The zonal currents and transports at 35°W in the tropical Atlantic

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[1] The total of 13 existing cross-equatorial shipboard current profiling sections taken during the WOCE period between 1990 and 2002 along 35°W are used to determine the mean meridional structure of the zonal top-to-bottom circulation between the Brazilian coast, near 5°S, and 5°N and to estimate mean transports of the individual identified shallow, intermediate and deep current branches. One of the results is that, on the equator, a mean westward Equatorial Intermediate Current below the Equatorial Undercurrent exists. *INDEX TERMS:* 4576 Oceanography: Physical: Western boundary currents; 4231 Oceanography: General: Equatorial oceanography; 4532 Oceanography: Physical: General circulation; 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; 9350 Information Related to Geographic Region: North America. **Citation:** Schott, F. A., M. Dengler, P. Brandt, K. Affler, J. Fischer, B. Bourles, Y. Gouriou, R. L. Molinari, and M. Rhein, The zonal currents and transports at 35°W in the tropical Atlantic, *Geophys. Res. Lett.*, *30*(7), 1349, doi:10.1029/2002GL016849, 2003.

1. Introduction

[2] The region off northeastern Brazil near 35°W is a crucial region for the circulation of the tropical Atlantic, with a large part of the Atlantic Meridional Overturning Circulation (MOC) passing through it. The 35°W section encounters the northeastern corner of the South American continent at 5°S, and the North Brazil Current (NBC) and the South Equatorial Current (SEC) are confined and intensified in the first 100 km of its northward extent (Figure 1). The South Equatorial Undercurrent (SEUC) follows north of the NBC and below the SEC, at 3–5°S [*Schott et al.*, 1998]. On the equator, the Equatorial Undercurrent (EUC) flows eastward above 250 m, supplied out of a retroflection of the NBC at and north of the equator. North of the EUC lies the northern SEC branch, followed by the North Equatorial Undercurrent (NEUC) at 3–5°N, which is dominantly supplied out of the NBC retroflection. The NEUC also carries ingredients of northern water masses that point to partial supply out of a recirculation from the North Equatorial Current (NEC) as part of the northern subtropical cell [*Bourlès et al.*, 1999].

[3] At intermediate levels, westward equatorial currents have been reported and identified as the Equatorial Intermediate Current [EIC, *Schott et al.*, 1998, *Boebel et al.*, 1998]. The existence of a mean EIC is, however, a matter of dispute since it is not consistently simulated by numerical models [*C. Böning, pers. communication*, 2002]. The available observations also suggested that currents between 1–3° of either hemisphere are eastward (the Northern and Southern Intermediate Countercurrents, NICC and SICC, respectively), although so far the evidence for the existence of these currents is not as consistent as for the EIC [*Schmid et al.*, 2001].

[4] At the bottom, the 4500 m-deep "Equatorial Channel" between 0°40′N and 1°40′S is the only gateway for the Antarctic Bottom Water (AABW) to cross the equator into the northern hemisphere [*Hall et al.*, 1997] (Figure 2). The Equatorial Channel thus not only guides the westward flow of AABW but also the eastward flow of lower North Atlantic Deep Water (lNADW) which is encountered as a focussed velocity core just north of the Parnaiba Ridge [*Rhein et al.*, 1995], while the upper NADW (uNADW) can also propagate along the topography closer to the coast (Figure 1).

[5] The objective here is to determine the mean near-equatorial structure of the zonal circulation at a well-observed location in the western basin, based on today's observational status of direct current measurements. We present the zonal-mean currents from the 35°W section that cuts through this important flow regime (Figure 1) and from which 13 current profiling surveys, carried out by research groups from Germany, France and the US, are available for the time period between 1990 and 2002. These results will hopefully provide useful guidance for further model simulations.

2. Mean Currents and Variability

[6] In the sections used here, the upper 300–500 m were covered by shipboard Acoustic Doppler Current Profiler (ADCP). For deep current profiling, a mix of Pegasus drop sonde profiling (only 1992–94) and lowered ADCP (LADCP) was applied. LADCP station separation was typically 20 nm, and better near the southern topography and near the equator. The 13 sections consist of six from "Meteor" (M) and one each from "Sonne" (S), "L'Atalante" (A), "Le Noroit" (September 1995, only to 300 m depth), "E. A. Link" (E), "Thalassa" (T), "Oceanus" (O) and "Ron Brown" (R). The seasonal distribution (Figure 4) shows a concentration of observations during spring. While all sections covered the upper 300 m, only 9 went to the full water depth.

