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Geostrophic circulation of the Brazil–Falkland confluence

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Abstract—The Brazil Current geostrophic volume transport, relative to 1400 m across 38°S, of $19 \times 10^6\ m^3\ s^{-1}$ towards the south, represents an increase of approximately $12 \times 10^6\ m^3\ s^{-1}$ over the transport across 19–24°S. The increase is less than that found for the Gulf Stream, but the 5% growth rate per 100 km is similar. This increase may be associated with a recirculation cell in the South Atlantic. Near 38°S, the Brazil Current encounters the northward flowing Falkland Current. At this confluence both currents separate from the continental margin, with the Brazil Current continuing poleward before looping back to the north, forming a large quasi-stationary extension of South Atlantic Central (thermocline) Water. Numerous warm core eddies are observed near this feature. The extension stands 70 dyn cm above the axis of the cyclonic trough formed by the Falkland Current and its return to the south. The transport of the Falkland Current, relative to the 1400 m level (or sea floor is shallower) across 46°S, is $10 \times 10^6\ m^3\ s^{-1}$ or about half of the Brazil Current transport.

INTRODUCTION

THE BRAZIL Current, the western boundary current of the South Atlantic Subtropical Gyre, begins at the bifurcation of the South Equatorial Current near 8°S. It remains in contact with the continental margin to 38°S, extending over a distance of 3800 km before it encounters the northward flowing Falkland Current.

MIRANDA and FILHO (1981) determined a $5.5 \times 10^6\ m^3\ s^{-1}$ geostrophic volume transport across 19°S, with a maximum surface velocity of 72 cm s^{-1}, relative to the 130 cl ton^{-1} isosteric level (sigma-*t* of approximately 26.75) corresponding to the thermocline oxygen minimum near 500 m. The transport relative to 600 m, adjacent to Capo Frio (24°S), is $9.4 \times 10^6\ m^3\ s^{-1}$, contained in two branches with a peak surface geostrophic velocity of 55 cm s^{-1} (SIGNORINI, 1978). Two other hydrographic sections, within 60 km of that section, yield somewhat lower volume transports of 6.8 and $7.5 \times 10^6\ m^3\ s^{-1}$ also relative to 600 m (SIGNORINI, 1978). EVANS *et al.* (1983), using XBT and hydrographic sections from 19 to 24°S in conjunction with the regional potential temperature–salinity (θ–S) relation, found 3.8–6.8 $\times 10^6\ m^3\ s^{-1}$ relative to 500 and 1000 m, respectively, with 50 cm s^{-1} maximum surface velocity. EVANS and SIGNORINI (1985) found support for these estimates from direct current measurements of up to 50 cm s^{-1} in the surface current axis near 23°S, with a transport of $6 \times 10^6\ m^3\ s^{-1}$ seaward of the 200 m isobath and another $5 \times 10^6\ m^3\ s^{-1}$ over the continental margin. Thus a volume transport of $7 \times 10^6\ m^3\ s^{-1}$ with a maximum speed of 1 kn is characteristic of the Brazil Current as it crosses the 19–24°S zone.

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FU (1981), applying inverse methods to the trans-Atlantic IGY and *Meteor* hydrographic data, showed no Brazil Current north of 25°S. Possibly the Brazil Current north of 25°S is composed of a series of eddies drifting poleward rather than a well-defined quasi-steady state current. At the Abrolhos Banks at 20°S, the Brazil Current exhibits many meanders and eddies (SIGNORINI, 1978; MIRANDA and FILHO, 1982). These results are supported by ship drift data (WYRTKI *et al.*, 1976) and FGGE drifter data (PATTERSON, 1985) which shows a high ratio of eddy kinetic to mean kinetic energy. MELLOR *et al.* (1982) calculated the Atlantic Ocean general circulation using a geostrophic diagnostic model, with wind stress and realistic bottom topography. Their results indicate an intensified Brazil Current south of Capo Frio with the maximum transport of the South Atlantic Subtropical Gyre between 20 and 35°S within 300 km of the continental margin. Inspection of their transport stream function yields a Brazil Current flux in excess of 60×10^6 m^3 s^{-1} in this zone, a value much above the estimates based on hydrographic data for the baroclinic component. HELLERMAN and ROSENSTEIN's (1983) determination of the wind stress curl of the South Atlantic yields a maximum Sverdrup transport at 30°S of 30×10^6 m^3 s^{-1} with 20×10^6 m^3 s^{-1} at 24°S. While their value is half that of MELLOR *et al.* (1982), it is still significantly above hydrographic based estimates.

