JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. C5, PAGES 7223–7240, MAY 15, 1992

Thermocline and Intermediate Water Communication Between the South Atlantic and Indian Oceans

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A conductivity-temperature-depth and tracer chemistry section in the southeast South Atlantic in December 1989 and January 1990 presents strong evidence that there is a significant interocean exchange of thermocline and intermediate water between the South Atlantic and Indian oceans. Eastward flowing water at 10°W composed of South Atlantic Central (thermocline) Water is too enriched with chlorofluoromethanes 11 and 12 and oxygen to be the sole source of similar θ-S water within the northward flowing Benguela Current. About two thirds of the Benguela Current thermocline transport is drawn from the Indian Ocean; the rest is South Atlantic water that has folded into the Benguela Current in association with the Agulhas eddy-shedding process. South Atlantic Central water passes in the Indian Ocean by a route to the south of the Agulhas Return Current. The South Atlantic water loops back to the Atlantic within the Indian Ocean, perhaps mostly within the Agulhas recirculation cell of the southwest Indian Ocean. Linkage of Atlantic and Indian Ocean water diminishes with increasing depth; it extends through the lower thermocline into the Antarctic Intermediate Water (AAIW) (about 50% is derived from the Indian Ocean) but not into the deep water. While much of the interocean exchange remains on an approximate horizontal "isopycnal" plane, as much as 10×10^6 m^3 s^{-1} of Indian Ocean water within the 25×10^6 m^3 s^{-1} Benguela Current, mostly derived from the lower thermocline and AAIW, may balance deeper Atlantic export of North Atlantic Deep Water (NADW). The addition of salt water from the evaporative Indian Ocean into the South Atlantic Ocean thermocline and AAIW levels may precondition the Atlantic for NADW formation. While AAIW seems to be the chief feed for NADW, the bulk of it enters the subtropical South Atlantic, spiked with Indian Ocean salt, within the Benguela Current rather than along the western boundary of the South Atlantic.

1. INTRODUCTION

Wind-driven ocean circulation models as well as field observations reveal significant transfer of Indian Ocean Central (thermocline) Water (IOCW) into the South Atlantic Ocean [*Boudra and Chassignet*, 1988; *Semtner and Chervin*, 1988; *Gordon and Haxby*, 1990]. The transfer is accomplished by an eddy shedding process at the western end of the Agulhas Retroflection [*Olson and Evans*, 1986; *Lutjeharms and Gordon*, 1987; *Lutjeharms and Van Ballegooyen*, 1988] and by intermittent streams or plumes of Indian Ocean water injected into the Atlantic, perhaps encouraged by the presence of Agulhas eddies [*Olson and Evans*, 1986; *Lutjeharms*, 1988; *Lutjeharms and Valentine*, 1988]. Additionally, surface water from the shallow Agulhas Bank often is observed passing into the Benguela Current [*Nelson and Hutchings*, 1983; *Shannon*, 1985].

Agulhas eddies, and presumably the intermittent streams of Indian Ocean Central Water, drift into the interior of the South Atlantic subtropical gyre, where their positive surface temperature anomaly relative to the neighboring water is quickly removed by the relatively cool atmosphere of the southeast South Atlantic [*Walker and Mey*, 1988; *Olson et al.*, 1992]. Salt carried into the Atlantic from the Indian Ocean remains within the water column to boost the salinity of the South Atlantic. Injection of Indian Ocean water into the South Atlantic is expected to be of importance to the overall heat and salinity budgets of the South Atlantic and may play a role in the global thermohaline circulation [*Gordon*, 1985, 1986, 1988]. In effect, the Atlantic's salinity is increased by drawing salty water from the evaporative Indian Ocean (which north of 30°S loses fresh water to the atmosphere at a rate of 5.1×10^5 m^3 s^{-1}, only slightly less than the Atlantic Ocean [*Baumgartner and Reichel*, 1975]).

Estimates of the leakage of Indian Ocean water into the South Atlantic by eddies and plumes range from 3 to 20 Sv (1 Sv = 10^6 m^3 s^{-1}). It is not an easy matter of calculating this value, since the Indian Ocean Central Water and the South Atlantic Central Water (SACW) have very similar potential temperature-salinity (θ-S) structure [*Gordon*, 1985]. *Gordon et al.* [1987] calculate 10 Sv of IOCW and Antarctic Intermediate Water (AAIW) entering the Atlantic in late 1983; *Whitworth and Nowlin* [1987] show inflow of nearly 20 Sv in early 1984. *Bennett*'s [1988] evaluation of the 1983 and 1984 data arrives at lower values, 6.3 and 9.6 Sv, respectively. Bennett finds that only 2.8 Sv of water warmer than 9°C flowed from the Indian into the Atlantic Ocean using 1985 data. *Stramma and Peterson* [1990], with a compilation of archived data, find an Indian to Atlantic transfer of 8 Sv. *Gordon and Haxby*'s [1990] inventory of Agulhas eddies in the South Atlantic using Geosat altimeter data shows that 10–15 Sv of IOCW enters the South Atlantic within the eddy field. *McCartney and Woodgate-Jones* [1991], using the smaller radius of the water trapped within an inner cone of an Agulhas eddy observed near 23°S, suggest a smaller eddy annual transport value of 2 to 5.5 Sv. The varied estimates may be due to real variation in the interocean transport, rather than artifacts of the analysis methods. *Shannon et al.* [1990] show that a major incursion of Indian Ocean water rounded the Cape of Good Hope into the Benguela Current in late 1985 to early 1986, affecting sea surface temperatures of the southeast Atlantic Ocean.

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Paper number 92JC00485.
0148-0227/92/92JC-00485$05.00

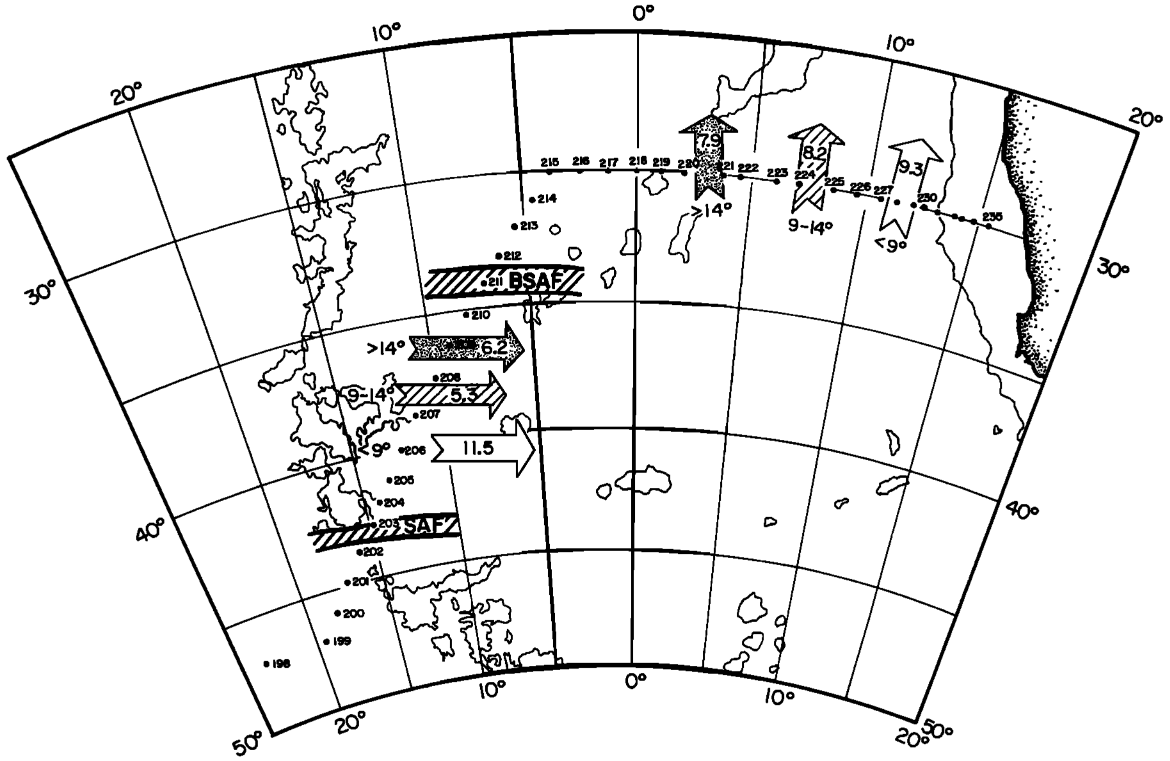

Fig. 1. The distribution of SAVE leg 4 CTD-tracer stations. BSAF is the Benguela–South Atlantic Current front; SAF is the subantarctic front. The arrows and numerical values represent the geostrophic volume transport relative to 1500 dbar within three ocean layers: stippled arrows, warmer than 14°C; hatched arrows, 9°–14°C; and open arrows, colder than 9°C but shallower than 1500 dbar.

