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The Intermediate Depth Circulation of the Western South Atlantic

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Abstract. The subsurface oceanic circulation is an important part of the Earth climate system. Subsurface currents traditionally are inferred indirectly from distributions of temperature and dissolved substances, occasionally supplemented by current meter measurements. Neutrally-buoyant floats however, now enable us to obtain for the first time directly measured intermediate depth velocity fields over large areas such as the western South Atlantic. Here, our combined data set provides unprecedented observations and quantification of key flow patterns, such as the Subtropical Gyre return flow (12 Sv; 1 Sverdrup = $10^6 m^3 s^{-1}$), its bifurcation near the Santos Plateau and the resulting continuous narrow and swift northward intermediate western boundary current (4 Sv). This northward flowing water passes through complex equatorial flows and finally enters into the North Atlantic.

Introduction

Both deep wintertime convection and Nordic Seas overflows in the North Atlantic form cold deep water which flows southward across the equator and is balanced by northward flow of warm upper layer water [*Broecker*, 1991]. The warm upper layer water has its origins as thermocline (50 m - 500 m depth) and intermediate (500 m - 1200 m) water in the South Atlantic. Intermediate water is thought to warm and upwell in the vicinity of the equator into thermocline water, which provides a source for North Atlantic deep convection and Nordic Seas inflow. In order to understand and model the overturning cell and meridional heat flux variations we need to understand the origins, pathways and underway modifications of intermediate water. Although intermediate water must flow from its formation site in the south northward through the South Atlantic, the pathways and advective velocity of intermediate water have remained poorly known due to the complexities of the South Atlantic circulation.

In contrast to surface flow patterns [*Peterson and Stramma*, 1991], which are available from satellite tracked drifters, basin-wide direct observations of the intermediate layer flow were unobtainable until recently and alternative indirect methods carried significant uncertainties due to the lack of a reference layer of known velocity. Significant progress has now been achieved through the tracking of large numbers of subsurface floats (Table 1), which drifted with the surrounding water mass for periods of one to three years. Some floats were tracked acoustically [*Rossby et al.*, 1986], and others by satellites when the floats periodically ascended to the sea surface [*Davis et al.*, 1996]. Our analysis combines for the first time historic and recent float trajectories from various independent float programmes. The study concentrates on data located within the intermediate depth layer between 650 m and 1050 m [*Reid*, 1994]. Currents in this layer exhibit little vertical shear [*Reid*, 1994] and, north of 50°S, represent well the intermediate water motions. The composite view of all trajectories (Plate 1) shows a complex but structured large-scale pattern of flow. The resulting space-time averaged flow pattern (Plate 2) reveals the probable main route of intermediate water through the South Atlantic, which is further clarified in a schematic interpretative summary (Plate 3). Below we will follow this overall flow pattern from south to north, comparing our finding with indirect observations and notions of the South Atlantic intermediate depth flow.

The Confluence Zone and the Subtropical Gyre

A region thought to be important to the exchange of waters between the Antarctic Circumpolar Current (ACC) and the Subtropical Gyre is the Confluence Zone near the western boundary at ~38°S [*Gordon and Greengrove*, 1986]. Mixing

Table 1. Float Data Obtained at Intermediate Depth in the Western South Atlantic.

Type of float	Data coverage[1]	Number of floats	Days of data
ALACE[2]	1990 - 1996	70	21694
MARVOR[3]	1994 - 1996	28	11762
RAFOS[4]	1992 - 1996	75	22390
SOFAR[5]	1989 - 1992	13	4562

[1]Data coverage indicates the period over which the array of instruments sampled data. It may be longer than the sampling period of an individual instrument. [2]Autonomous Lagrangian Circulation Explorer [*Davis et al.*, 1996]. [3]Breton word for Seahorse [*Ollitrault et al.*, 1994]. [4]Ranging and Fixing of Sound [*Rossby et al.*, 1986]. [5]Sound Fixing and Ranging [*Richardson and Schmitz*, 1993].