[7] For this study, all profile observations from each survey, i.e. shipboard ADCP, Pegasus and LADCP, were merged and then mapped on a grid of 11 km horizontal and 10 m vertical resolution, using mapping scales with a

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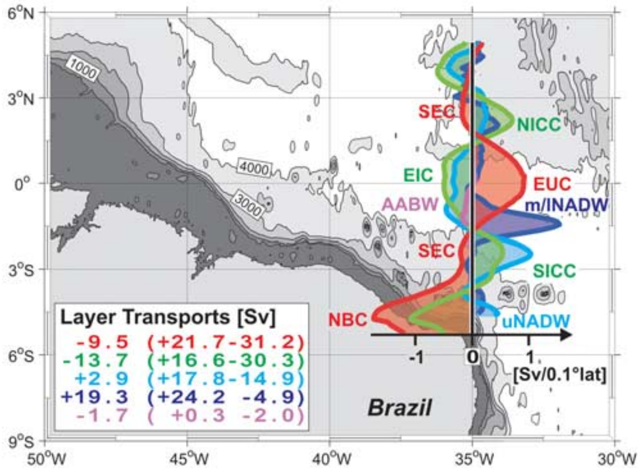

Figure 1. Location of 35°W section and layer transports per 0.1° latitude increments; several current branches are identified (compare with Figure 2); red: upper layers, above σ_θ = 26.8 kgm^{-3}; green: intermediate currents, σ_θ = 26.8 kgm^{-3} − σ_1 = 32.15 kgm^{-3}; light blue: uNADW, σ_1 = 32.15 kgm^{-3} − σ_2 = 37.00 kgm^{-3}; dark blue: middle NADW (mNADW) and lNADW, σ_2 = 37.00 kgm^{-3} − σ_4 = 45.90 kgm^{-3}; magenta: AABW, σ_4 > 45.90 kgm^{-3}. Inset shows net, eastward, and westward total layer transports between the coast of Brazil and 5°N.

horizontal half width scale of 45 km and cut-off scale of 78 km and vertical mapping scales of 80 m for half width and 120 m for cut-off, respectively. Above 300 m vertical mapping scales gradually decreased to 10 m half width and 15 m cut-off scales.

[8] ADCP profiling yielded good-quality data only below 20–25 m, and therefore the surface values had to be estimated by upward extrapolation. Besides the mapping described above and used in the following two other assumptions were tested for the surface layer: constant extrapolation of the 25 m level to the surface and linear shear extrapolation. However, only slight differences were found for the upper layer transport estimates.

[9] The zonal-mean currents were estimated by two different methods. First, by averaging all existing data at each grid point for the arithmetic mean; and second, by assuming that a seasonal cycle exists and can be determined by calculating a mean and annual plus semiannual Fourier harmonics in a five-coefficient fit (Figure 3). As a further constraint, the condition was included that each harmonic also had to retrieve the maximum possible variance (without this constraint, large and dominantly cancelling annual and semiannual harmonics were obtained in parts of the section). While in much of the section the arithmetic means and those determined from the 5-coefficient fit were quite similar, differences of several cm/s occurred in some regions, notably near the equator and the southern boundary.

[10] The transports of the individual current branches identified are marked in Figure 2. Layer transports (in Sv per 0.1° latitude) and their meridional integrals (net, eastward and westward) between the coast and 5°N are shown in Figure 1.

[11] Regarding the interpretation of our seasonal cycle results, caution has to be applied because of the possible contamination by the large intraseasonal variability. The comparison of the harmonic amplitudes on the equator derived from the 35°W sections with current meters from the *Hall et al.* [1997] array from 36°W shows that on the equator at 1300–4100 m depth typically the seasonal cycle explained less than 30% of the zonal current variance (Figure 3a). The moored currents are instead dominated by intraseasonal variability of 1–2 months period, while from the 13 or less of our section points much more of the variance is projected onto the seasonal cycle. There are exceptions, however. For example, near the Parnaiba Ridge more than half of the deep current meter variance is explained by the seasonal cycle. In the following we restrict our presentation to the mean currents, except for the EIC, where particularly drastic seasonal differences among section velocities are found.

