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Characteristics of the South Atlantic subtropical frontal zone between 15°W and 5°E

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Abstract

In this paper we present data from a number of crossings of the boundary between subtropical and subpolar water in the 15°W–5°E region of the South Atlantic and discuss the implications. The previous paucity of synoptic data sets near 40°S between 25°W and the Greenwich Meridian meant that up to now it has not been possible to fix the position of the boundary in the mid-South Atlantic or to deduce the effects of the midocean ridge on the strength of the South Atlantic Current (SAC). Using hydrographic and chemical tracer data we confirm that the transition from subtropical to subpolar waters occurs within a Subtropical Frontal Zone (STFZ), which constrains the South Atlantic Current flow and is bounded on each side by a distinct front. The northern one, the Northern Subtropical Front (NSTF), varies by only 1.5° of latitude, whereas the southern one, the South Subtropical Front (SSTF), the traditional Subtropical Convergence (STC, defined by Deacon, 1937), migrates over 2.5° of latitude and remains south of the island of Tristan da Cunha. This finding goes some way in resolving the disparity in the literature to the position and seasonal migration of the STC. The data confirm the existence of a subsurface salinity maximum lobe, which appears to be formed at the NSTF rather than at the SSTF. By closely investigating the mesoscale structure and comparing it with historical data from a number of meridional cruises, we have shown strong seasonality in the frontal structure between 30 and 45°S in the South Atlantic. Having resolved the fine structure, we have made an estimate of the geostropic flow of the SAC and suggest that there are east to west differences, which may be related to recirculation in the Argentine Basin rather than to a slowing down by the midocean ridge.

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1. Introduction

The boundary between the South Atlantic Subtropical Gyre and the northern limit of the Antarctic Circumpolar Current in the South Atlantic Ocean has traditionally been defined as one front, known as the Subtropical Convergence (STC) or the Subtropical Front (STF). It is seen as a sharp surface temperature/salinity discontinuity of at least 4°C and 0.005, which begins in the west in the Brazil/Falklands Confluence Zone and stretches eastwards to the South of Africa and beyond into the Indian Ocean (Deacon, 1937). The latitudinal position of the STC varies from about 38°S near the South American coast to 45°S in the eastern Argentine Basin, then moves north to somewhere close to 38°S near the midocean ridge (see Fig. 1). It remains at this latitude to about the Greenwich meridian, whereupon it bends south around the Agulhas Retroflection to about 40°S, and continues at this latitude eastwards beyond 60°E into the Indian Ocean (Deacon, 1937; Lujeharms and Valentine, 1984; Jacobs and Georgi, 1977; Belkin and Gordon, 1996). Latitudinal shifts of over 600 km have been reported in the vicinity of Tristan da Cunha (Deacon, 1937) and of 225 km south of Africa (Lujeharms and Valentine, 1984) with seasonal movements to the south in summer and to the north in winter. West of 45°W the boundary is not so distinct, since here it is often coincident with the Brazil Current Front. Consequently latitudinal variability at the Brazil–Falklands confluence is difficult to quantify, although it is expected to be high.

While there have been a number of hydrographic surveys (see, e.g. Deacon, 1933, 1937; Stramma and Peterson, 1990; Gordon et al., 1992; Lujeharms et al., 1993; Belkin,

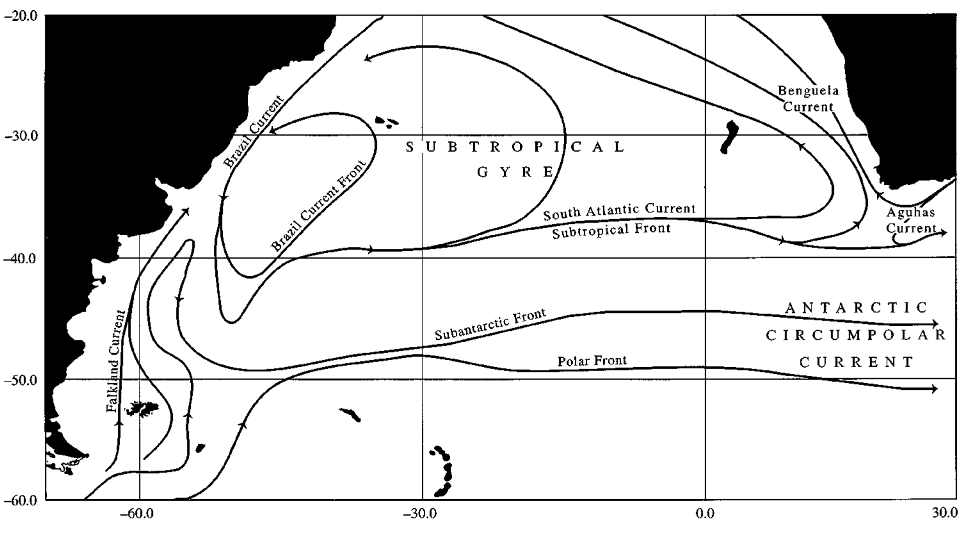

Fig. 1. Schematic representation of the frontal positions and the large-scale circulation of the South Atlantic (after Peterson and Stramma, 1991).

1993) to the area the general description given by Deacon in 1937 has been little questioned. In his paper Deacon states that the surface water to the north of the front has temperatures of 11.5°C in winter and 14.5°C in summer with a salinity of at least 34.9 and maybe as much as 35.5. Where there is a strong southward flow from the oceanic western boundary currents (viz the Brazil and Agulhas Currents, which flow east of South America and Africa, respectively) the meridional gradients are intensified, and temperatures north of the front may reach 20°C or more in summer.

According to Deacon (1933) subtropical water moves eastwards between 38°S and 30°S under the influence of westerly winds, and the STC discontinuity slopes downwards to the north. The eastward movement carries water across the Atlantic ocean towards Africa. Based on a number of data sets Stramma and Peterson (1990) give an account of the STC (but call it the STF) and its associated current, which they term the South Atlantic Current (SAC). They conclude that the SAC is the southern extension of the South Atlantic subtropical gyre, and from its similarity in temperature and salinity characteristics, it appears that the current closes the gyre by flowing into the Benguela current to the east. Like Deacon (1982) they commented that there was a paucity of synoptic data sets near 40°S between 25°W and the Greenwich Meridian, and so it was not possible to fix the position of the STC in the mid-South Atlantic or to deduce the effects of the midocean ridge on the South Atlantic Current. They found the transport of the SAC in the eastern basin to be less than that in the west, but were unable to conclude if there was a marked reduction as the current flows over the midocean ridge or whether the flow gradually reduces towards the interior of the subtropical gyre.

Gordon et al. (1992) further discuss the STF and SAC using data from Leg 4 of the South Atlantic Ventilation Experiment (SAVE). They conclude that there are two fronts in the region: the one traditionally defined by Deacon and a front further to the north, which they termed the Benguela-South Atlantic Current Front (BSAF), but which has since been renamed the North Subtropical Front (NSTF) by Belkin and Gordon (1996). Using CFC and oxygen tracer data, they suggest that the SAC does not totally close off the South Atlantic gyre but that some of it passes south of the Agulhas Current into the Indian Ocean. They conclude that only about one third of the Benguela Current water derives from the South Atlantic, the remainder coming from the Indian Ocean. Subsequently Garzoli and Gordon (1996) have estimated that half of the Benguela Current is derived from the SAC.

In this paper we present data from a number of crossings of the Subtropical Frontal Zone in the 15°W–5°E region of the South Atlantic and make further deductions about the position and strength of the SAC in that region. In addition we investigate the mesoscale structure of the front. The areas south of the Brazil and Agulhas Currents are known to have considerable mesoscale structure (Lenz, 1975; Lujeharms, 1981; Chapman et al., 1986), with eddies crossing the frontal zone in both directions. Whether such structure occurs in the region of the midocean ridge has, to now, been unknown.

2. Data and methods

Two meridional transects of the STFZ south of Tristan da Cunha were made during April 1989 and February 1990 along 13°W by the *RV Africana* and a further oblique transect between 3°W and 5°E in January 1993 by *RRS Discovery* during the WOCE A11 section across the South Atlantic. Fig. 2 shows the cruise tracks for the April 1989, February 1990 and January 1993 cruises together with those of SAVE leg 4 in January 1989, SAVE leg 5 in February 1989, Ajax leg 1 in October 1983 and *Professor Vodyanitsky* (V2) in December 1978. The April 1989 transect from 36–42°S, with CTD stations to 1500 m at latitude intervals of 30 nautical miles, effected the closest spacing achieved on a meridional line in that part of the South Atlantic. Various XBT lines between Cape Town and Gough Island have been run at closer spacing (Lujeharms et al., 1993), but these crossed the STFZ at an acute angle and are less useful for describing its structure. The transect in February 1990 extended to 44°S, but CTD spacing was limited to 60 nautical miles. The transect in January 1993 was at 30 nautical mile spacing.

