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Direct measurements of western boundary currents off Brazil between 20°S and 28°S

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Abstract. Current measurements from three moored arrays on the Brazilian continental slope between 20°S and 28°S are investigated for the existence and strength of western boundary currents from near the surface down to the North Atlantic Deep Water. The Brazil Current is found to deepen southward from 100 m to more than 670 m and to strengthen its volume transport to 16.2×10^6 m^3/s. Antarctic Intermediate Water is transported in a well-developed boundary current southward at 28°S and northward north of Cabo Frio (24°S). This result supports earlier suggestions derived from the analysis of hydrographic data that Antarctic Intermediate Water enters the Brazil Basin from the east and bifurcates as it meets the continental break off Brazil. North Atlantic Deep Water is transported southward in a weakly developed boundary current that leads to lower estimates of volume transport than expected from earlier hydrographic data analysis.

1. Introduction

The South Atlantic is known to be the highway on which the major interoceanic exchange of water masses and, consequently, of heat and salt occurs. As a result of the *Meteor* expedition 1925–1927 into the South Atlantic, *Wüst* [1935] and *Defant* [1936a, b] illustrated the South Atlantic's deep and near-surface circulation, which in its general structure still holds for the subtropical western South Atlantic off Brazil. Much of the associated volume transports is carried in western boundary currents that in early theories are required to balance the interior ocean circulation [*Stommel*, 1948; *Stommel and Aarons*, 1960]. Principally, this concept could apply to all layers of deep and intermediate waters. For the Brazil Basin, one therefore would expect not only the near-surface Brazil Current balancing the wind-driven circulation, but also boundary currents in the layers of the Antarctic Intermediate Water (AAIW), the Upper Circumpolar Deep Water (UCDW), the three layers of the North Atlantic Deep Water (NADW), and the Antarctic Bottom Water (AABW). While deep boundary currents carrying NADW southward and AABW northward have been described in the literature, a northward spreading of AAIW and UCDW within boundary currents has been less studied, and analysis was restricted to hydrographic data. For broad reviews of the present knowledge of the South Atlantic's water masses and general circulation as derived from hydrographic measurements, the reader is referred to *Reid* [1989], *Peterson and Stramma* [1991], *DeMadron and Weatherly* [1994], and *Tsuchiya et al.* [1994].

Few direct current observations were available from the boundary current system along the South American coast when the World Ocean Circulation Experiment (WOCE) began with its Deep Basin Experiment (DBE) in 1990. The then available records from moored current meters show the existence of a deep boundary current that carries bottom water of Antarctic origin equatorward as it enters the Argentine Basin north of the Falkland Ridge [*Whitworth et al.*, 1991], flows along the continental break at 38°S [*Weatherly*, 1993] and at 35°S [*Reid et al.*, 1977], and partly leaves the basin through the Vema Channel into the Brazil Basin [*Reid et al.*, 1977; *Hogg et al.*, 1982]. Within the level of the NADW, the few direct measurements from outside the tropics show poleward flow across the Santos Plateau [*Reid et al.*, 1977]. Farther south, at 38°S [*Weatherly*, 1993], the flow is equatorward, which is consistent with the hypothesis that a poleward boundary jet of NADW occurs further north at about 32°S [see *Weatherly*, 1993].

Within the other three layers, the only reported direct pre-WOCE current measurements made before 1990 stem from a Pegasus system [*Spain et al.*, 1981] that was used in the two western channels of the Vitoria Trindade Ridge (VT, 20°S, Figure 1), and twice off Cabo Frio (CF, 24°S; Figure 1 [*Evans and Signorini*, 1985; *Miranda et al.*, 1985]). As expected, in both regions their profiles show the Brazil Current flowing poleward while the AAIW flow was equatorward at speeds up to 35 cm/s. Only some profiles at the Vitoria Trindade Ridge were deep enough to measure the flow of NADW. These showed poleward flow where the sill depth is deep enough to let it pass.

The analysis of hydrographic data supported the hypothesis that at least part of AABW and NADW is transported by continuous western boundary currents along the South American shelf break [see *Reid*, 1989]. For AAIW, this hypothesis seemed not to hold. Instead, from the hydrographic data available at that time, *Taft* [1963], *Buscaglia* [1971], *Reid et al.* [1977], and *Reid* [1989] found the AAIW flowing equatorward as a boundary only until the confluence zone of the Brazil and Malvinas Currents at about 40°S, where it joins the anticyclonic subtropical gyre circulation. Following the gyre circulation, it then enters the Brazil Basin from the east at about 25°S, approaches the continental break just south of Cabo Frio, and then bifurcates into two branches, one poleward and one equatorward along the Brazilian coast. This scheme has been confirmed with more data by *Warner and Weiss* [1992] and *Suga and Talley* [1995]. Note that for the upper layer, *Tsuchiya* [1985] found that the subtropical gyre consists of two cells that are separated in the Brazil Basin at about the same latitude at

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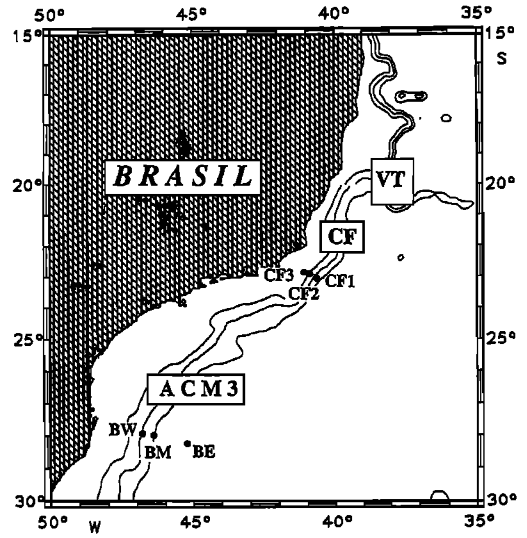

Figure 1a. Location of current meter mooring arrays off Brazil: Vitoria Trindade Ridge (VT; see Figure 1b for details) at 20°S with moorings BS1 and BS2, November 1989 to November 1990; Cabo Frio (CF) at 24°S with moorings CF1/347, CF2/348, CF3/349, September 1992 to August 1993; WOCE array ACM3 with moorings BW/333, BM/334, and BE/335, January 1991 to November 1992. The 200, 1000, and 2000 m depth contours are indicated.

which the AAIW enters the basin. Whether these cells were connected at the western boundary by a boundary current remained unclear from his analysis.

