

A REGIONAL STUDY OF THE BRAZILIAN SHELF/SLOPE CIRCULATION (13°-31°S) USING CLIMATOLOGICAL OPEN BOUNDARIES

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ABSTRACT. The oceanic features in the eastern and southeastern Brazilian shelf/slope between 13°-31°S are investigated using ROMS (Regional Ocean Model System). The model was integrated for 9 years and it was forced with: i) 6-hourly synoptic atmospheric data from NCEP; ii) initial and boundary conditions from OCCAM (Ocean Climate Circulation Advanced Modelling) monthly mean climatology and iii) tidal forcing from TPXO 7.1 global data set. The model results were compared with observations, which consisted in thermodynamic MDL (Mixed Layer Depth) climatology, satellite data, measurements from tide gauges along the shelf and currents measurements values from literature. The simulated currents represented the BC (Brazil Current)-IWBC (Intermediate Western Boundary Current) System. The BC-IWBC system at 22°S cross-shelf section represents our simulation capability of reproducing the western boundary currents, it showed poleward BC and a opposing IWBC. At this section, the BC velocity core is in 50 m with 0.41 m.s⁻¹ and the IWBC core around 800 m with 0.15 m.s⁻¹.

Keywords: Western South Atlantic, ROMS, Western Boundary Currents.

RESUMO. A circulação oceânica na região da plataforma/talude do Brasil de 13°-31°S é investigada utilizando o modelo ROMS (Regional Ocean Model System). O modelo foi integrado por 9 anos e forçado com: i) dados atmosféricos sinótico a cada 6 horas do NCEP; ii) condições iniciais e laterais provenientes da climatologia mensal do modelo global OCCAM (Ocean Climate Circulation Advanced Modelling) e iii) forçamento de maré do modelo global TPXO 7.1. Os resultados do modelo foram comparados com observações, estas consistem em dados da profundidade da camada de mistura climatológica, dados de satélite, medições de marégrafos ao longo da plataforma e valores de medições de correntes disponíveis na literatura. As correntes simuladas representaram o sistema da CB (Corrente do Brasil)-CCI (Corrente de Contorno Intermediária). O sistema CB-CCI na seção normal a costa em 22°S representou a capacidade de simulação das correntes de contorno oeste, mostrando a inversão de direção das duas correntes. Nesta seção, o núcleo de velocidade da CB em 50 m apresentou valores de 0,41 m.s⁻¹ e o núcleo da CCI em 800 m apresentou velocidade de 0,15 m.s⁻¹.

Palavras-chave: Sudoeste do Atlântico, ROMS, Correntes de Contorno Oeste.

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INTRODUCTION

The South Atlantic ocean is the major conduit of water mass exchange among the North Atlantic ocean, the Weddell Sea and the Antarctic Circumpolar Current (Gan et al., 1998). Its circulation shows some depth dependence and the inferred upper level circulation in the South Atlantic is reviewed by Peterson & Stramma (1991). The authors present the Subtropical Gyre of the South Atlantic formed by the Brazil Current (BC), as the southward Western Boundary Current that flows until it reaches the Malvinas Current near 38°S, at a confluence zone, where both currents separate from the coast and flows eastward as the South Atlantic Current. In the eastern South Atlantic, part of the South Atlantic Current turns north into the Benguela Current and finally into the South Equatorial Current (SEC) to close the Subtropical Gyre.

The western south Atlantic, where the Brazilian shelf/slope region is inserted, presents a complex circulation. The large scale processes, for instance, are very influenced by the SEC bifurcation, at the northern limb of South Atlantic subtropical gyre. When the SEC reaches the continental margin, between 5-15°S at surface and around 20°S at pycnocline levels (Stramma & England, 1999), the BC originates its southward flow. At an intermediate depth, Boebel et al. (1999) represented the northern limb of the subtropical gyre, that reaches the Brazilian continental margin near 28°S, as a northward flow associated to the Intermediate Western Boundary Currents (IWBC). Below this level, the Deep Western Boundary Current (DWBC) is again poleward and associated with the North Atlantic Deep Water (NADW).

According to Silveira et al. (2004), the BC-IWBC system consists of a baroclinic current system marked by a flow reversal between the upper and the intermediate portions of the water column. The authors presented a total baroclinic transport, at 22°-23°S, for BC (southwestwards) and IWBC (northeastwards) with values of 5.6 Sv and 3.6 Sv, respectively.

The mesoscale activity in the BC was investigated by Calado et al. (2008) using a feature-oriented regional modeling and simulations (FORMS), where they study the BC meander interaction with the coastal upwelling. The authors found that induction of upwelling in their simulation enhances the growth of the mesoscale activity for the BC meanders.

The coastal and continental shelf circulation is also affected by tidal currents. Mesquita & Harari (2003) analyzed the tides in the southeastern Brazilian shelf. They showed that M_2 and S_2 height components induce almost uni-directional SE-NW counter-clockwise ellipses of currents. A numerical tidal study in the South Brazil Bight by Pereira et al. (2007) explained that the M_2 tide phase is influenced by the existence of two amphidromic points located in the South Atlantic.

In this study, we present the results from a regional model simulation forced with 6-hourly synoptic atmospheric data from NCEP, realistic boundary conditions from a global ocean model and tidal forcing. The model ran over an integration period of 9 years, and was implemented offshore the Brazilian coast at 13°-31°S and 32°-52°W. Our goal is to evaluate the model representation of the large scale, the thermohaline conditions and the tidal circulation. This reproduction of the oceanic features in the western South Atlantic would allow us to provide conditions for a regional scale oceanic forecast system for the eastern and southeastern Brazilian shelf/slope regions. This initiative is part of the objectives of a research and development consortium called Oceanographic Modeling and Research Network (with Portuguese acronym REMO), which was built in 2007. REMO is a partnership between Brazilian universities and public institutions that works for the common objective of developing assimilative numerical oceanic models for the Brazilian shelf/slope region.

METHODOLOGY

Modeling setup

The numerical model implemented for the Brazilian shelf/slope region at 13°-31°S was the Regional Ocean Modeling System (ROMS) model (Shchepetkin & McWilliams, 2003, 2005), nesting enabled based on the ROMS-AGRIF (Adaptive Grid Refinement in Fortran) described in Penven et al. (2006). ROMS is a three-dimensional free surface, terrain-following model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic and Boussinesq approximations. The model is configurable to be used in realistic regional applications. This model is an advanced and robust rapidly evolving community-code model. ROMS has been applied in deterministic simulations in a wide range of space and time scales and oceanic systems types. A description of the model and its newest features can be found in Haidvogel et al. (2008).

ROMS has been used in many different coastal regions, such as the Californian, Iberian and Peruvian coasts. Centurioni et al. (2008), for instance, used ROMS to simulate the meanders in the California Current system, and the authors found their simulation in agreement with observation when they compared the number of produced meanders, the geostrophic time-mean currents and geostrophic eddy energy values. Other example is the implementation of Ivanov et al. (2009), that applied ROMS to study the meso/submesoscale currents off central California. The Peru Current system was simulated by Penven & Echevin (2005) using ROMS, where the authors investigated the mean

circulation, the seasonal cycle and the mesoscale dynamics for the Peru Current system. They showed that the model was able to reproduce the equatorward Peru Coastal Current, the Peru-Chile Undercurrent and the Peru-Chile Countercurrent. Other example is from Marta-Almeida et al. (2008) that used ROMS to study the biological processes off Gibraltar Strait.

In our model configuration, a curvilinear grid covering the Brazilian coast was used with an inclination that approximately follows the coastline. The domain extends offshore about 900 km from the latitude (at coast) of $\sim 31^\circ\text{S}$ to $\sim 13^\circ\text{S}$. The distance between the southern and northern boundaries is about 2400 km. The grid resolution was used with a range of 2 km near the coast, where higher bathymetric gradients are found, and ~ 12 km offshore in the alongshore direction. The vertical axis has 32 s-levels and the bathymetry was obtained from ETOPO1 Global Topography database (GLOBETaskTeam and others, 1999), which has a resolution of 1 km (Fig. 1).

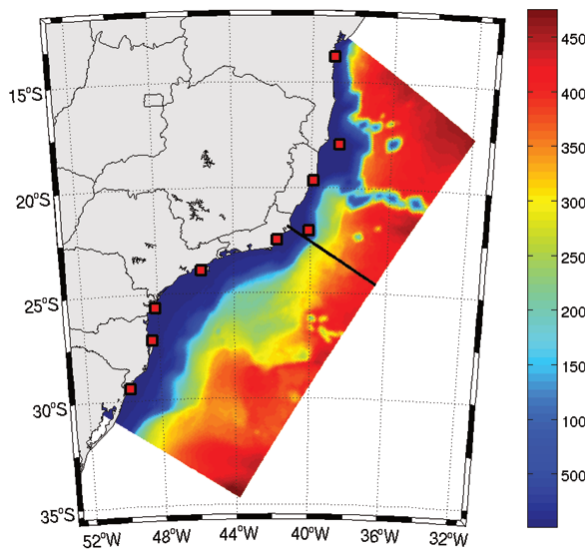


Figure 1 – Bottom topography (in meters) from ETOPO1 in the Brazilian shelf/slope region. The bold black line represent the location of the cross shelf section at 22°S used for the results. The red squares display the nine tidal gauge stations presented in Table 2.

