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On the baroclinic structure of the Brazil Current–Intermediate Western Boundary Current system at 22°–23°S

I. C. A. da Silveira, L. Calado, and B. M. Castro

Instituto Oceanográfico da Universidade de São Paulo, Departamento de Oceanografia Física, Química e Geológica, Praça do Oceanográfico, São Paulo, Brazil

M. Cirano

Centro de Pesquisa em Geofísica e Geologia, Universidade Federal da Bahia, Bahia, Brazil

J. A. M. Lima

Centro de Pesquisas Leopoldo A. Miguez de Mello (CENPES), Petróleo Brasileiro S.A. (PETROBRAS), Ilha do Fundão, Cidade Universitária, Rio de Janeiro, Brazil

A. d. S. Mascarenhas

Instituto de Investigaciones Oceanológicas, Universidad Autónoma de Baja California, Ensenada, Mexico

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[1] The baroclinic structure of the Brazil Current(BC)-Intermediate Western Boundary Current (IWBC) at 22°–23°S was investigated. A reanalysis of the pioneer velocity profile measurements of the TRANSCOBRA Experiment [*Evans and Signorini*, 1985] revealed that the BC-IWBC system is about 75–80% baroclinic. Mapped velocity structure showed flow reversal at about 450 m, an IWBC thickness of 1200 m and core velocities exceeding 0.30 m s^{-1}. Total (baroclinic) transports for BC (southwestwards) and IWBC (northeastwards) were 5.6 (4.2) Sv and 3.6 (4.1) Sv, respectively. The strong baroclinic character of the BC-IWBC system and the lack of direct velocity observations in the area yielded us to propose the use of the cross-shelf version of the Princeton Ocean Model to generate absolute baroclinic velocities from hydrographic data. These velocities presented a similar reversal depth, and the transports of about 6–7 Sv for both BC-IWBC were also comparable to values reported in the literature. *INDEX TERMS:* 4576 Oceanography: Physical: Western boundary currents; 4536 Oceanography: Physical: Hydrography; 4223 Oceanography: General: Descriptive and regional oceanography. **Citation:** da Silveira, I. C. A., L. Calado, B. M. Castro, M. Cirano, J. A. M. Lima, and A. d. S. Mascarenhas (2004), On the baroclinic structure of the Brazil Current–Intermediate Western Boundary Current system at 22°–23°S, *Geophys. Res. Lett.*, *31*, L14308, doi:10.1029/2004GL020036.

1. Introduction

[2] The Brazil Current (BC) has been reported in the literature as a shallow, warm and salty southward flowing Western Boundary Current (WBC) as it flows adjacent the Brazilian coastline between 20°S and 28°S. Most estimates of its volume transport are based on geostrophic calculations and vary from 5 to 13 Sv within this latitude range, as reviewed by *Garfield* [1990], *Campos et al.* [1995] and *da Silveira et al.* [2001]. The reference level choice considered by several authors for such calculations ranged mostly from 500 to 750 m. Those depths correspond essentially to the interface between the South Atlantic Central Water (SACW) and the Antarctic Intermediate Water (AAIW).

[3] The velocity profile measurements by *Evans and Signorini* [1985] at 23°S revealed that the BC vertical extent was indeed limited to pycnocline depths off SE Brazil. However, at intermediate depths, north-northeastward velocities exceeding 0.30 m s^{-1} were observed. This AAIW flow was predicted in the seminal article by *Stommel* [1965] in his attempt to explain the much lower transport values of the BC compared to the Gulf Stream in the North Atlantic, and raised the role of the thermohaline induced component in the WBCs. Nowadays, the BC is still thought as being dominantly wind-forced, i.e., the Sverdrup return flow of the South Atlantic Gyre. As for the AAIW flow, it can be posed that the intermediate component of the Meridional Overturning Cell (MOC) sets up an Intermediate Western Boundary Current (IWBC) along the SE Brazilian continental slope [*Schmitz*, 1995]. The IWBC flow patterns off the South American coast were described only recently by *Boebel et al.* [1999] by means of floater trajectory analysis.

