reviewed below.

There are three processes that transfer a fluid particle from the mixed layer to the permanent thermocline: vertical velocities acting on the particle; horizontal velocities transferring the particle through a sloping mixed layer base; and the vertical displacement of the mixed layer base along the seasonal cycle, which does not necessarily involve the particle displacement (Marshall et al., 1993). Considering a fluid particle leaving a mixed layer, with thickness h, and going into the permanent thermocline, the vertical distance between this particle and the mixed layer base is defined by a Δz. This distance is modified during each time interval Δt, according to the combination of the three different processes previously described.In the kinematic method, the instantaneous rate of water transference from the mixed layer to the thermocline is calculated, following Cushman-Roisin (1987), Nurser & Marshall (1991), Williams (1991), and Marshall et al. (1993), by:

$$S = \frac{\Delta z}{\Delta t} = -\frac{\partial h}{\partial t} - u_b \nabla h - w_b \qquad (1)$$

where h is the mixed layer thickness and u_b and w_b are the horizontal and vertical velocities through mixed layer base, respectively. The instantaneous subduction rates (S) take into account a temporal variation term of the mixed layer thickness (the first term of the right side of Equation 1), a term representing the lateral induction of fluid through the mixed layer base (the second term) and a term representing the vertical at the mixed layer base (the third term). In regions where the mixed layer base is relatively horizontal, the vertical velocities, mainly associated to Ekman pumping, are the main responsible for the water fluxes to the thermocline. In regions where the depth of the mixed layer presents a pronounced horizontal gradient, especially in the western boundary currents, the horizontal velocities associated to the surface current system can transport fluid through the mixed layer base.

However, the subduction considered as the definitive transfer of fluid to the permanent thermocline does not occur during all the year. In one of the first works about the thermocline ventilation, Montgomery (1938) revealed the relationship between the properties and circulation of central water in the North Atlantic ocean with the stratification in the main formation sites of these waters. Analyzing the seasonal cycles of the mixed layer, Iselin (1939) described for the first time the tendency of the thermocline temperature and salinity characteristics to approximate those of mixed layer in the end of the winter in the formation region. Stommel (1979), analyzing hydrographic data in the North Atlantic ocean, suggested that the mixed layer water transferred to the seasonal thermocline in the spring and in the summer is almost totally recaptured in the following winter, concluding that the subduction mechanism is intermittent, being effective only in the end of the winter. In an allusion to the term introduced by Maxwell in studies about property selection in kinematic theory of gases (Williams et al., 1995), Stommel created an allegory of the subduction process in which a kind of trapdoor at the base of the mixed layer would remain closed during the year and would be opened by a demon only in the end of the winter, allowing then