Recent South Atlantic conductivity-temperature-depth (CTD) and tracer data obtained as part of the South Atlantic Ventilation Experiment (SAVE) confirms that there is significant transfer of Indian Ocean Central Water and Antarctic Intermediate Water from the Indian Ocean into the South Atlantic within eddies and within the larger-scale circulation pattern.

2. SAVE 4 Sections

The SAVE leg 4 stations 199 to 235 in the southeast South Atlantic obtained in late December 1989 to early January 1990 (Figure 1) cross the eastward flowing southern limb (South Atlantic Current [*Stramma and Peterson*, 1990]) and the northward flowing eastern limb (Benguela Current [*Stramma and Peterson*, 1989]) of the South Atlantic subtropical gyre. These data provide a unique opportunity to inspect synoptically two supposedly connected segments of the gyre. Potential temperature, salinity, oxygen, and chlorofluoromethane-11 and 12 (CFM-11 and CFM-12) sections (Figure 2), geostrophic velocities (Figure 3), and dynamic anomaly maps (Figure 4) are used to study the water mass stratification and circulation pattern with reference to exchange of Atlantic and Indian Ocean water masses. For a discussion of the use of chlorofluoromethane concentrations for investigating ocean circulation between the Indian and Atlantic Oceans, see *Fine et al.* [1988].

3. Ocean Regimes Across SAVE 4 Section

Basic ocean zones and fronts encountered along the station 199 to 235 sequence, following the definitions reviewed by *Stramma and Peterson* [1990] are (Figure 1) the subantarctic front (SAF), marked by the rapid depth change of isotherms and isohalines near stations 202 and 203 (43°–44°S), and the subtropical front (STF) marked by the rapid depth change of the isotherms and isohalines near stations 207 and 208 (37.5°–38.5°S). An additional front, falling between stations 211 and 212 (33°–34°S), is defined as the Benguela–South Atlantic Current front (BSAF). It separates opposite flowing currents and significant changes within the CFM and oxygen fields (Figures 2*c*, 2*d*, 2*e*, 3, and 4). *Whitworth and Nowlin* [1987], inspecting the 1983 Ajax hydrographic section along the Greenwich meridian, place the SAF near 45°S and place the STF near 37°S.

The band between the BSAF and SAF marks the subtropical gyre's polar limb, referred to as the South Atlantic Current [*Stramma and Peterson*, 1990]. The station 212–235 segment transverses the eastern limb of the Benguela Current. The eastern end of the zonal section passes across one of the main upwelling centers of the Benguela Current regime at Hondeklip Bay near the mouth of the Orange River [*Nelson and Hutchings*, 1983; *Chapman and Shannon*, 1985].

The depression of the isotherms (Figure 2*a*) at two sites along 30°S, stations 220 (30°S, 2°E) and 223 (30°S, 6°E), indicates that SAVE 4 crossed two Agulhas eddies between January 6 and 9, 1990. Examination of the Geosat altimeter data confirms that these are isolated features of elevated sea level amounting to approximately 20–30 cm, justifying the contouring pattern of sea surface dynamic anomaly (Figure 4). Isopleths of salinity, oxygen, and CFM-11 reach to deeper depths within these eddies. The potential temperature and salinity profiles reveal homogeneous layers of

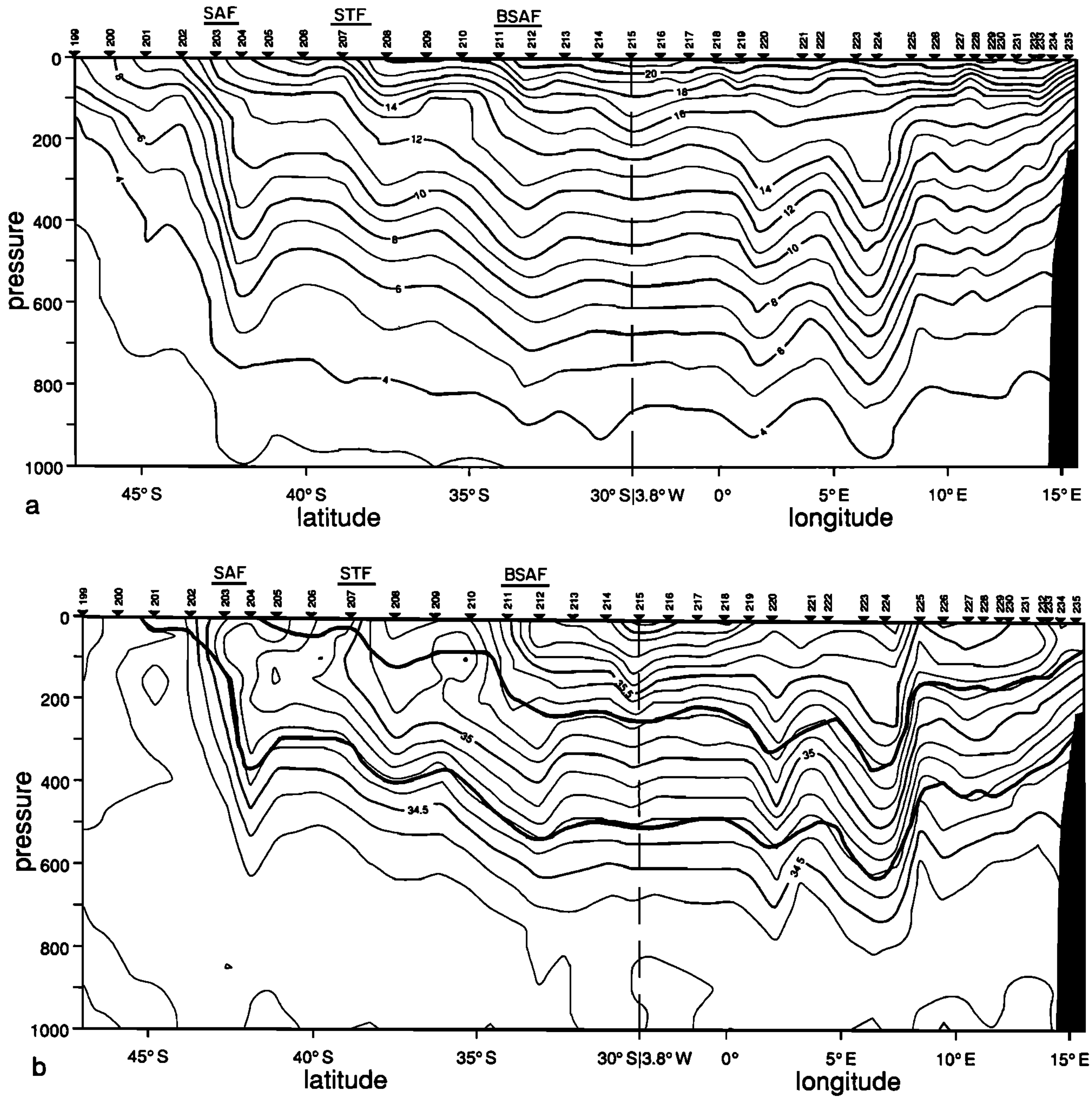

Fig. 2. (*a*) Sections of potential temperature θ in degrees Celsius, (*b*) salinity in parts per thousand, (*c*) oxygen in micromoles per kilogram, and (*d*) chlorofluoromethane 11 and (*e*) chlorofluoromethane 12 in picomoles per kilogram from SAVE 4 along 10°W (nominally) and 30°S. The 9° and 14°C isotherms are added to the salinity, oxygen, and chlorofluoromethane sections to show the position of this thermocline stratum relative to the tracer fields. The fronts shown in Figure 1 are included in Figure 2 with the addition of the subtropical front (STF).

16.2°C and 35.6 ppt, from 80 m to 180 m (station 220) and to 225 m (station 224). These "stads" represent remnant winter mixed layers formed at the eddy spawn region within and near the Agulhas Retroflection [*Gordon et al.*, 1987]. The Indian Ocean water trapped within these eddies is modified by sea-air interaction and eventually converted into "typical" South Atlantic Central Water [*Gordon and Haxby*, 1990; *Olson et al.*, 1992]. Based on a mean translation speed of 5 cm/s [*Gordon and Haxby*, 1990] the eastern eddy was shed in March 1989, and the western eddy in December 1988. Both have "seen" the same austral winter and have essentially the same core characteristics.