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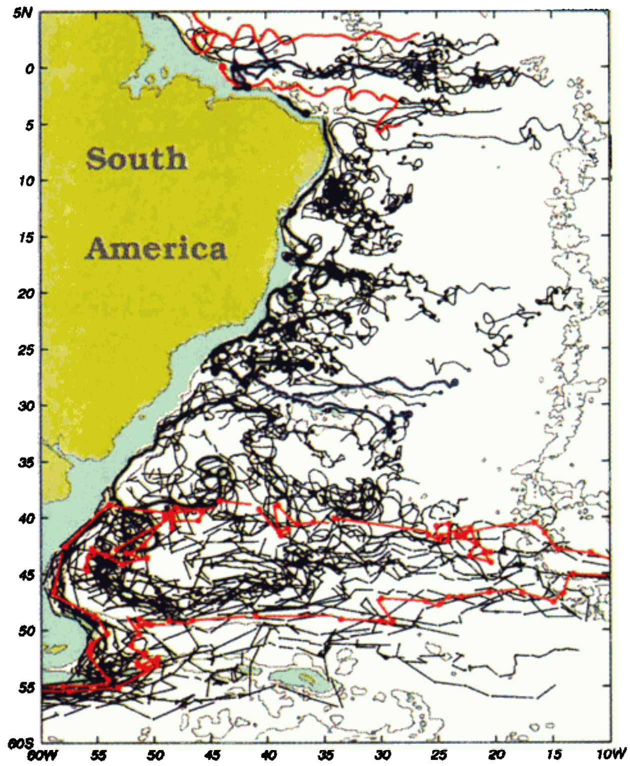

Plate 1. Summary plot of trajectories of 186 subsurface floats in the South Atlantic Ocean based on four different instrument types: ALACE [*Davis et al.*, 1996], MARVOR [*Ollitrault et al.*, 1994], RAFOS [*Boebel et al.*, 1998] and SOFAR [*Richardson and Schmitz*, 1993] floats. The launch positions of MARVOR, RAFOS and SOFAR floats are indicated by dots, with the subsequent, order of one to two years trajectories based on daily subsurface positions. In addition MARVOR floats surface every two or three months to transmit data. Each position at time of subsequent descent is marked by a dot. ALACE floats provide underwater displacements over two to three weeks intervals, indicated by a straight line with the descent positions (start of drift) marked by small dots. Selected floats in colour depict prominent flow patterns (red if the total displacement is eastward, blue if westward and thick black if trapped in western boundary currents). Contour lines indicate 3000 m and 1000 m depth and the coastline. The continent and the area between the coast and the 1000 m isobath are gold and light green, respectively. See Plate 3 for named features.

of ventilated (younger and fresher) and recirculated (older and saltier) intermediate water in the Confluence Zone is exemplified by the thick black and red trajectories (Plate 1) which converge at the western boundary near 38°S. Recirculated intermediate water (thick black trajectory) is derived from the westward Return Current of the Subtropical Gyre. The thick black trajectory approaches the Confluence Zone after travelling south-westward underneath the Brazil Current at a speed of 10 - 20 cm s^{-1}. Floats launched in the Drake Passage [*Davis et al.*, 1996] (red trajectory along the western boundary) depict a northward flow of 30 - 40 cm s^{-1}, following the Falkland Current up to 38°S [*Peterson et al.*, 1996]. Within the Confluence Zone, the intermediate layer is highly turbulent with velocities of 60 cm s^{-1} and higher. This vigorous eddy motion is a mechanism by which fresh intermediate water is injected into the Subtropical Gyre [*Boebel et al.*, 1999].

The intermediate water then flows eastward away from the Confluence Zone in the South Atlantic Current (SAC, red trajectory along 40°S). These flow patterns are confirmed by a statistical analysis of all the float velocity data. (Plate 2). The SAC (15±6 Sv at intermediate depth, see caption of Plate 2 for a description of the transport estimates) and the adjacent ACC (19±10 Sv at intermediate depth) both flow east at speeds of 10 - 20 cm s^{-1}, which increase with increasing southern latitude. The ACC derives most of its water from the Drake Passage (red trajectory along 50°S), but part stems from the Confluence Zone where recirculated intermediate water is entrained into the ACC.

