On the boundary flow off Brazil at 5–10°S and its connection to the interior tropical Atlantic

Friedrich A. Schott, Peter Brandt, Meike Hamann, Jürgen Fischer, and Lothar Stramma
Institut für Meereskunde an der Universität Kiel, Kiel, Germany

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[1] Within the context of the German CLIVAR program, an observational program in the western tropical Atlantic with shipboard sections, profiling floats and a moored array aims at studying the role of the shallow thermohaline subtropical cell (STC) in tropical-subtropical interactions and the cold water transports underneath. From 6 repeated shipboard profiling sections off Brazil near 5°S a northward warm water transport above 1100 m of 25.0 ± 4.4 Sv is determined, of which 13.4 ± 2.7 Sv occur in the thermocline layer supplying the Equatorial Undercurrent. Trajectories of 15 profiling floats released near the western boundary are presented that drift at shallow levels (200 m and 400 m) and delineate the different STC branches. For the southward flow of North Atlantic Deep Water (NADW) a section-mean transport of −31.7 ± 9.2 Sv was determined at 5°S. However, different from the steady NADW flow observed earlier along the topography north of the equator, the NADW currents at 5–10°S are much more variable with long periods of northward counterflow along the topography. *INDEX TERMS:* 4576 Oceanography: Physical: Western boundary currents; 4512 Oceanography: Physical: Currents; 4532 Oceanography: Physical: General circulation. **Citation:** Schott, F. A., P. Brandt, M. Hamann, J. Fischer, and L. Stramma, On the boundary flow off Brazil at 5–10°S and its connection to the interior tropical Atlantic, *Geophys. Res. Lett.*, *29*(17), 1840, doi:10.1029/2002GL014786, 2002.

1. Introduction

[2] The western margin of the tropical South Atlantic is a particularly interesting region for observing the thermohaline circulation. At the upper levels, as schematically shown in Figure 1, much of the equatorward warm water transfer from the Southern Hemisphere is focussed into a tight western boundary current, the NBUC. The NBUC has its velocity maximum of about 70 cm s^{-1} near 200 m depth, while at the surface the flow is weak or even southward, due to southward Ekman transports [*Stramma et al.*, 1995; *Schott et al.*, 1995, 1998].

[3] The NBUC transport has two different components. The first component has its origin in the Meridional Overturning Circulation (MOC) of the Atlantic in which approximately 20 Sv of North Atlantic Deep Water (NADW) passes southward through the equatorial zone. They are compensated by a net northward transport of warm and intermediate waters as well as by Antarctic Bottom Water (AABW) [*Ganachaud and Wunsch*, 2000]. The second component of the NBUC originates from the subtropical cell (STC). As part of the STC, the NBUC is the main connection between the subduction regions of the subtropical South Atlantic and the eastward equatorial and off-equatorial undercurrents that supply the equatorial and eastern-boundary upwelling regimes. At the surface the STC is closed by the southward Ekman transport returning upwelled waters to the subduction regions [*Stramma and Schott*, 1999; *Malanotte-Rizzoli et al.*, 2000; *Lazar et al.*, 2002]. The thermocline circulation of the STC is illustrated in Figure 1 by the climatological distribution of oxygen content on the isopycnal surface 26.8 kg m^{-3}. It shows a connection of high oxygen concentration from the southeastern South Atlantic to the western tropical zone, spreading from there eastward with the EUC. Since the northward warm water flow of the MOC near 10°S mostly occurs along the western boundary [e.g., *Schott et al.*, 1998], the total northward transport of the NBUC at 5–12°S will exceed the required MOC amount.

[4] Not much is known about the seasonal to interannual variability of the NBUC nor about the partition of the total MOC plus STC transports among the western boundary domain and the interior South Atlantic domain. The German CLIVAR tropical Atlantic project, of which a summary of results is presented in the following, focuses on observing the NBUC between the equator and about 11°S latitude by moored stations, repeated shipboard profiling sections and by profiling floats drifting at thermocline levels. One area of particular interest in our study is the source and supply of the SEUC and its potential relation to the NBUC.[1] As already determined in earlier water mass studies [*Hisard et al.*, 1976; *Tsuchiya*, 1986], and recently confirmed by the results from the WOCE section along 4.5°S [*Arhan et al.*, 1998], the SEUC, extending zonally along 3–5°S, is marked by a maximum in oxygen content. This maximum (which is not detectable in the climatology of Figure 1) that can be traced far eastward into the interior of the basin suggests that the source of the SEUC is the oxygen-rich NBUC. Yet, in our earlier observations [*Schott et al.*, 1995, 1998] no evidence for a direct outflow from the NBUC into the SEUC could be identified, and the shallow float trajectories are presumed to help resolving this puzzle.