[4] Hence, the BC-IWBC system seems to consist of a baroclinic current system with a single distinct flow reversal between upper and intermediate portions of the continental slope. An open question is: how baroclinic is the BC-IWBC system over this latitude range? Additionally, the relative geostrophic estimates presented in the literature vary as a consequence of arbitrary choices of the reference level and may preclude a reasonable representation of the total BC-IWBC flow from hydrography. Therefore, a second question to be posed is: what is an objective manner to estimate the BC and IWBC transports from temperature-salinity data in order to make them independent of an imposed reference level?

[5] We address the first question focusing on 22°–23°S and revisiting the pioneer Pegasus profiler measurements done by *Evans and Signorini* [1985] during the "Transport of the Brazil Current-TRANSCOBRA" Experiment (1982–

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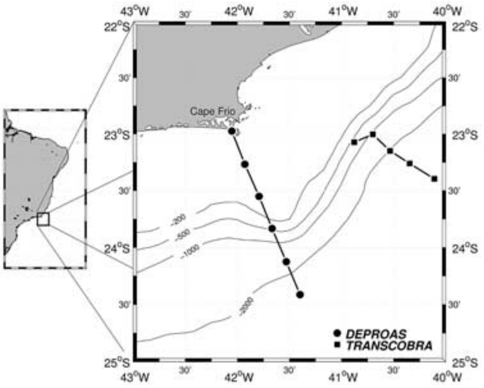

Figure 1. The TRANSCOBRA Pegasus velocity profile transect location by *Evans and Signorini* [1985] in April 1983, and the hydrographic DEPROAS transect location (January 2001 and repeated in July 2001).

1984). We then objectively map a velocity section of the TRANSCOBRA transect (Figure 1) from the Pegasus profiles and estimate barotropic and baroclinic transports for both BC and IWBC.

[6] To answer the second question, we propose the employment of the sectional version of the Princeton Ocean Model [*Mellor*, 1986] to obtain absolute baroclinic velocities for the BC-IWBC system from CTD data in lieu of the application of the classical dynamic method. As the historical TRANSCOBRA CTD data set was not available to us, we use recent hydrographic measurements made during the "Dynamics of the Coastal Ecosystem of the Western South Atlantic–DEPROAS" Experiment (Figure 1) to exemplify the numerically-generated BC-IWBC flow structure.

2. The TRANSCOBRA Data Set Reanalysis

[7] The *Evans and Signorini* [1985] article presented the velocity profiles of the BC region and described the vertical structure in terms of zonal and meridional components in a one-dimensional sense. Here, we follow the fundamentals of objective analysis presented by *Carter and Robinson* [1987] to map the cross-section velocity of the TRANSCOBRA transect. The anisotropic Gaussian correlation function considered in the interpolation procedure is given by

$$C(\Delta x, \Delta z) = \left(1 - \epsilon^2\right) e^{-\left(\frac{\Delta x^2}{L_x^2} + \frac{\Delta z^2}{L_z^2}\right)},$$

where Δx and Δz represent the along-section and vertical increments of the grid, $L_x = 25$ km and $L_z = 400$ m are the horizontal and vertical correlation lengths, and $\epsilon^2 = 0.10$ is the assumed random sampling error variance.

[8] Figure 2a shows the cross-section velocity field for the 18–19 April 1983 TRANSCOBRA transect. The barotropic component, taken as the vertical mean of the velocity was removed from the total velocity field to obtain the baroclinic velocity (Figure 2b). The normalized root mean square (*nrms*) interpolation error field is presented in the lower panel. Volume transports for the individual currents (i.e., BC and IWBC) were computed by limiting the flow structure by the 0.02 m s^{-1} isotach. This limit value corresponds to the Pegasus accuracy estimated by *Evans and Signorini* [1985]. Transport uncertainties were then computed based on *nmrs* values of each grid point of the interpolated fields (Figure 2c).