During their nearly parallel flow across the Argentine Basin, the ACC and SAC repeatedly exchange waters, in particular

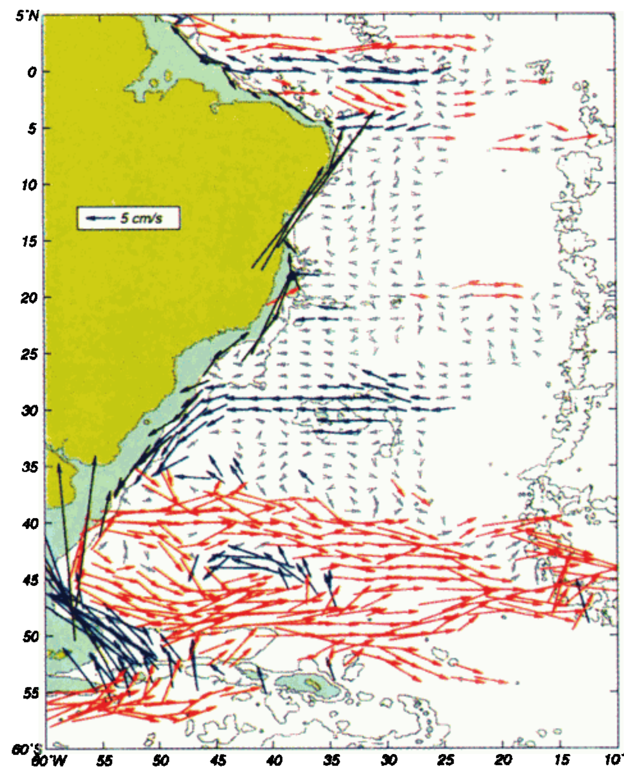

Plate 2. Space-time averaged mean velocities based on a total of 170 float years of velocity data. For the interior ocean, away from the 1500 m isobath, the box size is 2° of latitude x 4° of longitude on a 1°x 2° grid. The arrows, based on at least 60 days of data, are centred at the respective box centre and are red if the zonal component is eastward (blue if westward) and the speed is greater 3 cm s^{-1}. Transport estimates of the intermediate depth component of the ACC, SAC and the Subtropical Gyre Return Current are latitudinal integrals of zonal averages of these gridded mean velocities. Integration limits are derived from minima in the zonal transport function which clearly separate three transport bands: 21°S-36°S (the Subtropical Gyre Return Current), 37S°-44°S (the SAC) and 45°S-53°S (the ACC). A layer thickness of 400 m is assumed. The transport errors derive only from the statistical uncertainty of the mean gridded velocities and do not include uncertainties in the layer thickness, current width or vertical velocity shear. Along the western boundary at ~200 km intervals, data located between the coast and the 1500 m isobath was averaged within 200 km radius (black arrows, based on at least 15 days of data). Contours as in Plate 1.