2. Ship-Board Sections

[5] Six current profiling surveys of the 5°S section (Figure 1) were taken during 1990 and 2000 and the mean

[1]The SEUC, extending zonally along 3–5°S, is marked by a maximum in oxygen content [*Arhan et al.*, 1998].

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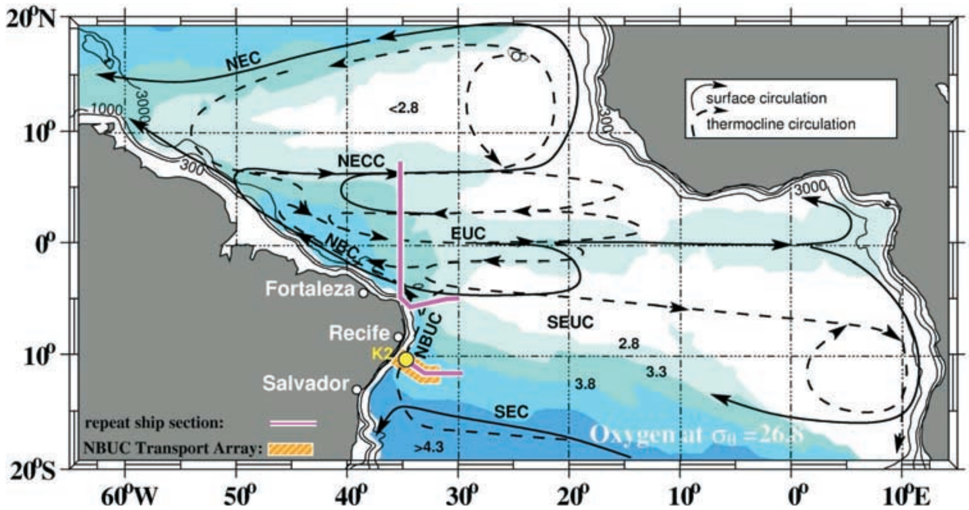

Figure 1. Schematic diagram of the shallow subtropical and tropical Atlantic circulation (solid: surface currents; dashed: thermocline currents) superimposed on the climatological distribution of oxygen concentration (ml l^{-1}) on the density surface 26.8 kg m^{-3} (depth about 250 m; based on the climatology of *Gouretski and Jancke* [1998]). Also shown is the location of the moored array (including station K2) at the western boundary near 11°S and of the repeat shipboard current profiling sections. Current branches marked are North and South Equatorial Currents (NEC, SEC), North Equatorial Countercurrent (NECC) North Brazil Current and Undercurrent (NBC, NBUC), South Equatorial and Equatorial Undercurrents (SEUC, EUC).

transport is shown in Figure 2. The individual-cruise current sections were determined by merging profiles obtained by Pegasus profiler (available only for the first three sections, 1990–92), by shipboard ADCP (above 300 m) and by lowered ADCP (for details of the earlier observations see *Schott et al.* [1995, 1998]. For the upper 25 m not covered by the shipboard ADCP data, shear extrapolation toward the surface was applied. Profiling currents were not corrected for tidal fluctuations, which have amplitudes of 2–3 cm s^{-1} over the deep ocean in the region (based on tidal models and own moored observations at position K2, see Figure 1). The reference level that approximately divides the northward warm water flow from the southward flowing NADW is the isopycnal surface σ_1 = 32.15 kg m^{-3} at 1000–1100 m. The mean northward transport above that isopycnal is 25.0 ± 4.4 Sv and the transport ranged from 22 Sv to 34 Sv among the 6 repeats of that section. In the density range of the undercurrent layer of σ_θ = 24.5–26.8 kg m^{-3} which dominantly supplies the EUC [*Schott et al.*, 1998] the mean northward transport is 13.4 ± 2.7 Sv. In the surface layer above σ_θ = 24.5 kg m^{-3} the northward transport is weak, only 2.7 ± 1.8 Sv, but 8.9 ± 2.0 Sv are carried in the lower part of the warm water sphere, made up by the colder parts of the Central Water, Antarctic Intermediate Water and upper Circumpolar Deep Water. The NBUC does not noticeably meander and its maximum is always located right at the shelf edge near 5°S. A seasonal cycle has not been confirmed from the observations.