The initial and lateral boundary conditions were based on the monthly mean climatological dataset from OCCAM model (Ocean Circulation and Climate Advanced Modelling Project), which provided the required data (momentum, temperature, salinity and free surface). OCCAM is a global model with improved model physics, parameterization and a full surface forcing. Its horizontal resolution is $1/4^\circ$ and consists on averages of monthly mean data from a 20 years integration, for the period of 1985 to 2004. The vertical coordinate has 66 levels at fixed depths, with

14 levels in the upper 100 m. A detailed description of the model can be found in Coward & Cuevas (2005).

The surface boundary conditions were based on the NCEP Reanalysis-2 fields of wind, humidity, pressure, temperature, precipitation and radiation (Kanamitsu et al., 2002). This data set has a horizontal resolution of 1.8° (192×94 Gaussian grid points or approximately 200 km horizontal spacing) and a time interval of 6 hours. Air-sea fluxes were derived from this dataset and calculated internally by the model through the bulk formulation. The integration period of the ROMS model was 9 years, from January 1st/2000 to December 31st/2008. Figure 2 presents the time evolution of the volume-average kinetic energy, showing that ROMS adjusts to the initial conditions on the first months of 2000.

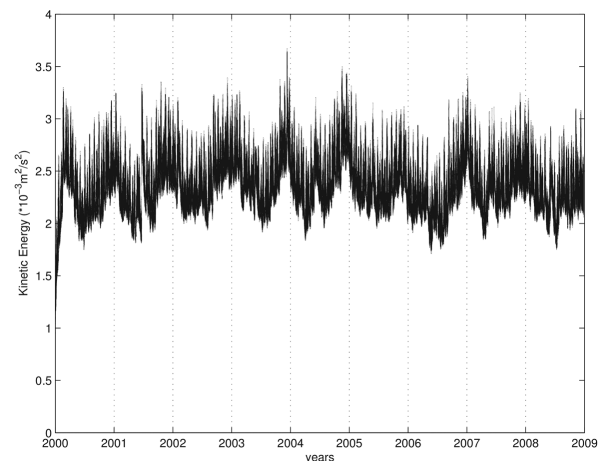


Figure 2 – Kinetic energy for ROMS run from 2000 to 2009.

The ROMS model was also forced with tidal forcing obtained from TPXO 7.1 global database (Egbert et al., 1994), which provides amplitudes and phases of sea surface elevation and barotropic currents for eight primary (M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 , Q_1) and two long period (Mf , Mm) harmonic constituents with a resolution of $1/4^\circ$.

This experiment was also used as a spin up phase for a development of a Brazilian regional operational ocean forecast system described in Marta-Almeida et al. (2011).

The model results (2D and 3D fields) described in the following section are based on averages stored at 5 days intervals. A set of stations was also hourly stored covering the whole domain at each 3 grid points. The quality of the model simulations relative to the observations made available and those described in the literature is assessed by means of basic statistic such as bias, root mean square, relative mean absolute error and correlation coefficients.

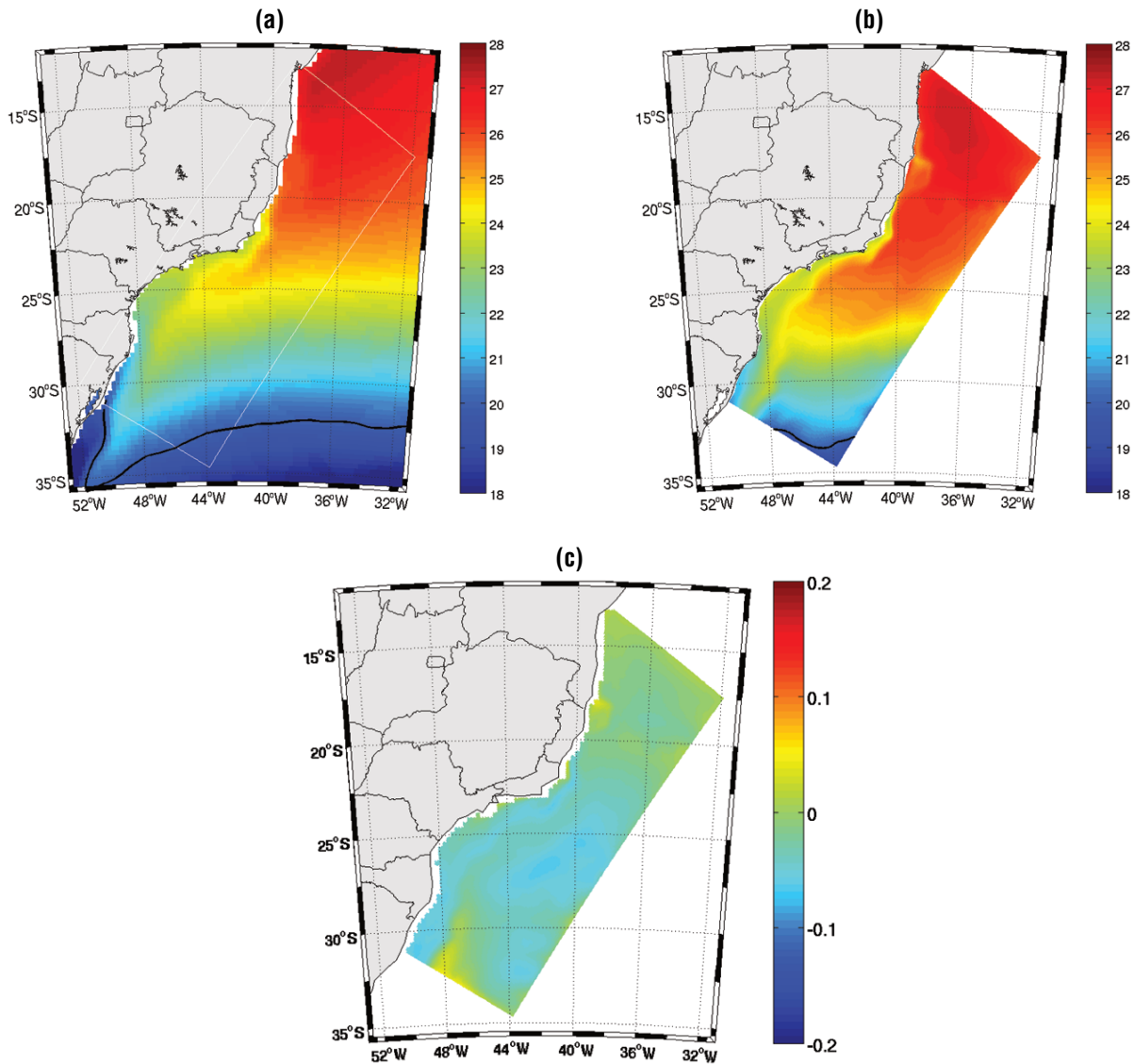


Figure 3 – Annual mean of Sea Surface temperature (SST), (in °C). a) from GHRSSST, b) from ROMS and c) the Relative Absolute Error (RMSE) between the modeled and observed SST (range are from –0.2 to 0.2), for the period from 12th June 2002 to 31st December 2008. The bold line represent the 20°C isotherm.

RESULTS AND DISCUSSION

Our main approach in this section is to develop a strategy to evaluate the ROMS long term simulation against the available data. We first present an analysis of horizontal maps of mean temperature and current fields at depths that are representative of the known water masses and Western Boundary Currents. The simulated mixed layer depth is then compared to Montégut et al. (2004) global climatology. To evaluate the Sea Surface Height simulated by ROMS we use satellite merged data. The variability of the BC and IWBC transport during the 9 years of simulation are also explored. Finally, the tidal circulation is compared against the FEMAR – Fundação de Estudos do Mar (Salles et al., 2000)

measurements along various locations at the Brazilian coastal and shelf region.

Temperature

The annual mean sea surface temperature (SST), from the period of June 12th 2002 to December 31st 2008, is presented for satellite data and for ROMS simulation in Figure 3a and 3b, respectively. Satellite measurements were obtained from GHRSSST L4 AVHRR AMSR OI available online on <http://www.ghrsst.jpl.nasa.gov>. This data set product is an optimally interpolated SST based on the analysis of both infrared and microwave derived SSTs, resulting in a daily output with a 1/4° × 1/4° resolution. The mean

simulated SST compared to the mean observed SST are represented. The SST mean field presents the maximum temperature values of Tropical Water (TW) of about 26°C between 10°-15°S, in both data set. This water mass limit to the south extends to 35°S where the isotherm of 20°C can be found. These results are in agreement with previous study in the region by Cirano et al. (2006). The mean temperature at 100 m depth, for the 9 years ROMS simulation, is shown in Figure 4. A remarkable feature that appears in this figure is the presence of shelf-break upwelling of the South Atlantic Central Waters (SACW) near the coast, between 20°-25°S, where the temperature are less then 20°C (Palma & Matano, 2009). This upwelling region was already observed by many authors (e.g. Castro & Miranda, 1998; Campos et al., 2000; Rodrigues & Lorenzetti, 2001; Castelao & Barth, 2006; Calado et al., 2008).