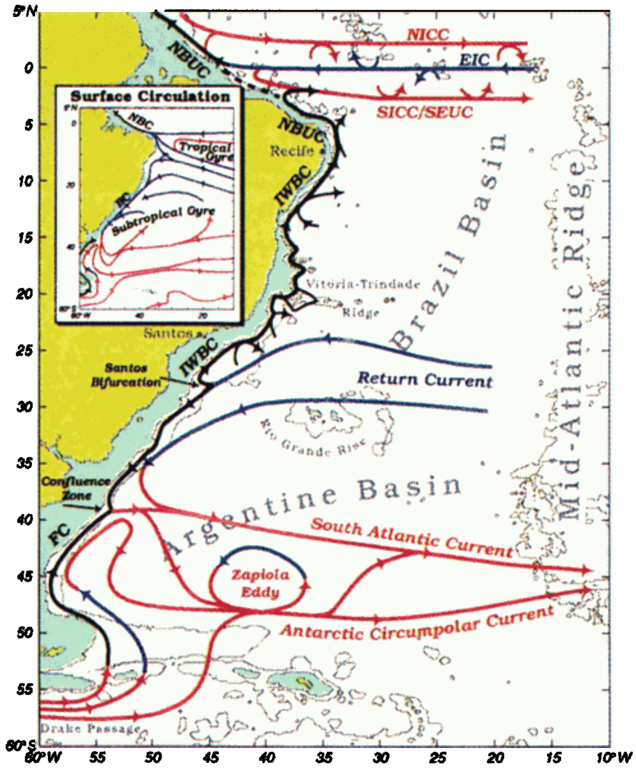

Plate 3. Schematic diagram of main flow patterns at intermediate depth in the western South Atlantic. Contour lines and hatching as in Plate 1. Abbreviations as follows: Falkland Current, FC; Northern Intermediate Counter Current, NICC; Equatorial Intermediate Current, EIC; Southern Intermediate Counter Current, SICC; South Equatorial Under Current, SEUC; Intermediate Western Boundary Current, IWBC; North Brazil Under Current, NBUC. For comparison, an insert based on a schematic diagram by *Peterson and Stramma* [1991], shows the near-surface flow with the southward Brazil Current (BC), the north-westward North Brazil Current (NBC) and the Tropical and Subtropical gyres.

near 45°S 37°W. There the flow circulates around the quasi-barotropic Zapiola Eddy [*Davis et al.*, 1996; *Flood and Shor*, 1988] (Plate 3), a stationary anticyclonic (anticlockwise) feature centred at 45°S 42°W. While approaching the Mid-Atlantic Ridge, the ACC and SAC become kinematically indistinguishable and encompass ~10° of latitude. North of this broad band, along ~35°S, the quiescent centre of the anticyclonic Subtropical Gyre separates the eastward flow from the slower westward Subtropical Gyre Return Current.

The ~400 km wide Return Current is predominantly zonal, centered at ~30°S (Plate 2, blue arrows), and flows westward at 3-5 cm s^{-1} rather uniformly, with transport estimates of 12±3 Sv at intermediate depth. Towards the west, the Return Current progressively reaches farther north. However, in contrast to the northern branch of the Subtropical Gyre at the sea-surface (Plate 3, insert), which flows north-westward diagonally across the South Atlantic [*Reid*, 1994], the intermediate depth flow remains south of the Vitória-Trindade Ridge.

Reaching the continental slope above the Santos Plateau, a previously hypothesised bifurcation [*Reid*, 1994] is now revealed near 28°S, which we suggest be named „Santos Bifurcation“ due to its vicinity to the Santos Plateau. Here, the Return Current splits into a narrow northward Intermediate Western Boundary Current (IWBC, northward thick black trajectories in Plate 1), and a wider south-westward flow band (Plate 2, black and blue arrows south of 28°S). The splitting ratio is estimated to be approximately 1:2, with the larger amount (~9 Sv) being recirculated south [*Schmid*, 1998]. Contrary to *Wüst's* scheme [1935], no northward flow is observed along the western boundary between the Confluence Zone and 28°S. *Wüst's* flow scheme was first challenged after 30 years by *Taft* [1963] and later by *Reid* [1994] who hypothesised the flow scheme which is *directly* observed here for the first time, after another 30 years.

The IWBC and the Equatorial Region

The northward flowing IWBC (Plate 2, black arrows north of 28°S) is observed quasi-continuously from 28°S to 2°S by seven floats which were entrained into the boundary current. Float trajectories and current meter records indicate a jet width on the order of 30±5 km (see *Schmid* [1998] for a detailed description of the IWBC width), a thickness of 400 m [*Boebel et al.*, 1997], and a mean speed of ~30 cm s^{-1} (Plate 2). This suggests a northward transport of 4±2 Sv for the intermediate layer, with the error including both the uncertainty in the current's width and its speed (±10 cm s^{-1}). This estimate compares well with estimates (7.7 Sv at 19°S, 4.0 Sv at 21°S and 2.7 Sv at 24°S) of the IWBC transport based on recent WOCE sections [*Schmid*, 1998], and fall in the lower range of estimates (4–8 Sv) presented by *Fu* [1981] and *Roemmich* [1983] for the 27.0–27.4 σ_θ density range at 24°S.