During both *RV Africana* and the *RRS Discovery* cruises, temperature and salinity were measured by CTD corrected against reversing thermometers and discrete salinity samples respectively. Oxygen and nutrient data (nitrate plus nitrite, silicate, and phosphate) were obtained from discrete samples taken with a 24-bottle rosette, and analysed on board. For the *RV Africana* cruises this was by manual Winkler titration and standard autoanalyser techniques (Mostert, 1983, 1988). For the *RRS Discovery* cruises oxygen was measured by automated amperometric titration (Smythe-Wright et al., 1993) and nutrients according to Smythe-Wright et al. (1992). CFC measurements made in 1989 were according to Smythe-Wright (1990) and those in 1993 by a single detector version of that described in Boswell and Smythe-Wright (1996).

3. Results

3.1. Tristan 1989

The data for the Tristan 1989 section (36–42°S, 13°W) show two distinct fronts (see Fig. 3), one in the region of 38°S and the other near 40°S. The northern front is characterized by a surface temperature change of 1°C (16–17°C) over approximately 0.5° latitude accompanied by a salinity front of 0.2 (34.9–35.1) over a similar distance. The southern front has a surface layer temperature change of 2°C (13–15°C) and a salinity change of 0.1 (34.7–34.8). Both fronts are marked by changes in the nutrient and oxygen profiles, with north to south increases in nitrate, phosphate and oxygen and a decrease in silicate at the surface. Probably the most striking feature is the salinity maximum centred around 100 m depth stretching from 36.5°S to beyond 40°S. This feature is mirrored to some extent by an oxygen minimum, and is quite definitely associated with a CFC-11 minimum extending from 37 to 39°S, which appears to be splitting a maximum moving northwards.

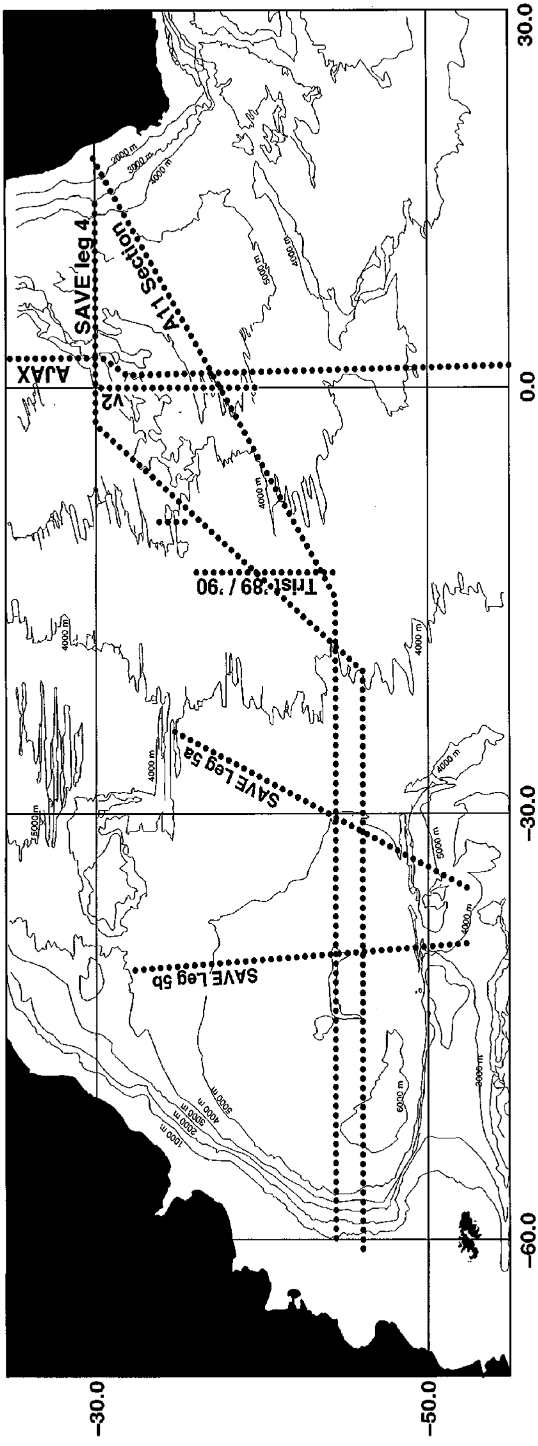

Fig. 2. Cruise tracks for Tristan 1989, Tristan 1990, and WOCE A11 cruises together with those for V2, AJAX leg 1 and SAVE legs 4 and 5.

Three days prior to the 13°W section, a further front was crossed at 35°S along a section at 7°W. This is also shown in Fig. 3, characterized by temperatures of 18–19°C and salinity 35.4–35.6.

3.2. Tristan 1990

The Tristan 1990 section also exhibits two frontal expressions: one close to 37.0°S of 2°C (18–20°C) and 0.2 (35.2–35.4) salinity, the other around 39.5°S, again of 2°C (15–17) and 0.2 (34.8–35.0) salinity (see Fig. 4). South of 40°S in the top 200 m there appears to be a large patch of low salinity, high oxygen, cold water. In addition, there is an interesting feature to the south at 43°S at about 100–150 m with a central salinity of 35.0 and temperature of 11.5–12°C. From the oxygen data there appears to be a suggestion of sinking near 40°S (the southern front) to about 300 m with oxygen poorer water from the north sinking below the oxygen rich subpolar waters. A slight indication of this is also seen in the April 1989 survey, but the effect only extends to 50 m. In general the thermal structure in February 1990 was similar to that observed in April 1989, but in salinity the sub-surface maximum south of 39°S was less intense in the earlier period. There was only a hint of a higher than 34.8 salinity tongue (at 150 m to the north of 39°S).

3.3. WOCE A11

The situation during the WOCE A11 cruise (see Fig. 5) is complicated by the presence of eddies at 33–34°S and just north of 37°S (Smythe-Wright et al., 1996), very close to the northernmost frontal position. This makes the northern front difficult to identify. It could be argued that the front lies just south of 35°S and is defined by temperatures of 18–20°C and 35.4–35.5 salinity, although features in the nutrient and CFC profiles perhaps suggest that it lies nearer 34°S. A second front lies just south of 39°S marked by temperature and salinity changes of 15–16°C and 34.7–34.9 and distinct changes in nitrate, silicate and phosphate. In addition south of 37°S there are three regions of >35 salinity and >12°C similar to that observed in the Tristan 1990 data.

4. Discussion

A tabulation of the major frontal positions and their characteristics during the three cruises is given in Table 1. These are compared with data from the Cape Basin obtained during the V2, AJAX leg 1 and SAVE leg 4 expeditions (see Figs. 6–8). During Tristan 1989 there appears to be two surface expressions corresponding to front 2, and both are given in Table 1. The coldest surface expressions of both fronts are in October during the austral spring, with highest temperatures in January and February. Such a seasonal variation in salinity is not so apparent. The mean temperature and salinity characteristics for front 1 are 18.6°C and 35.5 and for front 2 are 14.9°C and 34.9. We therefore conclude that front 2, with its temperature and salinity

