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Journal of Marine Systems 30 (2001) 115–138

JOURNAL OF
MARINE
SYSTEMS

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The Agulhas Return Current

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Received 4 April 2000; accepted 5 March 2001

Abstract

The Agulhas Return Current constitutes the intense flow along the Subtropical Convergence south of Africa. It forms the connecting link between the generically similar South Atlantic Current and the South Indian Ocean Current, thus contributing to the water exchange between these two basins. This general along-front flow is, however, substantially modified south of Africa by contributions from the Agulhas Current.

We have carried out a first study of the hydrography and dynamics of the Agulhas Return Current along its full length using a collection of available modern hydrographic data. It is shown that on average the current lies at a latitude of 39°30′S south of Africa, increasing slowly downstream to a latitude of 44°30′S at 60°E, except where it crosses a number of meridional ridges where northward shifts of up to 2°30′ are occasionally observed. Geostrophic speeds relative to 1500 m demonstrate a gradual eastward decrease in the velocity of the current from an average of 75 cm/s at the Agulhas retroflection to 13 cm/s at 76°E. Volume transports are similarly reduced from 54×10^6 m^3/s in the retroflection region to 15×10^6 m^3/s at 76°E. Temperature/salinity properties show water mass characteristics of the Agulhas Current to extend to at least 61°E.

Based on these results, we suggest that the Agulhas Return Current is zonally continuous and terminates between 66°E and 70°E. We therefore propose that the name South Indian Ocean Current be retained for the flow east of here only.

Keywords: Agulhas Return Current; Geostrophic speed; Volume transport

1. Introduction

The greater Agulhas Current system forms the intensified western component of the subtropical gyre of the South Indian Ocean (Stramma and Lutjeharms, 1997). The Agulhas Current is supplied with Indian Ocean Tropical Surface Water of lower salinity (34.8–35.1) from the tropics (Gordon et al., 1987) and with more saline (> 35.4) South Indian Subtropical Surface Water by the South West Indian Ocean subgyre (Wyrtki, 1971). The Agulhas Current follows the continental shelf break of south-eastern Africa closely (Gründlingh, 1983) until it reaches the southern tip of Africa. Here the Agulhas Current terminates, with its water flowing into both adjacent ocean basins.

Estimates of the ratio of Agulhas Current water that enters the South Atlantic Ocean against that which flows back into the South Indian Ocean have varied enormously ever since the very first calculations of this kind were made (Lutjeharms et al., 1992). It is now recognised that the Agulhas Current

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PII: S0924-7963(01)00041-0

retroflects almost completely south of Africa (Gordon, 1985; Gordon et al., 1987; Lutjeharms and van Ballegooyen, 1988), and that the leakage of Agulhas water between the South Indian and South Atlantic Oceans is by way of large Agulhas rings (van Ballegooyen et al., 1994) and to a lesser extent by Agulhas filaments (Lutjeharms and Cooper, 1996). The remainder of the waters of the Agulhas Current flows back into the South Indian Ocean as the Agulhas Return Current (see Fig. 1).

The trajectory of the Agulhas Return Current has not, to date, been determined with any degree of reliability and may in fact be very variable. Drifting buoys have shown (Gründlingh, 1978; Daniault and Ménard, 1985; Hoffman, 1985) that its general motion is zonal, with extensive meridional excursions that may be related to changes in the bottom topography (Darbyshire, 1972; Lutjeharms and van Ballegooyen, 1984) along its path. The region is one of extreme mesoscale variability, (e.g. Cheney et al., 1983) as a result of recurrent eddy generation (e.g. Lutjeharms and Valentine, 1988) but also to shifts and time-varying meanders in the path of the Agulhas Return Current along the Subtropical Convergence.

The Subtropical Convergence is a weak front in the South Atlantic (e.g. Lutjeharms et al., 1993). (The classical term Subtropical Convergence will be used throughout, instead of the more trendy Subtropical Front, since no argument has to date been forthcoming that contradicts the findings that this front is indeed a convergence). South of Africa the frontal characteristics of the Subtropical Convergence are greatly strengthened by the adjacent warm, salty water of the Agulhas Return Current. Here the Agulhas Return Current tends to follow the Subtropical Convergence, but is sometimes separate from it (Lutjeharms, 1985). Then a distinct Agulhas Front in addition to the Subtropical Convergence proper can be observed (Belkin and Gordon, 1996).

The Agulhas water returned to the South Indian Ocean in the Agulhas Return Current may undergo modification by mixing with adjacent water masses, as well as by air–sea interaction. Mean heat losses of up to 200 W/m^2 at the Agulhas retroflection (Mey and Walker, 1990) and an excess of evaporation over precipitation change the temperature/salinity characteristics of the upper layers in this region here. Downstream losses of water from the Agulhas Return Current to the interior flow of the subtropical gyre have, furthermore, been thought to reduce the flow of this current on its way eastward (Harris, 1970).

Belkin and Gordon (1996) have considered the Agulhas Return Current to extend as far east as 72°E, since they found that water of Agulhas Current origin was clearly evident over the South-east Indian Ridge at 78°E. Park et al. (1991, 1993) have come to the same conclusion based on investigations in the Crozet Basin. They have found that the current, having undiminished Agulhas Current characteristics at 60°E, has dissipated totally by 75°E. Others (Veronis, 1973; Stramma, 1992; Stramma and Lutjeharms, 1997) have suggested such a large degree of branching northward of Agulhas water along the eastward flow path, that the Agulhas Return Current would already be utterly exhausted much farther to the west.

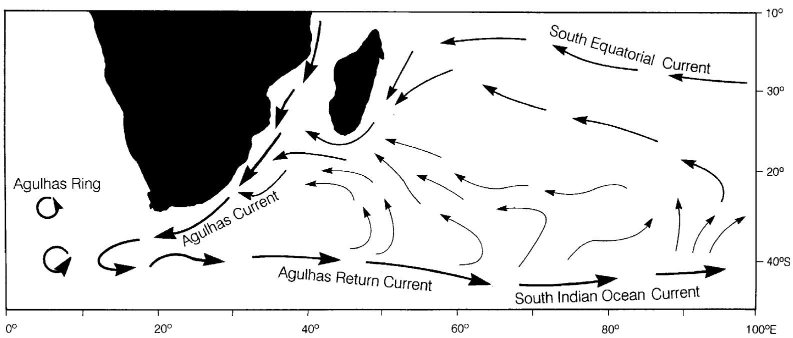


Fig. 1. A conceptual portrayal of the Agulhas Return Current as a component of the greater Agulhas Current system (modified from Lutjeharms and van Ballegooyen, 1988; Stramma and Lutjeharms, 1997).

It is therefore as yet unclear how rapidly the Agulhas Return Current dissipates or how coherent it remains downstream. A thorough along-stream analysis of its changing hydrographic characteristics has yet to be undertaken. We therefore present here the results of such an analysis of the mass flux, velocity and T/S characteristics of the Agulhas Return Current along its full length to determine its zonal coherence and its rate of downstream modification.

2. Data and methods

Two data sets have been employed for this investigation: a collection of CTD (conductivity–temperature–depth) station data from six modern cruises and a collection of XBT (expendable bathythermograph) data from a further six cruises that fill gaps between the CTD station lines (vide Fig. 2). CTD data sets were selected geographically to cover the Agulhas Return Current and to overlap with the upstream South Atlantic Current as well as with the downstream South Indian Ocean Current (Fig. 2). To be considered for inclusion in this data set, the station spacing along these cruise lines could not exceed 75 km (mostly ranges between 20 and 60 km) in order to allow accurate determinations of the geostrophic velocity, the volume transport and the hydrographic characteristics of the currents. Data were collected over a period of about 20 years, with most of the data having been collected during the austral summer. CTD data were all collected between 1983 and 1991. No statistically reliable evidence on either inter- or intra-annual variations can therefore be expected to be gained from this data set.

The resultant geographic coverage, extending over 76° longitude, is not ideal (Fig. 2). Station spacing differs between cruises. In general, cruise lines are relatively wide apart except in the region south of Africa where the Agulhas Return Current originates. In this important genesis region, data coverage is ample, allowing the current to be investigated in considerable detail. Information on each cruise is set out in Table 1. Full accounts of the data collecting

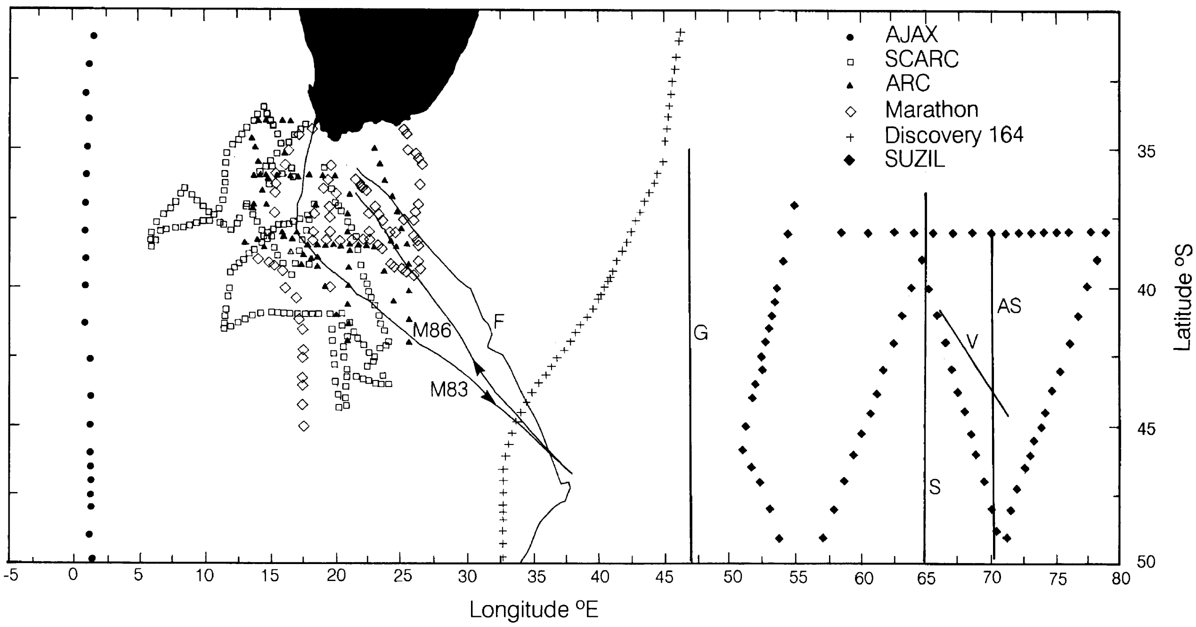


Fig. 2. The geographic distribution of cruise lines and stations that constitute the hydrographic data set used for this investigation. CTD (conductivity–temperature–depth) stations are indicated by symbols; solid lines show cruise lines on which closely spaced XBT (expendable bathythermograph) measurements were made. Details on each of these individual cruises is given in Table 1.