[9] The total velocity field (Figure 2a) depicts a BC confined to 450–500 m, and exhibiting a well defined core of speeds exceeding 0.5 m s^{-1}. The BC, using the 0.02 m s^{-1} isotach to bound it, occupies the whole TRANSCOBRA transect section at upper levels. The BC volume transport of 5.6 ± 1.4 Sv (1 Sv = 10^6 m^3 s^{-1}) southwestward computed here is very close to the original estimate of 6 Sv by *Evans and Signorini* [1985]. It is important to point out that this transport value is related to the flow offshore of the 200-m isobath (i.e., the depth of

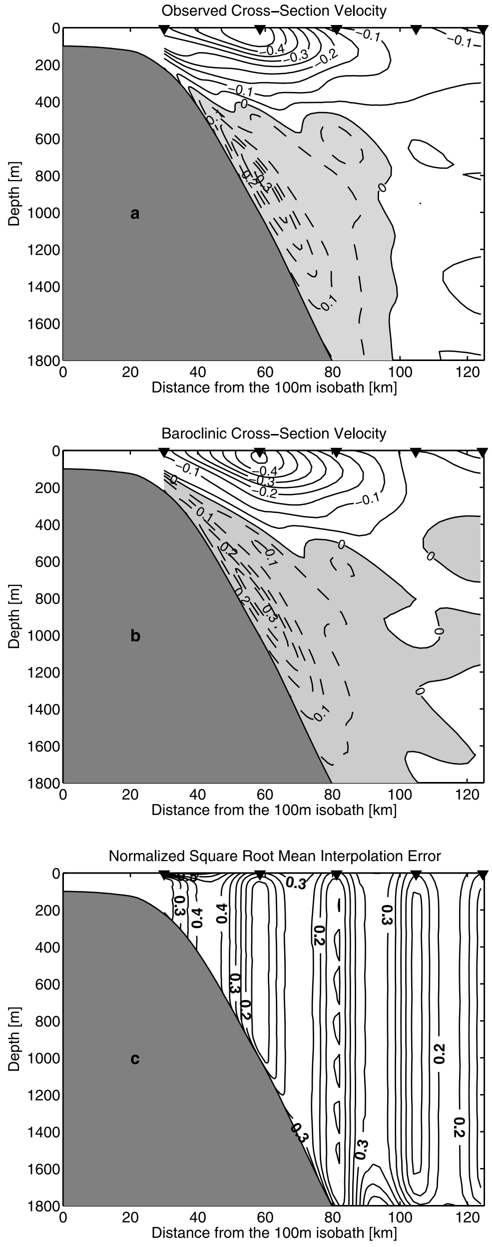

Figure 2. The April 1983 TRANSCOBRA Cross-section Velocity: (a) the total field, (b) the baroclinic field, and (c) the normalized roots mean square interpolation error. Negative velocities are southwestward. Contour intervals are 0.05 m s^{-1}.

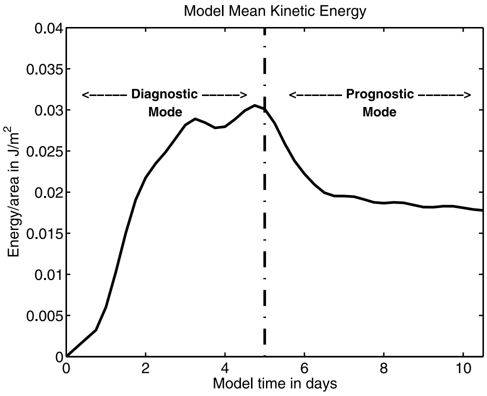

Figure 3. Mean kinetic energy (KE) per unit area as function of time. The decrease of the level of KE after day 5 of simulation represents the switch from the diagnostic to the prognostic mode.

the inner Pegasus station). From Figure 2a, it is clear however that the BC extends onto the shelf and the calculated transport does not include the whole current structure.