3. Results

3.1. The NBC, SEC and Embedded Undercurrents

[12] In the 35°W section mean, a clear separation of the NBC and the SEC located just north of the NBC is not

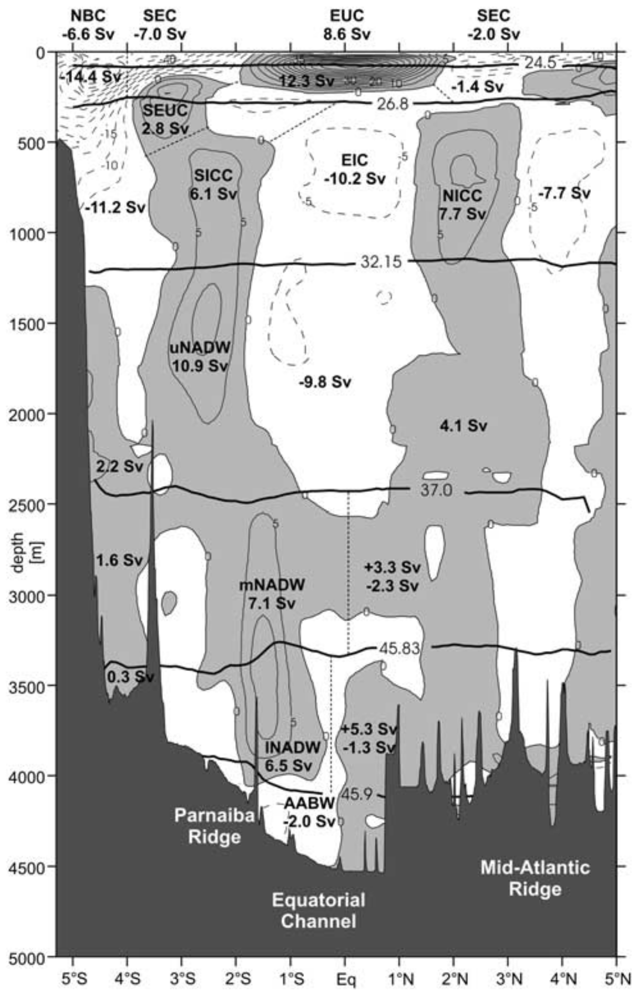

Figure 2. Mean zonal current distribution across 35°W from the 13 sections, with transports (in Sv = 10^6 m^{3}s^{-1}) of the different current branches marked (curves of layer transports are shown in Figure 1).

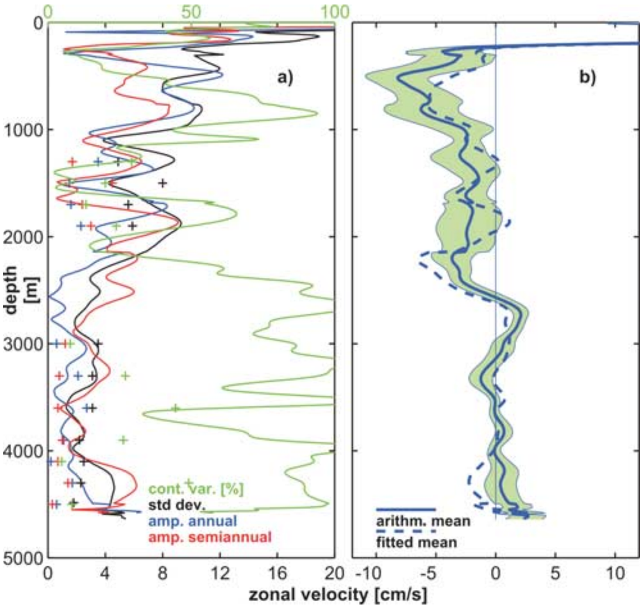

Figure 3. Equatorial profiles of zonal currents at 35°W a) standard deviations (black), amplitudes of annual (blue) and semiannual harmonics (red) and explained variance (green, %, top scale); also shown (crosses) are the corresponding values from moored current time series at 36°W. b) arithmetic mean (solid) and its standard error (shaded); also shown is the mean determined by fit including annual and semiannual harmonics (dashed).

possible (Figure 2). If one limits the NBC to south of 4°S, then its total transport is 32.2 Sv (northwestward) above the $\sigma_1 = 32.15$ kgm^{-3} isopycnal for the section average.