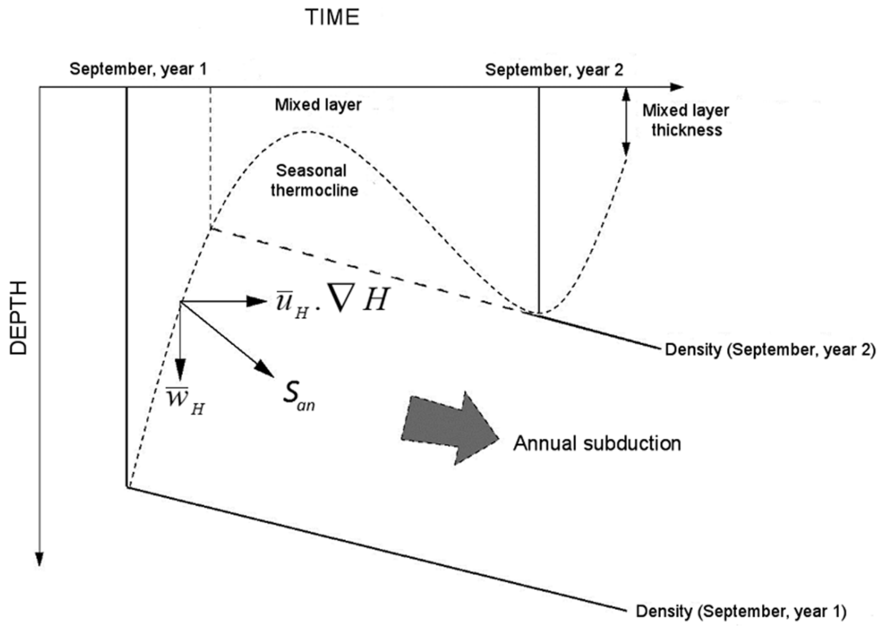

Figure 1 – Schematic diagram illustrating the seasonal cycle of the mixed layer in the South Hemisphere in a Lagrangean approach (adapted from Marshall et al., 1993). The dashed line illustrates the mixed layer depth as it is "perceived" by a fluid portion that moves along the subtropical gyre towards the low latitudes during the year. Only the subducted water in the end of the winter (september in the south hemisphere) will definitively be transferred to the permanent thermocline. All the fluid transferred from the mixed layer to the deep ocean beyond this period will be recaptured during the mixed layer deepening in the following winter, occurring only in the seasonal thermocline.

the ventilation of the permanent thermocline of the oceans. Marshall et al. (1993), using climatological data, estimated the effective time during which this "trapdoor" would be opened in the North Atlantic ocean from one to two months in the end of the winter and in the beginning of the spring. The subduction process is summarized in Figure 1 in a Lagrangean framework. Although we use in this work an Eulerian approach, a Lagrangean approach is more illustrative of the physical process.

The subduction will be addressed, therefore, as the definitive transfer of the mixed layer fluid to the permanent thermocline, which is also referred as the annual subduction. Beyond the end of the winter, the fluid is temporarily transferred to the seasonal thermocline and is recaptured in the following winter. For a pratical calculation, Equation (1) is integrated during the year and, disregarding the interannual variability in the mixed layer depth, we obtain:

$$S_{an} = -\bar{w}_H - \bar{u}_H \cdot \nabla H \qquad (2)$$

where the superscript bar denotes the annual average, H represents the fixed layer depth in the end of the winter and the subscript H indicates that the variables are evaluated at the base of the winter mixed layer (Marshall et al., 1993).

The vertical velocity at the mixed layer base w_H is evaluated from the vertical velocities associated to Ekman pumping (w_{EK}) added to the effect of the meridional transport, considering the planetary vorticity gradient (Williams, 1991):

$$w_H = w_{Ek} - \frac{\beta}{f}\int_{-H}^{0} v dz \qquad (3)$$

in which f is the Coriolis parameter, β is the meridional gradient of the planetary vorticity, v is the meridional velocity component, and Ekman pumping is expressed by (Pond & Pickard, 1983):

$$w_{\vec{E}k} = \left(\nabla \times \frac{\tau}{\rho f}\right) \qquad (4)$$

where τ is the wind shear stress and ρ is the sea water density. Substituting in equation 2, we obtain:

$$S_{an} = -\bar{w}_{Ek} + \frac{\beta}{f}\int_{-H}^{0} \bar{v} dz - \bar{u}_H \cdot \nabla H \qquad (5)$$

which is the equation used in this study to calculate the subduction rates.

THE NUMERICAL SIMULATION

The subduction calculation was carried out based on the results of a numerical simulation described in Gabioux (2008), using the HYCOM model in a domain covering the South Atlantic ocean and including the Equatorial region, between 65°S and 10°N and 70°W and 20°E. The model grid is based on a Mercator projection centered on the equator, with nominal horizontal resolution of 1 degree. The model was configured with 21 σ_θ layers, in which the first 18 are hybrid (isopycnal and/or geopotential) and the 3 deepest are only isopycnal.

The model experiment was forced with surface heat, mass and momentum fluxes, interpolated to the model grid from the COADs (Comprehensive Ocean Data Set) monthly climatology. A Newtonian relaxation of surface temperature and salinity to the WOA (World Ocean Atlas, 2001) monthly climatology was added, according to the methodology proposed and discussed in Paiva et al. (2000). The horizontal mixing follows the Smagorinsky formulation and the vertical mixing follows the KPP (nonlocal K-profile parameterization) method. The bathymetry was interpolated from the NOAA/NGDC (National Oceanic and Atmospheric Administration/National Geophysical Data Centre) Terrain-Base, with 5 minute spatial resolution. The experiment was initialized based on the WOA January climatology.