Table 1
Origin and characteristics of hydrographic data used in this analysis

Cruise	Data	Period	Vessel	Reference
AJAX	CTD	Oct 1983–Jan 1984	Knorr	(Whitworth and Nowlin, 1987)
SCARC	CTD	Feb–Mar 1987	S.A. Agulhas	(Valentine et al., 1988)
ARC	CTD	Nov–Dec 1983	Knorr	(Camp et al., 1986)
Marathon	CTD	Feb–Mar 1985	Thomas Washington	(Bennett, 1988)
Discovery 164	CTD	Dec 1986–Jan 1987	Discovery	(Pollard et al., 1987)
SUZIL	CTD	Apr–May 1992	M. Dufresne	(Park et al., 1993)
A. Shirshov (AS)	CTD	5 Nov 1970	Akademik Shirshov	(Belkin and Gordon, 1996)
Y.M. Shokalskii 33 (S)	CTD	July 1976	Yu. M. Shokalskii	(Belkin and Gordon, 1996)
Vitayaz 4 (V)	CTD	Jan 1983	Vitayaz	(Belkin and Gordon, 1996)
Marion 83 (M83)	XBT	Nov 1983	S.A. Agulhas	(Lutjeharms and Gordon, 1987)
Marion 86 (M86)	XBT	May 1986	S.A. Agulhas	(Lutjeharms and Matthysen, in preparation)
FIBEX (F)	XBT	Feb–Mar 1981	S.A. Agulhas	(Lutjeharms, 1985)
Gallieni 72 (G)	XBT	1972	Gallieni	(Park et al., 1991)

Brackets denote the prime papers on a cruise for which data in electronic form were made available.

procedures, instrument calibration, data processing, and thus the resultant accuracy to be expected, are found in the references given in this table. This information is not repeated here. Suffice to say that all these data are of high quality and considerably more accurate than any previously available.

From these data vertical sections for temperature, salinity and dissolved oxygen have been drawn and, where appropriate, curves of potential temperature/salinity (Θ/S) and potential temperature/dissolved oxygen (Θ/O_2) relationships for individual stations and for groups of stations constructed to characterize various water masses. Geostrophic velocities and the volume transport between adjacent stations for each cruise line have been calculated at every 20-db pressure level in the upper 500 m and either every 50 db or every 100 db in the rest of the water column measured. The 1500 m is the deepest common depth for all full hydrographic stations of this data set; 3000 m is the deepest common depth for the stations occupied as part of the SUZIL and the Discovery 164 cruises.

3. Geographic location of the Agulhas Return Current

In order to establish a reliable baseline for the zonal flow along the Subtropical Convergence without the presence of the Agulhas Return Current, a meridional line of stations was selected at the Greenwich meridian (Whitworth and Nowlin, 1987). The farthest westward extent of the Agulhas retroflection loop, and its products, that has been reported to date (Lutjeharms, 1988) is 5°E. This line of stations should therefore be well upstream of the influence of the Agulhas Current. On this cruise line the Subtropical Convergence and the attendant South Atlantic Current were found at about 37°30′S latitude (Fig. 3). The temperature change across the front was from 14.3 to 12.1 °C and the salinities from 35.17 to 34.63 at the sea surface. Both these surface gradients are weak in comparison to those observed south of Africa (Lutjeharms and Valentine, 1984) and in more western parts of the South Atlantic (e.g. Stramma and Peterson, 1990; Lutjeharms et al., 1993). The middle temperature is also slightly lower (13 °C) than the average found over a more extensive zone (14.2 °C; Lutjeharms and Valentine, 1984). These results are, however, in substantial agreement with subsequent observations made here (Le Groupe CITHER-3, 1996). In general, the salinity seems a more reliable indicator of the meridional termination of the subtropical surface regime (Fig. 3c) than the temperature (Fig. 3b).

This section upstream of the influence of the Agulhas Current gives a good representation of the Subtropical Convergence in its unenhanced state. Further eastwards this frontal expression becomes considerably more complex and it will be more difficult to distinguish the Subtropical Convergence

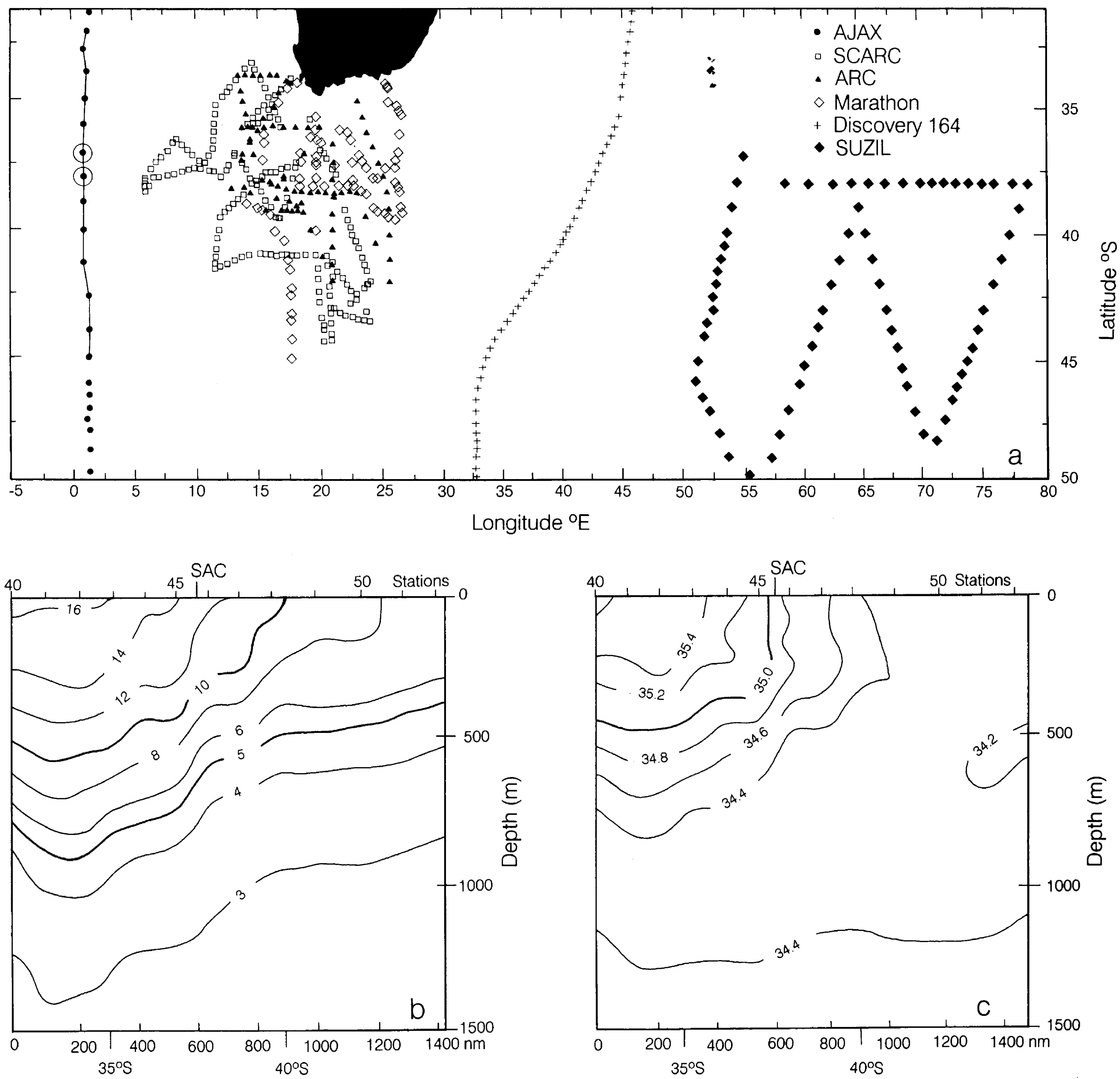


Fig. 3. (a) The geographic location of an AJAX cruise line and the stations between which the South Atlantic Current was located (circled); (b) the vertical temperature section to 1500-m depth along this line showing the location of the South Atlantic Current; and (c) the vertical salinity section for the same line. Note that for clarity some isotherms have been omitted.

from the Agulhas Front (Belkin and Gordon, 1996). No objective definition of frontal characteristics will suffice to make this distinction entirely unambiguous. Downstream of the Agulhas retroflection (Fig. 1) any enhancement of the Subtropical Convergence in the South Atlantic has therefore been deemed to represent the presence of the Agulhas Return Current; any secondary front to the north, the Agulhas Front.

By contrast, the gradients south of Africa are much stronger (Fig. 4) and the frontal and current portrayal much more complicated. This is evident in both the temperature, salinity and the dissolved oxygen sections shown in Fig. 4. From an abundance of

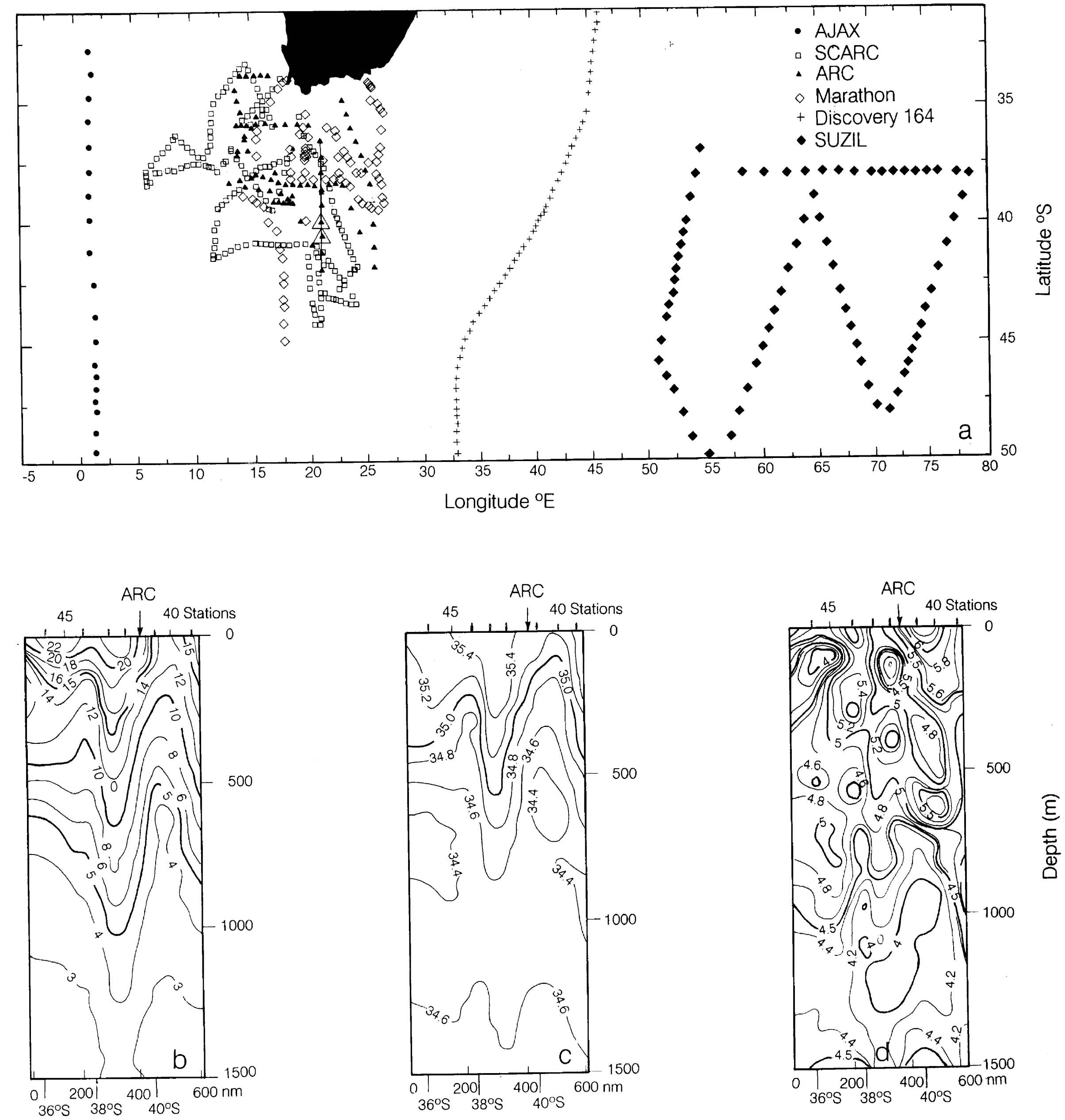


Fig. 4. (a) The geographic location of an ARC cruise line with the stations between which the Agulhas Return Current was located shown by triangles; (b) the vertical temperature section to 1500-m depth along this line showing the location of the Agulhas Return Current; (c) the vertical salinity section; and (d) the vertical oxygen for the same line.

station lines from this region (vide Fig. 2), this particular one was selected for inclusion here for its near-meridional nature and its good coverage of the Agulhas Return Current. All other sections were used to locate the current (Fig. 8), but are for the sake of brevity not reproduced here. In the representative section portrayed in Fig. 4, the Agulhas Return Current is found to lie between 40°40′S and 39°20′S. At a 200-db level, a depth thought best to represent the location of the core of the Agulhas Current (Gründlingh, 1983) and therefore also the Agulhas Return Current, the temperature range at the southern front of this current was from 18 to 11 °C, salinity from 35.57 to 34.80 and oxygen values from 5.1 to 5.3 ml/l. The current may be considered to have been adjacent to the Subtropical Convergence at this time, but its flow is complicated by a westward flow lying slightly to the north and a possible warm eddy to the south.