At station 226 (30°S, 9°E), and to a lesser extent at station 227 to the east, and at stations 233 to 235 over the continental slope there are well-defined oxygen minimum features (Figure 2*c*). The oxygen concentrations within the 200- to 700-m depth interval are generally less than 200 μM kg^{-1} but reach as low as 150 μM kg^{-1} in the deeper parts of the offshore feature. The temperature range of oxygen minimum features is 6°–9°C for the slope feature and 5°–12°C for the offshore feature. They temperature range of oxygen minimum features is 6°–9°C for the slope feature and 5°–12°C for the offshore feature. They are associated with reduced chlorofluoromethane concentrations (Figures 2*a*, 2*c*, 2*d*, and 5)

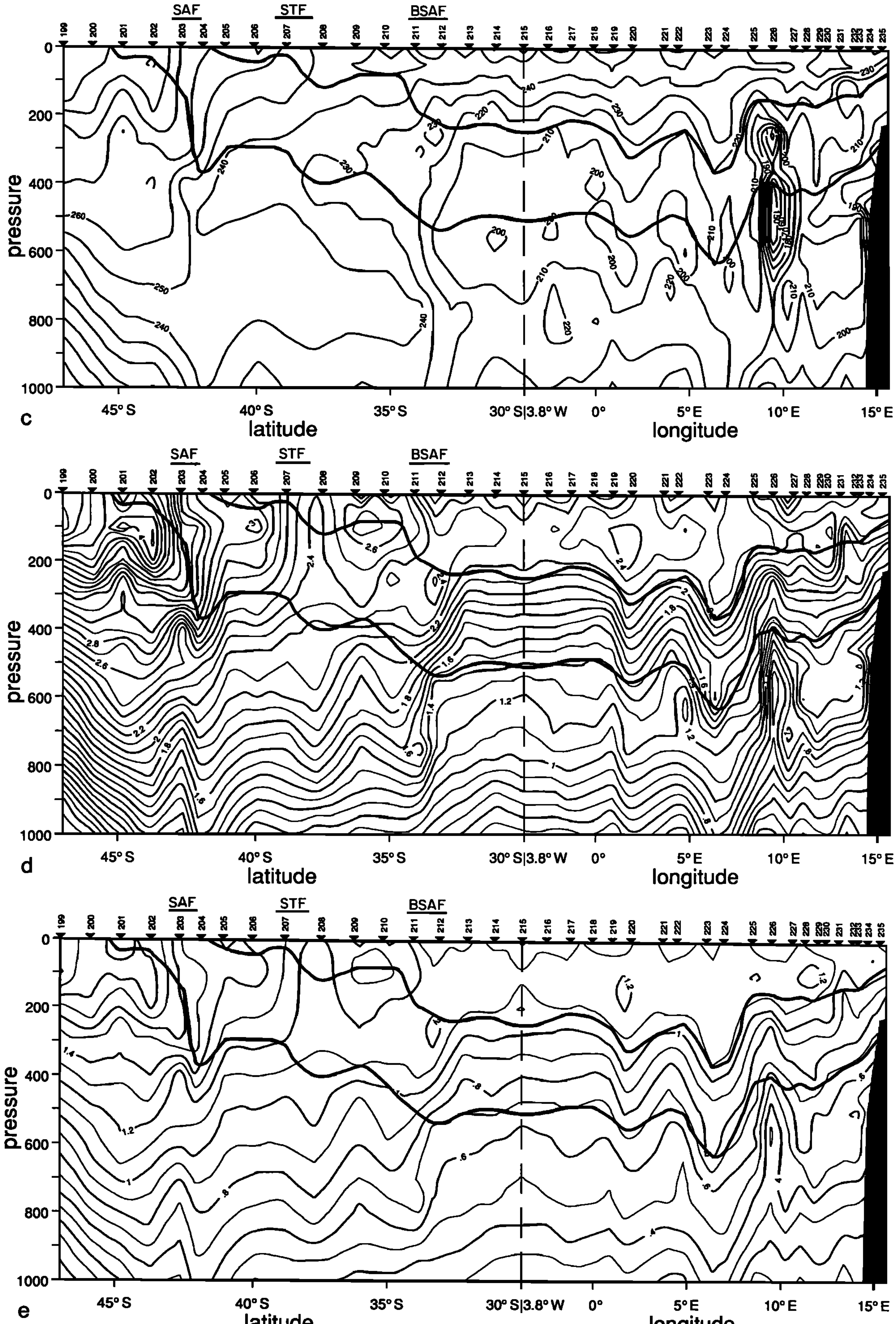

Fig. 2. (continued)

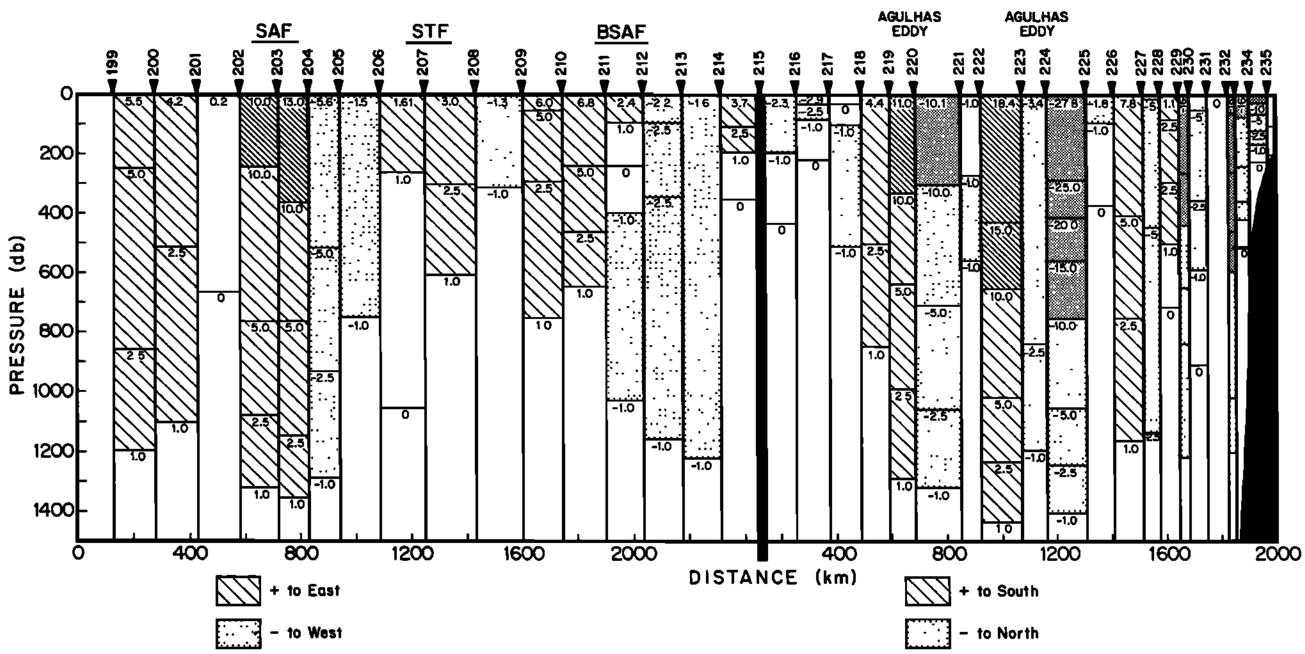

Fig. 3. Geostrophic speeds crossing the SAVE 4 section relative to a 1500-dbar zero reference level. For the continental margin stations where the seafloor is shallower than 1500 dbar, the flow at the seafloor is taken as zero. The Benguela–South Atlantic front (BSAF); subtropical front (STF), and subantarctic front (SAF) are labeled.

relative to water of similar θ-S characteristics. The Benguela Current displays an extensive subsurface oxygen minimum [*Nelson and Hutchings*, 1983; *Chapman and Shannon*, 1985, 1987]. These authors contend that the Benguela subsurface oxygen minimum north of 30°S is derived from the larger mass of thermocline oxygen minimum water in the eastern tropical Atlantic, north of the Angola-Benguela Front (also see *Gordon and Bosley* [1991]), with localized enhancement by biological processes of the upwelling regions. The SAVE legs 2 and 3 sections in the eastern tropical latitudes reveal very low oxygen concentrations, well below 100 μM kg^{-1} within a temperature stratum of 5° to 15°C, and it seems reasonable to conclude that the oxygen minimum water near 30°S observed by SAVE 4 stations 226 and 233–235 in the depth interval 200–700 m is derived from the tropical South Atlantic. This is partly supported by various studies of poleward flow along the African margin: subsurface poleward flow is well defined north of 30°S in the Benguela Current [*Hart and Currie*, 1960], but its existence near 30°S has not been substantiated [see *Shannon*, 1985, Figure 18; *Chapman and Shannon*, 1985, Figure 6]; *Nelson* [1989], using direct current measurements, shows a general poleward flow at a depth of approximately 900 m over the African continental margin between 30° and 35°S, with poleward flow dominated at a depth of 243 m off Cape Columbine between 32° and 33°S. One can surmise that poleward flow is also found between 243 and 900 m.