[6] Much larger variability among the repeat sections than for the NBUC transport was found below for the southward flow of NADW. The current core was not always attached to the topography. In some sections it was displaced offshore with northward flow near the continental slope. The mean southward NADW transport between σ_1 = 32.15 kg m^{-3} and potential temperature 1.75°C (separating the NADW from the AABW) within the common reach of the section, i.e. west of 33°W was −31.7 ± 9.2 Sv (Figure 2), and the range was 23–48 Sv. This variability appears to be larger than found by *Fischer*

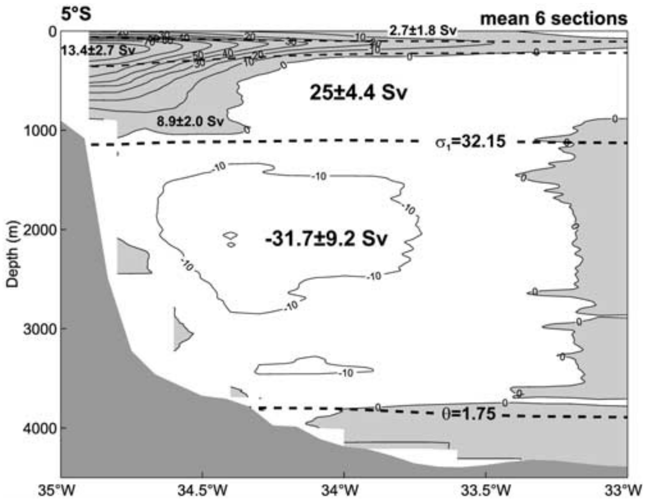

Figure 2. Mean alongshore current distribution (cm s^{-1}, positive is northward) off Brazil at 5°S (for section location see Figure 1). Mean transports and standard deviations in Sverdrups (Sv = 10^6 m^3 s^{-1}) are based on 6 sections, and are for the northward warm water flow above the isopycnal surface σ_1 = 32.15 kg m^{-3} and for the southward NADW flow between this isopycnal and the potential temperature of 1.75°C. Small numbers are for transports in the surface layer above σ_θ = 24.50 kg m^{-3}, in the thermocline layer σ_θ = 24.50–26.80 kg m^{-3} and in the layer σ_θ = 26.80 kg m^{-3} −σ_1 = 32.15 kg m^{-3}.