Near 38°S, the Brazil Current separates from the continental slope as it encounters the northward flowing, cold Falkland (Malvinas) Current, forming a major frontal confluence of subtropical and subantarctic water (BRENNECKE, 1921; DEACON, 1937; LEGECKIS and GORDON, 1982). The two currents turn seaward after the encounter, with the

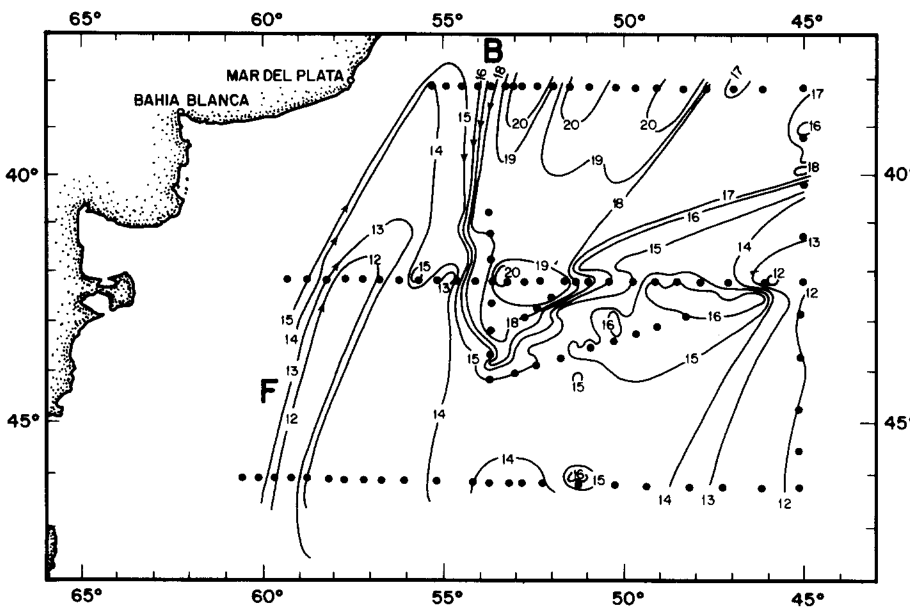

Fig. 1. Sea surface temperature from XBT and CTD stations obtained from the R.V. *Atlantis II* during cruise 107-3, 10 December 1979; 10 January 1980 (GUERRERO *et al.*, 1982). The dots represent the CTD station positions (see Fig. 2b for station numbers). A schematic representation of the Brazil (B) and Falkland (F) currents' location and direction is given by arrows superimposed on isotherms.

poleward momentum of the Brazil Current usually dominating and forcing further poleward movement of warm water (Fig. 1). After attaining a latitude well south of 40°S, the Brazil Current water executes an anticyclonic turn to the north, establishing a quasi-stationary meander of the subtropical South Atlantic Central (thermocline) Water, SACW aligned along the 53°W meridian. The poleward extension of the Brazil Current is characterized by a complex array of eddies and filaments (LEGECKIS and GORDON, 1982). To the west of the Brazil Current extension is a cyclonic trough of cold subantarctic water formed by the Falkland Current and its return. An overview of the regional oceanography (water masses and stratification) is provided by REID *et al.* (1977), GORDON (1981) and GEORGI (1981).

In this study, the relative geostrophic circulation or baroclinic structure of the Brazil–Falkland Confluence is presented based on CTD/Rosette hydrographic data obtained from R.V. *Atlantis* II cruise 107-3 in December 1979–January 1980 (GORDON, 1981; GUERRERO *et al.*, 1982). An additional objective of this paper is to determine the relative geostrophic transport within the thermocline layer of the Brazil Current near its separation point. This transport is then compared to the Brazil Current transport further upstream to quantify along-axis transport variations.

RELATIVE DYNAMIC TOPOGRAPHY

The anticyclonic structure of the Brazil Current extension and the cyclonic trough associated with the Falkland Current are clearly portrayed by the relative dynamic topography (Fig. 2). The pattern is similar to that of sea surface temperature (Fig. 1).

Table 1. FGGE (First Global Garp Experiment) Drifters

Drifter	Area	Days in region Julian days (Total days)	Ave. Vel. (cm s^{-1})
17622	Region	352/78–145/79	
	Falkland Current	352 – 8 (21)	40.3
	Falkland Return	8 – 17 (9)	54.7
	Brazil Return	17 – 61 (44)	27.2
	At Confluence	15 – 20 (5)	97.9
17623	Region	351/78–150/79	
	Brazil Current	15 – 28 (13)	68.0
	Brazil Return	28 – 46 (18)	63.8
	At Confluence	21 – 32 (11)	84.9
	Eastward Drift	46 – 76 (30)	40.4
17649	Region	192/79–311/79	
	Falkland Current	198 – 222 (24)	35.4
	Falkland Return	222 – 229 (7)	64.9
	Eddy (46°S, 50°W)	229 – 260 (31)	45.4
	Eastward Drift	262 – 311 (49)	30.0
17662	Region	181/79–1/80	
	Eddy	206 – 312 (106)	33.7
	Eastward Drift	313 – 364 (51)	33.8
17764	Region	32/79–115/79	
	Brazil Return	32 – 50 (18)	42.0
	Eastward Drift	92 – 115 (23)	50.2