An XBT section (Marion 83, Table 1, Fig. 2), taken shortly before, located front and current at more or less the same latitude, but with a simpler, singular, current portrayal. The general location and thermohaline nature of the Agulhas Return Current at this time may be considered quite representative (Lutjeharms, 1990). It is important to note that the vertical disturbance caused in the thermohaline field by the presence of the Agulhas Return Current extends to depths exceeding 1500 m (Fig. 4). On this occasion, it was not evident below 2000 m (not shown here). The oxygen distribution demonstrates (Fig. 4c) that at 200-m depth, the Agulhas Return Current had a core of oxygen lower than its immediate surroundings. At a depth of 500 m there is, by contrast, a core of higher oxygen. The subsurface core of slightly higher oxygen values is also evident in a section lying farther to the east, but still part of the collection of stations south of Africa (Fig. 5).

The water mass distribution in the roughly meridional section shown in Fig. 5 is in many ways considerably less complicated than that of Fig. 4. It resolves the inflow of the Agulhas Current off the coast of Africa (stations 277–280, Fig. 5b,c) that is exemplified by the strong downward thermohaline gradient in a southerly direction. As a near-mirror image, the Agulhas Return Current was found further south at about 39°S with a width of only about 70 km. This can in many ways be considered as representing the outflow of the Agulhas Return Current from the Agulhas retroflection region (vide Fig. 5). A comparison of the two currents across this section shows that all the surface water with temperatures in excess of 22 °C in the Agulhas Current inflow had disappeared in the Agulhas Return Current outflow, probably due to cooling by interaction with the atmosphere. This modification of surface waters extended to a depth of at least 150 m. The subsurface salinity maximum, representing South Indian Subtropical Surface Water, is nevertheless still clearly evident in the outflow.

The location of the Agulhas Return Current on this section was considerably farther to the north than that of the section shown in Fig. 4. This was most probably due to an extensive meander in the current deflecting it northwards around the Agulhas Plateau that is found at this longitude. This conclusion is supported by the results of the two XBT sections carried out through this region (vide Fig. 2). These temperature sections also show the core of the Agulhas Return Current lying to the north of the Agulhas Plateau. During the Marathon cruise, on which the section in Fig. 5 is based, the core of the current—as exemplified by the place at which the 15 °C isotherm cuts the 200-m depth horizon—lies over a depth of 2700 m. In previous surveys (e.g. Gordon et al., 1987; Harris and Bang, 1974), this contour was found over a water depth of 4200 m. One may therefore assume that the Agulhas Return Current tends to meander northwards around the Agulhas Plateau, but that the extent and location of this meander is very variable in time. East of here, any possible meanders in the path of the Agulhas Return Current that are due to bottom obstructions may be considerably less severe, but this perception may be due in part to the dearth of data for this region (vide Fig. 2).

The first good hydrographic section downstream of the region south of Africa is found at about 40°E (Fig. 6) and shows the Agulhas Return Current distinctly separate from the Subtropical Convergence, lying 160 km north of this front. The thermal disturbances associated with these two features were observed to a depth of at least 3000 m here (Read and Pollard, 1993), in substantial agreement with those of previous studies in the region (e.g. Jacobs and Georgi, 1977). The distinctive current features evident in this section are in contrast to what is found in the farthest eastern section of this hydrographic data set, at 75°E, shown in Fig. 7.

Here, there is no longer any evidence of a separate Agulhas Return Current. The possible remnant of a feeble Agulhas Front tentatively indicated in

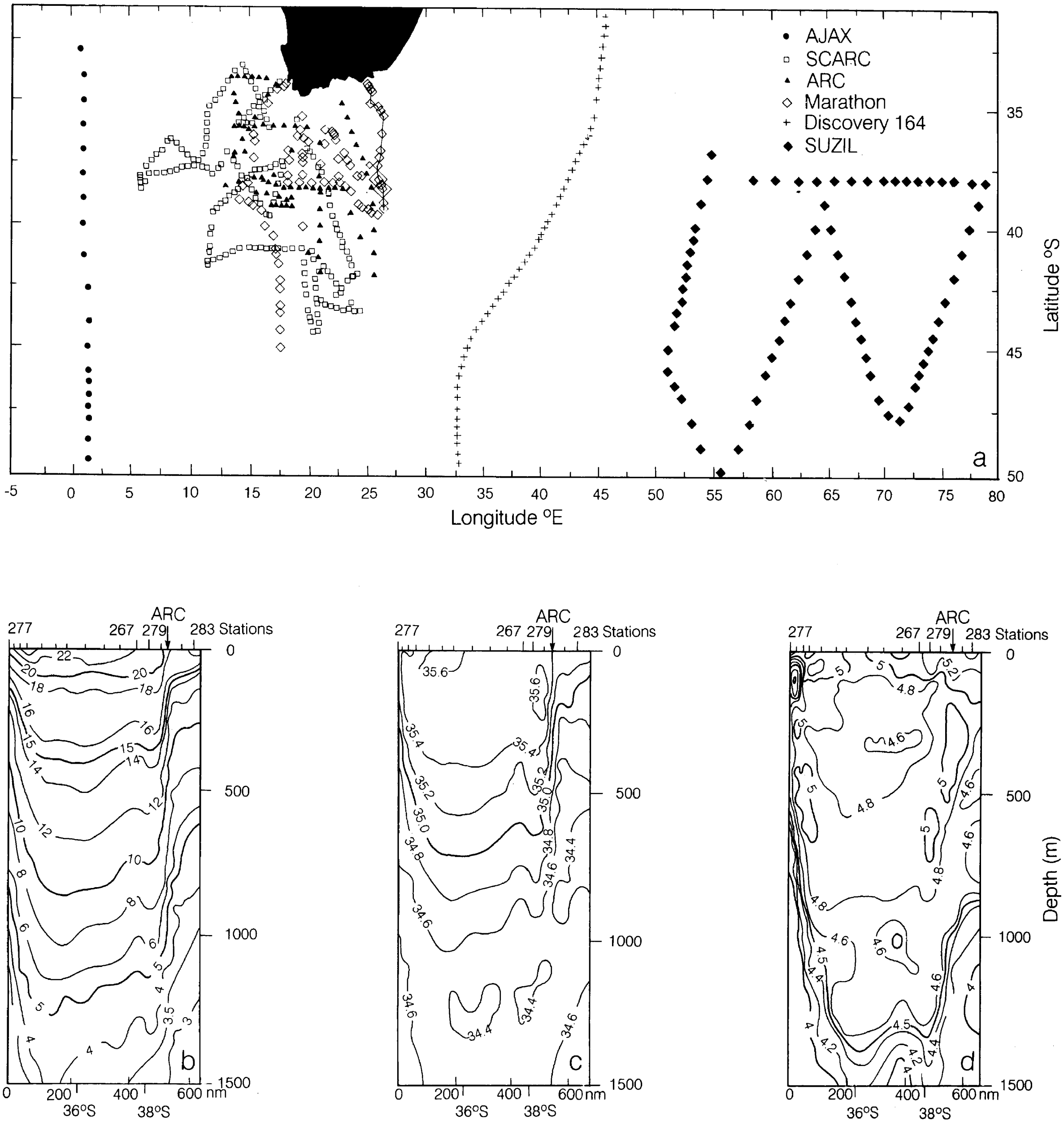


Fig. 5. (a) The geographic location of a Marathon cruise line and the stations along this line between which the Agulhas Return Current was located (indicated by diamonds); (b) the vertical temperature section to 1500-m depth along this line showing the location of the Agulhas Return Current; (c) the vertical salinity section; and (d) the vertical oxygen section for the same line.

Fig. 7 does not penetrate below 2000-m depth. Although the frontal thermohaline characteristics of the Subtropical Convergence were well developed during this crossing, there no longer is any evidence (vide Fig. 7c) for high salinity water associated with Agulhas water, the highest values being only 35.2