Since 1989, several experiments were carried out within or related to the DBE to directly measure currents within the western boundary currents. From a RAFOS float trajectory analysis, it seems unlikely that AAIW flows as a continuous western boundary current along the western slopes between 25°S and 35°S toward the Equator [*Boebel et al.*, 1997]. However, north of 25°S, *Campos et al.* [1996] quote that 1 year long current meter measurements recently made at the slope show a steady northward flow at the level of the AAIW, which is in agreement with *Reid* [1989]. Further north, one float was launched into the AAIW core off Salvador at 12°S. That float was carried for some 30 days within the boundary current northward until it began to move offshore at about 9°S [*Ollitraut et al.*, 1994].

Also within the DBE, a current meter mooring array was set offshore near the equator [*Schott et al.*, 1993]. While for the AAIW, even the flow direction is unclear due to coarse spatial resolution, the NADW flow direction is pronounced and southward. From 19°S just north of the Vitoria Trindade Ridge, *Harkema and Weatherly* [1996] report data from WOCE array ACM24. Here, the AAIW flows northward as a thin jet, while the NADW is deflected to the deep basin by the ridge on its way south.

To further investigate the vertical structure of the western boundary current system down to the NADW off Brazil between 20°S and 28°S, we use the current measurements from three moored arrays (Figure 1, Table 1): WOCE array ACM3 at 28°S [*Tarbell et al.*, 1994], data from the array CF across the slope off Cabo Frio at 24°S, and data from two moorings in the two western channels of the Vitoria Trindade Ridge (VT) at 20°S [*Hinz et al.*, 1991]. For a discussion of AABW flowing into the Brazil Basin through the Vema Channel, see *Speer and Zenk* [1993], *Zenk and Hogg* [1996], and *Hogg and Zenk* [1997].

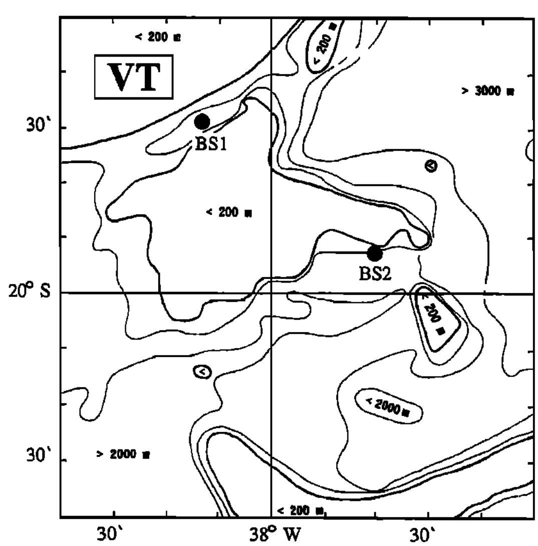

Figure 1b. Location of VT array with moorings BS1/330 and BS2/331 in the two western channels of the Vitoria Trindade Ridge. The 200, 1000, and 2000 m depth contours are indicated.

2. Current Meter Data and Methods

Two moorings were set in the two western channels of the Vitoria Trindade Ridge at 20°S during *Meteor* cruise 11/2 in November 1989 and recovered 1 year later during *Meteor* cruise 14/3 [*Hinz et al.*, 1991], providing record lengths of up to 368 days. Each had two Aanderaa type current meters in the South Atlantic Central Water (SACW) range, one at the core depth of the AAIW and one about 50 m above the bottom. Unfortunately, the two upper instruments of the western mooring (BS1/330) were lost (probably due to fishing), and the meters in the AAIW level of both moorings provided data for only 157 days (BS1/330) and 112 days (BS2/331) due to instrument failure.

The CF array was set from N/Oc. *Prof. W. Besnard* in September 1992 and recovered by the same vessel 1 year later in 1993 with record lengths up to 327 days. It consisted of three moorings that were set on a line normal to the slope at 2260 m (CF1/347), 980 m (CF2/348), and a single instrument mooring on the shelf at 210 m water depth (CF3/349) close to its break. Because of fishing activity, the two uppermost instruments were cut from mooring CF2/348. While the meter at 500 m depth was lost, a fisherman returned the meter from 240 m depth with a 284 day record. Also, the instrument at 920 m of that mooring recorded no data between days 35 and 154 because of a bad piece of tape. To complete the record, the missing 119 days were linearly interpolated between the averages of the two good parts; this procedure does not change the average much but underestimates the variances of the interpolated record.