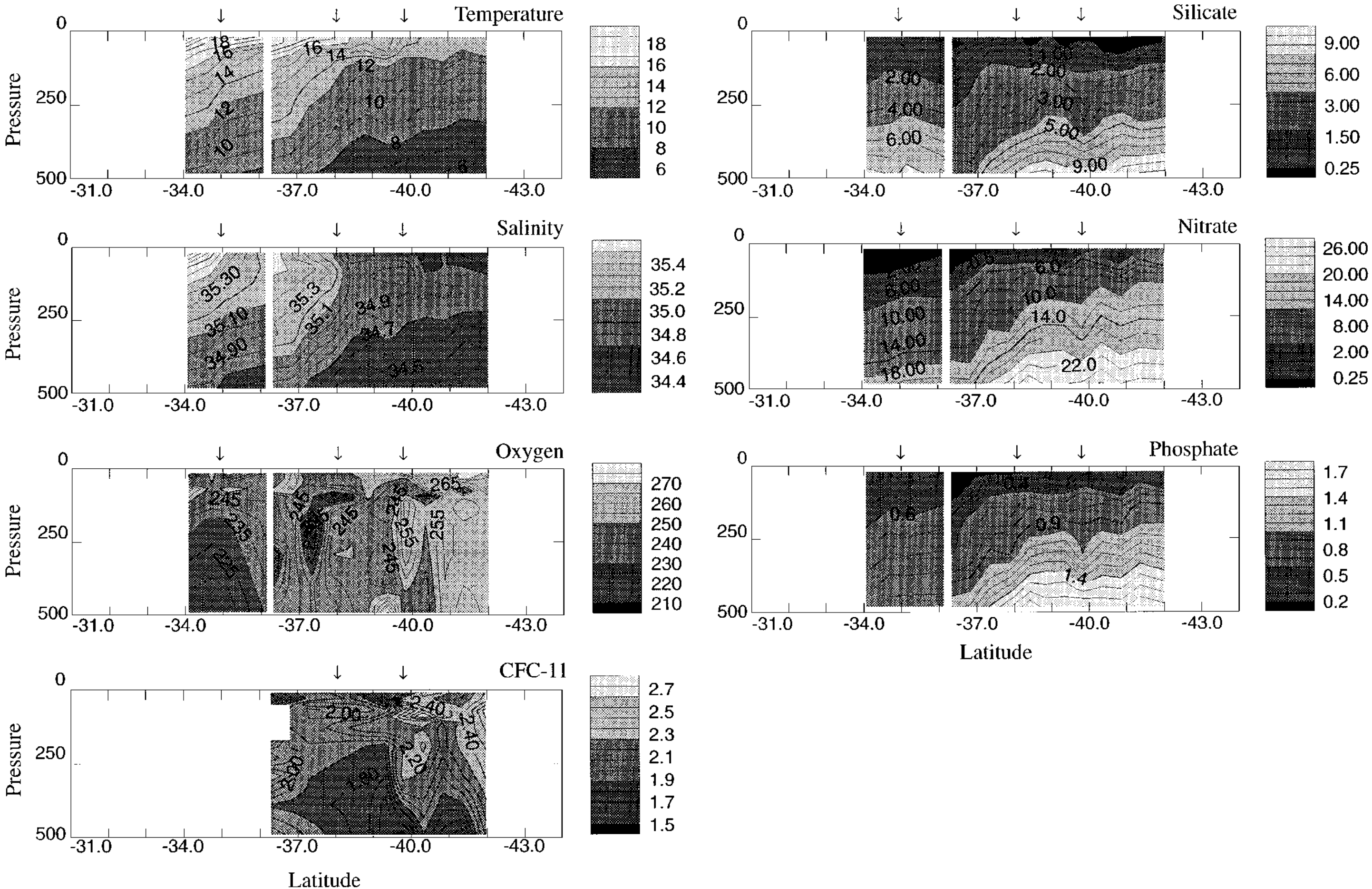

Fig. 3. Temperature (°C), salinity, dissolved oxygen ($\mu mol\,l^{-1}$), CFC-11 ($pmol\,l^{-1}$), silicate ($\mu mol\,l^{-1}$), nitrate ($\mu mol\,l^{-1}$), and phosphate ($\mu mol\,l^{-1}$) for the Tristan 1989 cruise. The discontinuity at 35.5°S results from the profile being a composition of two sections: the one north of 35.5°S being carried out at 7°W and the one to the south at 13°W. Arrows indicate the positions of the fronts; pressure in dbar (1 dbar ~ 1 m).

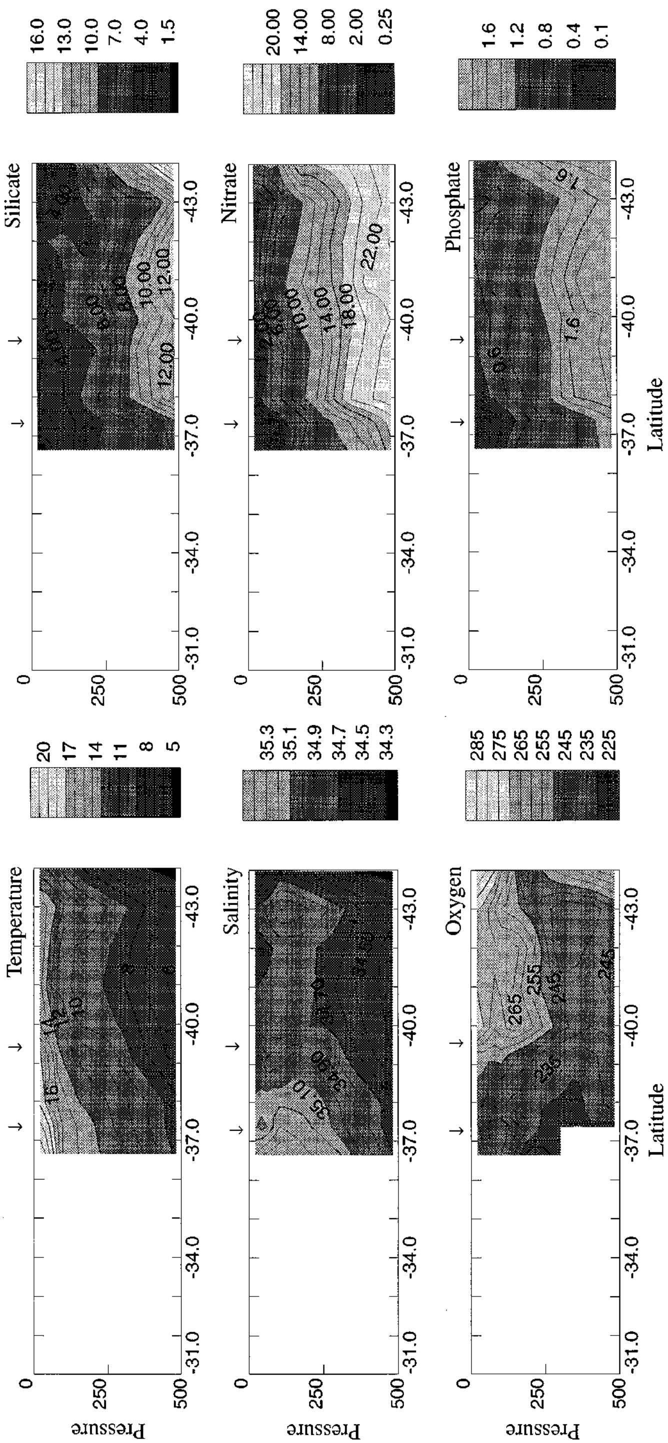

Fig. 4. Temperature (°C), salinity, dissolved oxygen (μmol l^{-1}), silicate (μmol l^{-1}), nitrate (μmol l^{-1}), and phosphate (μmol l^{-1}) for the Tristan 1990 cruise. Arrows indicate the positions of the fronts; pressure in dbar (1 dbar ~ 1 m).