In the western boundary, a constant barotropic flux of 110 Sv, associated to the Antarctic Circumpolar Current (ACC) transport, was implemented with variable meridional distribution. In the eastern boundary, the barotropic transport was spatially divided in two segments: the southern part with 120 Sv leaving the domain (ACC), and the northern part, representing the Agulhas Current transport, with 10 Sv entering the domain. The northern and southern boundaries were closed, with temperature and salinity relaxation to climatology performed at 3 degrees wide buffer zones (Chassignet et al., 1996; Paiva et al., 2000). The experiment was integrated for 40 years and the last 10 years were used in this work, with results saved every 15 days.

Subduction calculation in the model

The subduction was calculated using Equation (5), in an area between 10°S and 50°S and 60°W and 0°. The annual average Ekman pumping ($\bar{w}_{Ek}$) was obtained using COADs wind stress monthly climatology (Equation 4). Each term of Equation (5) was analyzed separately, in order to quantify and understand the contribution of each one for the annual subduction. Numerical errors in the results of the mixed layer depth diagnosed by the model were minimized using a Butterworth filter. The S_{an} value was converted to meters by year (m/yr).

RESULTS

Ekman pumping (Fig. 2a) varies between 10 and 20 m/yr within the South Atlantic Subtropical Gyre, following the negative wind stress curl in the the region, increasing in the NW direction and reaching a maximum of around 40 m/yr. The pattern calculated according to the COADs dataset is similar to the pattern obtained from other bases, although it presents reduced values when compared to those calculated based on the Hellerman and Rosenstein wind climatology (Karstensen & Quadfasel, 2002), for instance. The relative contribution of Ekman pumping to the subduction in the South Atlantic ocean is similar to other oceans: Marshall et al. (1993) based on the winds computed by Isemer & Hasse (1987) present values around 25 m/yr in the outcrop region in the North Atlantic ocean, reaching 50 m/yr in the tropical region, while Qu et al. (2002) present values from 10 to 50 m/yr in the North Pacific ocean using Hellerman & Rosenstein (1983) winds. It is interesting to observe in Figure 2a the line of zero wind stress curl close to the Subtropical Front and the positive values of 10 to 20 m/yr of pumping in the Southeast region of Brazil, near Cabo Frio, associated to the surface divergence and the upwelling of subsurface waters. The total vertical velocity field (Fig. 2c) is slightly modified by the term associated to the planetary vorticity gradient (Fig. 2b) in most part of the domain, but it is significantly altered the intense meridional flux of the Brazil Current induces vertical velocities reaching 70 m/yr.

The lateral induction of fluid through the mixed layer base (Fig. 2d) presents rates higher than 100 m/yr along all Subtropical Front. It is also important to note three cores in the front region, with maximum lateral induction of 200 to to 300 m/yr: the first near the Brazil-Malvinas confluence at 30°S and 40°W, the second in the central region around 35°S and 20-30°W and the third located further east between 35°S and 8°W. The lateral induction dominance over other processes in annual subduction is verified in many studies in other oceans. In the North Atlantic ocean, for example, high rates around 100 to 150 m/yr are presented by Marshall et al. (1993) based on the climatologic data analysis, while rates of 150 to 200 m/yr were obtained by New et al. (1995) based on the numerical results.

The resulting annual subduction resulted from the sum of the Ekman pumping contribution, the planetary vorticity gradient effect and the lateral induction of fluid through the mixed layer base is presented in Figure 3. The subduction pattern along the subtropical front is very similar to the pattern presented by the lateral induction (Fig. 2d), with rates higher than 100 m/yr and the three maximum subduction cores. Total rates of approximately 350 m/yr are present in the central and western cores, and rates higher than 200 m/yr occur in the core located to the east of the front. Integrating along the subtropical front, a total subduction of approximately 25 Sv corresponds to the total amount of water that ventilates to the mid and upper portions of the South Atlantic thermocline, corresponding to the SACW formation. In latitudes