While a tropical Atlantic source for the oxygen minimum of stations 226 and 233–235 seems most likely, an Indian Ocean contribution should not yet be ruled out, particularly for the easternmost stations. The geostrophic flow relative to the deepest common depth or 1500 dbar, whichever is shallower (Figure 3), within the 200- to 700-m interval is directed toward the south at station 226 and toward the north along the continental slope from stations 233 to 235. The flow at the 1500 dbar appears to be a good choice for a zero reference level for the Benguela Current [*Reid*, 1989], but the flow along the seafloor for stations pairs with shallower common levels is unknown. Assuming that the bottom flow at these stations is weaker than the flow within the water column (a reasonable assumption), the oxygen-depleted water observed at slope stations 233–235 is flowing toward the north. Thus it is possible that the oxygen minimum over the continental slope is derived from the Agulhas system, presumably with local enhancement of the oxygen depletion due to the biologically active upwelling system. Low-oxygen thermocline water is found along the inner, "shore" edge of the Agulhas Current, which is drawn from low latitudes of the Indian Ocean [*Gordon*, 1986; *Gordon et al.*, 1987]. A variety of transit features observed along the inner edge of the Agulhas Current near the Agulhas Bank, which are associated with shear edge effects [*Catzel and Lutjeharms*, 1987] are frequently observed extending northward along the Atlantic coast of Africa. *Chapman* [1988] inspects in some detail the oxygen field within the Agulhas Retroflection and Benguela Current. He uses the oxygen minimum of the Agulhas water to trace the movement of Indian Ocean water within the Benguela Current. He finds that the Indian Ocean oxygen minimum can be traced to at least 32°S.

Might the continental slope oxygen minimum feature displayed by stations 232–235 curl back to the south further offshore to account for the oxygen minimum at station 226? Inspection of the θ-S relationship for the oxygen minimum feature at station 226 indicates that in the interval 5°–9°C (the temperature interval of the slope feature) the oxygen minimum at station 226 is associated with higher salinity than is observed over the slope. Salty thermocline water is a telltale indicator of the large pool of oxygen-depleted water in the tropical South Atlantic [*Gordon and Bosley*, 1991], so it seems reasonable to conclude that the deeper portion of the oxygen minimum at station 226 is drawn at least in part from the north and not entirely from the nearby slope feature. The

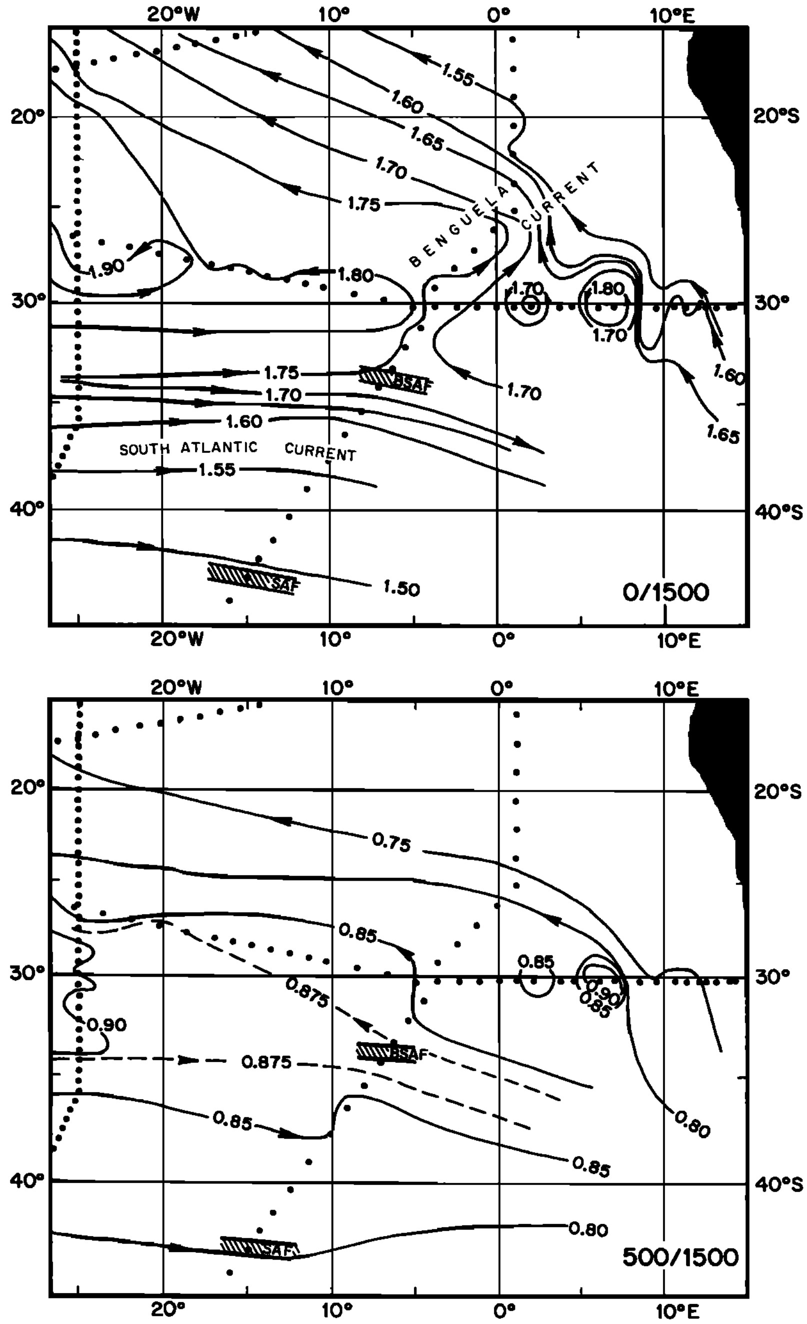

Fig. 4. Sea surface and 500-dbar isobaric surface topography relative to 1500-dbar surface based on SAVE 3 and 4 data for the southeast South Atlantic.

salinity increase at station 226 relative to the slope feature is 0.04 ppt, somewhat less than half of the full salinity anomaly associated with the tropical oxygen minimum [*Gordon and Bosley*, 1991]. It is suggested that the slope oxygen minimum mixes with tropical Atlantic oxygen minimum and curls back to the south. The shallower part of the station 226 oxygen minimum feature (note that at station 226 there appears to be a separation of the upper and lower parts of the oxygen minimum (Figure 2*c*)) does not have a positive salinity anomaly and is a bit too warm to be drawn from the slope feature but may be drawn from oxygen minimum water of the outer shelf, which was not sampled by SAVE 4 but is well represented in the shelf part of the Benguela Current [*Nelson and Hutchings*, 1983].

While a totally tropical Atlantic source for the oxygen minimum features observed at stations 226 and 233–235 may be expected from eastern boundary current dynamics, there is some ambiguity. The slightly enhanced salinity of the deeper portions of the oxygen minimum observed at SAVE station 226 indicates tropical Atlantic contribution, but the slope feature represented by stations 233–235 without this salinity enhancement may be derived from Indian Ocean water, with further depletion of oxygen due to the biological effects of the local Benguela upwelling processes. This distribution of oxygen minimum water no doubt changes with time as the two pools of oxygen minimum water interact within the Benguela Current near 30°S, perhaps in association with shedding of Agulhas eddies.