South of the Vitória-Trindade Ridge, small scale recirculation cells are frequently found offshore the IWBC. Farther north, between 5°S and 17°S, the IWBC occasionally detrained floats into the interior ocean. This indicates a mechanism by which intermediate water of subtropical origin is injected into the tropical regime. In the interior tropical ocean, box averaged velocities are small (< 1 cm s^{-1}, grey arrows in Plate 2) and randomly oriented. Here intermediate water can be gradually dispersed and lose its distinctive physical properties.

Before flowing northward into the subtropical gyre of the North Atlantic, the intermediate water must pass through the western ends of swift zonal equatorial jets [*Schott et al.*, 1998]. For a long time it has been questioned whether the northward equatorial crossing of intermediate water occurs directly along the western boundary or via zonal excursions in the equatorial current system [*Richardson and Schmitz*, 1993]. Floats turn westward at the north-eastern corner of South America and feed into the North Brazil Under Current (NBUC). However, instead of a direct cross-equatorial continuation of this flow, Plate 2 suggests that the NBUC retroflects at 2°S into the eastward Southern Intermediate Counter Current [*Schott et al.*, 1998] (SICC, red arrows south of equator). Subsequently, the SICC is seen to feed northward (see Fig.3, float #115 in *Boebel et al.* [1998] for a higher resolution depiction of this process) into the Equatorial Intermediate Current (blue trajectory along equator in Plate 1) which flows west at 5-10 cm s^{-1} mean velocities. However, in agreement with hydrographic studies [*Schott et al.*, 1998], the float data suggest an intermittent, seasonally reversing flow of the Equatorial Intermediate Current [*Boebel et al.*, 1998].

When the intermediate water once again approaches the shelf near 44°W, it retroflects into the Southern or Northern Intermediate Counter Currents or continues into the North Atlantic via the shelf-trapped NBUC or in North Brazil Current rings [*Richardson and Schmitz*, 1993]. Although no float has directly crossed the equator near the western boundary we cannot exclude that intermediate water does chose this path sometimes and therefore show an interrupted NBUC at intermediate depth in Plate 3.

Summary

Fresh and ventilated intermediate water is injected into the South Atlantic circulation at the Brazil-Falkland Confluence Zone where this water is mixed with older, recirculated intermediate water. The freshened intermediate water then flows east with the South Atlantic Current [*Peterson and Stramma*, 1991] (15 Sv). Downstream, strong cross frontal exchanges between the subtropical and subpolar circulation are observed, suggesting additional injection sites of newly formed intermediate water into the subtropical gyre. East of the Mid-Atlantic Ridge and beyond our area of study part of this flow band is believed to turn north and west, recirculating a large amount of intermediate water within the subtropical gyre. At its easternmost position, the Atlantic intermediate water is subject to influx from the Indian Ocean, which possibly modifies the heat and salt budget of the intermediate layer water.

The intermediate flow re-enters the study area with the Subtropical Gyre Return Current near 30°S (12 Sv) which bifurcates at the western boundary with 9 Sv going south and 4 Sv going north. The resulting northward flow between the „Santos Bifurcation“ and the equator is within a narrow swift continuous intermediate western boundary current. This IWBC flows counter to the overlying southward Brazil Current and is particularly relevant for the calculation and modelling of the anomalous northward heat flux found in the South Atlantic since it introduces a shallow level of no motion near 750 m within the Brazil Current. Whether the sluggish offshore flow field of the Tropics provides an additional northward flux of AAIW, as suggested by hydrographic studies, has yet to be examined. Further studies are also needed in the equatorial region, where strong zonal excursions and seasonal variability result in a complex flow field, which finally guides intermediate water across the equator into the North Atlantic.

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