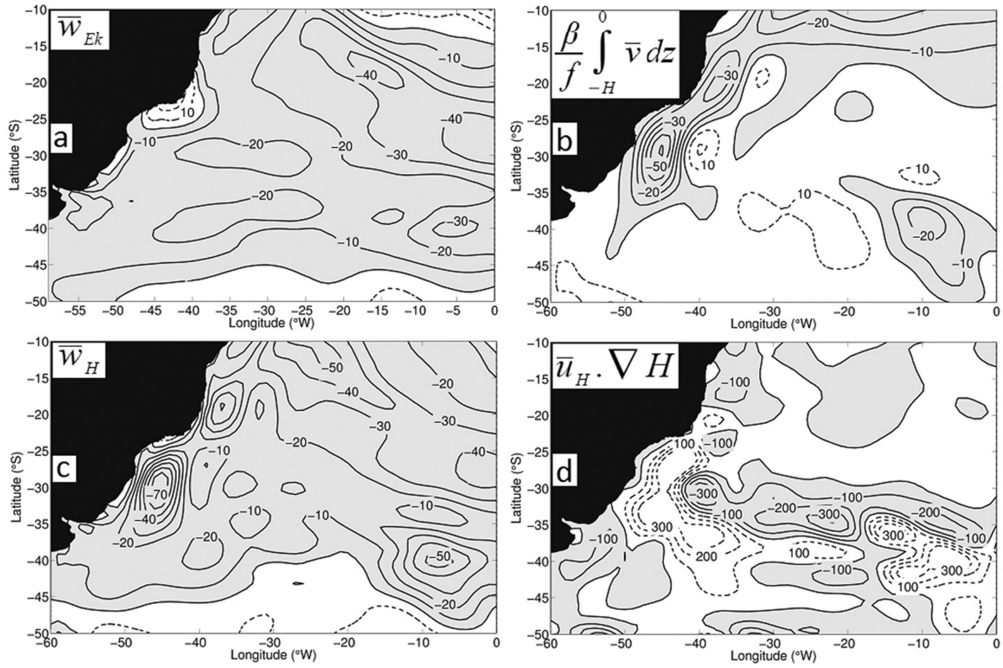

Figure 2 – Annual mean (a) vertical velocities induced by Ekman pumping; (b) vertical velocities induced by meridional transports; (c) total vertical velocities at the mixed layer base; (d) lateral induction of fluid. The rates are presented in m/yr. The shaded areas indicate the fluid transfer from the mixed layer to the thermocline.

lower than 25°S, subduction rates that reach values higher than 100 m/yr are associated with the formation of Tropical Water.

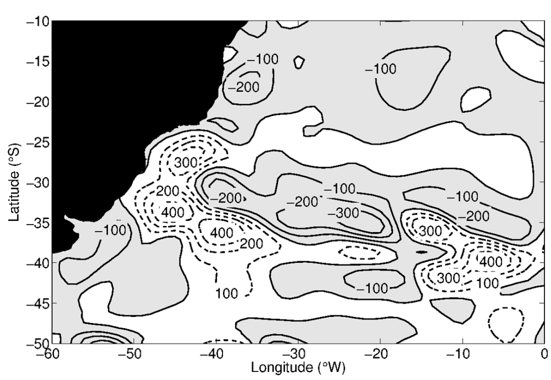

Figure 3 – Annual subduction (S_{an}). The shaded areas indicate the fluid transference from the mixed layer to the permanent thermocline.

To elucidate the lateral induction dominance in the South Atlantic subduction, it is necessary to analyze the mixed layer depth in the end of the winter and the mixed layer circulation. The mean mixed layer depth in september (solid lines in Fig. 4) deepens along Subtropical Front, with distinct regions maximum mixed layer depth gradient. The superposition of mean mixed layer depth and circulation in September (indicated by the vectors in Fig. 4) shows how the maximum lateral induction cores arise. In the regions highlighted by bold traced lines in Figure 4, the strong flow in the Subtropical Front promotes the passage of waters to the thermocline through the intense gradients of mixed layer depth.

To each maximum subduction cores, there is a correspondence of a mode water in the simulation, that appears as a region of relative spatial extent with maximum values of layer thickness. In the present case, the three cores in the subtropical front region correspond to maximum thickness in layers 9 (25,28 σ_θ), 10 (25,70 σ_θ) and 11 (26,18 σ_θ) of the model, which represent the upper and mid portion of the SACW (Fig. 5).