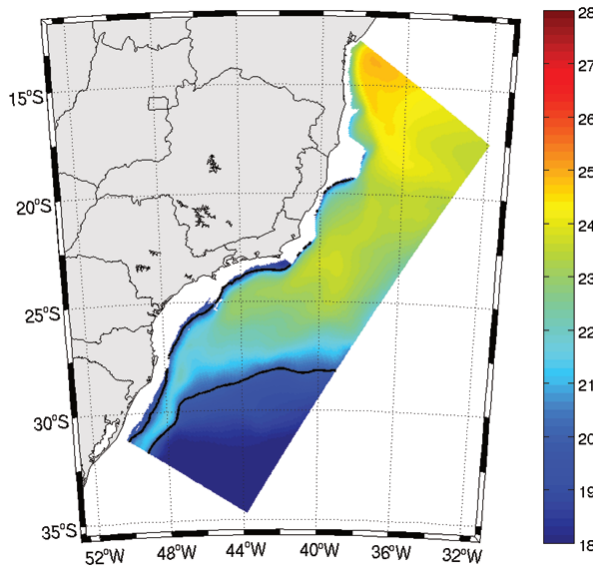


Figure 4 – Annual mean of temperature (in °C) at 100 m depth, from ROMS. The bold line represent the isotherm of 20°C.

To evaluate the model efficiency to represent the sea surface temperature, we used the Relative Mean Absolute Error – RMAE (Eq. (1), modified from Willmott & Matsuura, 2005) between the model results and the GHRSSST.

$$RMAE_{i,j} = n^{-1} \sum \frac{(O_{i,j} - P_{i,j})}{O_{i,j}} \quad (1)$$

where P and O represent, respectively, the SST from ROMS and from observations at a given point with coordinates i, j . With this approach we obtained the mean absolute error relative to the observations, where $RMAE > 0$ ($RMAE < 0$) the model underestimates (overestimates) the observations.

Figure 3c show for most of the domain a values for RMAE near zero. Only, at south and north boundaries the values are around 0.1 that represent the model underestimates the observations, in these regions.

Thermodynamics sensibility

In order to evaluate the parameterization of the air-sea fluxes in our simulation, we present a thermodynamic sensibility analysis based on the evolution of the Mixed Layer Depth (MLD). The MLD represents the lower limit of the upper ocean mixed layer (ML), being one of the most intuitive and useful features for upper ocean studies. Recently, most of the MLD studies emphasize that it plays a key role in several ocean processes (e.g. Montégut et al., 2004; Gonzalez-Pola et al., 2007), since it defines the extent of turbulent penetration into the ocean due to air-sea fluxes, establishing the atmosphere-ocean heat exchange regime (Gonzalez-Pola et al., 2007).

The temporal variabilities of the MLD are linked to various processes occurring in the ML, such as the surface forcing, lateral advection and internal waves. Therefore, the properly prediction of the MLD is of primary importance for ocean modelers in validating and improving ocean general circulation models (Montégut et al., 2004). For this purpose, Montégut et al. (2004) created a global MLD climatology based on three different criteria (Temperature criterion, Fixed density criterion and Variable density criterion, available on <http://www.locean-ipsl.upmc.fr/cdblod/mls.html>), computed for more than five million individual profilers obtained from the National Oceanographic Data Center (NDOC), from the World Ocean Circulation Experiment Database (WOCE) and from the ARGO program covering the period from 1941 to 2008.

Since the density depends on both temperature and salinity, the estimation of the MLD for the Atlantic ocean based on the density criterion should be avoided due to the large geographical salinity data gaps. The temperature criterion is then a possible alternative in estimating the MLD, since it has a nearly complete seasonal coverage (Montégut et al., 2004). The calculation of the MLD based on the temperature criterion consists in finding the depth where there is a increase of 0.2°C in comparison to the temperature value at 10 m depth. This reference depth was chosen to avoid the diurnal cycle of the mixing layer. According to (Montégut et al., 2004). this criterion is fairly successful at estimating the MLD and is particularly good at capturing the first springtime restratification. Thus, to evaluate the efficiency of the ROMS model in representing the thermodynamics of the study region, we compared its MLD, calculated based on the temperature criterion described above, with the seasonal MLD climatology

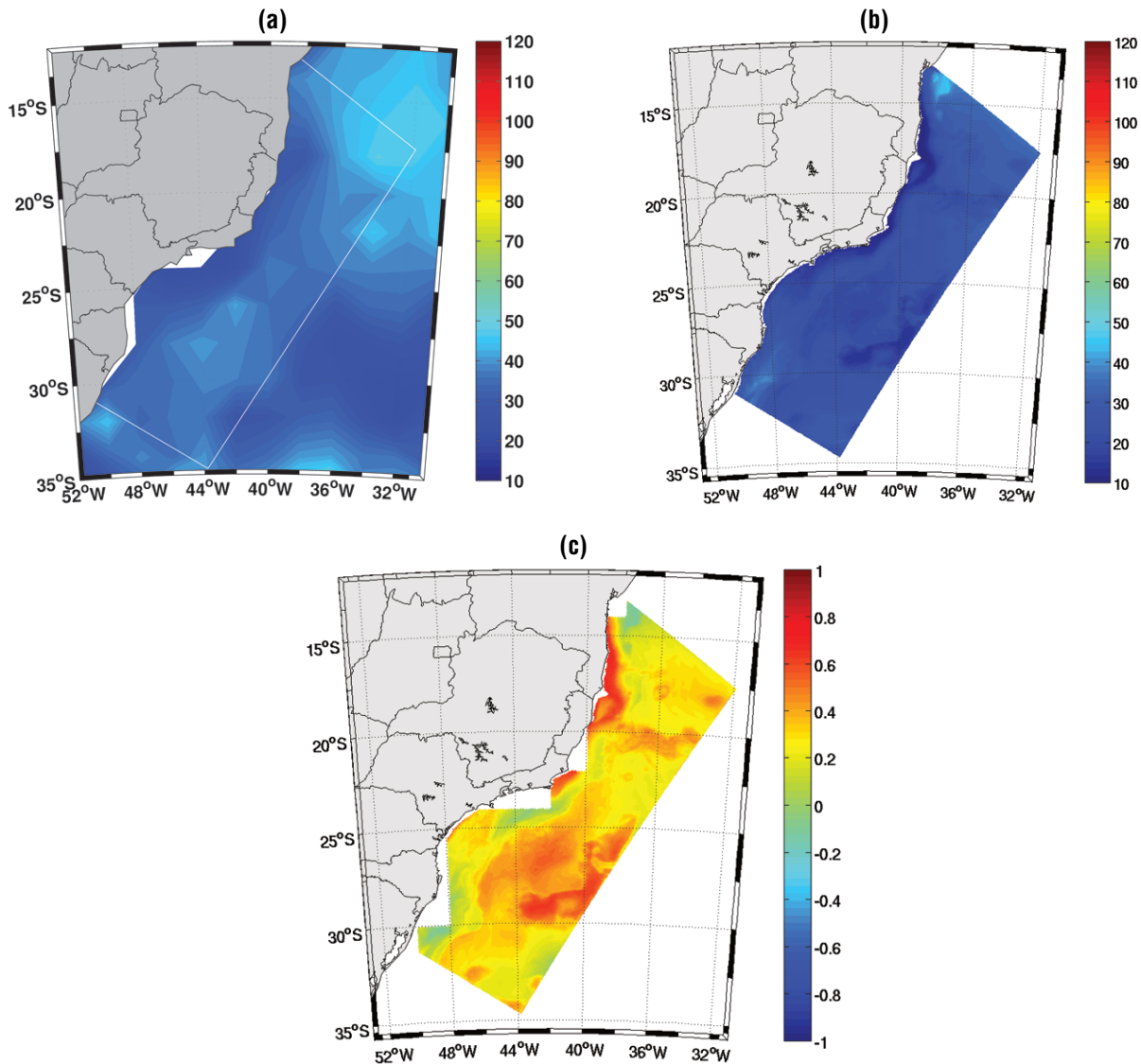


Figure 5 – Mixed layer depth (MLD) a) based on the climatology proposed by Montégut et al. (2004), b) derived from ROMS outputs (2000-2008) and c) the Relative Absolute Error (RMAE) between the modeled and observed MLD for March.

proposed by Montégut et al. (2004). The comparison was made for March, August and September. These months were chosen due the fact that there is a strong difference in the processes involved in the MLD formation during the Summer and Winter seasons, because the atmosphere-ocean heat exchange differences result in discrepant MLD values. The September month represents the first springtime restratification, when the deeper MLD observed during the wintertime starts to shoal toward the summertime, where the thinner MLD is observed.