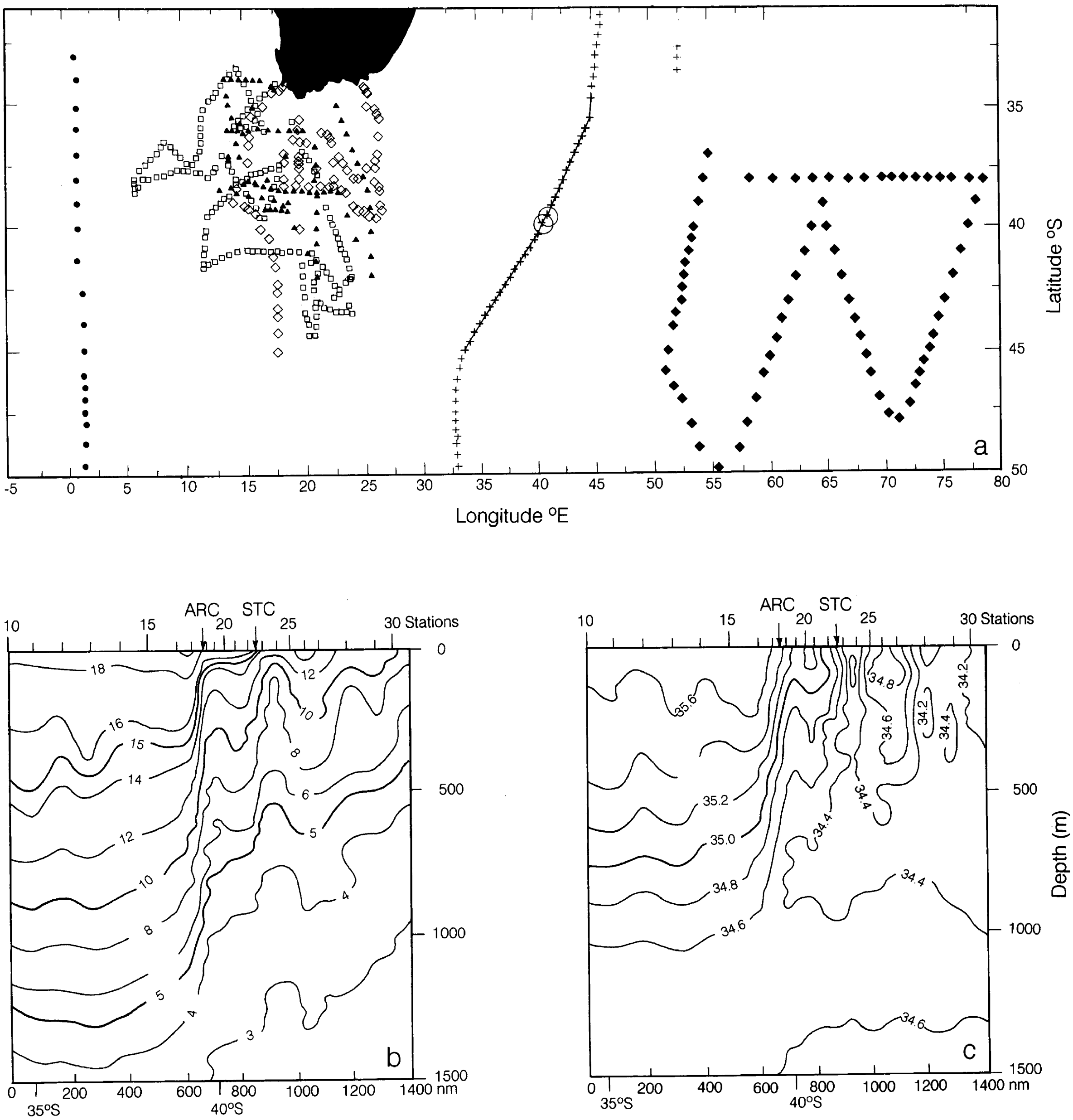


Fig. 6. (a) The geographic location of a Discovery 164 cruise line and the stations shown by circles along this line between which the Agulhas Return Current was located; (b) the vertical temperature section to 1500-m depth along this line showing the location of the Agulhas Return Current and the Subtropical Convergence; and (c) the vertical salinity section for the same line.

instead of 35.6 (Fig. 5). In this respect, this section shows a close resemblance to that portrayed in Fig. 3, i.e. upstream of the influence of the Agulhas Current. It is, however, noteworthy that the Subtropical Convergence is more distinct here, in the central Indian Ocean, than in the far eastern South Atlantic.

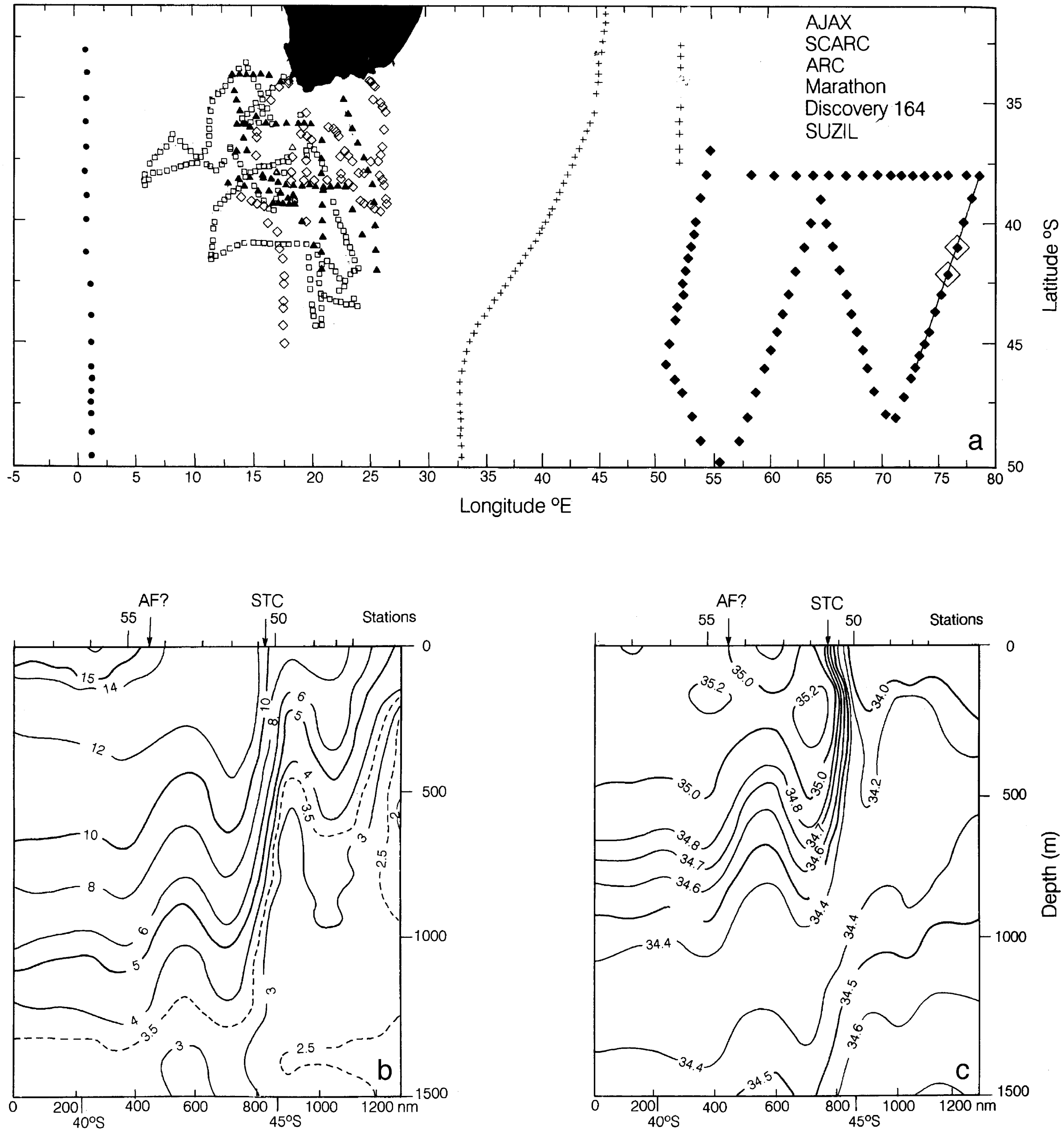


Fig. 7. (a) The geographic location of a SUZIL cruise line and the triangular stations along this line between which possible remnants of the Agulhas Return Current were located (diamonds); (b) the vertical temperature section to 1500-m depth along this line showing the location of a doubtful Agulhas Front and the Subtropical Convergence; and (c) the vertical salinity section for the same line.

The salinity of surface water in the South Indian Ocean Current, along the Subtropical Convergence in Fig. 7c, is lower than at about 200-m depth, or further north. This suggests an overflow of low salinity, Subantarctic Surface Water from the south (Park et al., 1993).

Using the sections portrayed in Figs. 3–7 as well as the results of all other sections for which the geographic locations are given in Fig. 2 but that have not been portrayed in the figures, the geographic location of the Agulhas Return Current emerges as given in Fig. 8. The first clear evidence for the presence of the Agulhas Return Current has been found at about 16°E. Between here and 30°E, it lies in a broadish band. The width of this band may be due to temporal variability elucidated by the dense data coverage south of Africa. An extensive meridional meander is due to the influence of the Agulhas Plateau at about 25°E. East of here, the Agulhas Return Current exhibits a tendency to lie increasingly farther to the south (Fig. 8). Any time-dependent motion of the current cannot be resolved here due to a lack of appropriate data. From about 66°E the current becomes increasingly hard to distinguish. By 70°E longitude, it may be considered to be no longer present in any recognisable form. An inspection of the detail of the hydrographic characteristics of the water masses involved may shed some additional light on the changing downstream characteristics of the Agulhas Return Current and the location of its termination.

4. Hydrographic characteristics

Two components of the hydrographic data set used for this investigation are potentially of considerable utility in establishing the nature of the inflow into the Agulhas Retroflection region. The first consists of those stations that typify the inflow from the South Atlantic Current, and the second those that cover the inflow from the Agulhas Current proper (Fig. 9). These two water mass contributions are quite distinct and characteristic.

The salinity minimum typifying the Antarctic Intermediate Water is much sharper in the South Atlantic since it is unaffected by Red Sea Water (Shannon and Hunter, 1988). Red Sea Water penetrates far into the South Indian Ocean (Gründlingh, 1985), is carried southwards by the Agulhas Current (Gordon et al., 1987) and forms a not inconsiderable component of the intermediate water mass characteristic of the Agulhas retroflection region (Valentine et al., 1993). The influence of Red Sea Water at intermediate depths in the Agulhas system is particularly noticeable in the oxygen content (Fig. 9c). Unadulterated Antarctic Intermediate Water in the South Atlantic presents as an oxygen maximum; in the

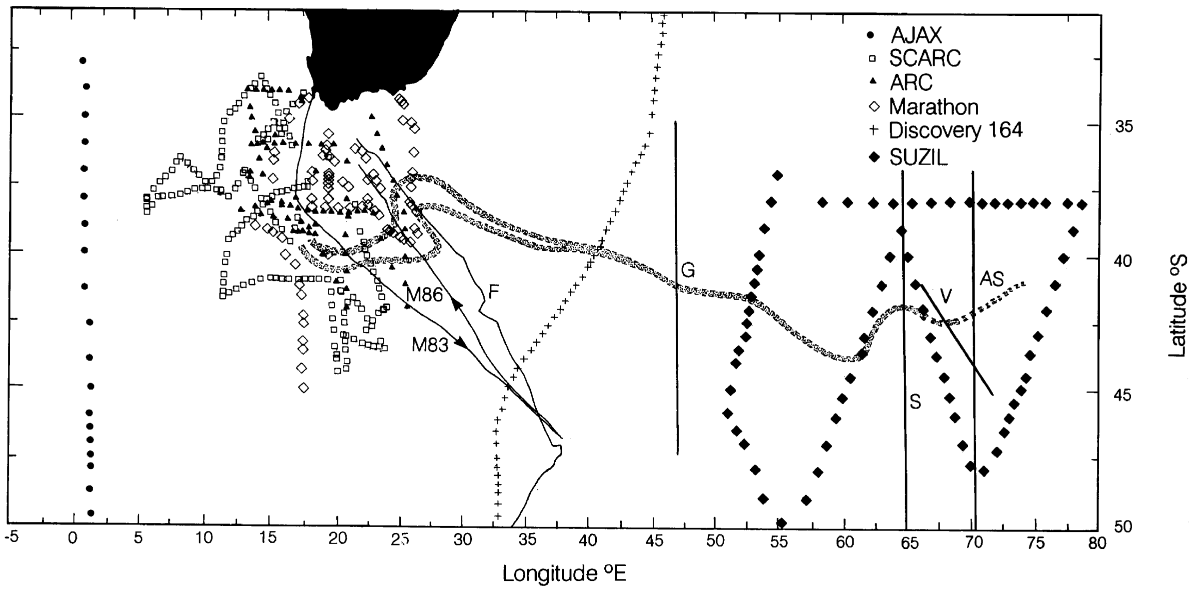


Fig. 8. The geographic location of the Agulhas Return Current based on all the full hydrographic sections as well as the XBT lines used for this study.