Each core, associated to different STMW, reaches maximum thickness of more than 200 m, representing a significant portion of the permanent thermocline. The western core (Fig. 5a), around 48°W and 40°W and 25°S and 38°S, is located in a region of intense recirculation associated to the Brazil-Malvinas Confluence (Fig. 4). The central core (Fig. 5b), around 30°W and 15°W and 25°S and 35°S, with larger area and greater volume then the western one, can also be observed in a meridional section in Figure 5d. This figure shows the typical aspect of a mode water as pycnostad that stands out in the characteristic intense vertical gradients of the thermocline. The third core (Fig. 5c), that appears to the east of 15°W and around 30°S and 40°S, extends beyond the analyzed region suggesting that its origin is associated in part to the local subduction and in part to the waters formed to the east

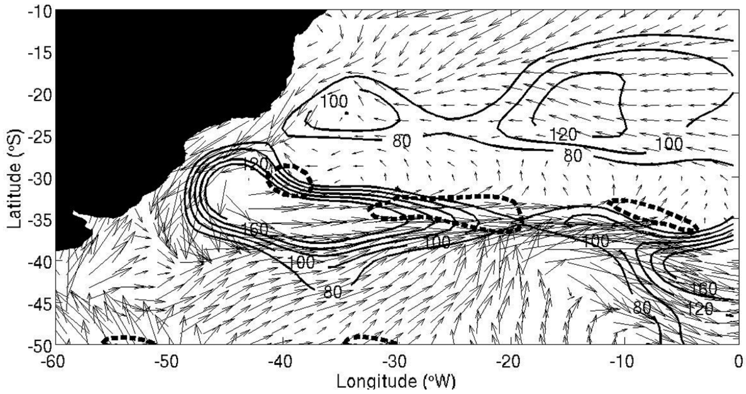

Figure 4 – Model averaged (10 year mean) September mixed layer depth (solid contours) and circulation (vectors). Solid lines show mixed layer contours between 80 m (external contour) and 160m (internal contour), with a 20 m interval. The bold dashed lines delimit the regions where the lateral induction is higher than 200 m/yr.