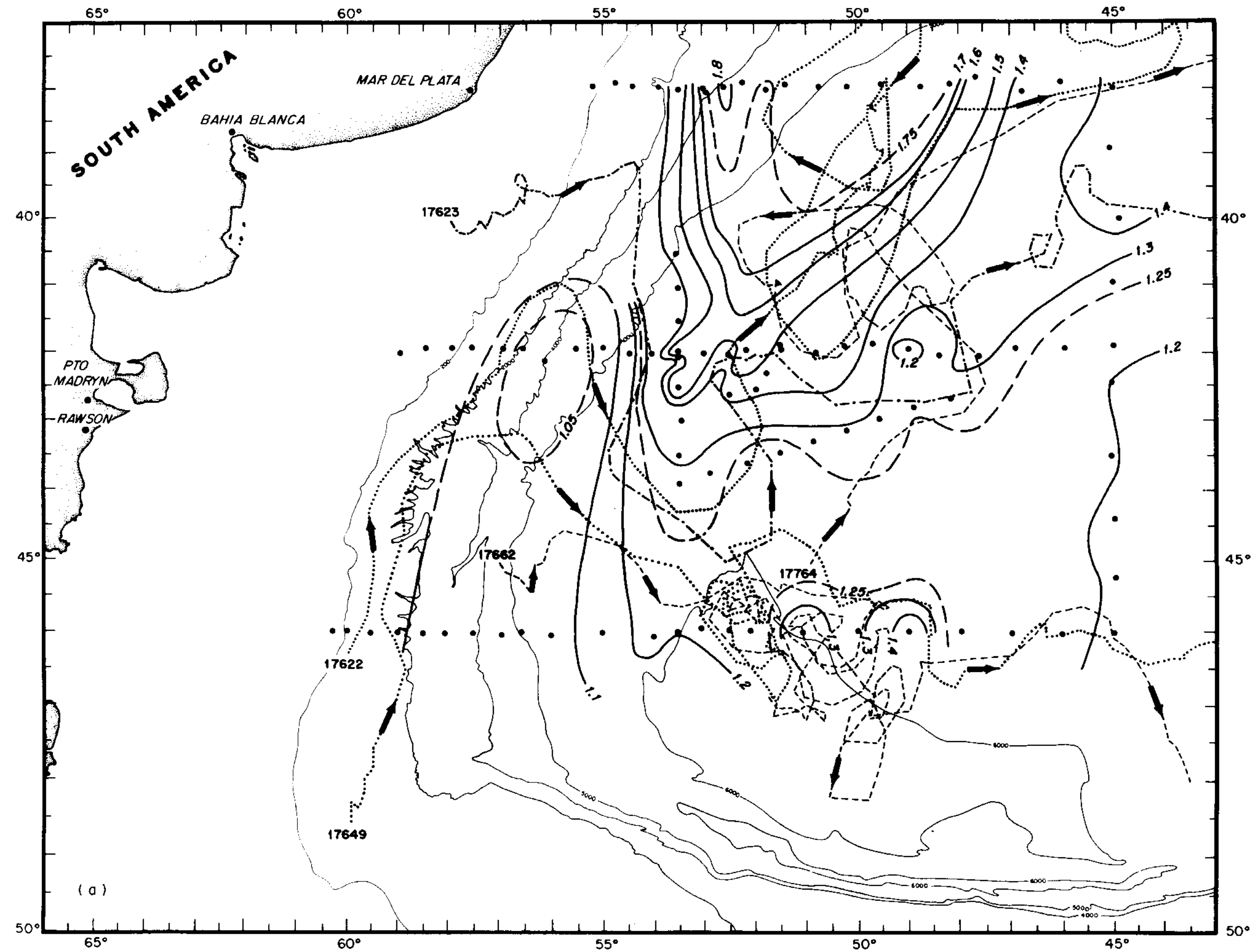

Fig. 2a. Dynamic topography of the sea surface relative to 1400 m in dyn m. The finer dotted and dashed lines represent FGGE drifter trajectories (Table 1).