[13] North from there, another 7.0 Sv of SEC flow are added, yielding a total of 39.2 Sv flowing toward the equator in the upper 1200 m and south of 2°S. North of the equator, the northern SEC carries 3.4 Sv westward in the top two layers, augmented underneath by a core in the third layer of 7.7 Sv (Figure 2).

[14] The EUC has a total eastward transport of 20.9 Sv in the mean section, of which 8.6 Sv occur in the near surface layer above $\sigma_\theta = 24.5$ kgm^{-3}. The Intertropical Convergence Zone migrates seasonally from near the equator in boreal spring to near 10°N in boreal summer and fall. Thus, the EUC is sometimes superimposed by an eastward surface jet due to the absence of upwelling-favorable westward wind stress in boreal spring which causes the large fraction of the EUC transport in the surface layer [*Schott et al.*, 1998].

[15] Embedded in the SEC, between 2.5–4°S, is the South Equatorial Undercurrent (SEUC) in the depth range 200–500 m (Figure 2), with a mean transport of 2.8 Sv. In the mean section it can be clearly distinguished from the eastward SICC core, located below and equatorward of it, by a current minimum. The existence of the North Equatorial Undercurrent (NEUC) is more uncertain at 35°W than that of the SEUC, which was found in all the sections. In the overall mean there is an eastward maximum at 4–5°N (Figure 2) that might be associated with the NEUC.

3.2. Intermediate Currents

[16] Below the EUC there is a large depth range of westward mean flow on the equator and to about 1.5° of either hemisphere, down to 2500 m (Figure 2), with a maximum of 7 cms^{-1} near 500 m. This mean is different from zero by more than its standard error (Figure 3b). The part of the westward mean flow above about 1000 m or $\sigma_1 = 32.15$ kgm^{-3} that is typically associated with the EIC carries a mean westward transport of 10.2 Sv. The harmonic analysis of the EIC velocities (Figure 4) suggests strong seasonal variability in the depth range of 700–900 m and within ± 1° of the equator, with maximum westward EIC in boreal fall. This result of minimum or reversing EIC during boreal spring to summer agrees with the float observations of [*Boebel et al.*, 1998] but needs confirmation by more observations, given the large intraseasonal variance and the spring bias in the section coverage.

[17] At 1.5–3.5°S there is an eastward core below the SEUC and above about 1000 m, identified as the SICC, with a mean transport of 6.1 Sv. Its northern hemisphere counterpart, the NICC, is marked by an eastward core between 1.5–3.5°N and carries 7.7 Sv above $\sigma_1 = 32.15$ kgm^{-3}. North of the NICC follows another westward branch of about the same strength.

3.3. Deep-Water and Bottom Water Flows

[18] There are several current branches associated with the southeastward NADW transfer. One is directly along the boundary, in continuation of the DWBC core observed further upstream along 44°W [*Fischer and Schott*, 1997], carrying 4.1 Sv below 1400 m, and the other one is located offshore at 1.5–3.5°S, underneath the SICC (Figures 1 and 2), carrying 10.9 Sv of uNADW between 1200 m and 2400 m. On the equator, underneath the EIC level, there is, however, westward flow of the same magnitude in the uNADW density range.

[19] For the lNADW, below $\sigma_4 = 45.83$ kgm^{-3}, there is only one passage to cross the 35°W section and that is through the "Equatorial Channel" between 1°40′S and 0°40′N (Figure 2). This flow is trapped along the Parnaiba Ridge which forms the southern rim of the Channel [*Rhein et al.*, 1995]. There is a well-defined current core associated with the lNADW and its transport is 6.5 Sv. Between the uNADW and lNADW cores, i.e. between $\sigma_2 = 37.0$ kgm^{-3} and $\sigma_4 = 45.83$ kgm^{-3}, there is a mNADW transport of 7.1 Sv.