[10] While the BC structure was discussed in depth by *Evans and Signorini* [1985], the IWBC was not. This current has a lateral extension similar to that of the BC and has its core centered at 800 m, which seems to coincide with the salinity minimum associated with AAIW. The maximum velocities (0.3 m s^{-1}) are located near the continental slope. The IWBC computed transport is 3.6 ± 0.8 Sv in the northeast direction, a value which matches well with the 4 ± 2 Sv estimate from floater data analysis by *Boebel et al.* [1999]. Within the 0.02 m s^{-1} isotach bounds, the IWBC vertical extent exceeds 1200 m, and is much thicker than the 400 m value presented by *Boebel et al.* [1999] in the surroundings of the Rio Grande Rise (about 30°S).

[11] The barotropic velocities ranged from -0.2 m s^{-1} at the most inshore station to 0.01 m s^{-1}, a value found approximately at the center of the section. The barotropic transport integrated along the TRANSCOBRA section is 2.4 ± 0.7 Sv directed southwestward. The baroclinic velocity field (Figure 2b) differs very little from the total field. Moreover, the velocity inversion depth from the baroclinic BC and IWBC is virtually the same of the total field: 500 m on average. The BC core is weakened and the IWBC core is strengthened. The baroclinic transports calculated are 4.2 ± 1.0 Sv for the BC and 4.1 ± 1.2 Sv for the IWBC. Those figures are more directly comparable to previous geostrophic calculations. *Evans et al.* [1983] found a BC transport (relative to 500 db) of 4.4 Sv and *Signorini* [1978], who used a variable reference level ranging from 500–1300 db, reported a computed BC relative baroclinic transport of 5.2 Sv at 22°S and 4.4 Sv at 23°S. The surface maximum velocities obtained by those authors were also compatible to those depicted in Figure 2: about 0.5 m s^{-1} in both *Signorini* [1978] and *Evans et al.* [1983].

3. The DEPROAS Baroclinic Velocity Fields

[12] In the previous section, we reevaluated the classical TRANSCOBRA data set and showed that the current structure at 22°–23°S is essentially baroclinic (about 75–80%) offshore of the 200 m isobath. In this section, we use an independent hydrographic data set from the DEPROAS Experiment (Figure 1) to generate an absolute baroclinic velocity field for the BC-IWBC from CTD data. As mentioned in Section 1, we do however not apply the Dynamic Method to the DEPROAS data set. Instead, we build on *Lima*'s [1997] ideas and employ the cross-shelf circulation version of the Princeton Ocean Model (POM) originally developed by *Mellor* [1986]. Our model grid consists of 65 sigma levels and 129 *x-grid* points with constant $\Delta x = 2$ km. The inshore section domain is closed and limited by the 30 m isobath, while the offshore boundary is open and set up with a buffer zone of 43 grid points. The actual physical model domain is therefore 86 *x-grid* points or 172 km and the temperature-salinity values of the 86th *x-grid* point are repeated until the end of the model domain. This procedure was successfully used by *Lima* [1997]. Radiational boundary conditions were used for both baroclinic and barotropic velocities. The model implementation considers a constant value of horizontal diffusivity (60 m^2 s^{-1}). In analogy to the TRANSCOBRA data set, the DEPROAS temperature-salinity profiles were also interpolated to the model grid using objective analysis. Sensitivity experiments were conducted to determine if the designed grid would introduce any horizontal pressure gradient errors in the velocity field. A prognostic run with no other forcing apart from a horizontally flat stratification derived from the CTD data resulted in steady state velocities of the order of 10^{-3} m s^{-1}. As both BC and IWBC velocities are expected to be two orders of magnitude higher, the grid was considered adequate.