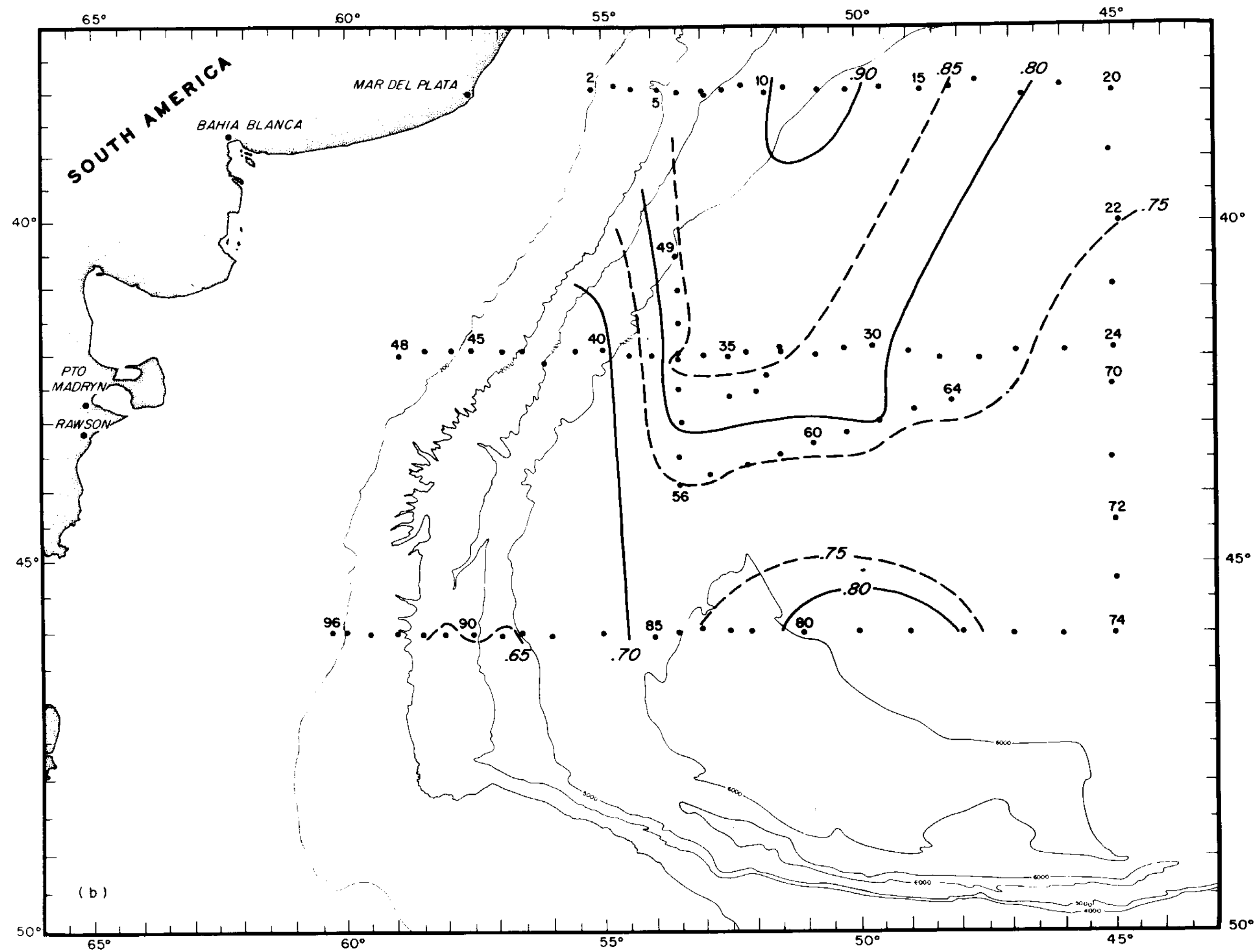

Fig. 2b. Dynamic topography of the 1400 m surface relative to 3000 m, given in dyn m. The numbers for the CTD stations (dots) are shown.

The warm surface water of the Brazil Current extension stands 70 dyn cm above the cold subantarctic water relative to the 1400 m level. The baroclinic pattern of 1400/3000 m is similar, with a total relief of 25 dyn cm.

The geostrophic streamlines associated with the Brazil Current inflow across 38°S (1.4–1.8 dyn m in Fig. 2a) exit the station array across the northern boundary, though all other streamlines exit via the eastern boundary with significantly reduced baroclinicity. The 1.3 and 1.4 streamlines sharply diverge east of 49°W marking the division between the warm Brazil Current and the colder Falkland Current. The anticyclonic circulation extends to the southern section at 46°S, with a pair of anticyclonic eddies observed along 46°S near 50°W. These eddies are also apparent in the 1400/3000 m interval indicating a deep reaching baroclinic effect.

Trajectories of a representative set of undrogued FGGE drifters (Table 1; GARRETT, 1980) follow the general confluence flow pattern (Fig. 2a). Drifters 17622 and 17649 traveled cyclonic paths associated with the Falkland Current trough. Drifter 17622 was joined by 17623 in following the anticyclonic loop of the Brazil Current extension. Drifters 17649 and 17662 were captured by the anticyclonic eddies along 46°S and then ejected to drift towards the east. The two drifters remained in eddies for 31 and 106 days, respectively. Assuming the drifters were in the same eddies revealed 3 months later (Table 1) by the hydrographic data, the eddy translational velocity is approximately 4 km day^{-1} towards the east.

GEOSTROPHIC VELOCITY AND TRANSPORT

Geostrophic velocity and volume transport across the three zonal sections (38, 42 and 46°S) relative to 1400 m provide a view of the thermocline baroclinic structure (Fig. 3) of the Brazil–Falkland Confluence region. The deepest common depth is taken as the reference level if it is shallower than the designated reference level. The 1400 m reference level allows higher horizontal resolution as it employs the full set of hydrographic data (only 40% of the stations reach beyond this depth to the sea floor). The sea surface dynamic height calculated relative to 1400 m represents on average 63% of the sea surface dynamic height relative to the deep reference level at 3000 m. Thus the 0/1400 m map serves as a useful representation of the overall thermocline geostrophic flow.

38°S (*Fig.* 3a)

The most intense geostrophic shear is associated with the poleward flowing thermocline water within the Brazil Current between Stas 6 and 8 and its return flow between Stas 16 and 18. The maximum surface flow within each component is 74 and 52 cm s^{-1}, respectively. Between these high velocity features flow is sluggish, generally <10 cm s^{-1}, alternating between north and south in direction, including a number of reversals of the shear within the water column. West of Sta. 6, the thermohaline stratification is characteristic of the Falkland Current and its return to the south (GORDON, 1981).