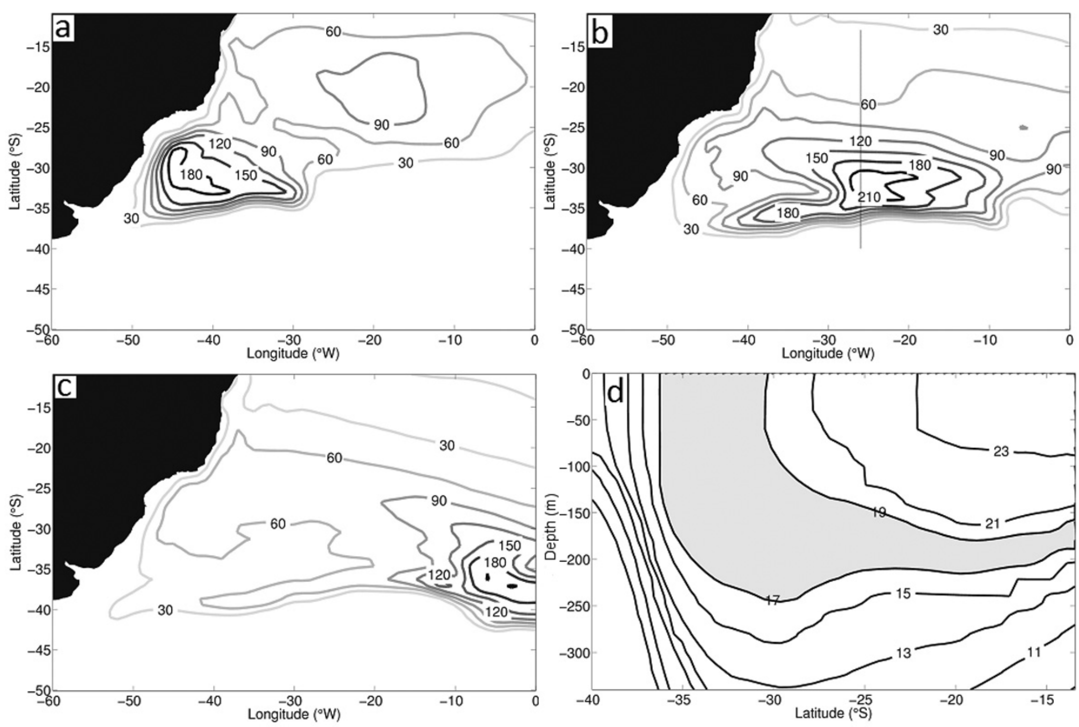

Figure 5 – Mean thickness in september of: (a) layer 9; (b) layer 10; (c) layer 11. The vertical line in (b) represents the position of the meridional temperature section of the layer temperature at 26°W, presented in (d), that shows a mode water in layer 10, characterized by a thermostad between 17 and 19°C.

of this domain. It is interesting to note that the same model layer can represent distinct water masses or distinctive mode waters. This is the case of layer 9 (Fig. 5a), in which a second core of maximum thickness appears near 30°W and 10°W and 25°S and 15°S, corresponding to a region of maximum subduction (Fig. 4) and to the simulated tropical mode water.

The regions of maximum thickness in the model simulation can be associated with the three STMWs described by Provost et al. (1999) in the South Atlantic ocean. The first mode water described by these authors presents thermostads between 16 to 18°C, salinity of 35.9 to 36.2 and is mostly formed near to 35°S and 45°W; the second have thermostads of 14 to 16°C, salinity of 35.5 to 35.9 and is formed near to 35°S and 28°W; the third have temperatures between 12 and 14°C, salinity between 35.2 and 35.5 and it was formed between 40°S-35°S and 30°W-5°W. The model results show a warm bias in the mixed layer, producing lighter mode waters than observations. This is reflected in the model as a small drift from the initial conditions, and results in a migration of the lower layers to the upper portions of the thermocline. However, this does not affect the dynamics of the subduction process, and the three STMWs in the model are analogous to the observed ones.

DISCUSSION AND CONCLUSIONS

This work presents a numerical investigation of the South Atlantic Central Water ventilation through the subduction process in the South Atlantic ocean, based on HYCOM simulation. The contribution of the Ekman pumping, the meridional gradient effect of the Coriolis parameter and the lateral induction to the total subducction was evaluated separately. The subduction rates were analyzed and compared to the formation of the South Atlantic Subtropical Mode Waters.

The results show that subduction occurs along all the South Atlantic Subtropical Front, with subduction rates higher than 100 m/yr, and with three cores of maximum subduction with values higher than 200 m/yr, reaching more than 300 m/yr on the central core. The value integrated along the front corresponds to 25 Sv of fluid being transferred to the permanent thermocline, similar to the 21 Sv found by Karstensen & Quadfasel (2002) based on climatological data. These values are significant when compared to other oceans and they suggest that the South Atlantic ocean plays an important role on the surface water transformation and on the subsurface water formation. Subduction rates similar to the rates found in this study, higher than 100 m/yr, were calculated for the North Atlantic ocean (Marshall et al., 1993; Williams et al., 1995; New et al., 1995; Peng et al., 2006) in studies based on the kinematic method too, while little smaller values, between 70 and 90 m/yr, were obtained by Jenkins (1987) for the same ocean using tracer data. According to Qiu & Huang (1995), the kinematic method tends to increase the subduction rates in the regions near to oceanic fronts, where there is a pronounced gradient of the mixed layer depth, suggesting that the values found in this study may be overestimated.

The lateral induction of fluid through the mixed layer base proved to be the dominant contribution to the total subduction in the South Atlantic ocean, similar to studies carried out in other oceans (Marshall et al., 1993; New et al., 1995; Qu et al., 2002; Peng et al., 2006). In the subtropical front, the spatial distribution pattern and the magnitude of the lateral induction rates are very close to the total annual subduction. This dominance of the lateral induction is associated to the maximum gradients of the mixed layer depth in the frontal region. The Ekman pumping contribution is less important, but is more homogeneously distributed within the subtropical region. Karstensen & Quadfasel (2002), based on geostrophic calculations using climatological datasets, suggest that half of the subduction rates in the South Atlantic ocean results from the Ekman pumping contribution and that lateral induction of fluid is dominant only in the Brazil-Malvinas Confluence region. This difference in the results indicates that the calculation of subduction rates can be very sensitive to the applied methodology, and points out to the need of improving the data coverage in the South Atlantic.