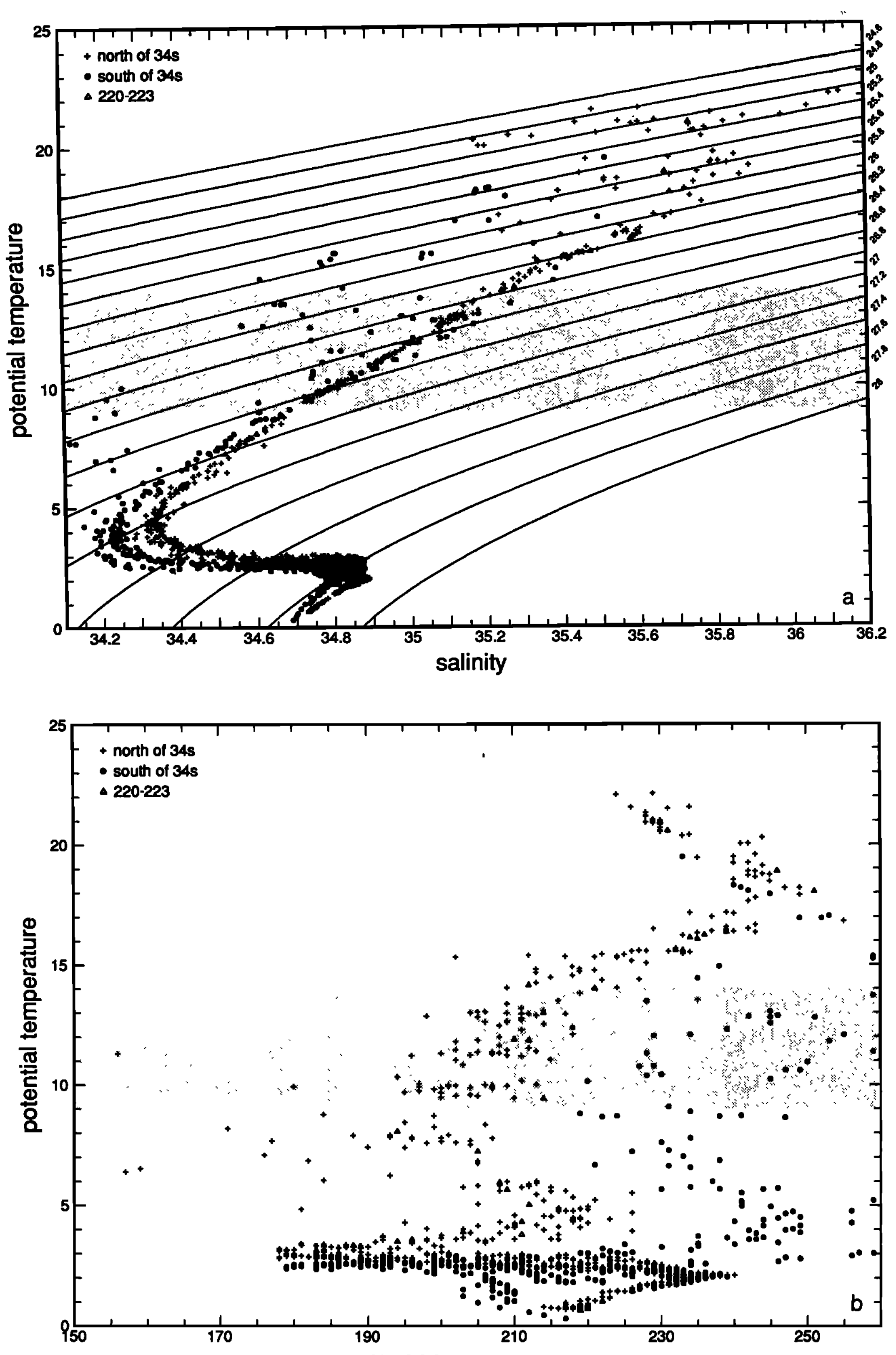

Fig. 5. Potential temperature versus (*a*) salinity in parts per thousand, (*b*) oxygen in micromoles per kilogram, and (*c*) chlorofluoromethane 11 and (*d*) chlorofluoromethane 12 in picomoles per kilogram for the SAVE stations shown in Figure 1. The 9°–14°C thermocline stratum is stippled.

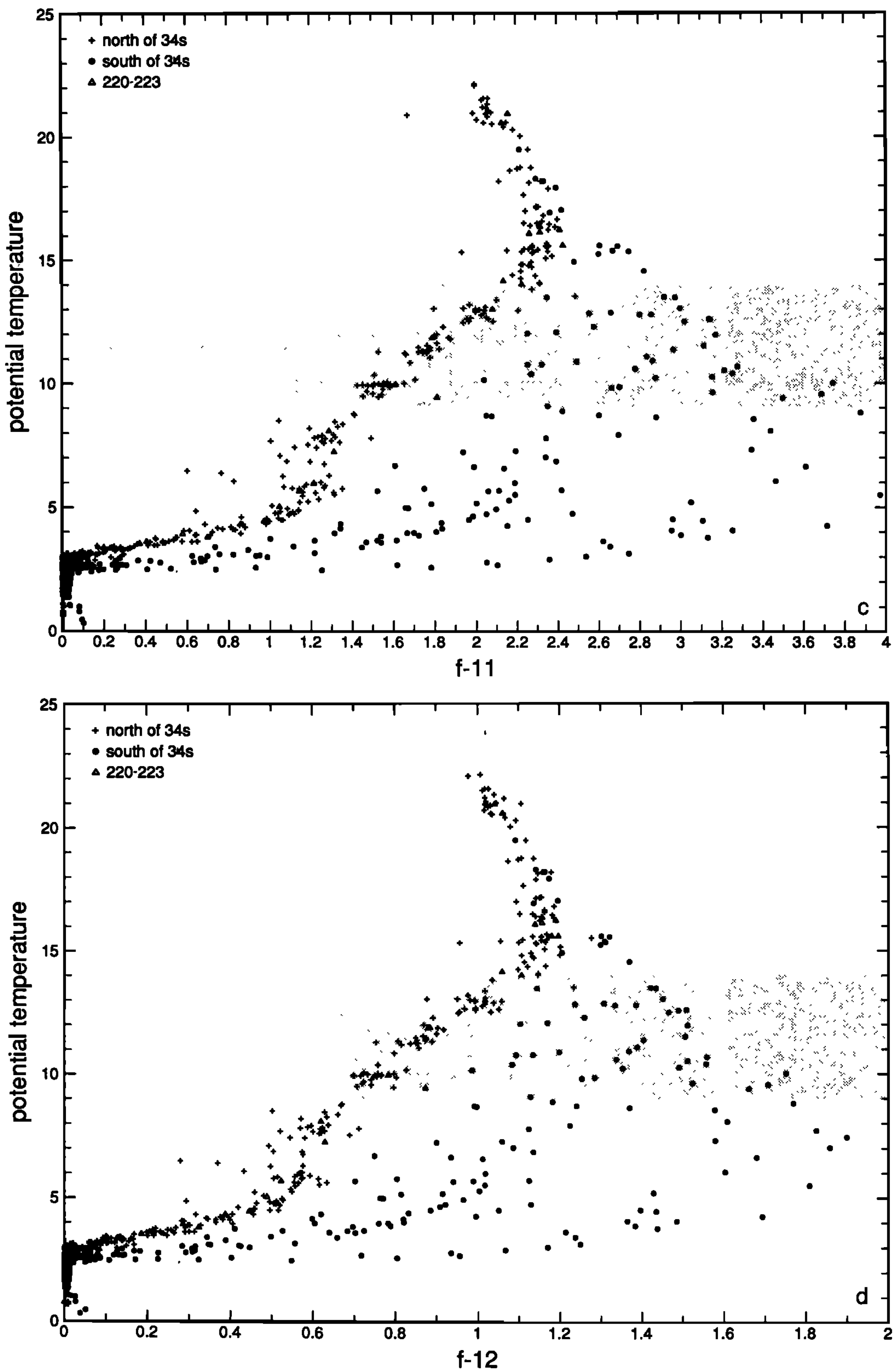

Fig. 5. (continued)

4. SOUTH ATLANTIC–INDIAN OCEAN WATER MASS EXCHANGE

4.1. *Thermocline Stratum*

Within the transition zone from the BSAF to SAF, from 34°S to 43°S (Figures 1 and 2) the water of approximately the upper 500 m is too warm and salty to be derived from the Drake Passage; it must contain SACW. It is likely that the SACW is introduced into this zone in the southwest Atlantic, at the complex mixing regime of the Brazil-Malvinas Confluence [*Olson et al.*, 1988]. South of the BSAF, most θ-S points fall within the SACW curve, though from 13° to 15°C, station 208 exhibits slightly more saline water. This may be remnant eddies shed from the Brazil Current. The cores of these eddies display positive salinity anomaly relative to SACW and may be an important source of salt for the transitional zone [*Gordon*, 1989]. SAVE 4 southern Argentine Basin stations 184, 186, and 189 near 47°S and 50°W cross isolated pockets of relatively warm surface water, all of which display strongly positive salinity anomalies near the 10°–13°C range. The SAVE 4 eastern Atlantic data indicate that Brazil Current eddies survive to at least to 10°W within the South Atlantic Current. In this regard, *Haxby and Gordon* [1990] note that Agulhas eddies also cross most if not all of the South Atlantic in the opposite direction. Trans-ocean transfer of water mass characteristics by warm core eddies seems to be a characteristic feature of the South Atlantic.