To evaluate the model efficiency to represent the mean MLD evolution we also used the RMAE, Eq. (1), between the model

results and the available data derived from the climatological MLD proposed by Montégut et al. (2004).

The climatological MLD proposed by Montégut et al. (2004) for March, August and September months at the Brazilian shelf/slope at 13°–31°S is presented in Figures 5a, 6a and 7a. This climatology shows thinner MLD during March (Fig. 5a) with a mean of 30 m near the coast and 50 m offshore at the northern domain. The MLD deepens progressively towards in August (Fig. 6a) as a result of the surface ocean layer cooling, and reaches values of 60 m near the coast and values greater than 120 m at the northern region. During September (Fig. 7a),

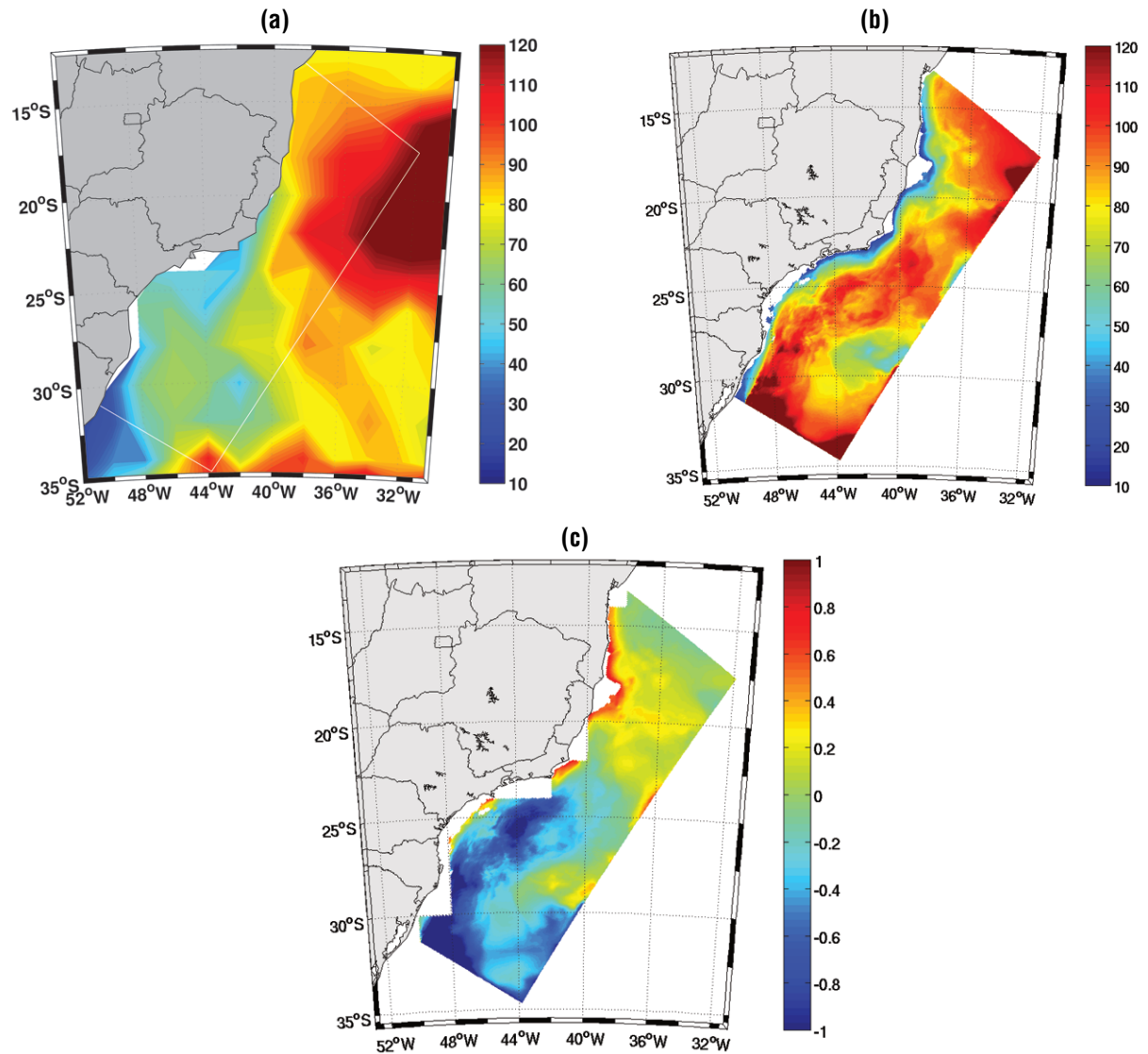


Figure 6 – Mixed layer depth (MLD) a) based on the climatology proposed by Montégut et al. (2004), b) derived from ROMS outputs (2000-2008) and c) the Relative Absolute Error (RMAE) between the modeled and observed MLD for August.

the restratification process takes place as a response of the surface ocean layer heating, and the MLD decreases gradually toward in March.

For March the model did not capture the deeper MLD observed at offshore region (around 44°W; 28°S) in the southern part of the domain (~45 m depth, Fig. 5a and 5b), where the highest values of RMAE were observed (~0.4; Fig. 5c). Also, the model underestimate the MLD at the coastal region in the northern region (RMAE~0.6). The absolute RMAE for the entire domain is 0.3 on average.

For August, the ROMS model captured the main features observed in the climatology at the northern domain, with deeper

MLD values offshore and a decrease toward the Abrolhos Bank (around 18°S; Fig. 6a and 6b). At this part of the domain, disregarding the coastal region, the lower RMAE values was observed (absolute mean of 0.2). South of 24°S the model overestimate the MLD and the RMAE values can be observed around ~-0.6 (Fig. 6c).

During September, the restratification process at the northern domain is better captured around the Abrolhos Bank (18°S; Fig. 7a and 7b) with a slight tendency to overestimate the climatology (RMAE ~-0.2; Fig. 7c). Also in September, the model overestimate the MLD at the coastal region south of 24°S (Fig. 7a and 7b), where the RMAE values is observed around ~-0.8 (Fig. 7c).

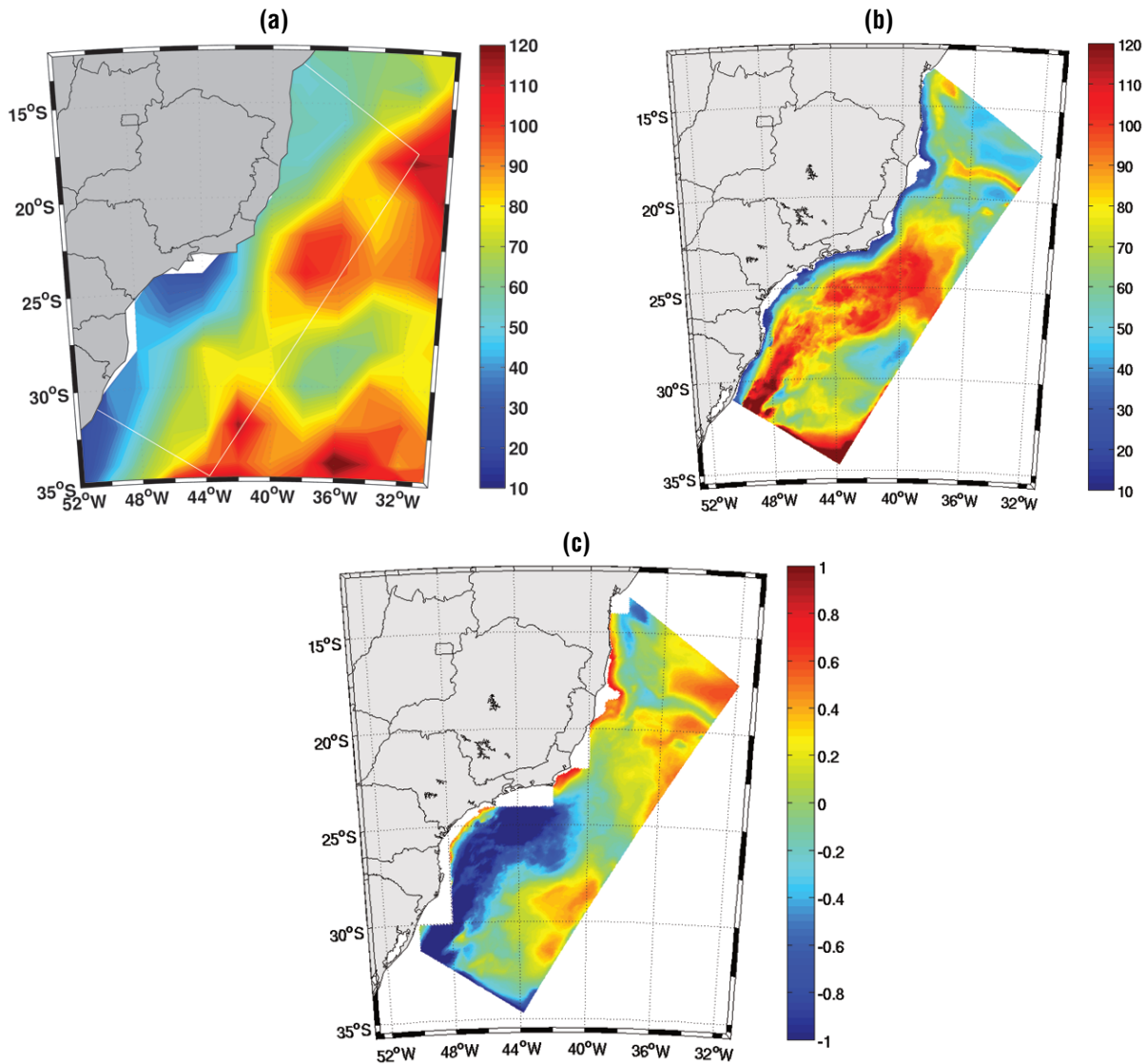


Figure 7 – Mixed layer depth (MLD) a) based on the climatology proposed by Montégut et al. (2004), b) derived from ROMS outputs (2000–2008) and c) the Relative Absolute Error (RMAE) between the modeled and observed MLD for September.