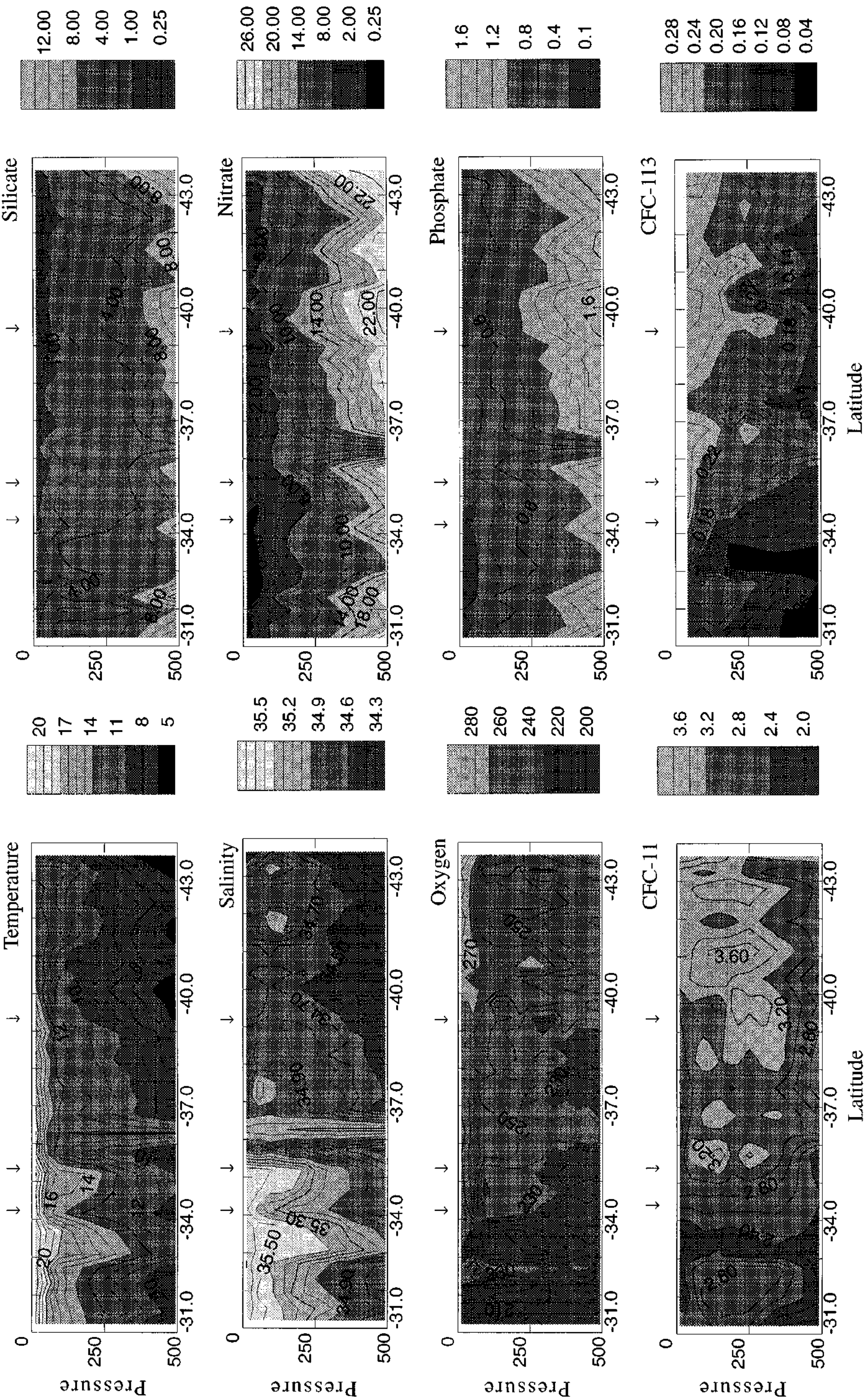

Fig. 5. Temperature (°C), salinity, dissolved oxygen (μmol l^{-1}), CFC-11 (pmol l^{-1}), silicate (μmol l^{-1}), nitrate (μmol l^{-1}), phosphate (μmol l^{-1}) and CFC-113 (pmol l^{-1}) data for the WOCE A11 cruise. Arrows indicate the positions of the fronts; pressure in dbar (1 dbar ~ 1 m).

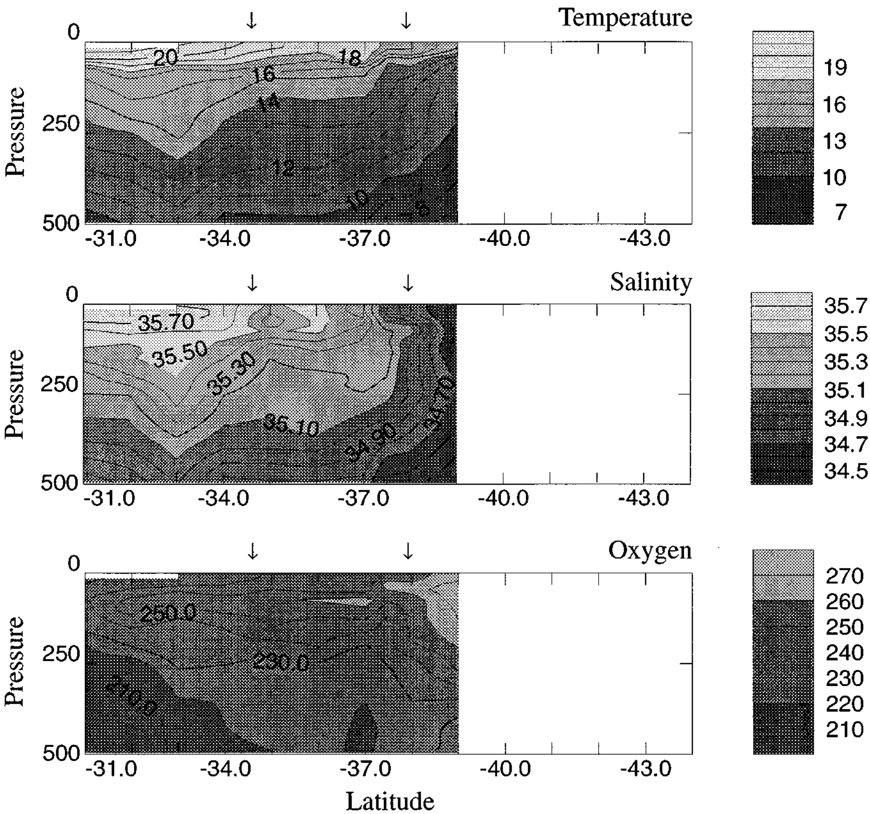

Fig. 6. Temperature (°C), salinity and dissolved oxygen (µmol l^{-1}) data from V2 cruise. Arrows indicate the positions of the fronts; pressure in dbar (1 dbar ~ 1 m).

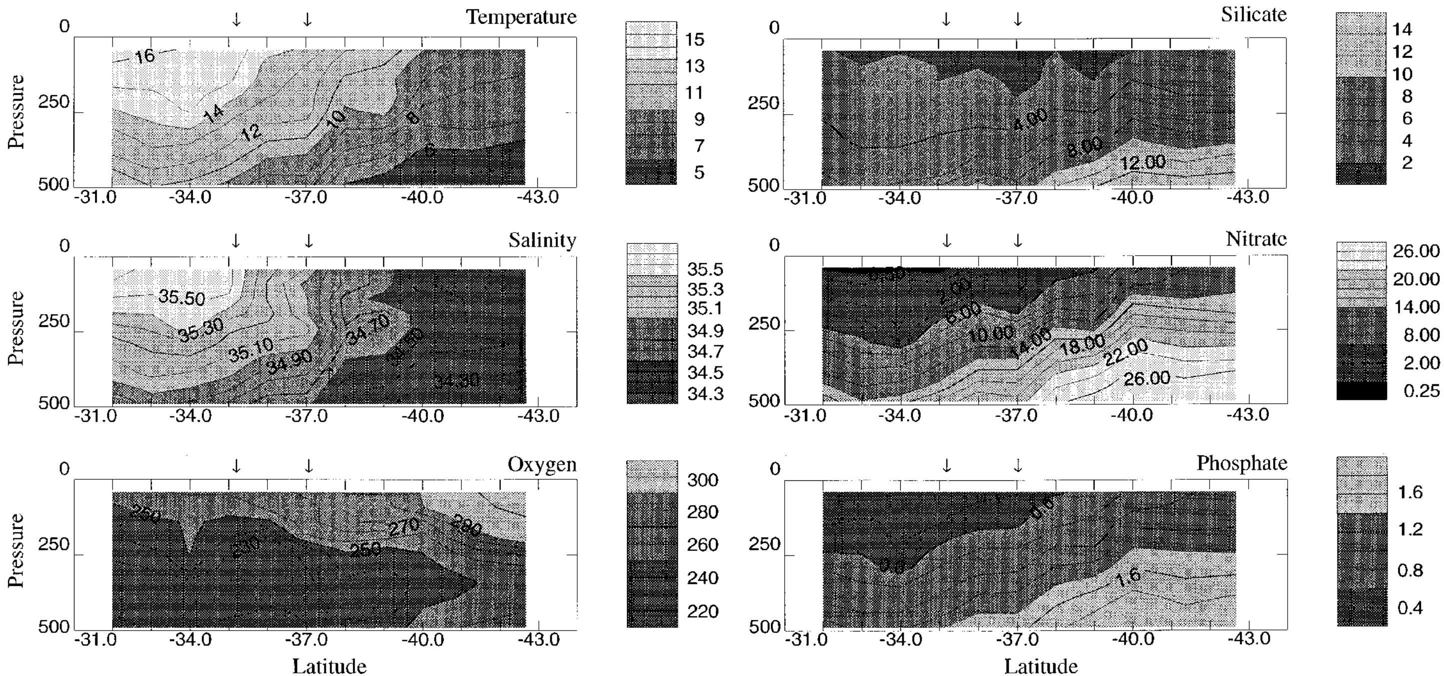

Fig. 7. Temperature (°C), salinity, dissolved oxygen (μmol l^{-1}), silicate (μmol l^{-1}), nitrate (μmol l^{-1}), and phosphate (μmol l^{-1}) data from AJAX leg 1. Arrows indicate the positions of the fronts; pressure in dbar (1 dbar ~ 1 m).