The WOCE arrays ACM3 and ACM12 were combined to cover a section almost normal to the slope across the Santos Plateau to the Vema Channel. It was set during *Meteor* cruise 15/1 in December 1991 and recovered after 23 months later during *Meteor* cruise 22/3-4 [*Tarbell et al.*, 1994], providing 685 days of data. Since the eastern moorings did not show any

Table 1. Information on Moorings Off the Brazilian Coast Used in This Analysis

Mooring	Latitude, °N	Longitude, °E	Water Depth, m	Record Start Date	Record Days	Instrument Depths, m
VT						
BS1/330	−19.487	−038.203	1076	Nov. 14, 1989	368	775, 1015
BS2/331	−19.890	−037.653	1288	Nov. 15, 1989	364	100, 300, 700, 1200
Cabo Frio						
CF1/347	−23.081	−040.431	2260	Sept. 20, 1992	325	173, 375, 880, 1980
CF2/348	−22.979	−040.704	980	Sept. 19, 1992	327	240, 920
CF3/349	−22.948	−040.811	210	Sept. 19, 1992	327	100
ACM3						
BW/333	−27.910	−046.707	1179	Jan. 1, 1991	683	50, 120, 170, 220, 460, 670, 875
BM/334	−27.987	−046.342	2187	Jan. 1, 1991	682	280, 530, 930, 1430, 2137
BE/335	−28.270	−045.230	3258	Jan. 3, 1991	682	50, 140, 220, 280, 550, 950, 1450, 2545, 3208

boundary current structure above the level of the AABW [see *Tarbell et al.*, 1994], we restrict this analysis to the three western moorings BW/333 at 1179 m water depth, BM/334 at 2187 m, and BE/335 at 3258 m. Both BW/333 and BE/335 carried upward looking acoustic Doppler current profilers (ADCP, 150 kHz) from which we took three bins as characteristic for the flow in the upper 250 m. All other instruments were vector averaging Aanderaa RCM8. All records were complete in this array.

For this analysis, we use low-pass filtered (36 hour cutoff period) daily values. For all moorings but BS1/330, pressure records are available from the upper instruments. They are used to determine time series of depths for all current meters in a mooring. These depths were used when calculating transports within water mass layers. The depth ranges of the water masses are taken from conductivity-temperature-depth (CTD) stations obtained during the mooring cruises. They correspond to *Zangenberg*'s [1995] water mass classification in potential temperature salinity space (see Table 2) and encompass the corresponding core densities of extrema that *Reid* [1989] and *Tsuchiya et al.* [1994] used for their analysis of water mass circulation.

At array ACM3 the pressure records show some severe drawdowns of the current meters during strong current events [see *Tarbell et al.*, 1994]. Worst case estimates show that the associated errors in speed are negligible (<2 cm/s, or 5%, compared to 40 cm/s for the daily values during an event; <1% for the record average). Also, the temperature records show that the uppermost instrument never left the layer of the SACW which would be critical for the transport estimates described below.

The basic statistics of the low-pass filtered daily values are displayed in Table 3. Here SPD and DIR are mean speed and direction of the current vector with east and north components u and v, respectively, and T is in situ temperature (not measured by ADCPs). The directional stability parameter STAB is defined as the ratio of the current's vector and scalar means. STAB = 1 for a current that does not change direction and thus is an indicator for boundary currents that are expected to be directionally stable. Angle brackets denote record averages, and primed quantities are deviations from record means. The timescale is defined as an integral of the autocorrelation function to its first zero crossing. Timescales are calculated for u, v, and T. For the present records, they are of the order of 20 days or less, corresponding to 18 degrees of freedom in a year-long record. From the momentum flux $\langle u'v'\rangle$ and the variances $\langle u'^2\rangle$ and $\langle v'^2\rangle$, the main axis $\langle u'v'\rangle_d$ of momentum flux is estimated. Although the covariance terms with few exceptions are low, they are presented for completeness.

Transport time series are calculated for the layers of SACW, AAIW, UCDW, and NADW at the WOCE ACM3 array, for the layers of AAIW and NADW at the CF array, and for the flow of AAIW through the western channel of the Vitoria Trindade Ridge. Layer thicknesses were kept constant (see Table 2). For the ACM3 and CF arrays, the widths were defined from the distances of the western mooring to the shelf edge, by the halfway distance between neighboring moorings, and by a symmetric extension to the east from the eastern mooring. At the Vitoria Trindade Ridge, the width of the western channel (10 km) is taken to calculate the transport of AAIW through this channel. Velocities used are the current components normal to the mooring sections (parallel to the channel). Velocities are from meters within the layer and from linearly interpolated values at the layer boundaries. For calculations within the SACW, the velocity at the uppermost current meter is assumed constant to the surface. For mean transports the 95% confidence limits are estimated using the maximum of the integral timescales of the current components involved divided by the record length.

Table 2. Water Masses as Defined by *Zangenberg* [1995] Between Levels of Potential Density

Water Mass	Water Mass Classification: Upper Limit, kg/m³	Water Mass Classification: Lower Limit, kg/m³	Depth Interval, m
SACW		$\sigma_0 = 27.10$	0–744
AAIW	$\sigma_0 = 27.10$	$\sigma_0 = 27.35$	744–1062
UCDW	$\sigma_0 = 27.35$	$\sigma_2 = 36.70$	1062–1317
NADW	$\sigma_2 = 36.70$	$\sigma_4 = 45.87$	1317–3406

The corresponding depth levels were used for transport calculations.