The highest absolute values of RMAE over the entire domain (0.3), observed during March, can be ascribed to the fact that during this month there is a strong stratification in the surface layer, which may introduce instabilities that are very difficult to be represented in the MLD. However, the MLD represented by our simulation at the northern domain for August and during the first month of spring time restratification (mean absolute RMAE ≈ 0.2) are close to the climatological MLD calculated based on observations.

ROMS simulations represented the MLD through these months (March, August and September), with a slight tendency to underestimate the observed MLD value. Silva et al. (2009)

found the same tendency when evaluated ROMS derived MLD with the MLD calculated from Pirata buoys *in situ* observations. The less representative values of RMAE were found at coastal region of the southern domain (south of 24°S) during August and September. The same results were found by Cirano et al. (2006), who found the higher error values of annual MLD derived from OCCAM model south of 30°S, and attributed these results to the Brazil-Malvinas confluence dynamics. It is also important to mention that intense baroclinic gradients related to Patos Lagoon and La Plata river plume affects the Southern Brazilian Shelf (28°S–35°S) during later austral winter or early austral spring (Soares & Moller, 2001). This can largely affect the

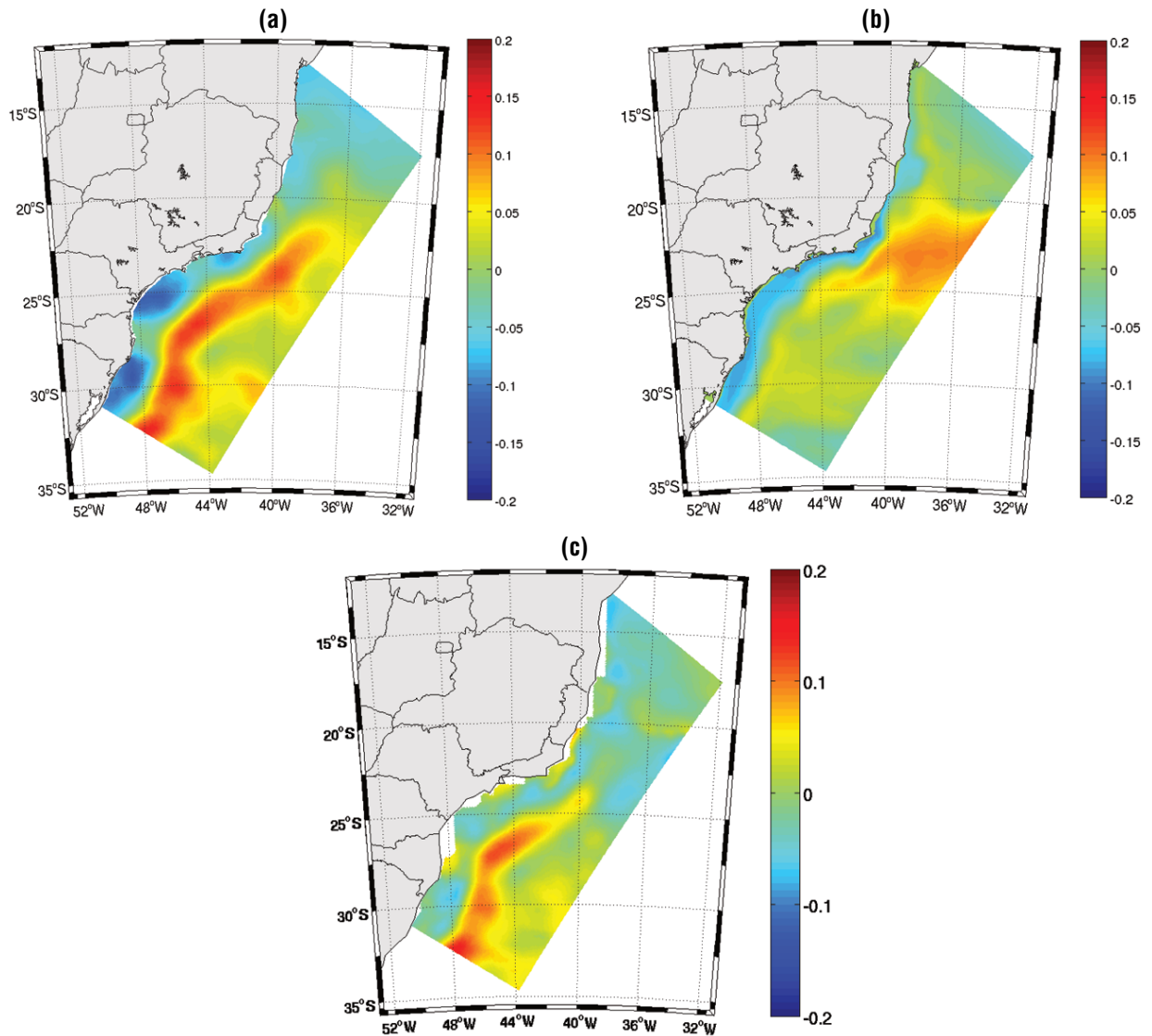


Figure 8 – Annual mean of Sea Surface Height (SSH), (in meters). a) from AVISO, b) from ROMS and c) the Absolute Error (MAE) between the modeled and observed SSH (range are from -0.2 to 0.2), for the period from 22-August-2001 to 31-December-2008.

model thermodynamics at this region if the river discharges are not accounted.

Sea Surface Height

The annual mean sea surface height (SSH), for the period from August 22nd 2001 to December 31st 2008, is presented for satellite altimeter data and for ROMS simulation in Figures 8a and 8b, respectively. Altimeter measurements were obtained from AVISO (<http://www.aviso.oceanobs.com>). The maps of absolute dynamic topography (ADT) represent the sum of the sea level anomaly (SLA) and mean dynamic topography (MDT). The MADT fields with resolution of $1/3^\circ \times 1/3^\circ$ are merged based on satel-

lites (Jason-2/Envisat or Jason-1/Envisat or Topex/Poseidon ERS) with the same groundtrack. The simulated and observed SSH present similarities. Two distinct patterns are visible, near the coast there are negative values both in the model and observations. It reaches a minimum value of -0.1 m for the model (Fig. 8b) and -0.15 m for the satellite (Fig. 8a). The maximum values for the model and for the satellite are found offshore, 0.1 m and 0.15 m, respectively. The largest differences are more noticeable south of the domain. These differences are provided from the climatological lateral forcings used in ROMS, that provides the simulated SSH a smooth gradient. The mesoscale activity in the southwestern tropical Atlantic margin were also analyzed by

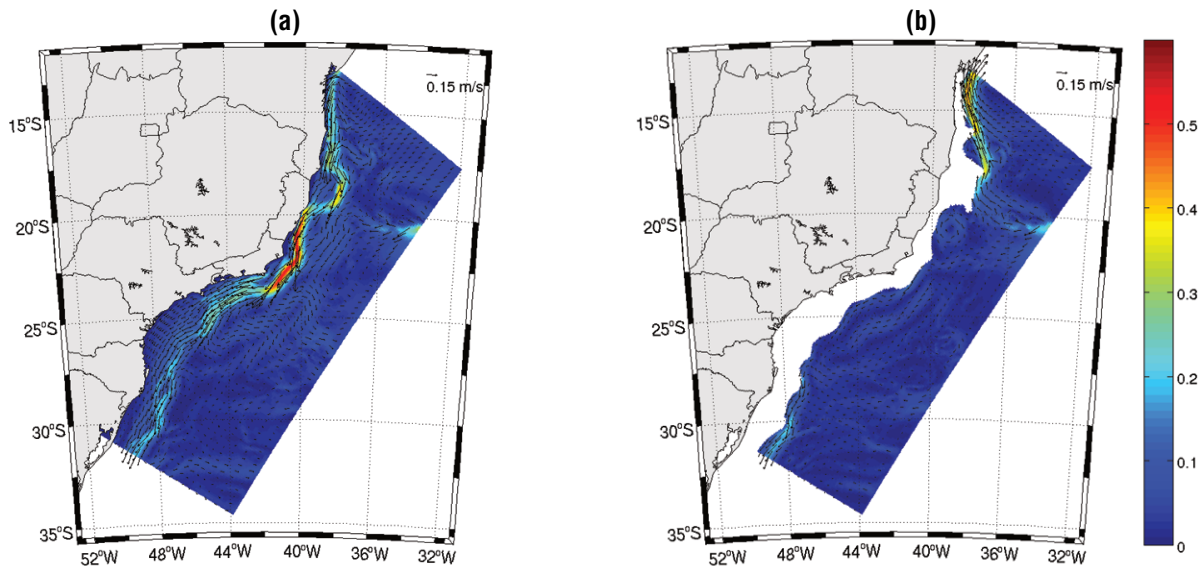


Figure 9 – Annual mean of a) Surface velocity field and b) velocity at 300 m depth.