The volume transport of the Brazil Current between Stas 6 and 8 is 19.0×10^6 m^3 s^{-1} with a return transport between Stas 16 and 18 of 19.4×10^6 m^3 s^{-1}. The 5.7×10^6 m^3 s^{-1} poleward transport west of Sta. 6 can be attributed to the southward return of the Falkland Current. The net transport across 38°S of SACW (Stas 6–18) is 3.6×10^6 m^3 s^{-1}

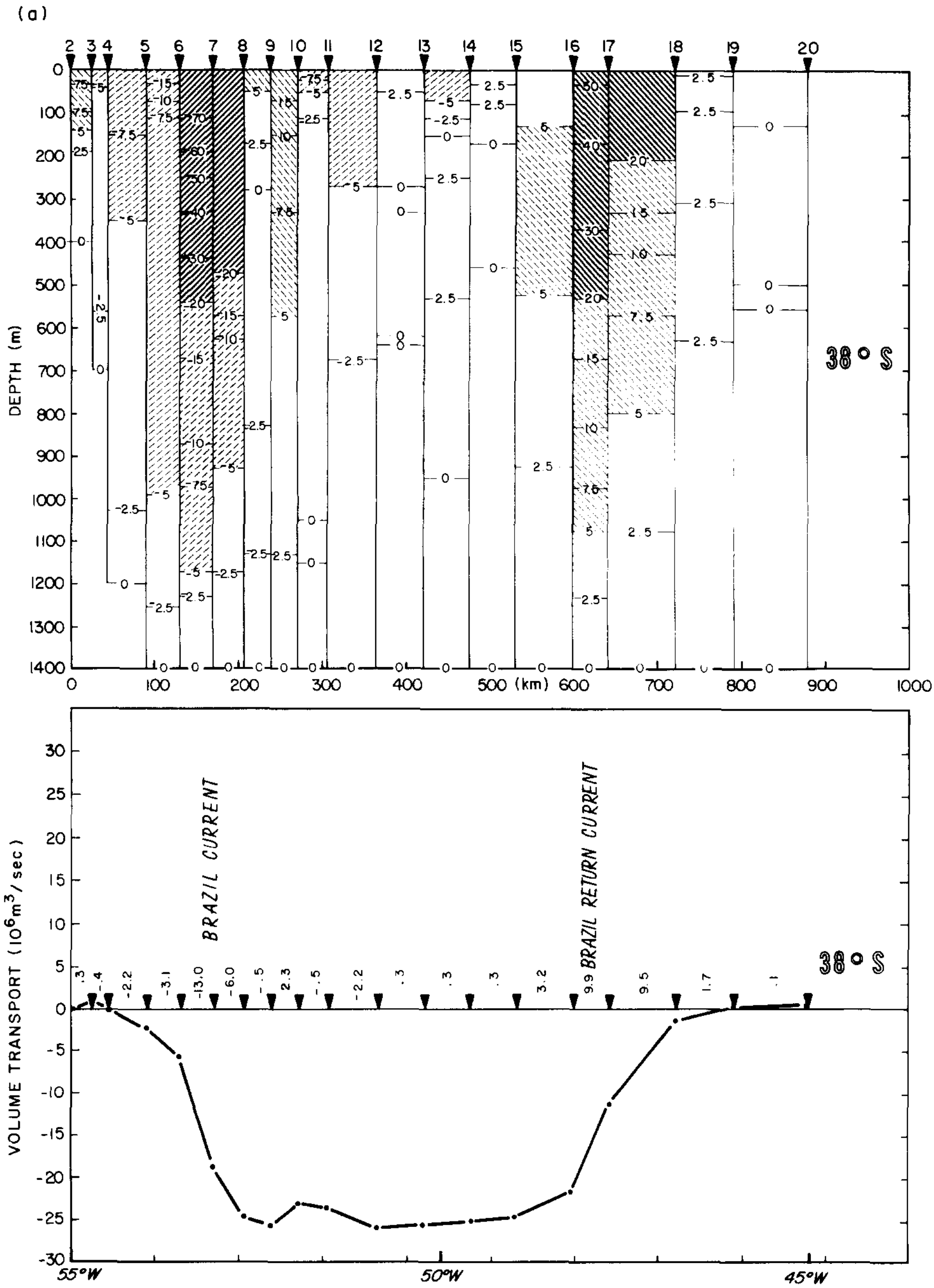

Fig. 3a. Geostrophic velocity and accumulated transport section along 38°S, with a reference level of 1400 m. Left sloped hatching indicates southward (negative) flow and right sloped hatching is northward (positive) flow. The heavy hatching is for velocities >20 cm s^{-1} and lighter hatching for 5–20 cm s^{-1}.