The results discussed in this work do not consider the mesoscale contribution to the subduction. Along the oceanic fronts, mesoscale processes can play an important role in the transference of fluid to the thermocline (Spall, 1995; Marshall, 1997; Hazeleger & Drijfhout, 2000; Qu et al., 2002). The mesoscale variability affects the subduction in two ways: modifying the mixed layer depth, and modifying the velocity field responsible for the fluid advection through the mixed layer base (Qu et al., 2002). The eddy field can transport waters with homogeneous characteristics in the isopycnal outcrop areas and inject anomalous properties in the thermocline (Marshall, 1997).

In an isopycnal numerical model under idealized forcing to simulate the circulation of the South Atlantic Subtropical Gyre, Hazeleger & Drijfhout (2000) found maximum subduction rates induced by mesoscale variability of approximately 100 m/yr. Similar subduction rates were found by Qu et al. (2002), who investigated the subduction in the North Pacific ocean using a high resolution ocean circulation model. In the South Atlantic ocean, de Miranda et al. (1999) using the results of a high resolution numerical simulation with a sigma coordinate model showed that the mesoscale influences the subduction only in the Brazil-Malvinas Confluence region, providing mixing and property changes of newly formed waters and injecting potential vorticity anomalies in subsurface. This result is supported by Mill (2009), based the analysis of a high resolution simulation with a hybrid coordinate model, which suggests also that total subduction rates are not significantly affected by the model resolution. Low resolution models, like in the present study, cannot address this issue since they simulate the bulk effects of the subduction process without explicitly solving the mesoscale activity, and this approach has been used by several authors (New et al., 1995; Williams et al., 1995; Paiva & Chassignet, 2002).

The three cores maximum subduction found in this study correspond each to a region of maximum layer thickness and volume in the model. This result indicates that, although thermocline ventilation and mass transfer to the SACW occur along all the Subtropical Front, mode waters with distinct characteristics, belonging to the mid and upper portion of the SACW, are formed in preferential regions by the subduction process. In order to investigate the model dependence to vertical discretization, additional simulations were carried out increasing the number of isopycnal layers representative of the thermocline region. This resulted in a spreading of the SACW modal structure, with a correspondence between the number of model layers and the number of cores of localized maximum thickness. However, the spatial pattern of subduction, with three cores of maximum subduction, was invariant to the vertical discretization in the simulations, suggesting this is a robust result, independent aspect of the model vertical resolution. These results also suggest that the division of the STMWs in the South Atlantic ocean in three distinct classes, as proposed by Provost et al. (1999), may be arbitrary. To the contrary, the modal structure seems to be better represented by a continuum of colder and denser mode waters eastward along the Subtropical Front.

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NOTES ABOUT THE AUTHORS

Guilherme Nogueira Mill. Master degree in Ocean Engineering at COPPE/UFRJ (2009); undergraduated in Oceanography at Universidade Federal do Espíirito Santo (2007). Presently is a doctoral student at Ocean Engineering Program at COPPE/UFRJ and develops his thesis on Subtropical Mode Waters characteristics and variability, subduction and density fluxes in the South Atlantic ocean. Main research interest: oceanic numerical modeling, meso and large scale ocean circulation, ocean-atmosphere interaction and Argo profilers.

Afonso de Moraes Paiva. Doctor degree in Physical Oceanography at Rosenstiel School of Marine and Atmospheric Sciences at University of Miami – RSMAS/UM (1999), Master degree in Ocean Engineering at Universidade Federal do Rio de Janeiro – COPPE/UFRJ (1992) and undergraduate in Oceanography at Universidade do Estado do Rio de Janeiro (1985). Presently professor at COPPE/UFRJ, in the Coastal and Oceanographic Engineering group of the Ocean Engineering Program. His main research interest is Physical Oceanography, with emphasis in geophysical fluid dynamics, thermodynamic processes in the oceans, oceanic modeling and climatic variability.