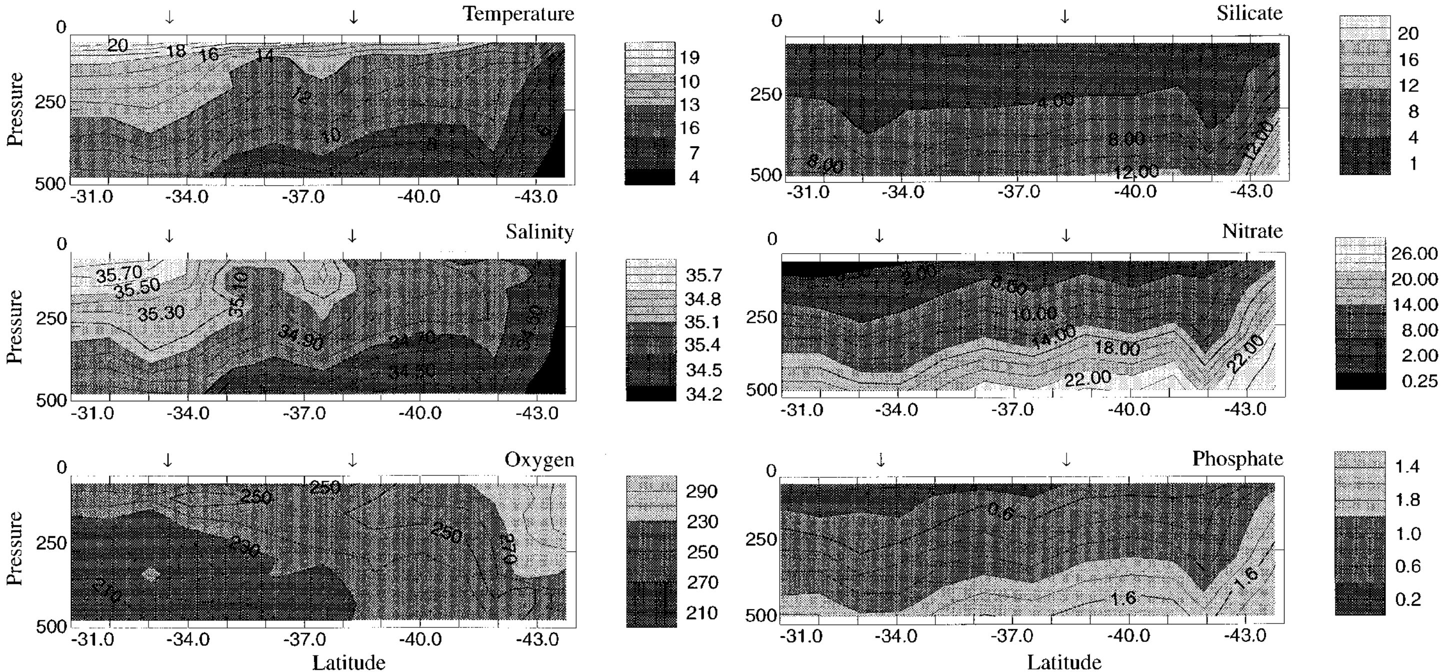

Fig. 8. Temperature (°C), salinity, dissolved oxygen ($\mu mol\,l^{-1}$), silicate ($\mu mol\,l^{-1}$), nitrate ($\mu mol\,l^{-1}$), and phosphate ($\mu mol\,l^{-1}$) data from SAVE leg 4. Arrows indicate the positions of the fronts; pressure in dbar (1 dbar ~ 1 m).

characteristics almost identical to those defined by Deacon (1937), is the traditional Subtropical Front (which we hereafter call the South Subtropical Front or SSTF in line with Belkin and Gordon (1996)) and that front 1 is the NSTF identified by Gordon et al. (1994) and Belkin and Gordon (1996). However, we believe that the track did not penetrate sufficiently far north to cross the NSTF during the Tristan 1990 cruise, and so the data given in Table 1 for front 1 are unlikely to correspond to the NSTF.

4.1. Seasonal variation in the STFZ

According to Deacon (1937) the position of the STC is very variable, with data from the early Southern Ocean cruises showing at least a 5–6° variation in its latitude in the vicinity of Tristan da Cunha (37.05°S 12.15°W). Deacon (1937) states that in January 1926 the STC was just south of Tristan da Cunha, and although no exact position is given one may conclude that it was somewhere in the 37–39°S region. In contrast in June 1926 and 1927 it was just north of the island and in November 1933 quite definitely 5–6° to the south of the island. It is on these data that he bases his is 5–6° variation, but he goes on to imply that the November location was rather unusual and was probably due to large scale movements related to meteorological changes rather than the norm. We further examined Deacon's 1926/27 data and conclude that while there might be slight evidence of a double front, the sparseness of data is inconclusive, leading Deacon to the conclusions he made.

It is clear from the data presented here that the position of the SSTF does not vary by more than 1.5° and that it remains south of Tristan da Cunha. This is in contrast to the 1978 SST data set used by Lujeharms et al. (1993), from which they concluded that the surface expression of the Subtropical Convergence lies north of Tristan da Cunha from October to January and south in February to May. However, they also suggested that the data set may not be representative since data from other years showed a more complicated pattern, with the strongest thermal gradients found at distinctly different latitudes in different months.

Although no data for the austral winter are presented in Table 1, results from the *Vize* and *A. Shirshov* cruises (Stramma and Peterson, 1990) along 30°W in May suggest that the SSTF is around 41°S at this time, while close inspection of the *RRS Discovery ll* data for June 1926 and 1927 would suggest that all water in the vicinity of Tristan da Cunha is warmer than 14.5°C which would, by Deacon's definition, put it north of the front in both the summer and winter months. Indian Ocean data (Wyrtki, 1971) do suggest that there is a 3–4° latitude shift in the average position of both the 15°C surface isotherm and the surface salinity front. However, from the data presented here a 5–6° variation in the position of the SSTF seems unlikely.

4.2. Nature of the water mass bounded by the two fronts and the subsurface salinity maximum

The hydrographic and chemical profiles from the six cruises listed in Table 1 (see Figs. 3–8) show the variable nature of the water between the fronts. Such complex

Table 1
The major frontal positions and their characteristics during the Tristan 1989, Tristan 1990 and WOCE A11 together with those from the *Professor Vodyanitsky* (V2), AJAX leg 1 and SAVE leg 4 expeditions

Cruise	Date	Lat front 1	Long front 1	Temp front 1	Salinity front 1	Lat front 2	Long front 2	Temp front 2	Salinity front 2
Tristan	Apr 89	35°S	7°W	18–19°C	35.4–35.6	39.8°S or	13°W	13–15°C	34.7–34.8
						38°S	13°W	16–17°C	34.9–35.1
Tristan	Feb 90	37.3°S	13°W	18–20°C	35.2–35.4	39.5°S	13°W	15–17°C	34.8–35.0
A11	Jan 93	35.3°S or	5°E	18–20°C	35.4–35.5	39.3°S	3°W	15–16°C	34.7–34.9
		34.2°S	5°E	19–20°C	35.5–35.6				
V2	Dec 78	34.5°S	0°	19–20°C	35.5–35.6	37.7°S	0°	16–18°C	34.8–35.1
Ajax	Oct 83	35.2°S	0°	15–16°C	35.4–35.5	37°S	0°	13–14°C	35.0–35.1
Save 4	Jan 89	33.5°S	3°W	19–20°C	35.6–35.8	38.3°S	11°W	15–16°C	34.9–35.1

structure results from variations in mixing between the subantarctic and subtropical water, as a consequence of the large scale wind field and convective and advective thermohaline processes.

The Ajax data were collected in the early austral spring (October), when the NSTF and the SSTF are less than 2° apart. The surface temperatures between 31°S and 44°S are low, not exceeding 16°C, and in general the isotherms and isohalines show a regular north-south decrease, almost perpendicular to the surface in the top 500 m. An exception is the salinity feature at 250 m between 38°S and 39°S. Data for the summer months (V2, Save leg 4, WOCE A11) are similar. Here the temperatures are higher and all three sections show a patch of higher salinity water (>35.2) sandwiched at the surface between 36°S and 39°S. The feature is more distinct in January (Save leg 4 and WOCE A11) than in December (V2 data) resulting in a salinity maximum of >34.7 extending from the surface to 250 m between 36°S and 43°S. In April (Tristan 1989 cruise) the salinity maximum is very distinct with a core at 100 m.