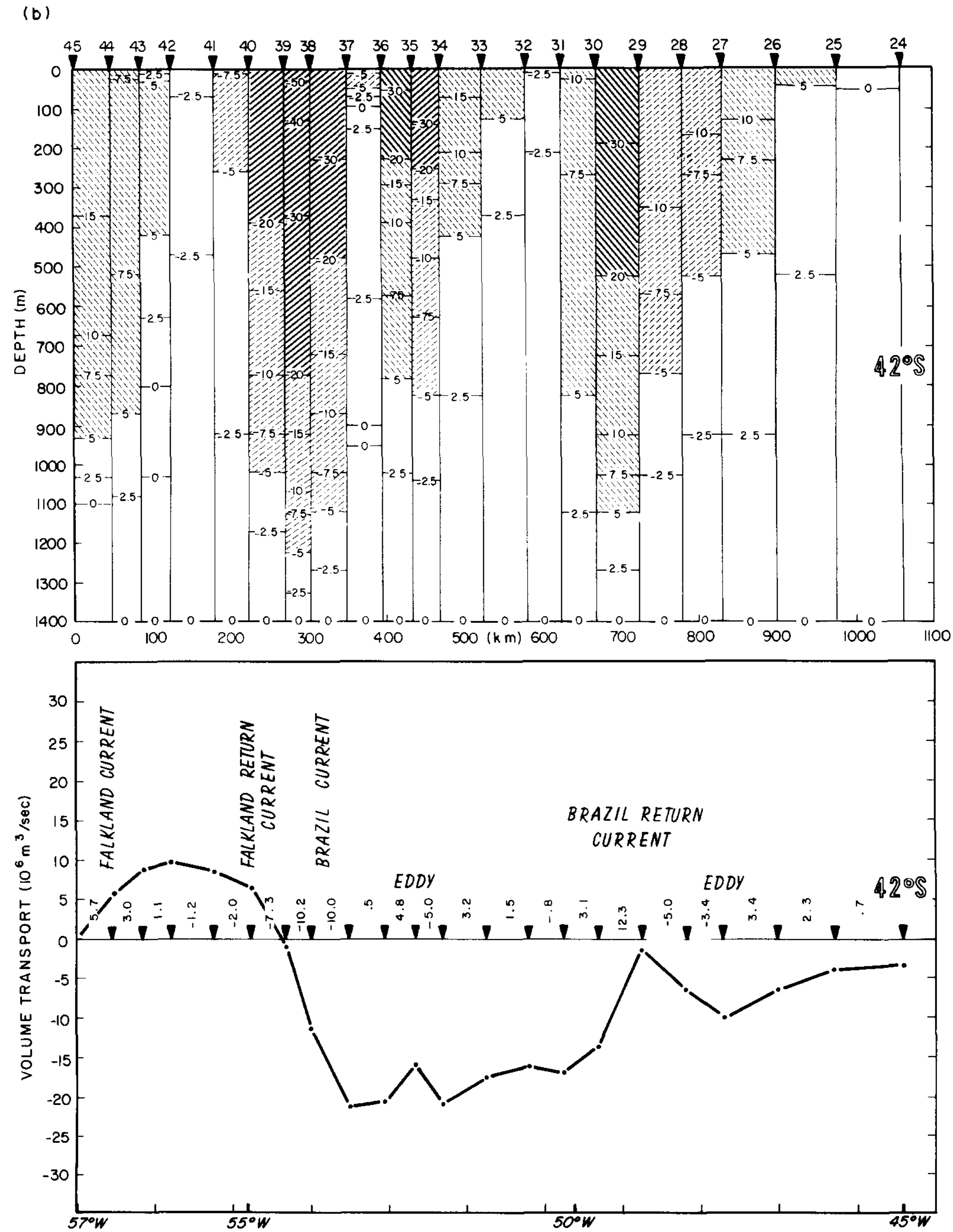

Fig. 3b. Geostrophic velocity and accumulated transport section along 42°S. Same sign convention as (a).