The SACW north of the BSAF is fairly uniform in θ-S characteristics, including the water within the Agulhas eddies, though the water remnant mixed layer water within the eddy cores is slightly saltier than the surrounding water (Figure 5*a*) [*Olson et al.*, 1992].

South of the BSAF, water within the 9°–14°C thermal layer has salinity well below that of the SACW thermocline curve. These points are derived from stations 203–207, from depths shallower than the weak 100- to 200-m salinity maximum. The low-salinity surface water represents subantarctic water capping a layer enriched with SACW south of the STF (*Deacon* [1937] shows that this feature is commonly found in the Antarctic circumpolar belt). Northward movement of the subantarctic water may be induced by Ekman transport. Within the 9°–14°C layer of the station 203–211 transition zone the concentrations of oxygen and CFM-11 and CFM-12 are much greater than concentrations in the same stratum within the Benguela Current (Figures 2 and 5). The BSAF near 34°S marks a strong oxygen and CFM front within the thermocline. The South Atlantic Current 9°–14°C stratum displays average oxygen concentration of 30 μM kg^{-1} (Figure 5*b*) above that of the Benguela Current, with the CFM-11 difference of about 1 pM kg^{-1} (Figure 5*c*).

Stramma and Peterson [1990] have suggested that most of the SACW flowing eastward in the South Atlantic Current folds into the Benguela Current and does not pass to the Indian Ocean south of the Agulhas Retroflection. The similarity of the θ-S structure (Figure 5*a*) within the South Atlantic and Benguela currents supports this conclusion. However, the oxygen and CFM patterns are not consistent with this picture (Figures 5*b*, 5*c*, and 5*d*). The high CFM concentrations in the South Atlantic Current relative to the Benguela Current clearly reveals that at least at the time of the SAVE 4 section, the South Atlantic Current is not folding entirely into the Benguela Current, but rather that much of the South Atlantic Current must continue to flow into the Indian Ocean. This is clearly supported by the *Meteor* 11/5 section along approximately 5°–18°E in February 1991 (W. Roether, personal communication, July 1991) as well as data displayed in the atlases of *Wyrtki* [1971] and *Gordon and Molinelli* [1982], which show water south of the Agulhas Return Current with characteristics similar to those found in the South Atlantic Current. This point is discussed in section 6 below.

While we might dismiss the reduced oxygen concentration of the SAVE 4 data within the Benguela Current relative to that of the South Atlantic Current as a sign of oxygen depletion, as the South Atlantic water flows into the biologically productive Benguela Current region, we cannot dismiss the difference in the biologically inactive CFM-11 and CFM-12. It would require about 1 year at 3 cm s^{-1}, assuming that the 9°–14°C stratum of stations 209–211 directly feeds the Benguela Current (Figure 3), for the SACW crossing 10°W to flow across 30°S. The CFM-11 to CFM-12 equilibrium atmospheric ratio for the 9°–14°C layer is approximately 0.55 (Figure 6), essentially modern exposure (during the last 10 years) to the atmosphere. The Benguela water is slightly "older" than the South Atlantic Current water, but not significantly so. The few values of near 0.51 equilibrium atmospheric ratio (exposure in early 1970s) are from the stations 227–229 east of the easternmost Agulhas eddy, within the oxygen poor regime derived from the "older," oxygen poor waters of the tropical South Atlantic.

The difference of the thermocline CFM concentration at 10°W versus that of 30°S indicates that the South Atlantic Current cannot fold directly into the Benguela Current. The similar of ages with differing concentrations suggest different mixing histories. It is proposed that the Benguela Current thermocline draws much of its water from the Indian Ocean Central Water (IOCW). Most of the Indian water is dominated by CFM ratios drawn from the atmosphere in the last 10 years as the thermocline water of the South Atlantic Current, but it has mixed to a greater extent with water of low CFM concentration presumably from the more northern, interior regions of the Indian Ocean thermocline.

While the South Atlantic Current is clearly not flowing into the Benguela Current, we need to show that the Benguela Current in turn can have been derived from the Indian Ocean. A plot of the CFM saturation (which removes time dependence from the atmospheric increase in CFM but assumes that the ocean is in quasi-equilibrium with the atmosphere and that the rate of increase of CFMs in the atmosphere has been constant, which is true since 1975) allows comparison of SAVE data with other regional data obtained during the period from late 1983 to early 1990 (Figure 7*a*). SAVE CFM data match the Ajax expedition data within the Benguela Current (Figure 7*b*). The CFM saturation within the South Atlantic Current (south of the BSAF) from the SAVE and Ajax data is much higher than that found in the Benguela Current. The Agulhas water (Agulhas Retroflection cruise) (ARC) data [*Camp et al.*, 1986]), which is derived from the Indian Ocean, has a CFM-11 saturation somewhat below that of the Benguela Current. This indicates that while the Benguela Current cannot be drawn entirely from the South Atlantic, it cannot be purely Indian Ocean thermocline water (a conclusion also reached by *Fine et al.* [1988]); a mix of IOCW and SACW is required. An IOCW to SACW admixture (as determined from Figure 7*b* by comparing CFM saturations along isotherms, which parallel isopycnals for the nearly single valued θ-S of the thermocline; the 100% saturated CFM surface water corresponding to the low-salinity 9°–14°C water shown on Figure 5 is not used to determine the mixing ratio) is approximately 60 to 65% Indian Ocean water and 35 to 40% SACW for the Benguela Current thermocline.

It is likely that the SACW water blends with the Indian Ocean water near the Agulhas Retroflection during the eddy-shedding process. *Lutjeharms and Van Ballegooyen* [1988] show the existence of northward flow of subantarctic surface water along the eastern edge of a newly shed

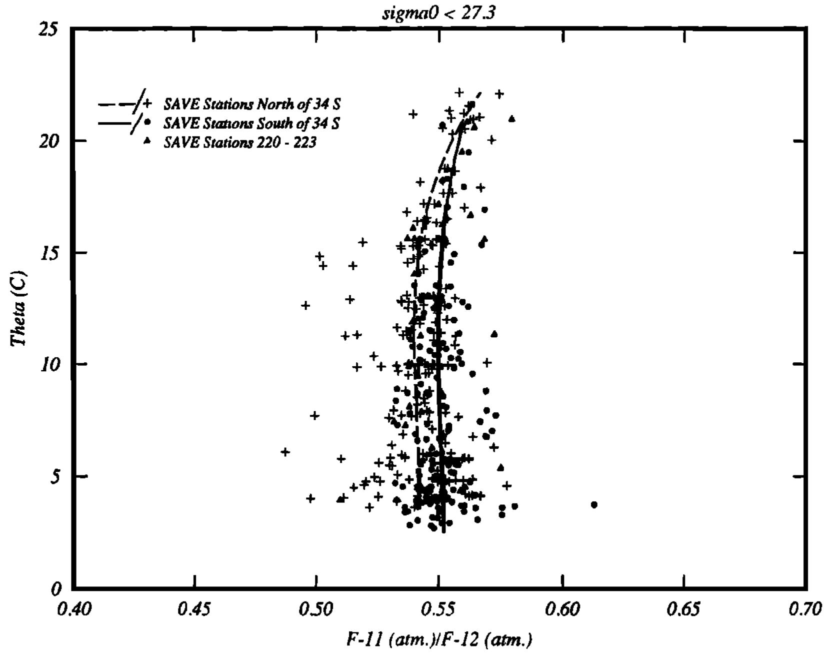

Fig. 6. Ratio of equilibrium atmospheric concentrations of chlorofluoromethane 11 to chlorofluoromethane 12 saturations for water less dense than 27.3 σ_0 for the SAVE 4 stations shown in Figure 1.