A salinity maximum between 100 and 300 m depth, extending as far south as the Antarctic Convergence near 50°S (Deacon, 1945), is a common feature of the STFZ in the Atlantic and Indian Ocean; it lies deeper in the Pacific Ocean. Heath (1976) discusses its mode of formation and suggests that the saline balance is mainly between horizontal diffusion and northward advection, with the vertical scale being determined by weak shear in the horizontal flow and vertical diffusion. He concludes that the tongue is generated at the STF by shear in the upper few hundreds of meters. Our data suggest that the high salinity lobe is formed at the NSTF rather than at the SSTF (the front defined by Deacon). The form of the lobe is consistent with the concept of poleward compensation of Ekman convergence in the surface layer further north, and it is conceivable that the quasi-discontinuous nature of the lobe (blobs) may be a consequence of the interruption of this compensation flow by convective processes during winter, i.e. cooling and sinking of overlying water.

4.3. *Transport across the fronts*

The scenario suggested above is reinforced by the occurrence of such high salinity patches in the A11 and Tristan 1990 data south of the SSTF. These high salinity patches are seen at 37.25°S, 41.9°S, and 43.2°S in the A11 data and at 43°S in the Tristan 1990 data. They correlate with low CFC-11 and CFC-113 concentrations, suggesting that the water has come from a warmer regime in which the gas is less soluble. While the slight CFC decrease would also indicate an earlier ventilation time, the ratios suggest that ventilation was relatively recent and that the patches likely broke off from the salinity tongue formed the previous year. South of the Agulhas and Brazil Currents, in areas of strong shear, eddies are known to form and cross the frontal zone in both directions (see, e.g. Smythe-Wright et al., 1996; Duncombe Rae et al., 1996). Similar southward movement of warm eddies across the polar front near 50–55°S in the South Atlantic has been described by Gouretski and Danelov (1994). From the present study it would appear that there is movement of water across the fronts in the mid-South-Atlantic where the shear is relatively weak.

4.4. Flow associated with the two fronts

According to Gordon et al. (1992) the band of water between the two fronts forms the southern limb of the subtropical gyre and its eastward flow has been referred to by Stramma and Peterson (1990) as the South Atlantic Current. As described earlier, the strength and position of this current is not well known in the mid-South-Atlantic. Fig. 9 shows a compilation of geostrophic currents in the upper 1500 m based on a 1500 m level of no motion for all six crossings shown in Table 1. Fig. 10 shows the associated transport. A 1500 m level of no motion was chosen since hydrographic and CFC-11 data from the A11 and Tristan 1989 cruises suggest that there is a clear boundary between Antarctic Intermediate Water flowing north and North Atlantic Deep Water flowing south in the Cape Basin at the 1500 m level.

At the time of the AJAX cruise (austral spring) the NSTF and the SSTF are slightly north of their summer positions. The strongest eastward current of 12.6 cm s^{-1} occurs at the SSTF giving rise to a transport of 8 Sv. The flow associated with the NSTF has a maximum of 11.5 cm s^{-1} resulting in 7.0 Sv of transport.

Data for the summer months (December, January, February) suggest that the situation is variable. During the V2, SAVE and A11 expeditions, there appears to be eastward flow at or just south of the NSTF and flow associated with the SSTF. However, the magnitude of the flows varies with cruise. During the V2 cruise, the flow associated with the NSTF is 11 cm s^{-1}, similar to the AJAX cruise, but the flow is narrow and only accounts for 4.5 Sv of transport. The flow associated with the SSTF at this time is about 12.8 cm s^{-1}, but due to limited data below 500 m it is not possible to calculate a transport in the top 1500 m. Between the two fronts there is a continuous westward flow of no more than 2.6 cm s^{-1}, but accounting for 4.3 Sv of flow. At the time of SAVE leg 4 the dominant eastward flow of 7 cm s^{-1} occurs at 34.5 just south of the NSTF giving rise to a transport of 4.6 Sv, and there is associated eastward flow of 4.8 cm s^{-1} and 3 Sv at 35.7°S. The flow associated with the SSTF (38.5°S) at this time is 3.6 cm s^{-1} with a transport of 3.4 Sv. Between the two fronts at 36.8°S the flow reverses to a weak westward flow of 1 cm s^{-1} and 1.2 Sv. A similar situation is seen in the A11 data: here the flow of the NSTF is 17.4 cm s^{-1} and that associated with the SSTF 16.5 cm s^{-1}. These give rise to transports of 10.3 Sv and 5.4 Sv respectively. Data from the Tristan 1990 cruise are inconclusive since the section did not penetrate sufficiently northwards to measure the flow at the NSTF, but there appears to be a flow of 6.4 cm s^{-1} with a corresponding transport of 4.4 Sv at 38.5°S associated with the SSTF.

In the austral autumn during the Tristan 1989 cruise, when the salinity maximum is at its greatest, the flows are also complex. There is a strong flow of up to 11.2 cm s^{-1}, amounting to 4.5 Sv, at 38°S and another of 8.8 cm s^{-1} at 39.5°S giving 0.4 Sv, which correspond to the two surface expressions of front 2 given in Table 1. However, there is a further strong eastward flow of over 18.7 cm s^{-1} at 37°S with a transport of 3.7 Sv and a westward flow of 10.8 cm s^{-1} and 3.6 Sv at 39°S. Unfortunately the cruise did not make one continuous section across the two fronts but did pass over the NSTF region 3 d earlier at 7°W, and from this crossing we have calculated a flow of 16.2 cm s^{-1} giving rise to 4.3 Sv of flow.

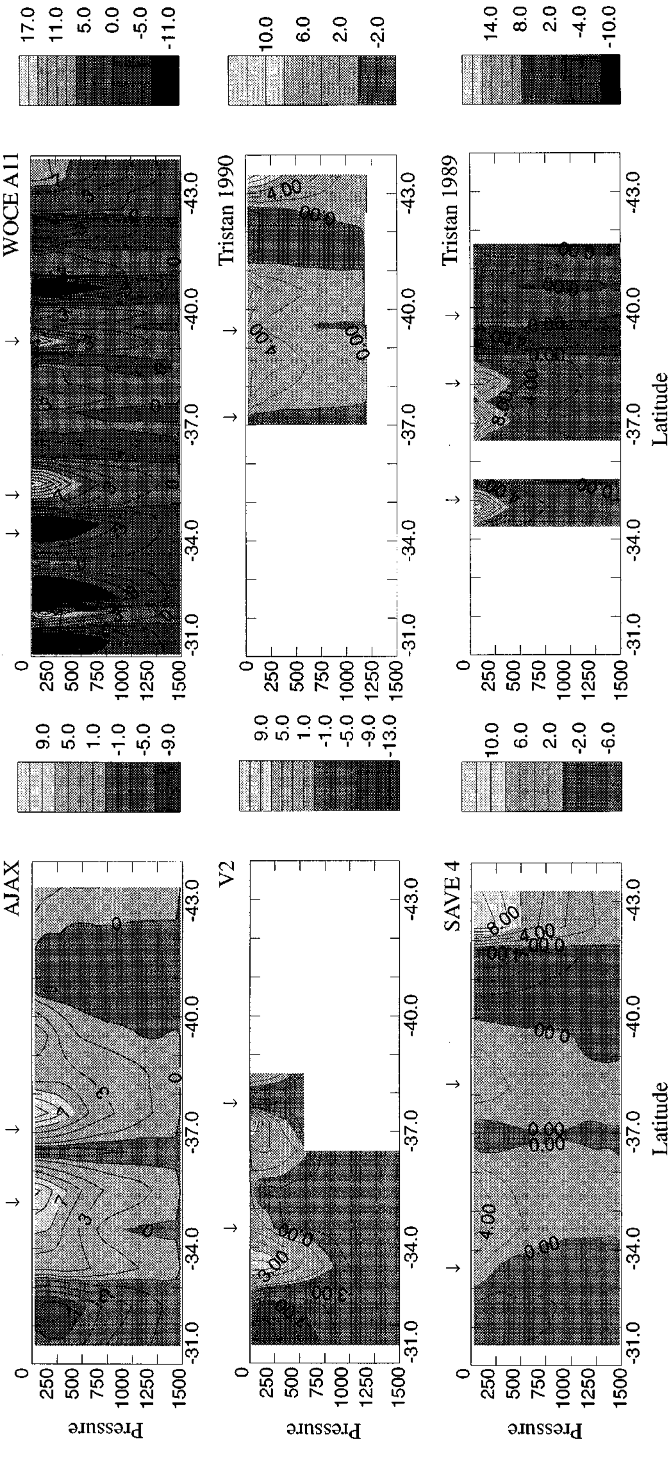

Fig. 9. Geostrophic velocities (cm s^{-1}) relative to a 1500 m zero reference level for AJAX leg 1, V2, Save leg 4, WOCE A11, Tristan 1989 and Tristan 1990 cruises. Arrows indicate the positions of the fronts; pressure in dbar (1 dbar ∼ 1 m).