[13] The actual experiments were conducted for both the January (EXP 2) and July (EXP 1) 2001 realizations of the DEPROAS transect and were initialized only with the thermohaline forcing, with the term related to the horizontal pressure gradient being ramped from the rest during the first 1.3 days. The experiments were carried out following the *Ezer and Mellor* [1994] method with a start in the diagnostic mode and a subsequent switch to the prognostic mode. While the diagnostic mode holds the initial temperature-salinity fields, the prognostic mode allows both the thermohaline and velocity fields to evolve. In this method, the evolution of the T-S fields aims to remove noise from the interpolated quasi-synoptic hydrographic data from the DEPROAS transect. This is done, according to those authors, by advection, diffusion and dynamic adjustment of the flow to bottom topography. We exemplify this procedure by showing the temporal evolution of the mean kinetic energy (per unit area) for EXP 1 and EXP 2 runs (Figure 3). It is seen that the adjustment was fast, occurring between days 3 and 5 of the diagnostic mode phase. After the run was switched to the prognostic mode, a decrease in kinetic energy was observed and was associated to the hydrographic data noise being removed. The mean energy reached an equilibrium state around the seventh day of simulation, but the run was carried out until 10.5 days of integration. The velocity fields were averaged over the last two days of simulation. In both simulations performed, the barotropic signal was, as expected, within noise level. Volume transports based on the simulated velocity for the BC and IWBC were computed again using the 0.02 m s^{-1} isotach to bound the current structures.

[14] We present the simulated velocity for EXP 1, which relates to the July 2001 cruise (Figure 4), because the output depicts a current system configuration with a BC-IWBC that more closely resembles the observed Pegasus velocity field (Figure 2). The BC is shown with a surface core that reaches 0.8 m s^{-1} and reverses at a depth of 450–500 m, exactly as shown for the TRANSCOBRA cross-section velocity. The BC baroclinic transport is 6.6 Sv. The IWBC configuration is qualitatively very similar to the observed field and presents a core of velocities higher than 0.3 m s^{-1} very close to the continental slope. The IWBC volume transport is 6.2 Sv. Both BC and IWBC transport values are higher than those of the TRANSCOBRA transect but fall within the range described in the literature from direct observations [*Lima*, 1997; *Boebel et al.*, 1999].

[15] The simulated velocity field for EXP 2 (Figure 5), exihibts a cyclonic eddy. It is known that the BC meanders widely as it flows off the southeast Brazilian coast and occasionally sheds eddies [*Signorini*, 1978; *da Silveira et al.*, 2001], a behaviour not usual to a WBC flowing along continental margins. The baroclinic eddy shown in Figure 5 also presents one single distinct flow reversal at depth, similarly to the non-meandering current system depicted in Figure 4. Due to the cyclonic structure, the BC flow is northeastward near the shelf break. The first mode character of the BC-IWBC eddy explains the IWBC flowing southwestward near the slope. It is however possible that the total IWBC flow (with the barotropic component included) will not reverse at depth. *Lima* [1997] analyzed current meter mooring time series at 22°S and did not find flow direction reversals below 600 m due to meso-scale activity of the current system.

4. Summary and Conclusions

[16] In this paper, we reanalyze the only velocity profile measurements described in the literature for the BC region between 22° and 23°S by *Evans and Signorini* [1985] during the TRANSCOBRA Experiment. From the original velocity profiles, a cross-section velocity field is objectively mapped. The total velocity field reproduces the main findings of *Evans and Signorini* [1985] about the BC: a 400–500 m deep WBC with maximum surface and a volume transport about 6 Sv (offshore of the shelf break). The BC therefore transports essentially Tropical Water and SACW. On the other hand, a new picture of the IWBC emerges from the reanalysis. It is depicted as a current with more than 1200 m of vertical extent, a swift narrow core of velocities centered at 800 m that exceeds 0.30 m s^{-1}. The current core is basically formed of AAIW and its associated minimum salinity. However, due to the IWBC vertical extent, the current probably transports mixtures of SACW-AAIW in its upper portion and AAIW-North Atlantic Deep Water in its lower end.