Agulhas eddy. *Shannon et al.* [1989] also show that during eddy shedding there is a substantial equatorial flow of subantarctic surface water, which they state "temporarily terminated the leakage of Agulhas water (in the surface layer, at least) into the South Atlantic . . . ." In both studies the subantarctic surface water they refer to has surface temperatures of near 17°C and can therefore inject subsurface 9°–14°C water, referred to in this study into the Benguela Current. Thus the interocean transfer of thermocline water (AAIW as well) may be "short circuited" within the intense eddy field of the western end of the Agulhas Retroflection. Within this mixing environment the high CFM concentration of the water composing the South Atlantic Current is injected into the Benguela Current.

Might the low-CFM water drawn from the tropical Atlantic, as discussed for the oxygen minimum water revealed at station 226, upon mixing with SACW be responsibly for the low CFM of the Benguela Current; i.e., the South Atlantic Current folds completely into the Benguela, where it mixes with low-CFM tropical Atlantic Water, and no Indian Ocean water is needed? On the basis of the CFM concentration and the volume transports of the contributing currents, this is unlikely. The South Atlantic Current surface to 1500 dbar geostrophic transport relative to 1500 dbar is 23 Sv, and the corresponding Benguela Current transport is 25 Sv (Table 1; section 5). Tropical Atlantic water first crossing southward across 30°S then curling back to the north as a mixture with SACW would not impact on the Benguela Current transport across the SAVE 30°S section. The CFM within the thermocline of the Benguela Current is considerably below that of the SACW (Figures 5*c* and 5*d*). The CFM within the oxygen minimum cells at the eastern end of the SAVE section is only slightly below that of the bulk of the northward flowing Benguela Current (averaging approximately 0.2 pM kg^{-1} across the thermocline). It is not reasonable to conclude that the tropical Atlantic water is injecting enough water into the Benguela Current to so dominate the Benguela Current's CFM concentration. A simple mixture of 23 Sv of SACW would require 100 Sv of tropical Atlantic water to yield the observed CFM concentrations of the Benguela Current! While some contribution from the tropical Atlantic may be present, it is not likely to be an important factor in determining the characteristics of the Benguela Current stratification, particularly as some SACW escapes into the Indian Ocean.

4.2. *AAIW Stratum*

Between 3° and 9°C the water south of the BSAF is significantly lower in salinity and higher in oxygen than to the north (Figures 5*a* and 5*b*). Within the AAIW salinity minimum layer near 4°C the change across the front for salinity is about 0.15 ppt and 30 μM kg^{-1} for oxygen. The enrichment of low-salinity, high-oxygen AAIW characteristics south of the BSAF is due to direct supply with newly formed AAIW from its formation region of the subantarctic zone of the southwest Atlantic [*Piola and Gordon*, 1989] and perhaps by further subduction at the polar front zone during the South Atlantic transit. The CFM-11 and CFM-12 concentrations near 4°C within the AAIW core change abruptly at the BSAF, the difference amounting to 0.8 pM kg^{-1} in CFM-11.

The Benguela Current CFM-11 saturation from the 3°C to 9°C isotherms (Figure 7*b*), representing the lower thermocline and AAIW layers, indicates a greater enrichment of Indian Ocean water with South Atlantic water than is encountered in the warmer water of the thermocline. At 9°C the ratio of Indian to South Atlantic water is approximately 65/35. The ratio is near 50/50 at the AAIW core, with further enrichment of Atlantic water as 3°C is approached. A 50/50 mix is suggested for the 3°–9°C layer.

Blending of the more saline AAIW from the Agulhas Current

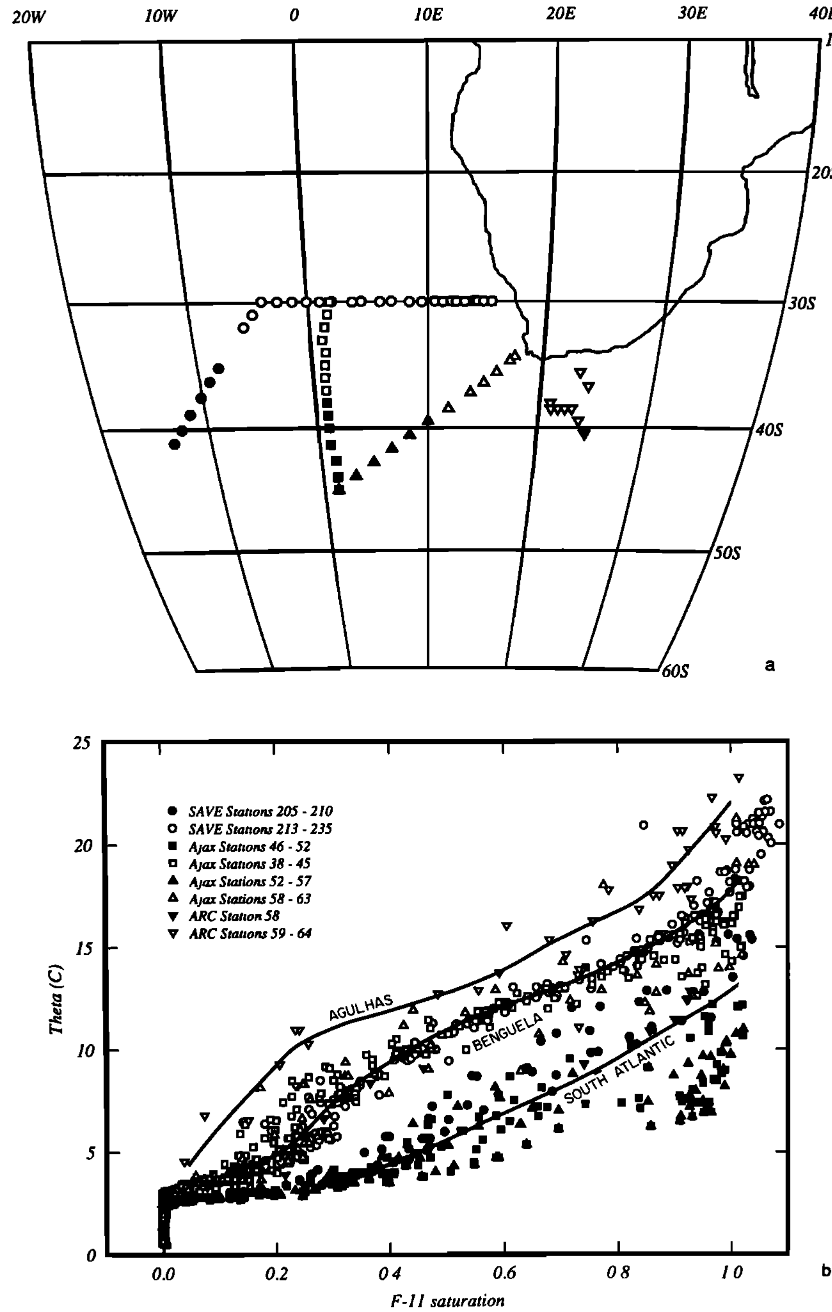

Fig. 7. (*a*) Oceanographic stations used to investigate regional CFM saturation levels, and (*b*) potential temperature versus CFM-11 saturation. The solid symbols represent stations within a regional eastward flow; the open symbols represent stations within a regional westward flow. The downward pointing triangles, from the ARC expedition [*Camp et al.*, 1986] are within the Agulhas Retroflection region [*Gordon et al.*, 1987]. Here the solid symbol is south of the Agulhas Return Current, while the open symbols are within the retroflection. The circles are stations from SAVE 4; the squares and upward pointing triangles are from the *Ajax Expedition* [1985].

with AAIW from the South Atlantic Current is also evident in the oxygen concentration. The Benguela Current AAIW core layer displays a slight maximum of near 215 to 220 μM kg^{-1} (Figure 5*b*). A 50/50 mix of South Atlantic AAIW, which has an oxygen concentration of about 245 μM kg^{-1} (Figure 5*b*), with Indian Ocean AAIW found within the Agulhas Retroflection, at 185 μM kg^{-1} oxygen concentration [*Gordon et al.*, 1987], yields the 215 μM kg^{-1} of the Benguela Current.

The injection of oxygenated, CFM-enriched AAIW of the South Atlantic Current into the Benguela Current most likely occurs within the eddy-shedding region of the western end of the Agulhas Retroflection, as was discussed above for the 9°–14°C layer and by *Fine et al.* [1988], *Lutjeharms and Van Ballegooyen* [1988], and *Shannon et al.* [1989].