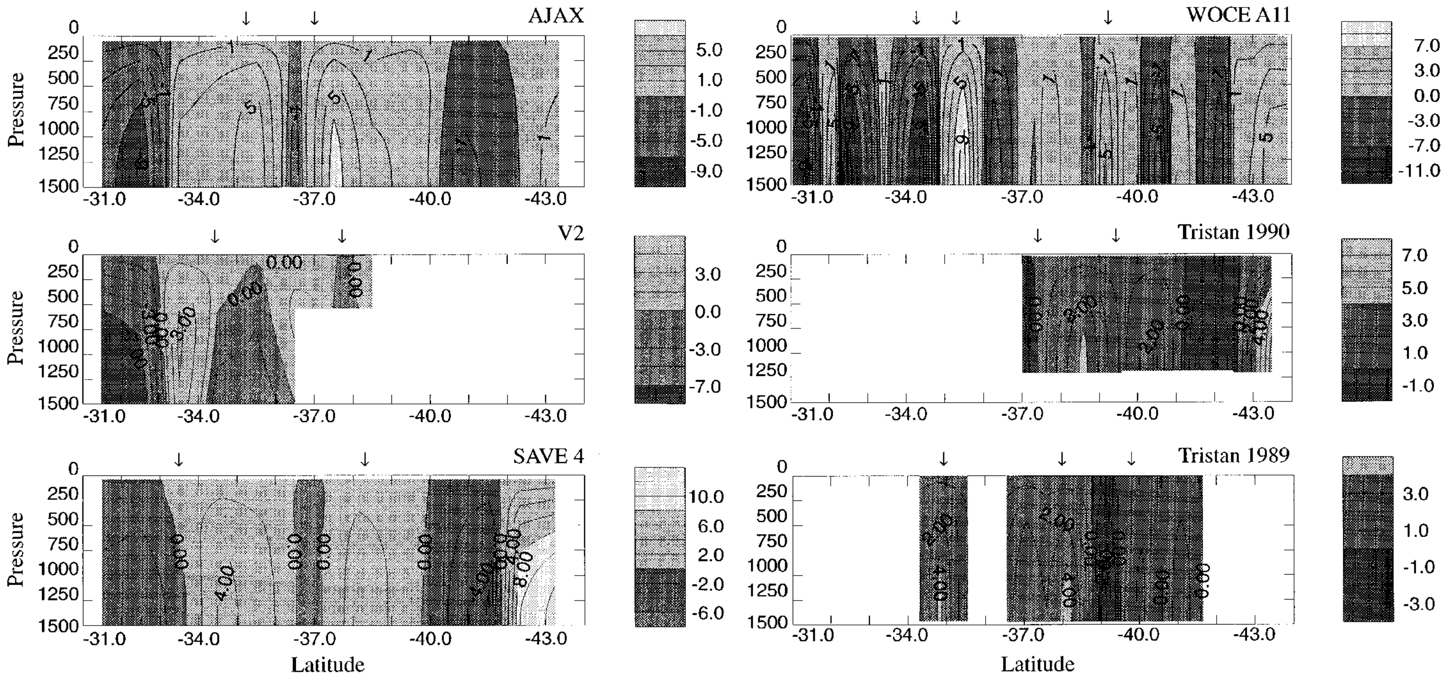

Fig. 10. Transport (Sv) in the top 1500 m relative to a 1500 m zero reference level for AJAX leg 1, V2, Save leg 4, WOCE A11, Tristan 1989 and Tristan 1990 cruises. Arrows indicate the positions of the fronts; pressure in dbar (1 dbar ~ 1 m).

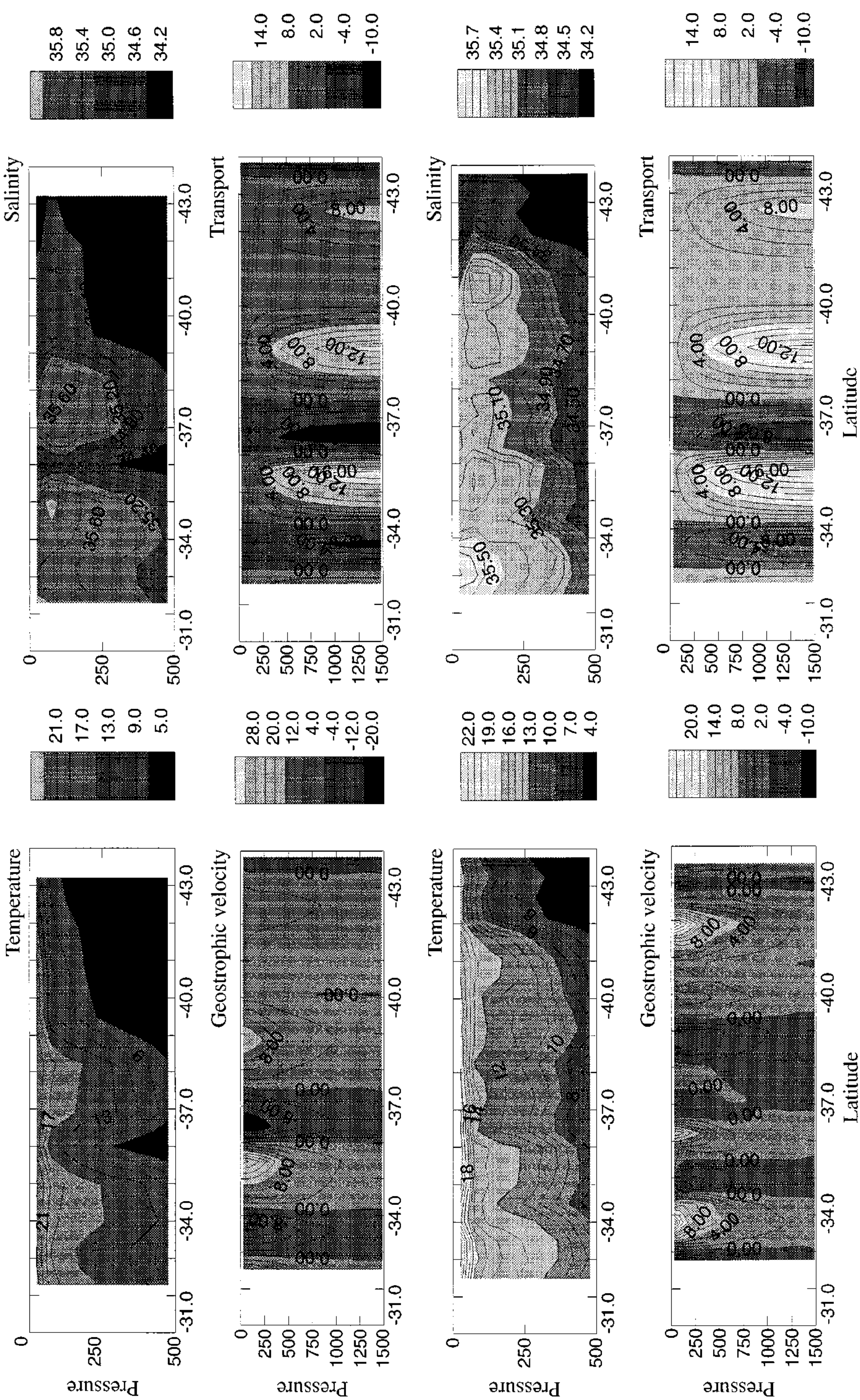

Fig. 11. Temperature (°C), salinity, geostrophic velocity (cm s^{-1}) and transport (Sv) relative to a 1500 m zero reference level for a (a) western (b) eastern crossing of NSTF and SSTF in the Argentine Basin during SAVE leg 5. Pressure in dbar (1 dbar ~ 1 m).