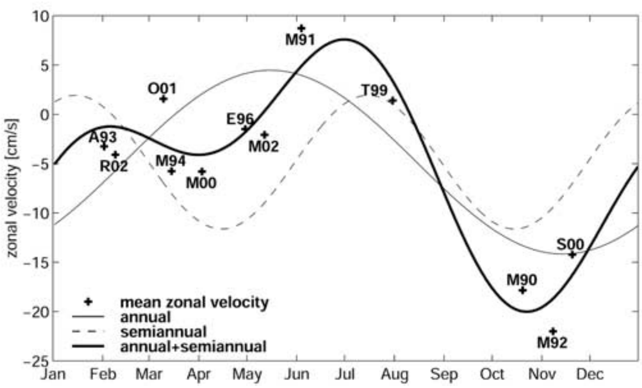

Figure 4. Average EIC velocities at 700–900 m depth and in latitude range 1°S–1°N from 12 ship sections vs. time of year and fit of annual and semiannual harmonics and their superposition; also marked are shipname and year of survey.

[20] The transport of AABW, passing westward through the Equatorial Channel underneath the lNADW, amounts to 2.0 Sv in the section mean, the same value as determined by *Hall et al.* [1997] from a moored array at 36°W.

3.4. Equatorial Zonal Current Profile

[21] An equatorial jet structure as described by *Gouriou et al.* [2001] is not recognizable in the mean, but is present in the individual profiles (not shown). Interestingly, the vertical profile of the standard deviation of the zonal currents shows a pronounced vertical structure with maxima at about 800 m, 1300 m and 1800 m, which is projected by our modal decomposition into large associated variations of the annual and semiannual harmonic amplitudes (Figure 3a). Correspondingly, there is more vertical structure in the mean determined from the 5-coefficient fit than in the arithmetic mean (Figure 3b), but this could, of course, also be caused by intraseasonal variability as discussed earlier. Due to only 9 sections reaching deeper than 2000 m, the 5-coefficient fit projects most of the deep variance onto the seasonal cycle, while only low variance fractions are explained by the seasonal cycle in the moored current meter records (Figure 3).

4. Concluding Remarks

[22] The transport calculation confirms that the 35°W section is a crucial bottle neck for the Atlantic overturning circulation. This is supported by the integral warm water and cold water transports through the section as marked in Figure 1. Adding the transports of the warm water and intermediate water currents above σ_1 = 32.15 kgm^{-3}, or about 1200 m, yields a net westward total transport of 23.2 Sv, and for the NADW layers the net transport is 22.2 Sv to the east.These numbers are of the magnitude as typically quoted for the "conveyor belt" overturning circulation [e.g. *Ganachaud and Wunsch*, 2000; *Lux et al.*, 2001]. However, the uNADW level, in the layer σ_1 = 32.15 kgm^{-3} to σ_4 = 45.83 kgm^{-3}, contributes only a small fraction of 2.9 Sv to the net NADW transfer, with 17.8 Sv flowing eastward and 14.9 Sv westward, suggesting that the deep northern-hemisphere MOC inflow into the tropical zone is mainly transported by the mNADW and lNADW levels. Our result is in good agreement with the inverse study of *Lux et al.* [2001] who find only 4 Sv of uNADW inflow but 20 Sv of mNADW and lNADW inflow from the north across 7.5°N towards the equator and then significant upwelling out of the mNADW and lNADW into the uNADW layer within the equatorial zone.

[23] A nearly closed budget along 35°W between the coast and 5°N would require zero net flux across the 5°N section between 35°W and Africa. Indeed, an evaluation of the 5°N section in the Miami Isopycnic model (MICOM) has yielded good agreement with our observational analysis: While through the 35°W model section south of 5°N about 22 Sv of warm (cold) waters flow westward (eastward), only minor meridional exchange occurs in MICOM across the 5°N latitude between 35°W and Africa [*Z. Garraffo, pers. communication*, 2003].

[24] On the equator, the existence of a mean westward EIC has been established. Furthermore, while the existence of the intermediate countercurrents (SICC, NICC) might have been disputed before, based on the first reports from only a few sections, they are well established in the 12-section mean.

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