Table 1 – Comparison of BC mean speed (m·s⁻¹).

Positions	Latitude (°S)	Longitude(°W)	ROMS	Oliveira et al. (2009)
1	20.25	39.75	0.22 ± 0.14	0.29 ± 0.13
2	22.75	40.75	0.44 ± 0.12	0.50 ± 0.19
3	24.25	43.25	0.20 ± 0.11	0.17 ± 0.15
4	26.25	47.75	0.06 ± 0.04	0.39 ± 0.25
5	30.25	47.75	0.14 ± 0.06	0.51 ± 0.16

Silva et al. (2009) using ROMS and AVISO. Their results show a similar geographic pattern, with stronger mesoscale activity in the observations as compared to their ROMS simulation.

To evaluate the model efficiency to represent the sea surface heights, the model results were compared with ones derived from AVISO. For this analysis we used the real form of the MAE, Eq. (2), since the sea level presents inflection points can not be used as fractional form. According to Willmott & Matsuura (2005), the mean absolute error (MAE) is the most natural and unambiguous measure of average error magnitude.

$$MAE_{i,j} = n^{-1} \sum (O_{i,j} - P_{i,j}) \quad (2)$$

Figure 8c show the MAE field with positive values around 0.2 south of 20°S that represent an understimation of the model in simulate the SSH. North of this regions MAE presents negative values near 0.1. This is probably due to climatological open boundary conditions, however MAE values throughout the entire domain are under 0.20.

Currents

At the surface, the model is able to capture the BC with different intensities along the Brazilian coast, reaching maximum values in the region between 20°-25°S. At 22°S, the simulated BC mean current field shows intensities around 0.6 m·s⁻¹ (Fig. 9a). Silveira et al. (2000) presented BC values of 0.4-0.7 m·s⁻¹ for the region of 20°-25°S. In addition, Silveira et al. (2008) based on current meter data show the BC core at 50 m depth with 0.41 m·s⁻¹. The BC simulated value, at 50 m depth, in this region is 0.41 m·s⁻¹ (not shown).

In agreement with Oliveira et al. (2009) drifting buoys observations, we simulated remarkable values in the BC speed, at some positions, for the 9 years mean run. The authors analyzed 13 years of surface drifter data binned into a 0.5° × 0.5° grid in the Southwestern Atlantic and presented some estimated values of the BC principal axis, as we compared in Table 1. At 22.75°S the BC speed simulated by ROMS is 0.44 m·s⁻¹ and the value observed by drifters was 0.50 m·s⁻¹. Also positions 1 and 3 (Table 1) simulated the BC speed of 0.22 m·s⁻¹ and 0.20 m·s⁻¹, and

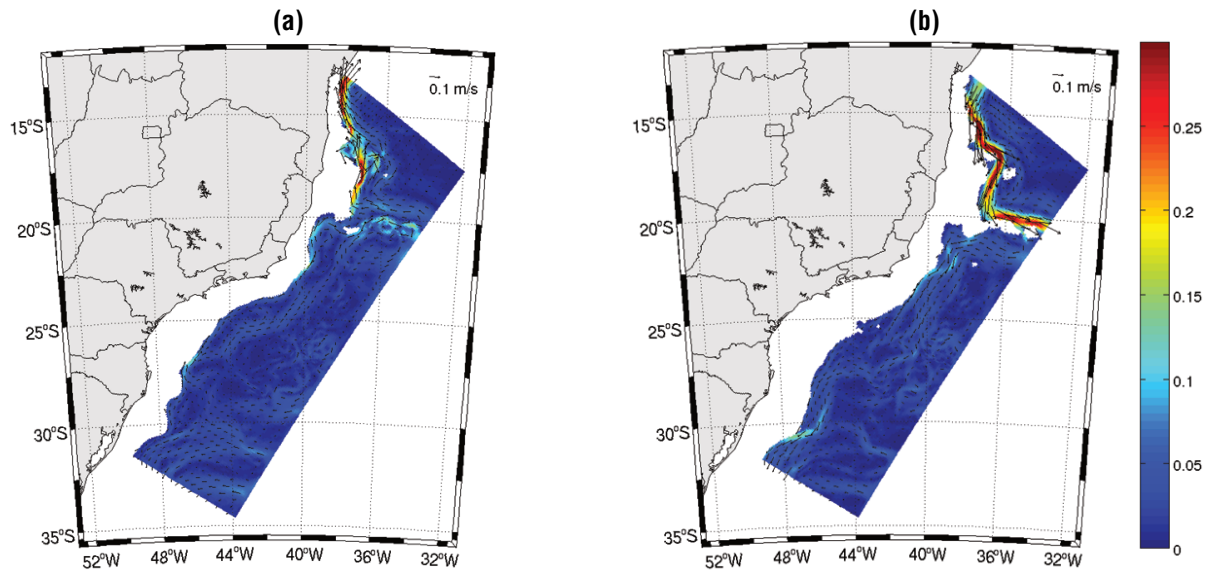


Figure 10 – Annual mean of a) Velocity field at 800 m depth and b) velocity at 2000 m depth.

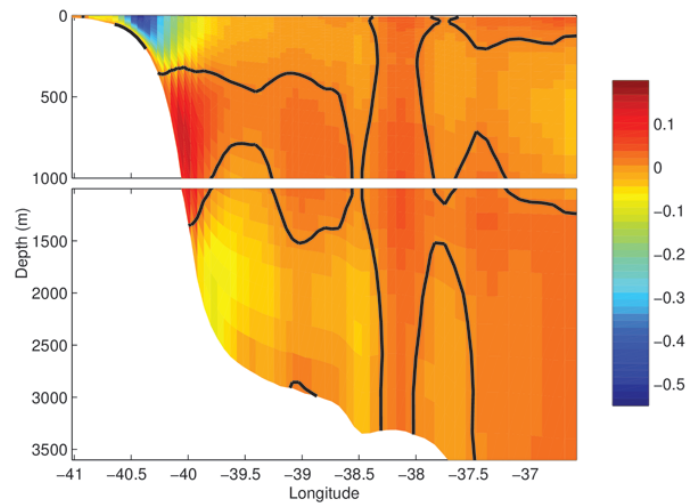


Figure 11 – Cross shelf section of annual mean alongshore velocity (in $\text{m}\cdot\text{s}^{-1}$) at 22°S (on the coast, see line in Fig. 1).

the speed presented by Oliveira et al. (2009) was $0.29 \text{ m}\cdot\text{s}^{-1}$ and $0.17 \text{ m}\cdot\text{s}^{-1}$, respectively. However south of 25°S, at positions 4 and 5 (Table 1) the simulated speed values are underestimated.

At sub-surface levels, Figures 9b and 10a,b present the mean current field at 300, 800 and 2000 m depth, respectively. In Figure 9b, the northern branch of the SEC bifurcation at the 300 m level shows a very intense northward flow of the North Brazil Undercurrent (NBUC) north of 19°S and a less pronounced southward flow, both associated with the South Atlantic Central Water circulation.

The IWBC can also be found by the simulated northward flow with $0.3 \text{ m}\cdot\text{s}^{-1}$ at 800 m depth (Fig. 10a), associated to the

Antarctic Intermediate Water (AAIW). Schmid et al. (1995) presented the maximum value for IWBC of $0.3 \text{ m}\cdot\text{s}^{-1}$ with its core centered between 800 and 1000 m. At 2000 m (Fig. 10b), the NADW flows southward at the Brazilian continental margin as a DWBC. The Vitoria-Trindade Ridge forms a bathymetric obstacle, lying perpendicular to the continental slope at 20°-21°S, to the DWBC as shown by Memery et al. (2000) in the A17 WOCE line.