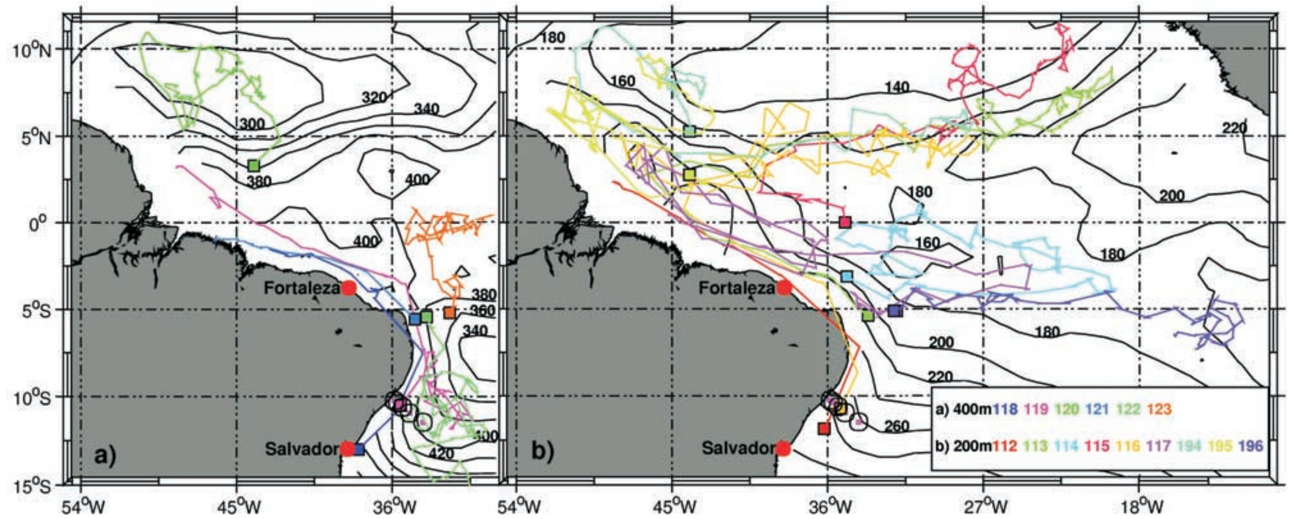

Figure 3. Trajectories (status 18 March 2002) of 15 APEX floats drifting at (a) 400 and (b) 200 m, respectively, and profiling from 1500 m to the surface at 10 day intervals (inset shows float numbers). Also shown in (a), (b) are climatological mean depths of isopycnal surfaces σ_θ = 27.00 kg m^{-3} (near 400 m) and σ_θ = 26.60 kg m^{-3} (near 200 m), respectively (based on the climatology of *Gouretski and Jancke* [1998]). The 10 floats 112–119, 121 and 122 were released in March 2000, the other 5 in November 2000.

and Schott [1997] in previous deep sections and a moored array north of the equator along 44°W.

3. Profiling Float Trajectories

[7] In March and November 2000 a total of 15 Autonomous Profiling Explorers (APEX) were deployed in the western tropical Atlantic. They drift at 400 m (6 floats, Figure 3a) depth and at 200 m depth (9 floats, Figure 3b), respectively, and take profiles of temperature and salinity at 10-day time intervals between 1500 m and the surface. Pathways from floats released in the NBUC regime show a complex structure of the flow regime, some expected and following the schematic pathways of Figure 1, but some rather unexpected. In the interpretation of the trajectories it has to be noted that the floats have two shortcomings regarding STC pathway studies: First, they do not exactly return to the water parcel that they were tracking before when they finish their surface cycle and profile. And second, the floats may not always follow isopycnal surfaces, as suggested by the climatological mean depths of the isopycnal surfaces 27.0 kg m^{-3} in Figure 3a and 26.6 kg m^{-3} in Figure 3b, respectively, that are near 200 m and 400 m, respectively, in the NBUC region. Floats sometimes even appear to move normal to isopycnal contours (e.g., float 120, upper left of Figure 3a). However, it has to be considered that climatological and actual isopycnal depths may differ.

[8] Five floats released in the NBUC core followed the continental slope along the Brazilian coast toward and across the equator with speeds exceeding 50 cm s^{-1} during some 10-day intervals. After crossing the equator, two of them (113 and 116 at 200 m, Figure 3b) turned eastward via the NBC retroflection into the North Equatorial Undercurrent (NEUC) or NECC at 3–5°N, and within about a year's time travelled all the way to the eastern basin, basically following the northeastward excursion of the isopycnal contours. None of the 15 floats followed a path along the western boundary toward the Caribbean, although two (120, 195) spent time in the northwestern region, before returning southward again. Unfortunately, four of the floats (112, 118, 119 and 121) were pushed into shallow water during their surface periods by the prevailing westward Trades and thus stranded on the shelf. A highly interesting path in the retroflection area is performed by the 200 m float 117 after crossing the equator, it follows a loop twice that carries it along the boundary to 4°N and back southward offshore and across the equator to 2°S.

[9] Three floats that were deployed east of the NBUC/NBC regime (114, 117 and 196) began their trajectories by first moving eastward with the SEUC. Float 114 (200 m), launched near 3°S, 35°W, first propagated eastward with the SEUC to about 19°W, then changed its propagation to northward where it exited the SEUC and returned westward with the SEC. During its westward phase, float 114 moved northward to the equator, then southward back to near its launch position. Similarly, float 117 (also at 200 m), deployed along 5°S outside the NBUC, did the SEUC to SEC transfer after having moved to 25°W, but rather than reaching the equator in the interior it was quickly carried to the western boundary by the SEC and then crossed the equator, doing the loops already mentioned above. Float 196 (200 m) moved straight eastward at 5–6°S and, after about a year's time, arrived at 12°W over the mid-Atlantic Ridge.

[10] Rather unexpected interior trajectories were produced by three 400 m floats released in the southern tropics (Figure 3a). Float 122 first moved southward from 5°S to near 10°S and then looped around at 8–11°S while float 118, released at 10°S began drifting northward with the NBUC but then left it near 7°S and also remained in the region for some time. Float 123 moved gradually northward from 5°S toward the equator, almost normal to the prevailing zonal currents and after about a year it continues to loop around the equator. Meridional STC outflow from the equator is suggested by float 115 (200 m), released on the equator at 35°W, which moved northward and then entered the eastward NEUC/NECC pathway.