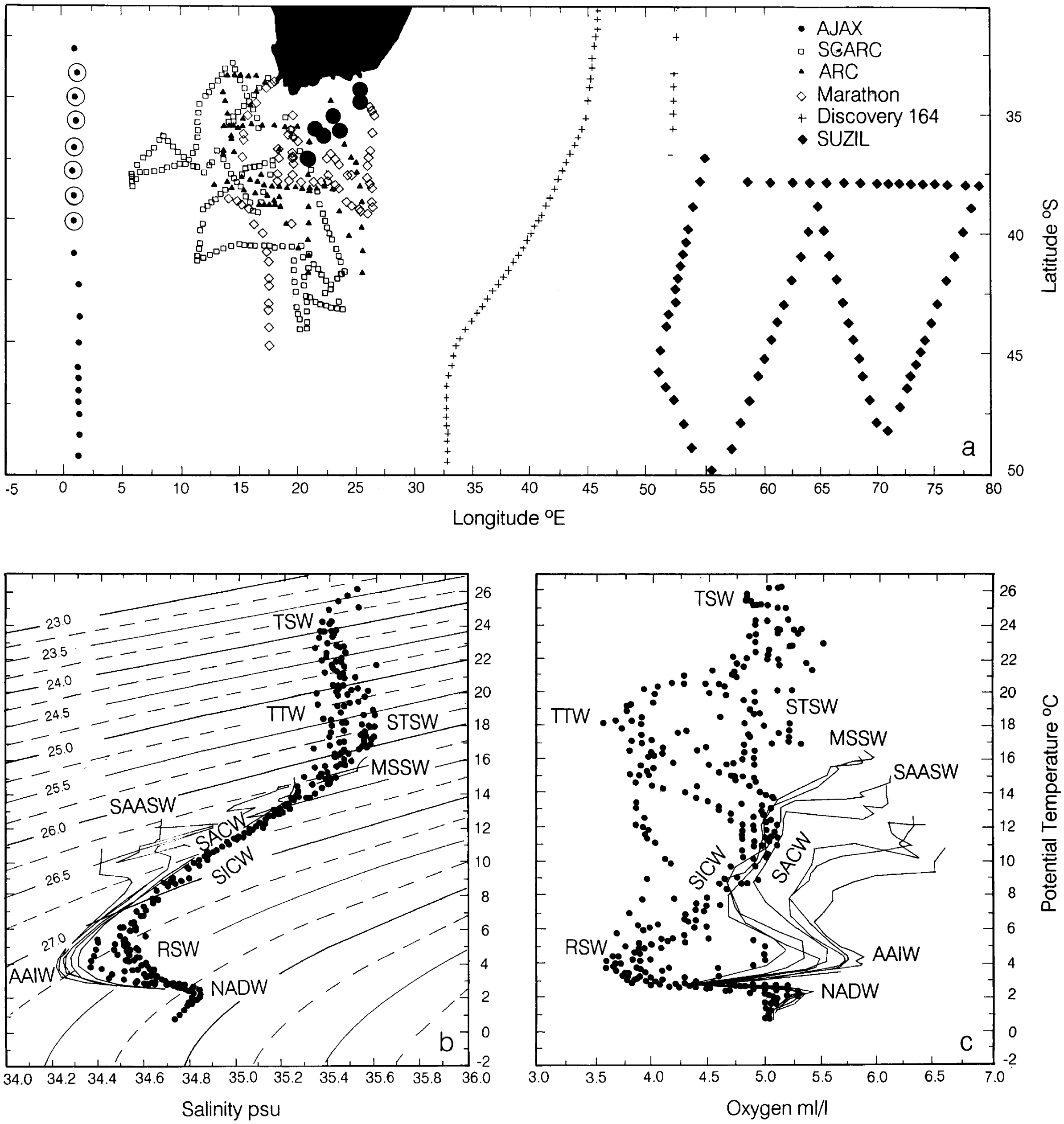


Fig. 9. (a) The geographic location of stations from the SCARC, ARC and Marathon cruises (to represent the Agulhas Current's inflow characteristics, dots) and from the AJAX cruise (to represent the South Atlantic Current's inflow characteristics, circles). (b) A Θ/S plot to compare these characteristics. Lines represent AJAX stations; dots stations from the other three cruises. (c) A Θ/O_2 plot comparing the Agulhas inflow (dots) with the South Atlantic Current inflow (lines). Water masses identified are: Subtropical Surface Water (STSW), Tropical Surface Water (TSF), Tropical Thermocline Water (TTW), Modified Surface Water (MSSW), Subantarctic Surface Water (SAASW), South Atlantic Central Water (SACW), South Indian Central Water (SICW), Red Sea Water (RSW), Antarctic Intermediate Water (AAIW) and North Atlantic Deep Water (NADW).

South Indian, mixed with Red Sea Water, as an oxygen minimum. These distinct differences in the intermediate waters have a noticeable influence on the central waters that extend upward to the surface waters (Fig. 9).

The stations along the 0° meridian extend into the Subantarctic, therefore showing the low salinity characteristics of the Subantarctic Surface Water, whereas the selection of stations for the Agulhas Current do not reach so far south. The Central Water masses of the South Indian and South Atlantic subtropical gyres show some distinctly different characteristic (Fig. 9b,c). South Atlantic Central Water is slightly less saline and considerably better oxygenated than its South Indian counterpart (Chapman et al., 1987). In the temperature range 8–13 °C, the two central water masses are the closest akin. This may be due to an exchange of water masses between the two basins at this level (Gordon, 1981, 1985).

The surface waters in the Agulhas Current (Fig. 9) are dominated by South Indian Subtropical Surface Water, Tropical Surface Water and Tropical Thermocline Water. The Tropical Surface Water derives from the South Equatorial Current at 10° to 15°S (Fig. 1), where the excess of precipitation over evaporation and the inflow of fresher tropical water from the Pacific (Warren, 1981) make this water type relatively fresh. It is thought to reach the Agulhas Current through the Mozambique Channel (Harris, 1972) and is found in the upper layers of the current, predominantly on the inshore side (Gordon et al., 1987). This upper layer is only about 100 to 150 m thick. Directly below it lies the considerably more saline Subtropical Surface Water.

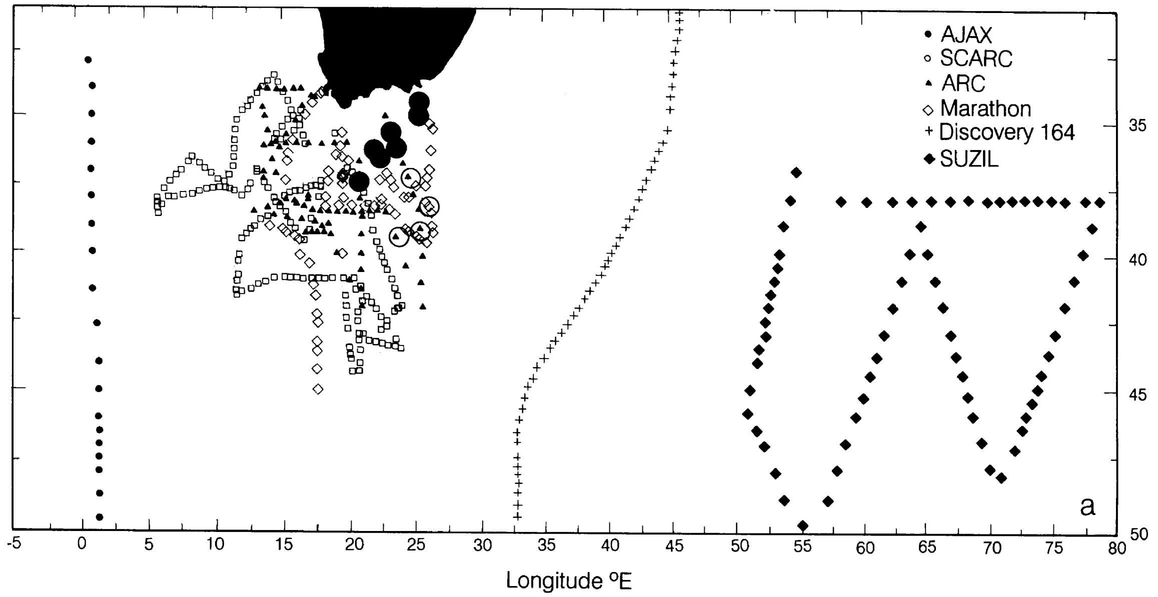
This water forms a distinct salinity and oxygen maximum (Fig. 9b) and originates in the subtropical gyre of the South Indian Ocean (Wyrtki, 1971), where there is an excess of evaporation over precipitation. Water with a lower salinity value at the same depths, Tropical Thermocline Water, is thought to be Subtropical Surface Water contaminated by Subantarctic Surface Water in the Agulhas retroflection region. On first reflection this seems unlikely, since Subantarctic Surface Water has an oxygen maximum (Fig. 9c) and Tropical Thermocline Water has an oxygen content lower than 3.5 ml/l. This oxygen minimum, at a depth of 200 m, is associated with a nutrient maximum and is formed by the oxidation of sinking detritus (Warren, 1981). Waters forming this oxygen minimum are transported southward by the Agulhas Current into the retroflection zone where it has been used as a tracer for Agulhas water (Chapman, 1988).

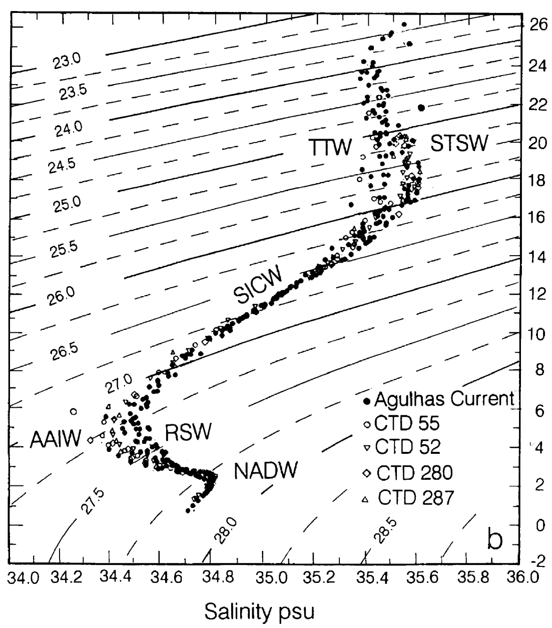
These three water masses, Tropical Surface Water, Subtropical Surface Water and Tropical Thermocline Water, are characteristic of the inflow only from the Indian Ocean into the source region of the Agulhas Return Current and have no South Atlantic counterparts (Fig. 9). Atlantic water from the subtropics with a somewhat comparable salinity, Modified Subtropical Surface Water (Fig. 9b), is thought to come about due to increased evaporation in the Southeastern Atlantic.

The inflowing water masses meet in the Agulhas retroflection (Gordon et al., 1987; Gordon et al., 1992) where a melange of water mass characteristics results (Valentine et al., 1993) and are subjected to further modifications by cooling and evaporation in this region. The changes that are thus brought about are evident when the Agulhas Return Current outflow from the Agulhas retroflection is compared to the inflow discussed above (Fig. 10).

The most obvious difference between the Θ/S characteristics of the in- and outflow of the Agulhas retroflection is the total absence of Tropical Surface Water in the station data representing the Agulhas Return Current. This has already been noted in the hydrographic sections displayed in Fig. 5 where the characteristics of the Agulhas and Agulhas Return Currents may be directly compared. One may therefore assume that by a process of lateral mixing and/or atmospheric interaction this water type is removed in the Agulhas retroflection region. The heat loss to the atmosphere may penetrate as deep as the Subtropical Surface Water (Fig. 10), but a degree of freshening may also be due to mixing with fresher South Atlantic water masses in the retroflection region (Fine et al., 1988).