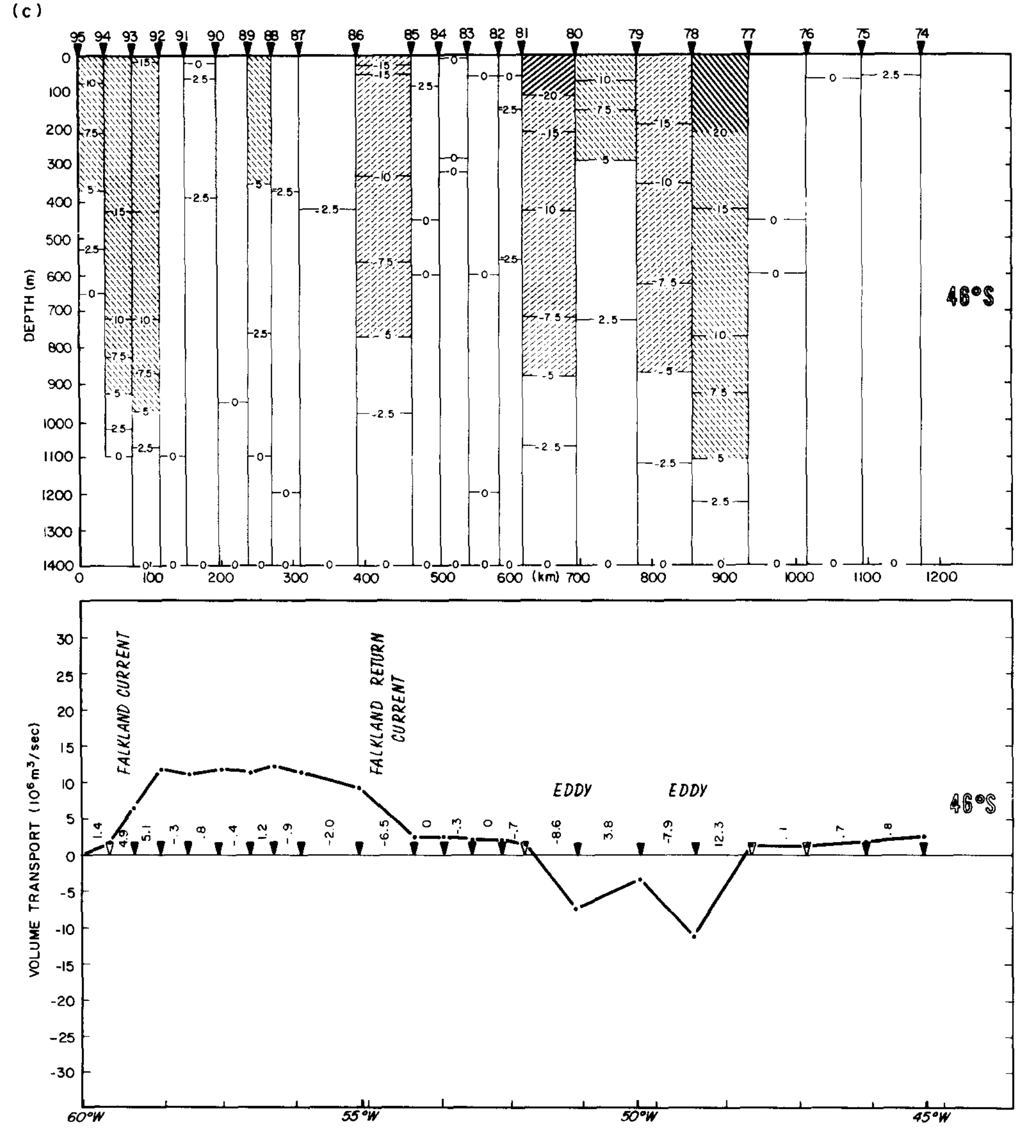

Fig. 3c. Geostrophic velocity and accumulated transport section along 46°S. Same sign convention as (a).

northward. This flow need not be zero, in that the volume of subtropical water to the south of 38°S may be changing.

The southward transport of the Brazil Current across 38°S is much greater than the observed transports across 19–24°S. The deeper reference level is responsible for only 20% of the average difference (Table 2), so the difference is not attributable to the choice of the reference level.

A volume transport increase from 24 to 38°S of about 12×10^6 m^3 s^{-1} is less than the 30×10^6 m^3 s^{-1} increase associated with the Gulf Stream from the Florida Straits (25°N) to its separation point at Cape Hatteras (35°N). However, its downstream growth rate of 5% per 100 km is remarkably similar to a 6% per 100 km Gulf Stream growth rate (KNAUSS, 1969). Both western boundary currents approximately double their transports in the 25–35° latitudinal belt.

The Brazil Current growth south of 24°S suggests the possibility of a recirculation cell of about 12×10^6 m^3 s^{-1} in the southwest Atlantic. GORDON (1981) showed that the thermocline of the southwest Atlantic is slightly saltier than the rest of the South Atlantic thermocline which may be taken as additional evidence for at least a partially closed circulation cell. TSUCHIYA (1985) identified two small recirculation cells associated with the Brazil Current. The dynamic height map for the Atlantic Ocean (REID *et al.*, 1977; TSUCHIYA, 1985) shows a zonally elongated ridge in sea level near 30°S across the South Atlantic. The Brazil Current growth may be associated with this feature, rather than a more restricted recirculation cell, as is the case with the Gulf Stream system (STOMMEL *et al.*, 1978). The existence of a recirculation cell in the southwestern Atlantic may be linked to the poleward displacement of the Brazil Current separation point beyond the maximum zonally averaged curl of the wind stress at 30°S (HELLERMAN and ROSENSTEIN, 1983), as required by non-linear, wind-driven models (FOFONOFF, 1981).

42°S (*Fig.* 3b)

Thermohaline stratification (GORDON, 1981) shows the SACW occupying the zone from Sta. 30 to 38, inclusive. Thermocline characteristics are re-established at Sta. 27, which is associated with a secondary poleward loop of the 1.3 dyn m line on the 0/1400 m map (Fig. 2a). The southward velocity of the Brazil Current between Stas 37 and 38 is 38 cm s^{-1} and at the 38–39 station pair, the surface velocity attains 52 cm s^{-1} poleward. The Brazil Current return, centered between Stas 29 and 30, is a northward surface current of 35 cm s^{-1}.

Table 2. Brazil Current volume transport ($\times 10^6$ m^3 s^{-1}) *across* 19–23°S *as a function of reference level*

Reference level	19–23°S*	38°S	Increase
500	4.7	14.5	9.8
600	7.9	15.5	7.6
1000	6.8	18.4	11.6
1400	–	19.0	–
Average	6.5	17.1	9.7

* Determined by averaging the values reported in the literature (MIRANDA and FILHO, 1982; SIGNORINI, 1978; EVANS *et al.*, 1983)

Corresponding drifter velocities associated with these areas one year prior to the hydrographic data discussed in this paper show comparable flows (Table 1; Fig. 2a). Drifter 17623 within the poleward jet of the Brazil Current traveled at an average rate of 68 cm s^{-1}. From the confluence and following around the Brazil Current extension, the average drifter velocity (17622 and 17623) was 91 cm s^{-1}, with a Rossby number of 0.05 indicating that the anticylonic Brazil Current extension is nearly in geostrophic balance. The drifters left the Brazil Current extension, heading northeast with velocities ranging from 23 to 55 cm s^{-1} with an average of about 40 cm s^{-1}.