3. Description of Flows and Transports

3.1. Subtropical Layer

The subtropical layer encompasses the depth range from the surface to the lower boundary of the SACW (see Table 2). In Figure 2, all vector time series from this depth range as measured in the three arrays are displayed on the same scale. In the north at the Vitoria Trindade Ridge (20°S), measurements are available only from the eastern mooring. Although this posi-

Table 3. Statistics of Low-Pass Filtered (36 Hour Cutoff Period) Daily Averages From Moored Current Meters

			Mean						Standard Deviation			Timescales			Flux			
	Depth	Days	SPD, cm/s	DIR, °N	STAB	$\langle u \rangle$, cm/s	$\langle v \rangle$, cm/s	$\langle T \rangle$, °C	$\langle u'^2 \rangle^{1/2}$, cm/s	$\langle v'^2 \rangle^{1/2}$, cm/s	$\langle T'^2 \rangle^{1/2}$, K	t_{ud}	t_{vd}	t_{Td}	$\langle u'v' \rangle$, cm/s^2	$\langle u'v' \rangle_d$, °N	$\langle u'T' \rangle$, K cm/s	$\langle v'T' \rangle$, K cm/s
									Vitoria Trindade Ridge									
BS1/330	775	157	20.8	64	0.93	18.7	9.1	4.4	10.5	5.2	0.2	4	4	2	47	66	−0.1	0.1
	1015	368	0.7	181	0.19	−0.0	−0.7	3.7	4.1	1.8	0.1	1	1	22	5	72	0.1	0.1
BS2/331	100	364	8.5	97	0.73	8.4	−1.0	21.0	10.2	5.0	0.7	4	4	16	6	86	0.1	−1.4
	300	364	2.5	297	0.20	−2.3	1.1	13.0	13.7	6.0	0.5	3	7	20	23	82	−0.5	−0.1
	700	112	6.1	309	0.46	−4.7	3.8	4.9	12.0	6.0	0.2	3	3	1	−23	−78	0.1	−0.1
	1200	364	0.6	280	0.18	−0.5	0.1	3.6	3.3	1.5	0.0	2	1	23	1	83	−0.0	−0.0
									Cabo Frio									
CF1/347	173	325	14.9	255	0.87	−14.4	−4.0	19.2	10.3	7.1	1.0	19	3	7	5	85	1.3	1.1
	375	325	4.8	310	0.55	−3.7	3.1	12.7	6.8	5.4	0.4	21	7	4	17	58	0.8	0.7
	880	325	8.6	35	0.97	4.9	7.1	3.5	3.1	2.8	0.1	8	9	5	5	50	0.1	0.1
	1980	325	4.3	234	0.53	−3.5	−2.5	3.6	6.8	5.8	0.1	5	4	5	35	50	0.1	0.1
CF2/348	240	284	7.8	311	0.80	−5.9	5.1	17.5	6.7	4.0	1.1	14	11	3	−3	−85	−1.9	−0.1
	940	327	12.2	60	0.95	10.5	6.2	4.2	6.8	4.0	0.2	3	3	3	26	60	0.3	0.1
CF3/349	100	327	13.8	238	0.68	−11.7	−7.3	20.5	14.2	11.7	1.7	15	12	4	116	53	−11.6	−8.1
									ACM-3									
BW/333	50	685	44.7	213	0.70	−24.3	−37.6		30.8	43.1	0.0	2	2		117	7		
	120	685	34.3	208	0.87	−15.9	−30.4		16.5	22.3	0.0	4	7		65	15		
	170	685	31.9	208	0.87	−15.1	−28.1		14.5	20.2	0.0	4	8		49	13		
	220	682	29.9	209	0.90	−14.3	−26.2	16.9	11.0	17.4	1.3	6	10	14	52	15	−0.5	−2.2
	460	682	16.0	212	0.88	−8.5	−13.6	11.1	5.4	10.7	0.9	4	10	7	18	11	−0.4	−1.6
	670	682	6.1	212	0.64	−3.3	−5.1	6.9	3.4	8.9	0.6	3	8	22	−2	−1	0.2	−2.0
	875	682	2.0	296	0.24	−1.8	0.8	4.6	2.2	9.8	0.2	3	8	7	−8	−5	0.1	−1.3
BM/334	280	682	10.3	214	0.65	−5.8	−8.5	15.3	10.4	11.9	1.8	7	8	9	−13	−18	2.6	6.0
	530	682	7.9	218	0.68	−4.8	−6.2	10.4	6.8	8.5	1.4	7	8	11	−3	−6	1.1	2.2
	930	682	3.7	218	0.59	−2.3	−3.0	4.5	4.1	6.0	0.3	5	8	10	2	5	−0.0	−0.0
	1430	682	3.2	202	0.57	−1.2	−3.0	3.5	2.9	5.3	0.1	5	7	12	7	17	−0.0	−0.0
	2137	682	1.2	15	0.30	0.3	1.2	3.6	2.3	4.6	0.1	4	5	11	9	25	−0.0	−0.0
BE/335	50	682	2.2	11	0.10	0.4	2.2		19.7	17.7	0.0	17	6		49	63		
	140	682	1.9	339	0.09	−0.7	1.8		18.8	15.1	0.0	15	6		28	78		
	220	682	1.0	339	0.06	−0.4	0.9		14.9	11.8	0.0	22	8		20	77		
	280	681	1.8	314	0.12	−1.3	1.2	15.1	13.3	10.2	1.1	23	9	13	23	74	−3.6	−2.4
	550	681	1.2	288	0.14	−1.2	0.4	10.3	8.9	6.2	1.0	23	9	19	6	81	−2.2	−1.0
	950	681	1.5	253	0.31	−1.5	−0.5	4.3	5.2	3.1	0.2	24	8	12	1	88	0.0	−0.0
	1450	681	3.5	247	0.60	−3.2	−1.4	3.3	4.4	4.0	0.2	19	8	35	2	63	0.1	−0.1
	2545	681	2.5	238	0.52	−2.2	−1.4	3.2	2.8	4.7	0.1	9	9	25	1	3	−0.1	−0.0
	3208	681	4.8	20	0.81	1.6	4.5	1.2	2.2	5.3	0.3	5	6	10	11	21	−0.2	−0.6

SPD and DIR are the current mean speed and direction with east component u and north component v; T is temperature; STAB is the directional stability defined as ratio of mean vector speed and mean scalar speed; angle brackets denote averages, deviations from means are primed; from the momentum flux $\langle u'v' \rangle$ and the variances $\langle u'^2 \rangle$ and $\langle v'^2 \rangle$, the main axis $\langle u'v' \rangle_d$ of the momentum flux is derived.