Central water in the Agulhas Return Current may have been similarly influenced, since it shows a much reduced effect of those Tropical Thermocline Water characteristics that normally are typical of South-Indian Waters (Fig. 10c). In three of the four stations used to define the waters of the Agulhas Return Current, the subsurface oxygen minimum usually associated with Tropical Thermocline Water





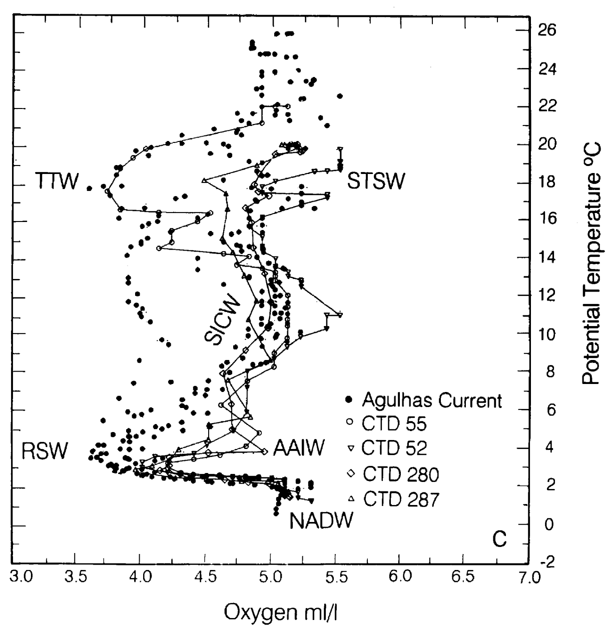


Fig. 10. (a) The geographic location of stations from the SCARC, ARC and Marathon cruises (representing the hydrographic characteristics of the Agulhas Current inflow, dots) and from the ARC and Marathon cruises (circles, representing the hydrographic characteristics of the Agulhas Return Current outflow from the Agulhas retroflection). (b) A Θ/S plot to compare these characteristics. Dots are inflow values, circles outflow stations. (c) A Θ/O_2 plot comparing the Agulhas inflow (dots) with the Agulhas Return Current outflow (circles, connected by lines). Water masses identified are: Subtropical Surface Water (STSW), Tropical Thermocline Water (TTW), South Indian Central Water (SICW), Red Sea Water (RSW), Antarctic Intermediate Water (AAIW) and North Atlantic Deep Water (NADW).

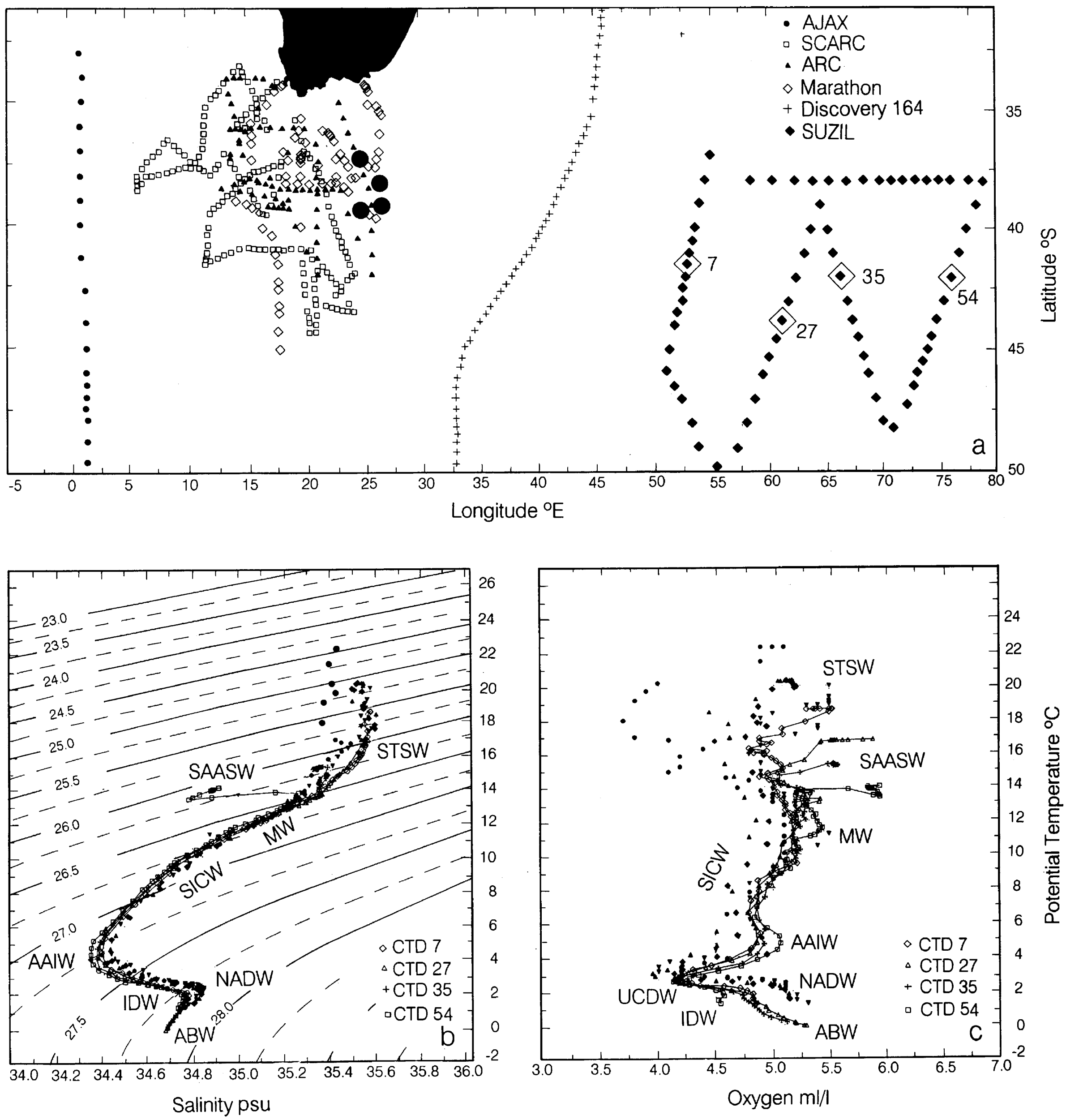


Fig. 11. (a) The geographic location of stations from the ARC and Marathon cruises (dots, representing the initial stages of the Agulhas Return Current) and of stations from the SUZIL cruise (circles, representing the far downstream stages of the Agulhas Return Current). (b) A Θ/S plot to compare the early and later characteristics of water of the Agulhas Return Current. Dots represent upstream stations, circles connected by lines the downstream stations. (c) A Θ/O_2 plot for the same stations. Water masses identified here are: Subtropical Surface Water (STSW), Subantarctic Surface Water (SAASW), Mode Water (MW), South Indian Central Water (SICW), Antarctic Intermediate Water (AAIW), Indian Deep Water (IDW), Upper Circumpolar Deep Water (UCDW) and Antarctic Bottom Water (ABW).

had been almost totally eroded. The effect of Red Sea Water is also considerably reduced, the Agulhas Return Current emerging from the Agulhas retroflection with much clearer Antarctic Intermediate Water characteristics than those found in the Agulhas Current proper (Fig. 10b,c). Since the South Atlantic Intermediate Water has a more recent history of ventilation (Fine et al., 1988), these waters should be noticeably purer than those in the South Indian, even without any Red Sea Water influence (Fig. 9). Gordon et al., (1992) have in fact estimated that 50% of the thermocline water of the South Atlantic Current flows into the South Indian Ocean, there, presumably, to join the alongfront flow.

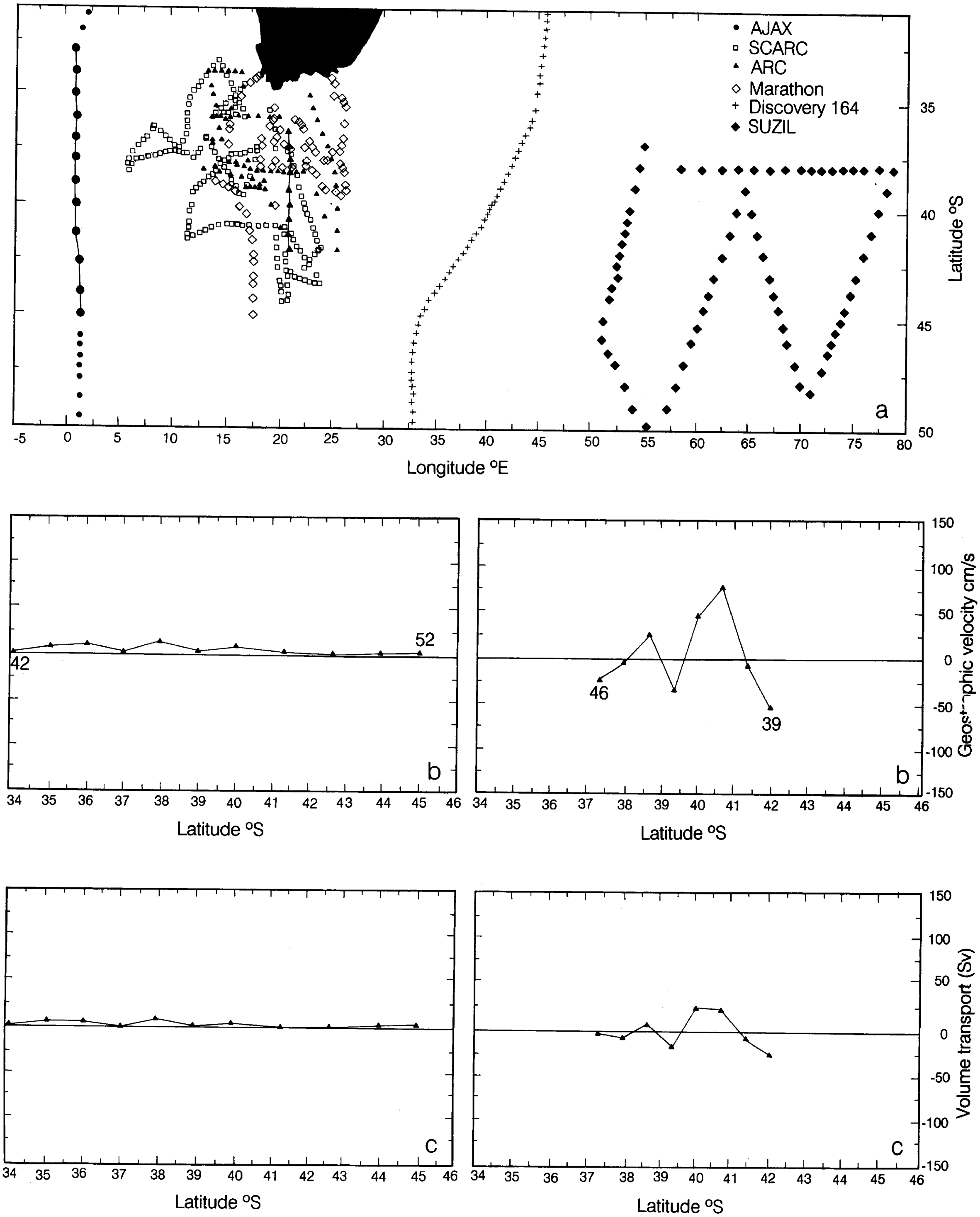
The final disposition of the water masses that characterise the Agulhas Return Current at its outset can be demonstrated by comparing it with stations selected to lie in its assumed core (vide Fig. 8) between 50° and 80°E longitude (Fig. 11). The downstream changes over this zone are substantial (Park et al., 1993). At the first section (CTD 7, Fig. 11), the characteristics of Subtropical Surface Water is indistinguishable from that in the Agulhas Return Current south of Africa. There is a steady eastward reduction in the presence of this water, so that by the last section (CTD 54, Fig. 11) all evidence for Subtropical Surface Water has disappeared. Since this water has traversed the same distance at a comparable latitude (Fig. 8) before reaching the SUZIL station network, one may assume that this disappearance within the SUZIL network is largely due to incorporation of the Agulhas Return Current flow into the interior of the subtropical subgyre of the South West Indian Ocean (Park et al., 1993; Stramma and Lutjeharms, 1997) and not due to more intense air–sea exchanges. The flow along the Subtropical Convergence is increasingly typified by Subantarctic Surface Water (vide Fig. 7).