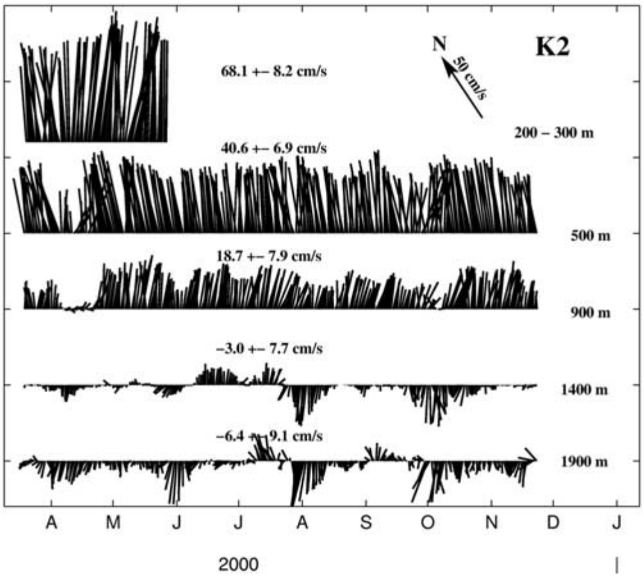

Figure 4. Vector time series (daily averages) of moored currents (see northward direction for orientation) from station K2 at 11°S (location see Figure 1; ADCP ended prematurely, because top float was lost, most likely due to fishing activity); record-length means and standard deviations of alongshore component (toward 35 true) indicated at the time series.

[11] The fact that two floats deployed just to the east of the NBUC were not drawn into it is in agreement with our earlier results obtained from the shipboard studies [*Schott et al.*, 1998] that the NBUC has its roots dominantly further south than 10°S. There was also no indication in the few available trajectories of a direct supply of the SEUC out of the NBUC. The eastward trajectories (floats 113, 115 and 196) are in agreement with the findings for the Pacific [*Rowe et al.*, 2000] that the SEUC and NEUC deviate poleward toward the east.

4. Moored Array Observations

[12] The array near 11°S, consisting of five moorings, has been deployed since March 2000. It was expanded seaward by Inverted Echosounders (IESs) of NOAA/AOML to study the relation to the larger scale. Two of the moorings were retrieved prematurely in November 2000 during Sonne cruise SO 151 due to loss of near-surface floatation, most likely caused by mechanical interference.

[13] Current vector plots for the time period March to November 2000 from station K2 located just off the shelf edge in 2320 m water depth (Figure 1) show the intense and steady flow of the NBUC (Figure 4). The station was equipped with an upward-looking ADCP measuring the current profile between 300 m and 30 m below the surface. Although station K2 is already located offshore of the current maximum as identified in the shipboard profiling sections, the mean northward speed still reaches nearly 70 cm s^{-1} at about 250 m depth. From this maximum the NBUC velocities decrease to 18.7 ± 7.9 cm s^{-1} at 900 m. Toward the surface the velocities decrease considerably, as well, making the NBUC a true undercurrent.

[14] At the NADW level of 1400 m and 1900 m of station K2 near the topography at 11°S, the currents fluctuate strongly (Figure 4) with mean southward components of 3.0 ± 7.7 cm s^{-1} and 6.4 ± 9.1 cm s^{-1}, respectively. There are long periods with northward flow along the continental slope, in agreement with the shipboard sections which at times showed an offshore displacement of the NADW core. This is an interesting contrast to the currents observed earlier just north of the equator at a similar distance from the topography by *Fischer and Schott* [1997]. Although they found that the NADW transport in the depth range 1000–3100 m had a strong seasonal cycle just north of the equator, ranging from about 5 Sv to 20 Sv southward, the NADW core there was never detached from the topography.

5. Relation to Other Studies in the Region

[15] Several other studies have recently been carried out in the region, such as the US NBC rings experiment, the French EQUALANT cruises or are going on during the time period of our observations. Most importantly, this is the moored array program PIRATA, for which we anticipate close cooperation in the evaluation of NBUC transport and water mass anomalies to look for potential STC links in variations of EUC transports, equatorial upwelling and SST anomalies.

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F. A. Schott, Institut für Meereskunde an der Universität Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany. (fschott@ifm.uni-kiel.de)

P. Brandt, M. Hamann, J. Fischer, and L. Stramma, Institut für Meereskunde an der Universität Kiel, Kiel, Germany.