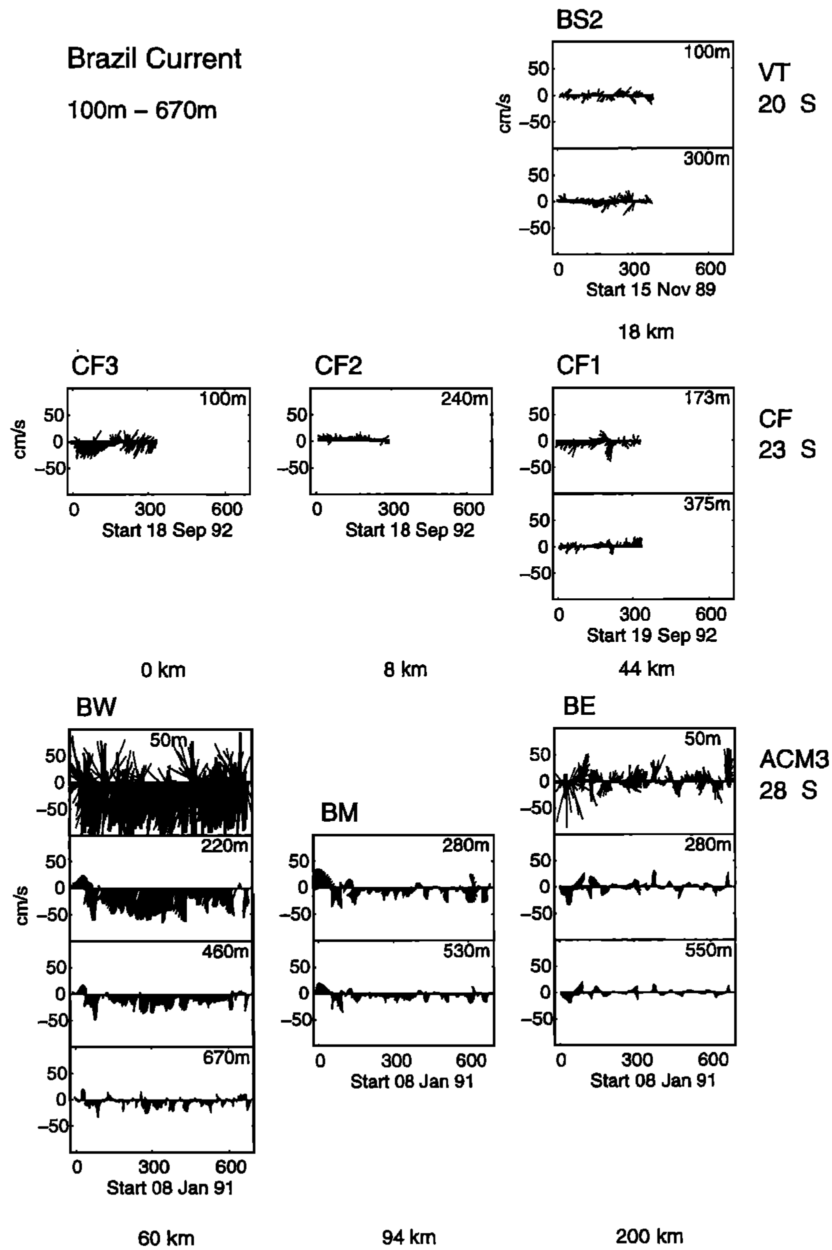

Figure 2. Vector time series (northward direction points upward) of low-pass filtered daily mean currents within the depth range of the South Atlantic Central Water (SACW) and the Brazil Current regime, 100–670 m. The plots are arranged from VT (north, top), to CF (middle) to ACM3 (south, bottom), and from east (right) to west (left). Within moorings, lowest levels are top. Distances of mooring sites from the shelf edge (200 m depth contour) are indicated.

tion is not in the core of the Brazil Current that may be expected further west on the continental slope [*Miranda and Castro Filho*, 1982; *Evans et al.*, 1983], part of the current obviously is deflected by the ridge to the east. This is suggested from the measured mean current of 8.5 cm/s toward 97° in the upper 100 m with relative high directional stability (STAB = 0.73) over 1 year. Also, the current is shallow and does not reach the 300 m level.

Further south, in the year-long records at Cabo Frio (23°S), the current still is shallow, with mean speeds of about 14 cm/s at both, 100 m depth on the shelf (mooring CF3, STAB = 0.68) and at 173 m depth over the continental break (mooring CF1, STAB = 0.87). The current is replaced at the central mooring CF2 (240 m depth) by a high stability (0.80) onshore (311°) flow. This flow compensates for upwelling off Cabo Frio [*Ikeda et al.*, 1974]. Upwelling events may also be documented by the large temperature flux on the shelf position CF1.