Below the surface water, at a depth of 200 to 600 m at a σt surface of 26.5 (Fig. 11b), there is considerable evidence for the presence of Mode Water. This water type is formed by deep winter convection in the area immediately north of the Antarctic Circumpolar Current and is characterised by a pycnostad with a subsurface oxygen maximum (Fig. 11c). Park et al. (1993) have noted that the winter overturning of Agulhas water with a subtropical origin (at CTD stations 7 and 27, Fig. 11b) produces warmer and more saline Mode Water (McCartney, 1977) than further downstream. Substantial differences are also evident in the central, intermediate and deep waters.

Central waters show a freshening and higher oxygenation downstream in the SUZIL station network. This may be due to mixing with purer Antarctic Intermediate Water from below (Fig. 11b). It has been demonstrated (Park and Gambéroni, 1997) that there are unprecedentedly strong, cross-frontal injections of newly formed Antarctic Intermediate Water in this region. It is possible that the northward recirculation of water from the Agulhas Return Current in the Crozet Basin, where the SUZIL stations were located, may be a major carrier of this injected Antarctic Intermediate Water into the subtropical gyre of the South Indian Ocean. This would confirm the suggestion made by Molinelli (1981) that this region is a prime source for Antarctic Intermediate Water in the Indian Ocean.

The distribution of the water characteristics of the Agulhas Return Current thus shows that it emerges from the Agulhas retroflection region with substantially modified water masses compared to the Agulhas Current. This is due to considerable admixture of South Atlantic water at the retroflection and from the South Atlantic Current, as well as loss of surface characteristics by intense air–sea exchange. From here to the Crozet Basin the water characteristics remain remarkably intact, but over the Crozet Basin this changes dramatically so that between 66° and 75°E, all hydrographic evidence for the Agulhas Return Current has been removed. Evidence for the presence of Agulhas water does not de facto imply that the Agulhas Return Current is still a distinguishable current entity. To establish this, the velocity and the volume transport of the current have to be investigated.

Fig. 12. (a) The geographic location of two hydrographic crossings of the flow along the Subtropical Convergence south of Africa, one upstream of and one across the Agulhas Return Current; (b) the geostrophic velocities across these sections, referenced to 1500 db, with eastward flow shown as positive; and, (c) the volume transport for the same sections.


AJAX
SCARC
ARC
Marathon
Discovery 164
SUZIL
a
Longitude °E
Latitude °S
b
Latitude °S
Geostrophic velocity cm/s
42
52
46
39
c
Volume transport (Sv)

5. Velocities and volume transports

Geostrophic velocities and volume transports were calculated in the manner described above using 1500 db as a reference level. This level was selected to facilitate the accommodation of as many hydrographic sections as possible. The central goal of the current investigation is to establish the relative changes to the downstream flow of the Agulhas Return Current and not to determine absolute velocity or transport values. To this end a choice of a 1500-db reference level therefore seems adequate. Calculations were made for all CTD sections forming part of this data set and shown in Fig. 2. Only those corresponding to the sections shown in Figs. 3–7 are reproduced here (Figs. 12 and 13).

The first section (Fig. 12b) is upstream of the Agulhas retroflection at 0°E (cf. Fig. 3) and shows a geostrophic flow eastward with a weak maximum, not exceeding 12 cm/s, at 36° and 38°S, the southern maximum corresponding to the location of the South Atlantic Current. The calculated geostrophic velocity is comparable to those observed here with drifters (e.g. Daniault and Ménard, 1985). The maximum volume transport between any two stations was about 3×10^6 m^3/s. The total transport calculated for the full Subtropical Convergence zone was 19×10^6 m^3/s. This may be compared to the flow behaviour south of Africa.

The geostrophic speed to 1500 db calculated for the Agulhas Current (not shown here) was 110 cm/s, which compares favourably with drifter speeds of 90–119 cm/s (Gründlingh, 1978) for this current as well as ADCP observations of 100–130 cm/s (Rouault et al., 1995). The volume transport at the same section was 49×10^6 m^3/s that may be extrapolated coastwards to include a full 70×10^6 m^3/s for the Agulhas Current (Gordon et al., 1987). This may be compared to the section across the Agulhas Return Current at 21°E undertaken during the same cruise (Fig. 12).

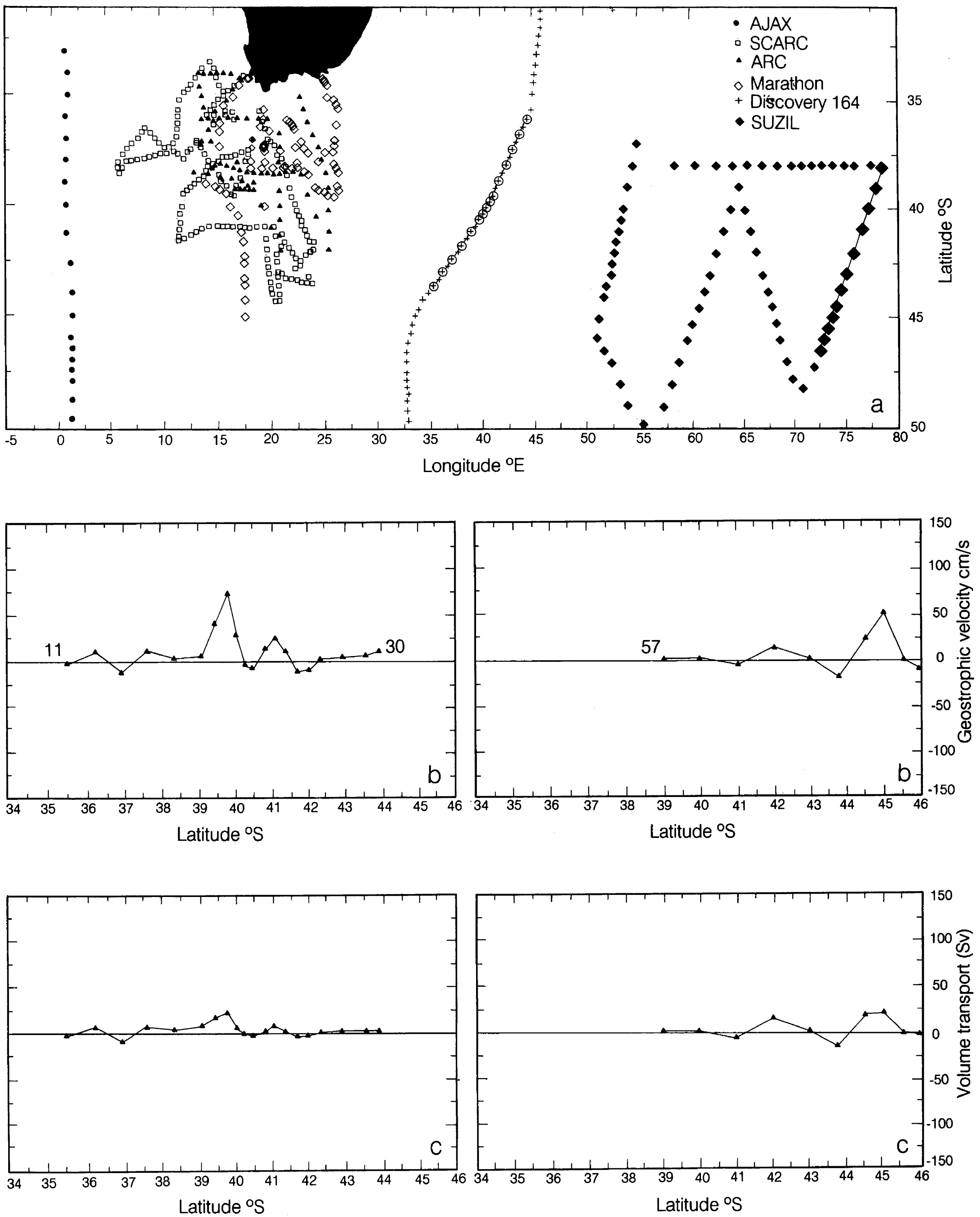
A maximum geostrophic speed of 75 cm/s was calculated, corresponding to the main peak at about 40°30′S in Fig. 12b. This constitutes a substantial reduction in speed from the Agulhas Current itself. The volume transport over the full width of the eastward flow that is part of the Agulhas Return Current was 54×10^6 m^3/s, i.e. at least 16×10^6 m^3/s less than the Agulhas Current itself. As may be expected for a region exhibiting a large variability, other sections across the Agulhas Return Current show a range of speed and transport estimates, of which the one presented here is roughly a middle value. On proceeding downstream, the speeds and transports decrease.

At 40°E (Fig. 13, cf. Fig. 6,) there were two distinct eastward flows, the major one being the Agulhas Return Current with the minor, separate, flow along the Subtropical Convergence. The maximum speed of the Agulhas Return Current was 72 cm/s, which may be compared to drifter speeds of between 73 and 84 cm/s (Gründlingh, 1978). The flow along the Subtropical Convergence was only 24 cm/s, comparable to the average drifter speeds of 26 cm/s reported by Hoffman (1985). Volume transports were 42×10^6 and 13×10^6 m^3/s, respectively. At the last section used for this study, this reduction has gone even further.

At 76°E (Fig. 13), the major flow is concentrated at the Subtropical Convergence (cf. Fig. 7) with a calculated surface speed of 53 cm/s relative to 1500 db. A weak and minor front was found to the north at about 42°S (Fig. 7). Here, there is a maximum geostrophic speed of only 13 cm/s and total eastward transport of 15×10^6 m^3/s. The transport along the Subtropical Convergence, by contrast, was 42×10^6 m^3/s. The ineluctable decrease in both speed and volume flux of the Agulhas Return Current along its eastward course, is summarised and shown graphically in Fig. 14.

For this portrayal, all appropriate sections in the data set have been employed, not only those presented in Figs. 12 and 13. No attempt has been made here to define the meridional extent of the Agulhas Return Current and to integrate the full volume flux along each meridional section, since such a defini-

Fig. 13. (a) The geographic location of two hydrographic sections across the central and terminal regions of the Agulhas Return Current; (b) the geostrophic velocities across these sections, referenced to 1500 db, with eastward flow shown as positive; and, (c) the volume transport across the same sections.