A cross shelf section (the line represented in Fig. 1) of the mean alongshore velocity at 22°S is presented at Figure 11. The model shows its capability of reproducing the Western Boundary Currents, with a poleward BC and a opposing IWBC. At depths

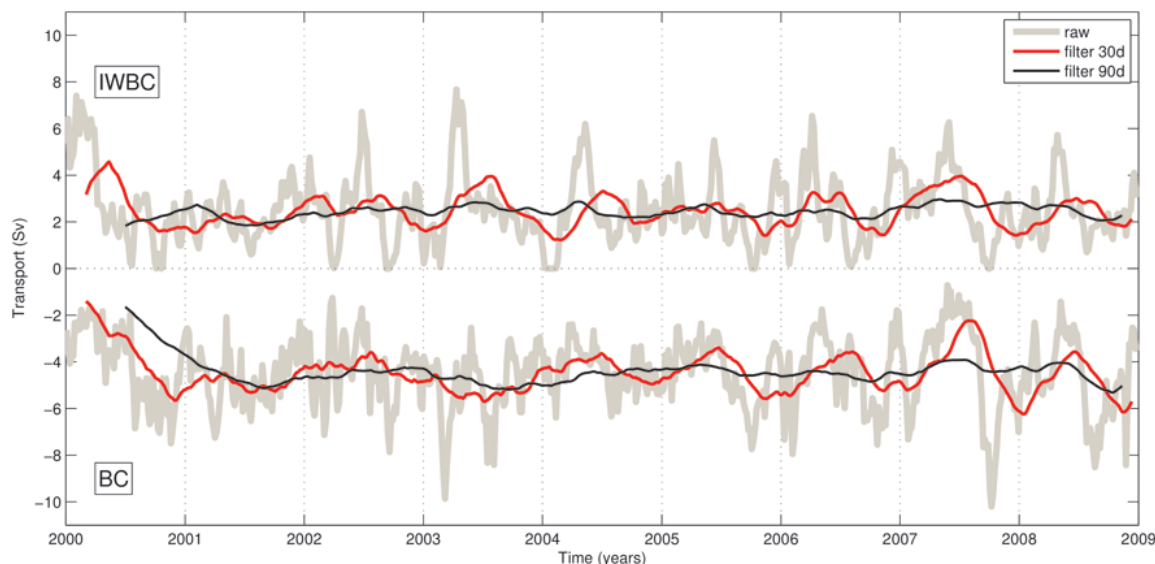


Figure 12 – Time Series of transport at section along 22°S (see line in Fig. 1). Negative values for Brazil Current (BC) with a mean transport of -5.27 ± 1.58 Sv and Positive for Intermediate Western Boundary Current (IWBC) with a mean transport of 3.06 ± 1.57 Sv.

below 1000 m, the flow is again poleward and associated with the NADW as shown in Figure 10b. The mean BC core shows velocity intensity of $0.45 \text{ m}\cdot\text{s}^{-1}$, reaching 200 m depth, and below this depth, around 800 m the mean IWBC core presents $0.15 \text{ m}\cdot\text{s}^{-1}$. Silveira et al. (2008) results from data analysis of Marlim Mooring at location 22.7°S - 40.2°W , found the mean BC core placed at 50 m and reaches $0.41 \text{ m}\cdot\text{s}^{-1}$. They also presented the mean IWBC core placed at the 900 m level with $0.22 \text{ m}\cdot\text{s}^{-1}$.

To evaluate the temporal variability of BC and IWBC transports, for this cross shelf section (Fig. 11), we calculated the transport time series, as can be seen at Figure 12. The criteria considered to calculate the BC transport are the following: i) the flow had to occur at depths shallower than 500 m and at regions west of 39°W and ii) only negative velocities values less than $-0.02 \text{ m}\cdot\text{s}^{-1}$ are considered. In the case of the IWBC transport we adopted a similar criteria: i) the flow had to occur at depths between 300 and 2000 m for the same geographical region and ii) only positive velocities values greater than $0.02 \text{ m}\cdot\text{s}^{-1}$ are considered. Silveira et al. (2004) also used the value of $0.02 \text{ m}\cdot\text{s}^{-1}$ to bound the current structures for the BC and IWBC. The BC transport time series (Fig. 12 – raw signal in gray) shows a variability range from -11 Sv to 0 Sv, and the mean value for the 9 years integration period is -5.27 ± 1.58 Sv. The maximum transport values found for IWBC are up to 7 Sv in 2000 and 2003, and the mean transport is 3.06 ± 1.57 Sv. Measurements, in the region between 22° - 23°S from Transcoba dataset (Silveira et al., 2004) exhibit the BC transport of

-5.6 ± 1.4 Sv and the IWBC transport of 3.6 ± 0.8 Sv. The calculated cross-correlation coefficient between BC and IWBC transport time series are 0.52, showing some similarity between the signals. Figure 12 also show the BC transport time-series with 30 days (red line) and 90 days (black line) low passed filters. A clear evidence of an annual cycle is presented in the red curve for both currents (Fig. 12). We also evaluated the Fourier spectral analysis of the temporal variability of BC and IWBC transports (Fig. 13). The 1 year period peak appears to be associated with the climatological forcing from the global ocean model OCCAM. The BC also shows a semi-annual signal (Fig. 13a), but this peak is not clear in the IWBC signal (Fig. 13b).

Tides

To evaluate the performance of tidal related oscillations in our model, comparisons with the closest high frequency sea level station (hourly sampled at each 3 grid points) are made. The sea level elevation for tide gauge from GLOSS (Global Sea Level Observing System) located at $22.96^\circ\text{S}/43.15^\circ\text{W}$ along the coast of Rio de Janeiro and the ROMS station at $23.11^\circ\text{S}/44.05^\circ\text{W}$ are presented for January 2008 in Figure 14 as an example. The time series were filtered using a 40 h low-pass filter to separate the subinertial and suprainertial variability. Figure 14a shows the suprainertial band for observed (blue) and modeled (red) time series with correlation coefficient of 0.96 (lag = 0 h). The subinertial band, with correlation coefficient of 0.84 (lag = 10 h), exhibit differences in the amplitude of time series between

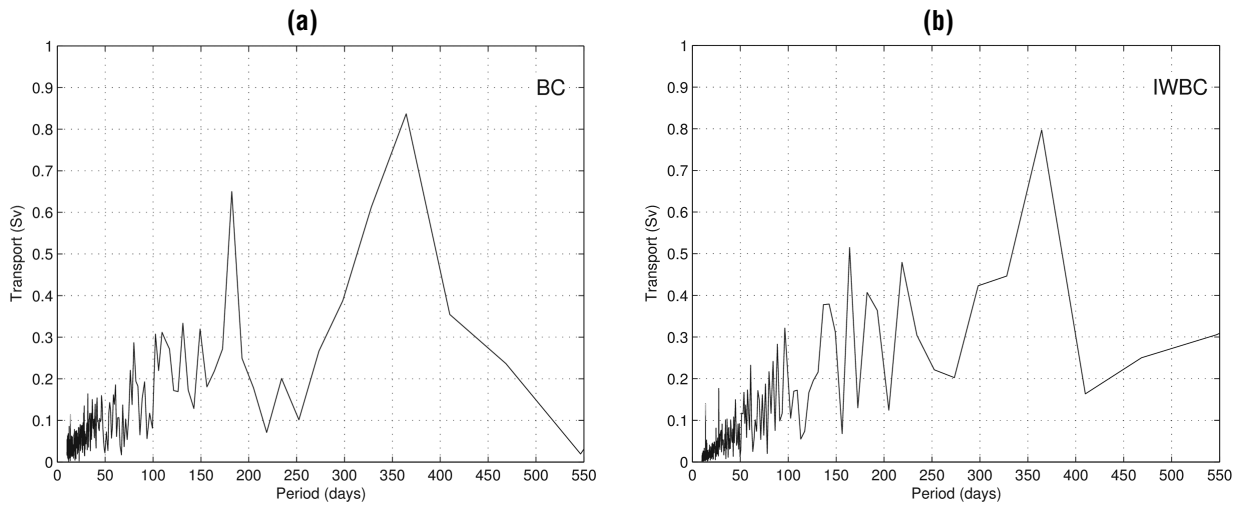


Figure 13 – Fourier spectral analysis of the time series of transport for a) Brazil Current (BC) and b) for Intermediate Western Boundary Current (IWBC).