At 28°S (WOCE array ACM3) the Brazil current has increased in strength as well as depth. It is confined to the shelf edge (mooring BW), where the current reaches from the surface (mean speed up to 44.7 cm/s) down to at least 670 m (6.1 cm/s). Its direction is rather stable (0.64–0.90) for 23 months, with the few reversals of flow restricted to near the surface. At larger depths, only one reversal is observed at the beginning of the record; the current keeps its direction for 20 months in its core. The current decreases in strength very quickly at 94 km

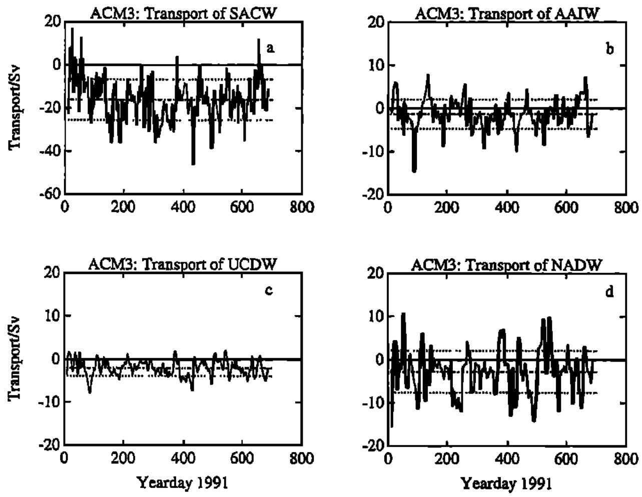

Figure 3. Time series of transports at WOCE array ACM3 within (a) the South Atlantic Central Water (SACW), (b) the Antarctic Intermediate Water (AAIW), (c) the Upper Circumpolar Deep Water (UCPDW), and (d) the North Atlantic Deep Water (NADW). The means and standard deviations are indicated by the broken and the dotted lines, respectively; 1 Sv = 10^6 m^3/s.

off the shelf edge (mooring BM, 10.3 cm/s at 280 m, 7.9 cm/s at 530 m), and it vanishes almost completely at 200 km off the shelf at mooring BE, where mesoscale eddies dominate and directional stability is low.

Many estimates of the Brazil Current's transport suggest an increase toward the south. Some values reported from geostrophic calculations are 4 Sv at 20°S [*Stramma et al.*, 1990], around 10 Sv at 23°S and 24°S [*Stramma*, 1989], 7.3 Sv at 25°S [*Campos et al.*, 1995], 20 Sv at 30°S across the western part of the WOCE section A10 until 43°W [*Zangenberg*, 1995], and 24 Sv at 34°S [*Zemba*, 1991]. Part of the increase may to be due to a recirculation cell [*Tsuchiya*, 1985; *Reid*, 1989; *Stramma*, 1989].

The WOCE moored array ACM3 for 23 months shows the eastern boundary of the Brazil Current between moorings BM and BE, and maximal flow at the western mooring BW (Figure 2, Table 3). It is unknown how far the Brazil Current extends onto the shelf in the west, but it seems reasonable to assume that the shelf edge marks the western boundary of the current. In Figure 3a, we show the horizontally integrated transport time series for the SACW layer (see Table 4 for parameters and single mooring averages). The transport is poleward during almost the whole record with exceptions of a few days only. The 23 month average is −16.2 Sv (poleward), to which the measurements at the western position BW contribute 80%. The standard error of the average induced by the fluctuative part of the flow is 2.4 Sv at the 95% confidence limit. In addition, a systematic error must be considered that stems from the assumed geometry, especially from the assumption on the westward extension at BW, where the mean flow is largest. Reducing the westward extension at BW from the shelf edge to a symmetric one would reduce the poleward transport at BW from −12.6 Sv (see Table 4) to −5.7 Sv, and decrease the total transport to −9.3 Sv. This value is close to the value (−9.5 Sv) that *Holfort* [1994] found from ACM3 data assuming a symmetric extension at BW, and it may be considered as a lower limit of the transport estimate. Note that since the poleward flow was strongest in the upper layers around BW and weaker in the lower parts of the SACW (see Table 3), different assumptions on the depth of the lower boundary of the SACW have less effect on the calculated transport (~1 Sv for 140 m less depth of the lower boundary for ACM3).

Fluctuations of transport (1 standard deviation; see Table 4) range from −7 to −26 Sv (Figure 3a). No obvious annual signal can be detected; however, note a timescale much larger than 1 year in the series with the maximum southward transport occurring around day 300, even northward transport at the beginning of the series, and low values also at the end of the record (Figure 3a).

3.2. Intermediate Layers

The next two layers encounter the AAIW and the UCDW (Table 2). Starting in the south (28°S), the observations of ACM3 show alternating currents between −20 and 20 cm/s near the bottom at BW (Figure 4). The mean is weak (2.0 cm/s)

Table 4. Transport Calculations Where Appropriate in Layers of Water Masses for the Three Arrays VT, CF, ACM3

				Transport, Sv			
Array	Mooring	Rotation Angle	Width, km	SACW	AAIW	UCDW	NADW
VT	BS1/330	35	10		0.7		
	SD				0.3		
	SE				0.1		
CF	CF1/347	25	32		0.8		−0.5
	CF2/348	25	22		0.5		
	Total		62		1.3		−0.5
	SD				0.4		1.6
	SE				0.1		0.3
ACM3	BW/333	20	77	−12.6	−0.2		
	BM/334	20	70	−4.2	−1.0	−1.1	−0.3
	BE/335	20	106	0.6	−0.2	−0.9	−2.5
	Total		253	−16.2	−1.4	−2.0	−2.8
	SD			9.4	3.4	1.9	4.9
	SE			2.4	0.5	0.3	0.8

All transports in Sv (1 Sv = 10^6 m^3/s). Standard deviations (SD) and standard errors (SE) due to fluctuations (on the 95% confidence level) are also given. The width of the western channel of the Vitoria Trindade Ridge within the AAIW layer is less (10 km) than that between the 200 m depth contours (14 km).