AJAX
SCARC
ARC
Marathon
Discovery 164
SUZIL
a
Longitude °E
Latitude °S
11
30
57
b
b
Geostrophic velocity cm/s
Latitude °S
Latitude °S
c
c
Volume transport (Sv)
Latitude °S
Latitude °S

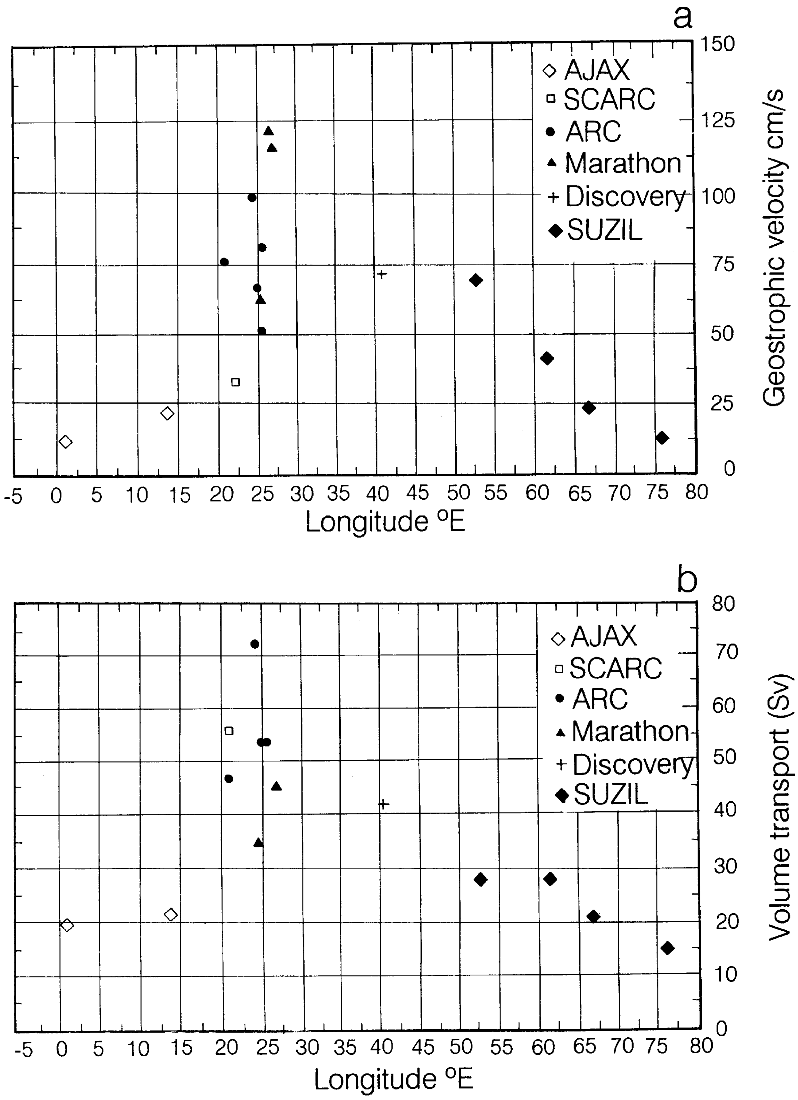


Fig. 14. (a) The calculated geostrophic velocities at the sea surface referenced to 1500 db for all stations located within the Agulhas Return Current for the six cruises indicated, from 1°E to 76°E longitude. (b) The calculated volume transport in Sv (10^6 m^3/s) to the same reference level for the same stations.

tion would be fraught with difficulties. Giving an absolute value for the volume transport when station spacing along the individual sections was not uniform would present additional problems. We have therefore elected to represent only the peak volume transport between any two adjacent stations along each section. Wherever the Agulhas Return Current was crossed more than once during the same cruise, all peak values of volume transport are indicated. In some cases (e.g. the ARC), this leads to a range of values, indicating the variability to be expected. Three important facts are immediately apparent from the results portrayed in Figs. 12 and 13.

First, the low speeds and volume transports along the Subtropical Convergence in the South East Atlantic Ocean are more or less replicated by the flow along this front at 76°E in the South Indian Ocean. Second, the enhancing influence of the Agulhas Return Current on this eastward flow is to be found between 20°E and about 70°E only. Third, the variations in geostrophic speeds and geostrophic volume transports south of Africa are large. This may be due to the known high variability in this region and due to the fact that this is the only location where the data availability allows numerous estimates to be made. In so far as the present data set allows such conclusions, it would seem that the eastward decline in volume transport is evenly spaced from 25° to 76°E.

6. Conclusions

Based on an eclectic, modern, hydrographic data set assembled for an otherwise undersampled region, a number of new conclusions on the location, hydrographic characteristics, and flow patterns of the Agulhas Return Current along its full length may be made (Fig. 15).

The characteristics of the Agulhas Return Current, as it emerges from the Agulhas retroflection, are considerably changed from that of the Agulhas Current proper. Its velocity has decreased from about 110 to 75 cm/s; the volume transport from 70×10^6 to at least 54×10^6 m^3/s. The assumption on which these comparisons rest is that the vertical structure of the two currents are similar and that the selection of the 1500-m reference level is therefore appropriate for both currents. This may not be the case (Y.-H. Park, personal communication). The assumption that the vertical structure of the Agulhas Return Current is less variant along its path may turn out to be more secure.

The characteristics of the water in the Agulhas Return Current also show distinct modifications from that in the Agulhas Current itself. All signs of Indian Tropical Surface Water are removed in the retroflec-

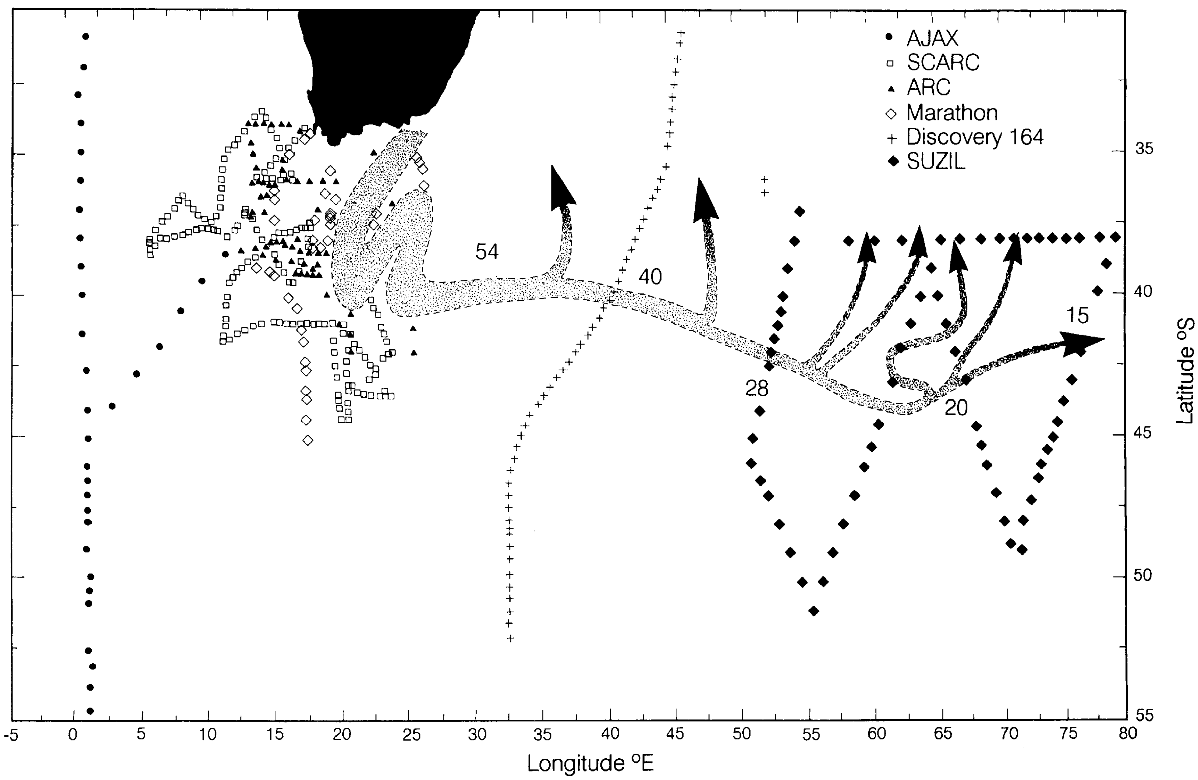


Fig. 15. The volume transport of the Agulhas Return Current system in 10^6 m^3/s along its full length, suggesting the locations of major leakage from the current. These locations are inferred from the reduced volume transport values between adjacent sections.

tion region, while a degree of freshening for central water masses shows the admixture of Atlantic waters at these depths. These modified waters of the Agulhas Return Current execute an equatorward meander of variable extent over the Agulhas Plateau before proceeding eastward.

The general location of the trajectory of the Agulhas Return Current lies ever farther south on proceeding eastward, starting at 39°30′S south of Africa and ending at 44°30′S. (Note that the difference between the location of the Agulhas retroflection in Figs. 8 and 15 comes about from the incorporation of XBT data in Fig. 8, but not in Fig. 15.) Leakages occur somewhere between sections shown in Fig. 15. Both velocity and volume transport steadily decline while the Θ/S characteristics stay remarkably unchanged. Over the Crozet Basin this decline removes the last remnants of the Agulhas Return Current. Characteristic South Indian Subtropical Surface Water is not found east of 61°E and a distinct velocity core disappears between 66°E and 70°E, the speed and volume flux along the Subtropical Convergence dropping back to that found in the South East Atlantic Ocean.

Based on the characteristic hydrographic variables of the water masses constituting the Agulhas Return Current, as well as the flow intensities, it is apparent that this current has a clear, although variable, geographical point of genesis as well as of termination. We therefore suggest that the flow parallel to the Subtropical Convergence in the South Indian Ocean be called the Agulhas Return Current, from the Agulhas retroflection region to the Crozet Basin, and that the name South Indian Ocean Current be used for this flow east of the Crozet Basin only.

It is remarkable that the extent and location of the Agulhas Return Current, typified in this way, corresponds almost exactly with one of the largest contiguous regions of high mesoscale variability in the world ocean (Cheney et al., 1983; Wakker et al., 1990; Feron et al., 1992; Wunsch and Stammer, 1995; Park and Gambéroni, 1995). All these altimeter results show a tongue of very high mesoscale turbulence starting at the Agulhas retroflection and extending eastward along the path of the Agulhas Return Current, as described here, to terminate over the Crozet Basin. The dimensions and geographical location of this band of high current variability is seen in many other data sets as well, e.g. drifting buoys (Daniault and Ménard, 1985) and sea surface temperatures (Lutjeharms and van Ballegooyen, 1984). It is therefore a notably persistent characteristic of global ocean circulation. Since it is so well correlated with the course of the Agulhas Return Current, it is most probably due to enhanced levels of meandering and eddy shedding along the Subtropical Convergence, where the Agulhas Return Current's presence causes increased horizontal shear and instability. This needs further investigation.

It has been inferred by some (Park et al., 1993; Stramma and Lutjeharms, 1997) that substantial parts of the Agulhas Return Current peel off equatorward (viz Fig. 15) specifically over ridge systems that are crossed along its eastward path. The meagre hydrographic data cover leaves this an open question. Drifter tracks give no unequivocal answer either. Furthermore, the lack of data in the region precludes a definitive answer about the representativeness of the results we have put forward here. The high variability along the course of the Agulhas Return Current, shown by satellite altimetry and other data sets, suggests a high level of variation in all flow parameters of this current along its full length.

Acknowledgements

We thank Mr R.C. van Ballegooyen for advice. We would also like to thank the following: Dr S. L. Bennett for the Marathon dataset, Dr A.L. Gordon for the ARC data, Dr Y.-H. Park for the SUZIL data report, Dr R.T. Pollard for the Discovery 164 cruise data report and Dr T. Whitworth for the AJAX data. The financial support of the South African Foundation for Research Development and the Department of Environmental Affairs and Tourism, through its Antarctic Programme, is gratefully acknowledged. The first author thanks the Nederlandsche Organisatie voor Wetenschappelijk Onderzoek for a visitor's bursary to complete this work at the Rijksuniversiteit Utrecht in the Netherlands. We are particularly beholden to an anonymous referee who went to extraordinary lengths to suggest improvements to the paper that have considerably increased its correctness.

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