Within the Falkland Current, the surface geostrophic velocity is 17 cm s^{-1} northward in the westernmost station pair, relative to the bottom (Fig. 3b). The Falkland return attains 28 cm s^{-1} between Stas 39 and 40 just to the west of the confluence front. Drifters 17622 and 17649 indicate speeds of 38 cm s^{-1} within the Falkland Current and 62 cm s^{-1} for its return, about twice that of the 0/1400 m or 0/sea floor geostrophic values. Thus, it is likely the Falkland Current reaches the sea floor, so the relative geostrophic values discussed here represent lower limits.

The southward flowing jet between Stas 37 and 42 is partitioned between the Brazil and Falkland currents which are initially brought into contact at the confluence. The volume transport of the Brazil Current between Stas 37 and 39 is 20.2×10^6 m^3 s^{-1} southward, while its return (between Stas 29 and 31) is only 15.4×10^6 m^3 s^{-1} northward. Not all of the 38–39 transport is thermocline water associated with the Brazil Current, as these station pairs straddle the confluence front (GORDON, 1981). The Falkland return transports 10.5×10^6 m^3 s^{-1} southward between Stas 39 and 42. The northward flowing Falkland Current is 9.8×10^6 m^3 s^{-1} between Stas 42 and 45, but the station pair 44–45 probably underestimates the transport since the shallow bottom is used for reference. This inference is supported by the larger drifter speeds as mentioned above. The net transport across the tip of the Brazil Current extension at 42°S (Stas 29–39) is only 0.6×10^6 m^3 s^{-1} southward.

Between the high velocity axis of the Brazil Current and its return, the flow is more vigorous than observed across 38°S. A cyclonic eddy is centered at Sta. 35, with a surface velocity of >35 cm s^{-1}. East of the Brazil return is a weaker anticyclonic eddy (about 15 cm s^{-1} surface velocity) centered at Sta. 27. These features attest to the presence of a complex array of eddies within the Brazil–Falkland Confluence region (LEGECKIS and GORDON, 1982).

46°S (*Fig.* 3c)

The anticyclonic eddies of thermocline water near 50°W are associated with surface currents of 15–25 cm s^{-1}. The average velocity around the eddies, as determined by drifters 17662 and 17649, is significantly larger: approximately 40 cm s^{-1}, with a broad range of 2–102 cm s^{-1}. Geostrophic dominance is indicated by a Rossby number of 0.05. The total transport between Stas 77 and 81 is only 0.4×10^6 m^3 s^{-1} to the south, while the transport associated with the eddies is about 6×10^6 m^3 s^{-1}.

The Falkland Current is located west of Sta. 92 with surface velocities of about 15 cm s^{-1}, carrying 11.4×10^6 m^3 s^{-1} of water northward; 9.4×10^6 m^3 s^{-1} is returned poleward in the Sta. 85–88 interval. This current velocity is much smaller than the drifter-determined velocity of 38 cm s^{-1} previously mentioned, suggesting that the bottom velocity adds to the Falkland transport.

CONCLUSIONS

The Brazil Current baroclinic volume transport of 19×10^6 m^3 s^{-1} is far less than that associated with the northern hemisphere western boundary currents at their separation from the continental margin (see Table 2 of Worthington and Kawai, 1972). Stommel (1957) suggested that opposing wind-driven and thermohaline circulation within the South Atlantic western boundary may be responsible for a weak Brazil Current. The Brazil Current is generally considered to be confined to the thermocline and does not include the poleward flow within the deep salinity maximum of the North Atlantic Deep Water (NADW). This convention is supported by the presence of a northward counter flow associated with Antarctic Intermediate Water below the Brazil Current (Evans and Signorini, 1985). Thus the deficit in Brazil Current transport relative to Sverdrup transport may be compensated with transport within the NADW deep western boundary current. Gordon and Piola (1983) supported this concept, noting that a general northward drift of thermocline water from the South Atlantic to the North Atlantic is required to balance the sinking of thermocline water to abyssal depths associated with NADW formation.

At the separation point from the continental margin near 38°S, the Brazil Current transport is significantly larger than its transport further north. The downstream growth rate of the Brazil Current from 24°S to its separation at 38°S is 5% per 100 km, similar to the Gulf Stream growth rate from the Florida Straits to Cape Hatteras. It is possible that the growth rate in the South Atlantic is supported by a recirculation cell as is the case for the Gulf Stream system (Stommel *et al.*, 1978). Non-linear, wind-driven models are required to explain a shift of the western boundary current separation point poleward from the latitude of the zonally averaged wind stress curl maximum at 30° in the North and South Atlantic (Hellerman and Rosentstein, 1983). Poleward shift, as seen in the Gulf Stream and Brazil Current systems, can be linked to an internal recirculation cell (Fofonoff, 1981).

The Brazil Current separates from the South American continental margin at its confluence with the Falkland Current, which carries subantarctic water northward at a rate of about 10×10^6 m^3 s^{-1} relative to 1400 m (or sea floor if shallower). Both currents turn seaward, with the Brazil Current momentum dominating, forcing warm SACW further south. The Brazil Current loops back to the north forming a large poleward meander of warm water centered along 53°W. Numerous warm core, anticyclonic eddies are observed near this feature.

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