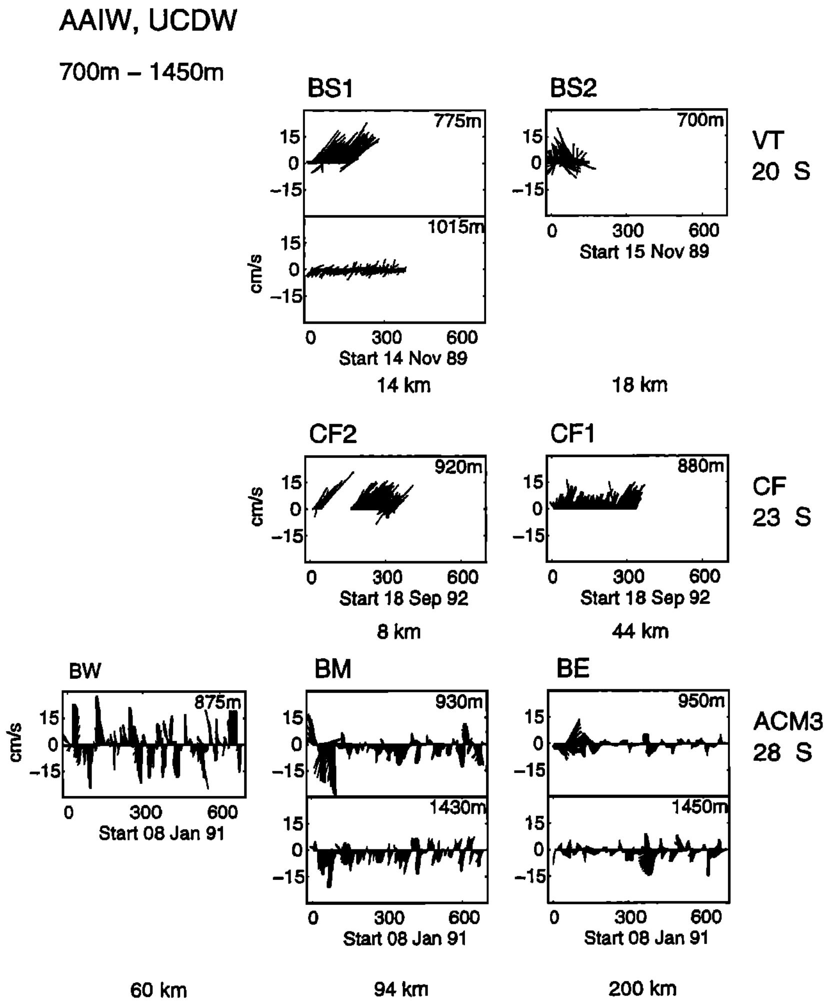

Figure 4. Same as Figure 2 but for AAIW and UCDW.

and poleward. Further off the shelf edge at BM, the mean flow is poleward in both layers at higher directional stability (about 0.57) and higher mean speed (about 3.5 cm/s). At the deepest mooring (BE), the flow in both layers is still poleward at 1.5 cm/s for the AAIW and 3.5 cm/s for the UCDW. Amplitudes of the speed again reach 15 cm/s. Directional stability for the UCDW is higher (0.60) than for the AAIW (0.31). The core of the AAIW poleward flow seems to be close to mooring BM.

Further north, at mooring arrays CF and VT the flow of intermediate waters is equatorward. We observed permanent and directional mostly stable (larger 0.95) equatorward flow of AAIW with almost no reversals off Cabo Frio. The mean is slightly higher in the center mooring CF2 than on site CF1 (12.2 cm/s for the interpolated series and 8.6 cm/s, respectively). At the Vitoria Trindade Ridge the western channel is deep enough (sill depth 950 m) to let the AAIW pass. The 157 day long record at BS1 shows stable (0.93) and northward flow of AAIW through this channel, with extremely high mean speed of 20.8 cm/s. In the second channel at BS2 the situation is not that pronounced. The mean flow of AAIW seems to pass the channel equatorward (309° due to topography) at 6.1 cm/s; however, the variability is high and stability is relatively low.

At ACM3 the predominant flow of both the AAIW and the UCDW is poleward. The resulting transport time series (Figures 3b and 3c) show higher variability in the AAIW layer than in the UCDW layer. The central mooring contributes most of the transport within the AAIW. The mean transport is southward in both layers, with a contribution of −1.4 Sv from the AAIW and −2.0 Sv from the UCDW (Table 4). The total of −3.4 SV (AAIW and UCDW) with low standard error (0.5 Sv) compares well with a result from a geostrophic calculation [*Zangenberg*, 1995] of −4 Sv at 30°S west of 43°W from WOCE section A10.

At Cabo Frio the transport of AAIW is permanently northward (Figure 5a; Table 4), with 1.3 Sv on average (0.1 Sv standard error) and with a standard deviation of 0.4 Sv. In the western channel of the Vitoria Trindade Ridge, an average northward transport of 0.7 Sv was observed (standard error 0.1 Sv; Figure 5c). As the average transports at Cabo Frio and through the channels of the VT regions should be similar, it is probable that part of AAIW also passes through the eastern channels of the Vitoria Trindade Ridge. However, the measurements at BS2 in the second channel are too variable and too short to give a reasonable transport estimate for that channel.