Table 2
The maximum flows together with any additional flow during six crossings of the NSTF and SSTF and in the Cape Basin together with data for the Argentine Basin from two crossings during SAVE leg 5

Cruise	Date	Max flow front 1 ($cm\,s^{-1}$)	Max tranprt. front 1 (Sv)	Max flow front 2 ($cm\,s^{-1}$)	Max tranprt. front 2 (Sv)	Assoc. eastward tranprt. (Sv)	Total eastward flow (Sv)	Total westward flow (Sv)
Ajax	Oct 83	11.5	7.0	12.6	8	13.2	28.2	2.0
V2	Dec 78	11	4.5	12.8	no	data	4.5[b]	4.3
Save 4	Jan 89	7	4.6	3.6	3.4	3.0	11.0	1.2
A11	Jan 93	17.4	10.3	16.5	5.4	10.5	26.2	5.7
Tristan	Feb 90	not	seen	6.4	4.4	5.1	9.5[a]	1.7
Tristan	Apr 89	16.2	4.3	11.2/8.8	4.5/0.4	11.75	20.95	3.6
Save 5w	Feb 89	33.1	19.8	22.6	16.7	9.2	45.7	13.5
Save 5e	Feb 89	25.5	6.4	24.6	8.7	21.9	37.0	9.7

[a] SSTF only.
[b] NSTF only.

The data show that the South Atlantic current flows primarily in the top 1000 m and that the flow between the two fronts is not consistently eastwards, but likely follows two major jets; one at or just south of the NSTF and the other associated with the SSTF. In general the flows associated with the SSTF are marginally higher, but in terms of transport there is little between them. Table 2 tabulates the maximum flows for both fronts, together with any additional flow during the six crossings in the Cape Basin discussed above and data for the Argentine Basin from two crossings during SAVE leg 5. Using results from a number of cruises Stramma and Peterson (1990) concluded that the volume transport of the SAC in the top 1000 m relative to a deep potential density surface ($\sigma_4 = 45.87\ \mathrm{kg\,m^{-3}}$) in the Argentine Basin is 30 Sv and can be as high as 37 Sv. To facilitate comparison we have examined data from the SAVE leg 5 expedition (see Fig. 11) using the same approach we used for the Cape Basin data. Our computations include transport associated with both the SSTF and NSTF, whereas those of Stramma and Peterson were mainly confined to the SSTF. Nevertheless our data do concur with those of Stramma and Peterson and suggest that a flow of 45.7 Sv is possible for the SAC in the Argentine Basin. This is far in excess of the 28.2 Sv maximum calculated for the transport of the SAC in the Cape Basin from the data sets presented here.

There are two possible explanations for the observed decrease. The first, as suggested by Stramma and Peterson (1990), is that there is a reduction in the flow of the SAC as it crosses the midocean ridge, but we do not agree with their inference that the flow gradually reduces towards the interior of the subtropical gyre since the flows calculated at 13°W, the Greenwich meridian and during the WOCE A11 transect show the same variation. The second explanation, and the one that we feel is the more likely, is due to the recirculation of subtropical water west of 20°W in the Argentine Basin. In his study of the fronts Roden (1986) has shown that the STFZ and the Brazil Current Front (BCF) are coincident at a number of locations west of 40°W, primarily at 49°W, 45°W and 42°W. Between 40 and 42°W they appear to finally split, with the BCF turning northwards. Since the South Atlantic Current is associated with the STFZ, it is not unrealistic to assume that the Brazil Current is associated with the BCF along its trajectory. It therefore seems plausible that the flows and transports measured in the Argentine Basin during SAVE leg 5 result from both currents. Since the BCF turns northeast at about 40°W it is possible that the Brazil Current also moves north in this region. This is confirmed by the results of Stramma (1989), which show that there is recirculation of subtropical water to the west of 35°W. In addition, diagrams of adjusted steric height at 500 and 1000 m given by Reid (1994) show recirculation occurring near 20°W between 30 and 40°S. Furthermore, the work of Holfort (1994), using data from WOCE cruises A9 and A10, shows about 12 Sv of northward flow between 16 and 22°W at 30°S and about 15 Sv of flow between 20 and 27°W at 23°S in the top 800 m referenced to 1200 m no motion. Holfort (1994) observed no net meridional flow between the midocean ridge and the Greenwich meridian. Thus it seems reasonable to suggest that a large fraction of the eastward flow observed at or west of 30°W during SAVE leg 5 could be deflected northwards west of the mid ocean ridge and does not enter the Cape Basin.

5. Conclusions

From the hydrographic and tracer evidence we believe that the boundary between the subtropical and subantarctic water in the South Atlantic between 15°W and 5°E occurs as two distinct fronts. One at 35–37°S, which we continue to call the North Subtropical Front as defined by Belkin and Gordon (1996), and the other at approximately 39°S, which has the classic properties of the STC as defined by Deacon (1931) and which we refer to as the South Subtropical Front. This is in contrast to the work of Stramma and Peterson (1990), who believed, using the Ajax data set alone, that the STC (STF) was the more northern of the two fronts and thought that the South Atlantic Current flowed to the south of the front at the Greenwich Meridian rather than to the north, as had been observed in the Argentine Basin. However, in their defence it must be remembered that their study was based on the Ajax data set of October 1983, when the two fronts were less than 2° apart with the isotherms and isohalines showing a regular north south decrease, almost perpendicular to the surface in the top 500 m.

It is apparent from the data that the subsurface salinity maximum, which is often seen in the South Atlantic, extends from the NSTF and not from the SSTF. Cruises during January, February, March, and April show an increasing penetration of the maximum salinity tongue from the NSTF to the SSTF, and we speculate that the less dense subtropical water accumulates to the south of the NSTF in the austral summer until its increasing volume or the weakening of the SAC causes it to advance towards the south. Large patches of subtropical water remain intact and move southward away from the STFZ, suggesting that there is movement of water from the subtropical to the subantarctic zone even in areas of relatively weak meridional gradients.

Two major water types meet in the STFZ, where owing to its greater density the subantarctic water sinks. Deacon (1936), however, suggests that the presence of the subsurface salinity wedge at 150 m prevents the subantarctic water from sinking further and that the subantarctic water can be pushed back southwards within the top few hundred meters. The presence of this subsurface salinity lobe together with its seasonal formation/degradation results in a complex mesoscale structure, and we believe it is this complex structure and paucity of data in the area that has caused some confusion as to the exact nature of the STFZ. From CFC-11 and oxygen data, it is clear that only a thin layer of subantarctic water extends north of the SSTF at the surface, and we suggest that the use of thermal data, in particular using a single isotherm (Lujeharms et al., 1993), is likely to over-emphasise possible zonal seasonal movements due to changes in insolation, stratification and mixing. In addition the presence of eddies from the Brazil and Agulhus Currents (Smythe-Wright et al., 1996; Duncombe Rae et al., 1996) are likely to cause mesoscale perturbations in the position and expression of the STFZ. In particular, eddies originating in the Brazil Current would have to cross the South Atlantic within the Antarctic Circumpolar Current or the South Atlantic Current and consequently would effect any inferences about the nature of the STFZ if they were present at the time of measurement. Nevertheless we believe from the data presented here that the seasonal migration of the SSTF is only about 2.5° in the mid-South Atlantic. The boundary between subtropical and subantarctic water, however, extends over a larger area between the NSTF and the SSTF, causing seasonal differences in mesoscale structure and the intensity and position of the South Atlantic Current, which flows between the two fronts. We believe that the variations in catches and water characteristics seen off Tristan da Cunha by local fishermen (various pers. comm.) are probably related to changes in stratification as a consequence of seasonal heating and cooling and the formation and degradation of the salinity maximum rather than any migration of the SSTF.

The maximum eastward transport calculated for the area was 28.2 Sv, which is considerably less than the 37 Sv calculated for the Argentine Basin by Stramma and Peterson (1990) and our calculations of 37 Sv and 45.7 Sv using data from SAVE leg 5. We speculate that this difference arises because the velocities and transports calculated for the Argentine Basin during SAVE leg 5 result from the combined effect of the flows associated with the STFZ and the BCF, which are coincident in this region. At about 40°W the fronts diverge, with the BCF turning northeast and taking with it the order of 12–15 Sv of transport in the top 800 m. Consequently a large fraction of the flow seen west of 30°W is deflected northwards and does not enter the Cape Basin. We do not reject the suggestion given by Stramma and Peterson (1990) that the midocean ridge may cause a restriction in flow, but in the light of the WOCE A9 an A10 data (Holfort, 1994) it seems that the recirculation explanation is more likely.

Finally we would like to suggest that the findings of this paper more typify the STFZ in the ocean rather than the structure deduced from a number of crossings of the STFZ in various choke points/confluence regions.

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