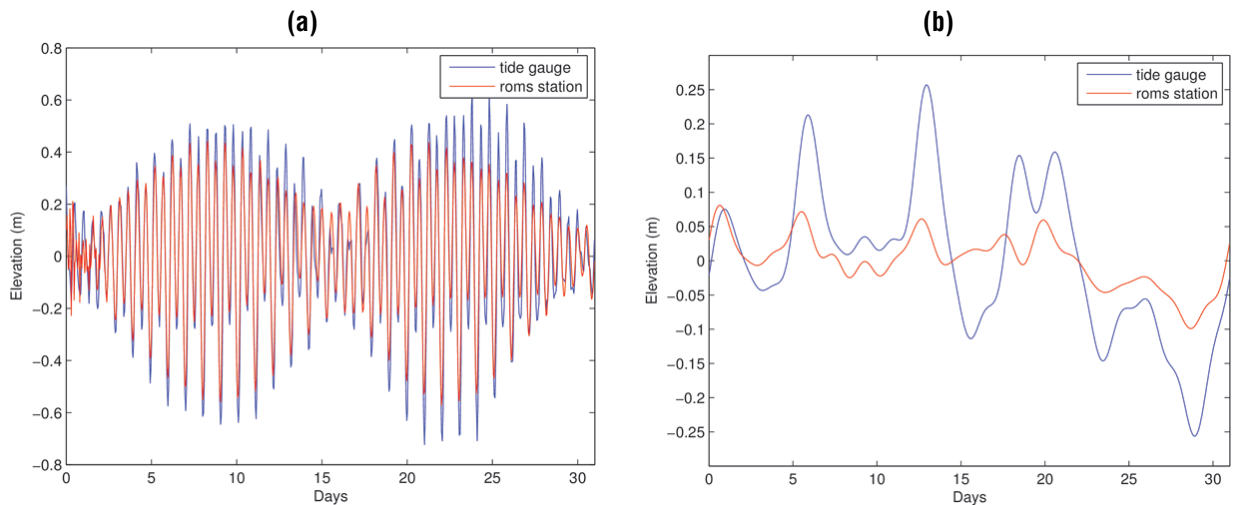


Figure 14 – Time Series of sea level elevation for Rio de Janeiro station observed (blue) and modeled (red) for January of 2008 a) supra-inertial band with correlation coefficient of 0.96 (lag = 0 hours) and b) sub-inertial band with correlation coefficient of 0.84 (lag = 10 hours).

the model and the tide gauge (Fig. 14b). This can be explained by the model climatological open boundaries and the model synoptic forcing. The synoptic forcing is every 6 hours and low horizontal resolution ($1.8^\circ \times 1.8^\circ$), and may not be a sufficient representation of the meteorological forcing.

Modeled and observed semi-diurnal (M_2 and S_2) and diurnal (O_1 and K_1) constituents were compared (elevations and phases) at nine locations (Table 2). Selected ROMS stations represent the closest corresponding model grid points (red squares in Fig. 1) for comparison with the tidal gauges provided from FEMAR (Salles et al., 2000). Harmonic analysis of ROMS stations time series were calculated using T_TIDE (Pawlowicz et al., 2002). The RMS is used to quantify the differences in amplitude and

phase between model (Mod) and observations (Ob) according to Eq. 3:

$$RMS = \frac{\sqrt{(Ob - Mod)^2}}{Ob} * 100 \quad (3)$$

The results show that the tides in the southwestern Atlantic are mostly semi-diurnal with the highest amplitudes for M_2 and S_2 constituents. Mesquita & Harari (2003) found a similar result for the southeastern Brazilian shelf. In our domain, the highest values for M_2 amplitude occur at the northern part (stations 1 and 2). At specific locations, an excellent agreement with the observation can be achieved. The RMS for M_2 amplitude, at the station 1, was only 0.8% (Table 2). The K_1 RMS at station 9 was zero for

Table 2 – Comparison of observed (FEMAR) and modeled (ROMS) harmonic analysis for M_2 , S_2 , O_1 , K_1 components. Amplitude (Amp) are in cm, Phase in Greenwich Phase and RMS in %.

Tide gauge						ROMS		RMS	
Site	Latitude	Longitude		Amp	Phase	Amp	Phase	Amp	Phase
1	13°53.8'S	38°58.4'W	M_2	69.8	190	70.4	188	00.8	01.0
			S_2	25.1	207	25.6	202	05.9	02.4
			O_1	06.5	159	05.1	160	21.0	00.6
			K_1	04.3	250	05.0	246	16.0	01.6
2	17°57.6'S	38°42.2'W	M_2	78.4	188	69.9	183	10.0	02.6
			S_2	33.1	209	27.4	198	17.0	05.2
			O_1	07.8	164	06.1	152	21.0	07.3
			K_1	04.4	228	05.0	235	13.0	03.0
3	19°39.0'S	39°50.0'W	M_2	39.1	181	46.1	175	17.9	03.3
			S_2	18.9	193	19.5	188	03.1	02.5
			O_1	08.5	136	07.2	140	15.0	02.9
			K_1	04.5	189	05.0	216	11.0	14.0
4	22°06.0'S	40°01.0'W	M_2	37.8	176	39.1	174	03.4	01.1
			S_2	17.0	185	16.9	186	00.5	00.5
			O_1	07.5	131	07.3	135	02.6	03.0
			K_1	03.8	212	04.9	209	28.0	01.4
5	22°24.4'S	41°42.4'W	M_2	36.5	164	35.1	168	03.8	02.4
			S_2	19.7	172	16.6	180	15.0	04.6
			O_1	10.6	128	07.7	130	27.0	01.5
			K_1	06.0	190	05.7	202	05.0	06.3
6	23°51.5'S	45°46.8'W	M_2	33.4	167	27.9	169	16.0	01.1
			S_2	19.9	170	16.2	174	18.5	02.3
			O_1	11.1	121	08.7	121	21.6	00.0
			K_1	06.1	177	06.5	191	06.5	07.9
7	25°34.3'S	48°19.2'W	M_2	37.6	167	25.3	159	32.7	04.7
			S_2	21.0	180	16.1	162	23.3	10.0
			O_1	12.1	118	08.9	114	26.4	03.3
			K_1	05.3	182	06.8	184	28.3	01.0
8	27°17.0'S	48°21.5'W	M_2	19.6	157	17.8	154	09.1	01.9
			S_2	14.2	153	11.7	155	17.6	01.3
			O_1	10.6	116	08.6	112	18.8	03.4
			K_1	09.7	176	06.4	181	34.0	02.8
9	29°20.8'S	49°43.5'W	M_2	07.3	162	05.8	149	20.5	08.0
			S_2	08.8	156	07.1	141	19.3	09.6
			O_1	11.0	110	09.1	105	17.2	04.5
			K_1	06.7	172	06.7	172	00.0	00.0

amplitude and phase. Overall and when all nine stations are considered the mean RMS values are always below 20%. These RMS mean values for each constituent are as follows: M_2 (Amp) RMS mean = 12.6% and M_2 (Pha) RMS mean = 2.9%; S_2 (Amp) RMS mean = 13.3% and S_2 (Pha) RMS mean = 4.2%; O_1 (Amp) RMS mean = 18.9% and O_1 (Pha) RMS mean = 2.9%; K_1 (Amp) RMS mean = 15.7% and K_1 (Pha) RMS mean = 4.2%.

SUMMARY AND CONCLUSIONS

The reproduction of the oceanic features of the Western Boundary Currents in the South Atlantic at latitudes between 13°-31°S is the aim of the present study. ROMS simulation are employed for this purpose. This experiment used ETOPO1 dataset for bathymetry and it was forced by NCEP winds, tides from TPXO 7.1 global

database and with OCCAM as lateral boundary climatological conditions. The model simulations for the eastern and south-eastern Brazil shelf/slope area exhibit a good representation of the ocean dynamics of this region. The results obtained from the model are compared with observations, which consisted in thermodynamic of Montégut et al. (2004) MLD climatology, satellite data from AVISO, measurements from tide gauges along the shelf and current measurements values from literature. The following items are the main conclusions:

- ROMS simulations present a response to the synoptic wind and the topographic features. The forcing conditions are able to reproduce the coastal upwelling between 20°–25°S, one of the major features of the dynamic processes in the region.
- In general, ROMS simulations represent the MLD variability through the analyzed months.
- The SSH pattern from model and observation are similar, with negative values near the coast and positive signal offshore. Over the shelf/slope region the SSH gradient from ROMS represents the Western Boundary Current features. The higher variability found in AVISO is probably ascribed to the interannual cycle, which is not represented by the model, due to the monthly climatological forcing.
- The simulated currents represent the BC-IWBC system. The southward BC flow shows velocity of 0.6 m.s⁻¹ and the northward IWBC velocity of 0.3 m.s⁻¹. This BC-IWBC system is more evident at 22°S cross-shelf section, where the mean alongshelf velocity represents our simulation capability of reproducing the western boundary currents, with poleward BC and a opposing IWBC. The BC velocity core at 50 m is 0.41 m.s⁻¹ and the IWBC core around 800 m is 0.15 m.s⁻¹. These simulated velocities are in agreement with the measurements analysis (Silveira et al., 2004, 2008).
- The calculated transport, at the 22°S section, for BC and IWBC are –5.27 Sv and 3.06 Sv, respectively. These are also representative transport values compared to the literature.
- ROMS simulated at positions 1, 2 and 3 (Table 1) values for the BC speed near to the surface drifters data. Although south of 25°S, ROMS represent a displacement of the BC axis.
- The correlation coefficient of the suprainertial band of the sea level elevation time series for January of 2008, between

ROMS simulation and observation data at Rio de Janeiro station, is 0.96.

- ROMS harmonic analysis, at nine coastal sites, for M₂, S₂, O₁ and K₁ components, exhibit low mean values of RMS (<20%) relatively to the available FEMAR data.

The ocean dynamics simulation for the Brazilian shelf/slope region, considering climatological boundary conditions using ROMS, was used for the development of a pilot Brazilian regional operational ocean forecast system. This system is in use since 2009, releasing daily forecasts online at <http://www.rederemo.org/>. The next update of the forecasting system is the incorporation of the sinoptic forcings based on daily data from HYCOM at the open boundaries.

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