3.3. North Atlantic Deep Water

Flow of NADW was observed off Cabo Frio and in the ACM3 array (Figure 6). Off Cabo Frio at CF1, we find NADW flowing southward in the mean (4.3 cm/s) with high variability

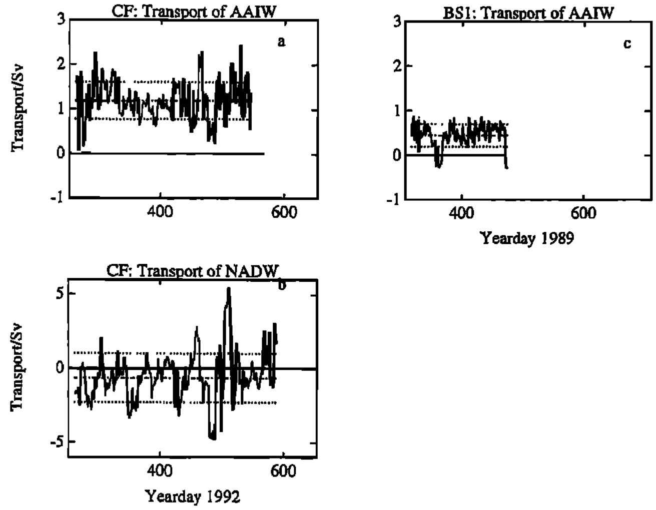

Figure 5. Same as Figure 3 but for the CF array within (a) the AAIW and (b) the NADW and (c) in the western channel of the Vitoria Trindade Ridge within the AAIW.

(±15 cm/s) and relative low stability (STAB = 0.53). From these measurements, it remains unclear if a boundary current of NADW is well developed off Cabo Frio. The measurements from the WOCE array ACM24 at 19°S north of the Vitoria Trindade Ridge [*Harkema and Weatherly*, 1996] show a well-developed deep western boundary current within the NADW layer that must be deflected to the east by the ridge system.

At ACM3 the NADW flows poleward in the mean. However, as at Cabo Frio, the flow is variable and the resulting poleward transport is weak (−2.8 Sv, with 4.9 Sv standard deviation and 0.8 Sv standard error, Figure 3d, Table 4). Geostrophic transport estimates at 30°S from WOCE section A10 give −10 Sv west of 41°W [*Zangenberg*, 1995], which due to a return flow decreases to −6.3 Sv if integrated across the whole western basin [*Zangenberg and Siedler*, this issue]. None of the direct measurements from WOCE array ACM12, which has been east of ACM3 at the same time and which covered the Santos Plateau until the Vema Channel, show a pronounced permanent poleward flow within the NADW layer [*Tarbell et al.*, 1994]. It therefore seems that south of the Vitoria Trindade Ridge, NADW starts to lose its characteristics

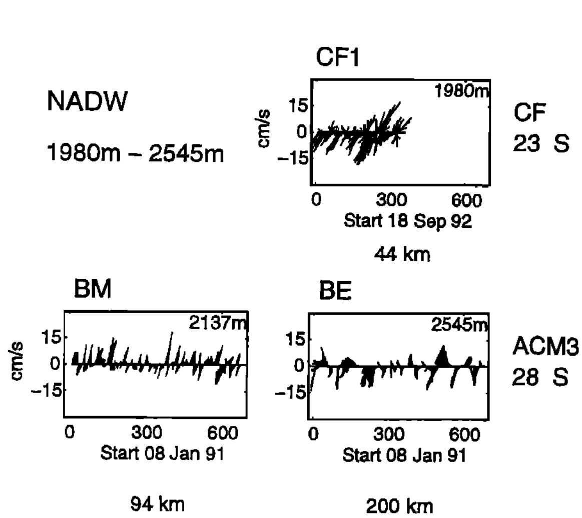

Figure 6. Same as Figure 2 but for the NADW.

of a well-developed western boundary current. It may even not reach the Malivinas and Brazil Current Confluence Zone [*Weatherly*, 1993]. *Zangenberg and Siedler* [this issue] argue that conservation of potential vorticity in the presence of the Vitoria Trindade Ridge and the Santos Plateau forces the NADW to leave the shelf break and to flow eastward and northeastward.

4. Conclusions

The direct measurements in three moored current meter arrays between 20°S and 28°S on the Brazilian continental slope establish the deepening and strengthening of the Brazil Current from 20°S to 28°S. At 28°S the records of 23 months' length show that it is a permanent boundary current that reaches down to more than 670 m, with an estimate of 16 Sv poleward transport west of 45°W (position BE).

For the layers of the AAIW and UCDW the direct measurements correspond well with the circulation pattern for the AAIW that was suggested from geostrophic and water mass analysis by *Reid* [1989] and confirmed later by *Suga and Talley* [1995]. It is also consistent with the results that *Boebel et al.* [1997] achieved from an analysis of WOCE float trajectories. The question that was posed by *Warner and Weiss* [1992] in their final figure for the path of the AAIW circulation off CF can be answered from direct measurements. The AAIW and the UCDW enter the southern Brazil Basin from the east [*Boebel et al.*, 1997] and split into two branches along the continental slope. One branch turns poleward and passes WOCE array ACM3 at 28°S with 3.4 Sv. The other branch is directed equatorward already at 25°S [*Campos et al.*, 1996], and it is well established as a boundary current at array CF off Cabo Frio at 24°S with a transport of at least 1.3 Sv and through the western channel of the Vitoria Trindade Ridge. Recently repeated measurements off Cabo Frio confirm the equatorward flow of intermediate waters (J. Lima and J. H. Middleton, personal communication, 1997).

Although a deep western boundary current carrying NADW is well established north of the Vitoria Trindade Ridge [*Harkema and Weatherly*, 1996], we were not able to identify it as clearly south of the ridge. It may exist on the slope at Cabo Frio east of array CF. At 28°S (ACM3), it is only weakly developed, with much less mean poleward transport (−2.8 Sv) than expected from geostrophic estimates [*Zangenberg and Siedler*, this issue], and with several reversals toward north. It remains unclear from the direct measurements along 28°S in ACM3 and ACM12 [see *Tarbell et al.*, 1994] if and where the NADW is transported southward in a more pronounced western boundary current.

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