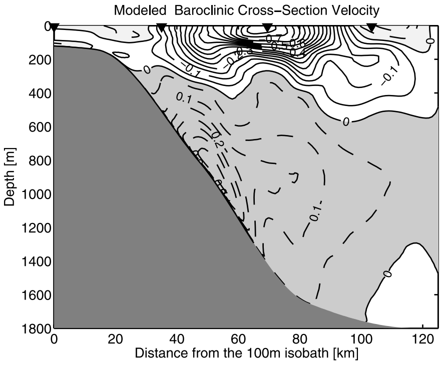

Figure 4. The baroclinic cross-section simulated velocity for the July 2001 DEPROAS temperature-salinity structure (EXP 1). Negative velocities are southwestward. Contour intervals are 0.05 m s^{-1}.

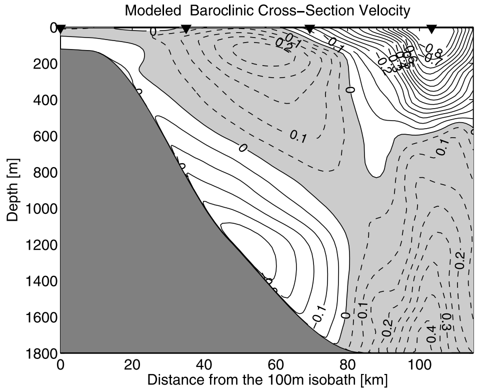

Figure 5. The baroclinic cross-section simulated velocity for the January 2001 DEPROAS temperature-salinity structure (EXP 2). Negative velocities are southwestward. Contour intervals are 0.05 m s^{-1}.

[17] We however aim to evaluate how baroclinic the BC-IWBC system is in the latitude range of interest. In order to do so, we compute the barotropic component and remove it from the total velocity map. We then find that the BC-IWBC velocity field is 75–80% baroclinic over the continental slope. On the other hand, direct velocity observations of the BC and its vertical structure are rare. We hence propose to employ the cross-shelf circulation version of POM to obtain absolute baroclinic BC-IWBC velocity fields from hydrographic data. The use of the numerical model with an initial temperature-salinity field derived from CTD as a substitute to the classical dynamic method eliminates the need of arbitrary choices of reference levels. An independent hydrographic data set of the DEPROAS Experiment taken in the vicinity of the TRANSCOBRA transect is used. The numerically generated absolute baroclinic velocity field for the July 2001 DEPROAS transect very closely resembles the observed velocity field in terms of current structure and velocity reversal depth. The simulated current transports are about 6–7 Sv for both BC and IWBC, therefore comparable to the TRANSCOBRA transport values as well as the few direct observations reported in the literature. The modeled velocities of the January 2001 DEPROAS transect captured a cyclonic eddy. Both model results in combination with the TRANSCOBRA baroclinic field suggest that the BC-IWBC system is dominated by the first baroclinic mode with a single distinct reversal at around 400–500 m. The barotropic component of the meso-scale eddies of the BC-IWBC system has yet to be determined from direct observations. Data analysis of an 11 current meter mooring at 22.5°S placed on the 1200 m isobath is currently being carried out to resolve this issue and obtain information about meander periodicity.

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L. Calado, B. M. Castro, and I. C. A. da Silveira, Instituto Oceanográfico da Universidade de São Paulo, Departamento de Oceanografia Física, Química e Geológica, Praça do Oceanográfico, 191, 05508-900 São Paulo, Brazil. (ilson@io.usp.br)

M. Cirano, Centro de Pesquisa em Geofísica e Geologia, Universidade Federal da Bahia–Campus Ondina, 40170-280 Salvador (BA), Brazil.

J. A. M. Lima, Centro de Pesquisas Leopoldo A. Miguez de Mello (CENPES), Petróleo Brasileiro S.A. (PETROBRAS), Ilha do Fundão, Cidade Universitária, Q7 s/n, 21949-900 Rio de Janeiro (RJ), Brazil.

A. d. S. Mascarenhas, Instituto de Investigaciones Oceanológicas, Universidad Autónoma de Baja California, km 106, Carretera Tijuana-Ensenada, Ensenada, BC 22860, Mexico.