4.3. *NADW Stratum*

At temperatures below 3°C the North Atlantic Deep Water (NADW) stratum is encountered. The oxygen and CFM

TABLE 1. Geostrophic Transport Relative to 1500 dbar for Various Strata Along SAVE Leg 4, Stations 202–235

Layer, <1500 dbar	Transport, 10^6 m^3 s^{-1}	
	South Atlantic Current	Benguela Current
Warmer than 14°C	6.2	7.9
9°–14°C stratum	5.3	8.2
Warmer than 9°C	11.5	16.1
Colder than 9°C	11.5	9.3
Total	23.0	25.4

The South Atlantic Current is defined by SAVE leg 4 stations 202–212; the Benguela Current is defined by stations 212–235 (see Figure 1).

concentrations differ little across the BSAF (Figures 5*b* and 5*c*), as CFM concentrations have not significantly reached this level yet. However, there are substantial meridional salinity gradients further south. An expanded θ-S plot for the water colder than 3.5°C (Figure 8) reveals that at the salinity maximum near 2°C, the water at and north of station 208 (37.5°S) is 0.06 ppt saltier, and hence is enriched in NADW, relative to the salinity maximum to the south. Stations 207 and 208 mark the STF and are situated over the Walvis Ridge crest. The water north of the Walvis Ridge has direct access to NADW spreading within the interior Atlantic Ocean [*Warren and Speer*, 1991]. The deep water south of the Walvis Ridge is too salty to be Pacific deep water; it must contain NADW. It most likely is supplied directly from the western boundary of the South Atlantic, which is a major conduit for NADW outflow from the north [*Reid*, 1989]. Thus at the STF there appears to be a confluence of the two major streams of NADW en route to the circumpolar belt.

Within the Agulhas Retroflection the salinity maximum is approximately 34.83 ppt [*Gordon et al.*, 1987], slightly below the value of 34.85–34.89 found in the Benguela Current. It is concluded that at the depths of NADW (greater than 1500 m) the Benguela Current region is influenced by water from the Atlantic, not from the Indian Ocean. *Reid* [1989] shows this in his adjusted dynamic topography maps: below 1500 m the flow in the southeast Atlantic is mainly from the northwest. Intrusion of Indian Ocean water into the South Atlantic does not extend below the AAIW stratum into the NADW layer. This agrees with *Gordon et al.*'s [1987] water mass analysis of the Agulhas retroflection region that finds Indian Ocean water inflow to the South Atlantic limited to density levels less than σ_0 = 27.5 (roughly shallower than 1500 m).

5. GEOSTROPHIC TRANSPORT

Reid [1989], using the distribution of ocean properties, resolves the likely form of the barotropic circulation for the South Atlantic. He uses this to adjust the baroclinic dynamic height anomaly to achieve an estimation of the absolute dynamic topography and mean geostrophic circulation of the South Atlantic Ocean. In the vicinity of the Benguela Current and along 10°W as far south as 45°S, near the SAF, the 1500-dbar reference surface is a good approximation to a zero reference layer. Applying a 1500-dbar zero reference level to the SAVE 4 stations north of the SAF provides a reasonable estimation of the geostrophic absolute flow (Figure 3, Table 1).

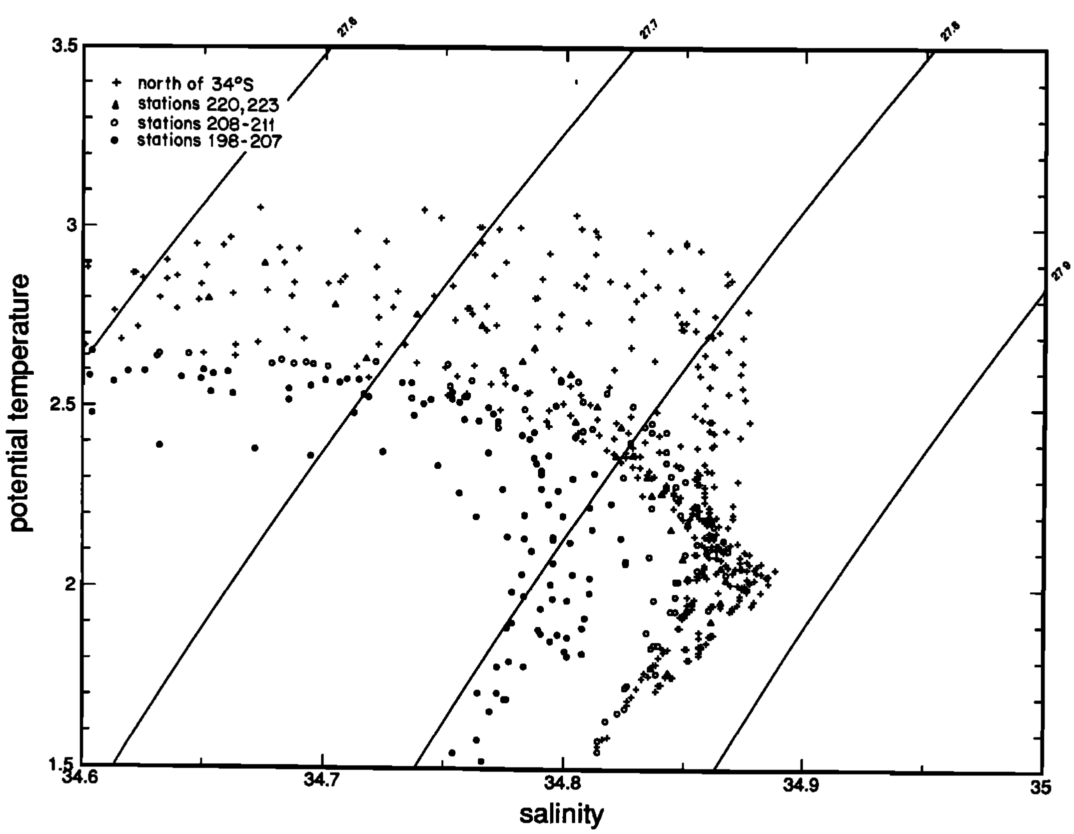

Fig. 8. Potential temperature versus salinity for water colder than 3.5°C from SAVE 4 stations 198–235.

South of the BSAF the geostrophic speeds across the SAVE 4 section relative to 1500 dbar (Figure 3) are weak and toward the east. The strongest flow occurs just south of the BSAF (stations 209–211) and at the STF and SAF. The westward flow just north of the SAF suggests the presence of an eddy, seen in the temperature and salinity fields (Figure 2) to be forced by the structure between 300 and 700 m. North of the BSAF the flow is toward the west or north into the South Atlantic interior, except along the western edges of the two Agulhas eddies. The shallow eastward flow between stations 214 and 215, on inspection of the dynamic topography maps, appears to be a local deviation of the flow field, perhaps a partial return of the westward flow between stations 211 and 214.

Using the 1500-dbar reference level the Benguela Current transport across the *Discovery* 1987 section amounts to 20 Sv for the 0- to 1500-dbar slab from Africa to the Walvis Ridge [*Gordon and Haxby*, 1990]. Using the density surface 27.40 and 27.75 (falling near 1200 dbar and 1800 dbar, respectively) for a zero reference level, *Stramma and Peterson* [1989] indicate a northward transport of 19 and 26 Sv, respectively, for the thermocline and AAIW segments of the Benguela Current. The SAVE 4 station pairs north of the BSAF yield a Benguela Current geostrophic volume transport of 25 Sv relative to 1500 dbar. Between the BSAF and SAF the corresponding South Atlantic Current transport is 23 Sv.

For the water warmer than 9°C the Benguela Current transport is 16 Sv. The water mass analysis discussed above suggests that about 65% or 10 Sv is drawn from the Indian Ocean via the Agulhas Retroflection. Transport of water warmer than 9°C within the South Atlantic Current is 12 Sv. As the 3°C isotherm is near the 1500-dbar level, the transport of water colder than 9°C but shallower than 1500 dbar is essentially the 3°–9°C layer. The northward transport of colder than 9°C water for the upper 1500 dbar water by the Benguela Current is 9.3 Sv, while the South Atlantic Current eastward transport of such water is 11.5 Sv.

From the mass continuity viewpoint alone, it would seem that the South Atlantic subtropical gyre closes at its eastern end, allowing the easterly flowing South Atlantic Current to fold directly into the Benguela Current and balance its northward transport. The additional 0- to 1500-dbar transport of 2.4 Sv within the Benguela Current may be a minor amount of Indian Ocean water or in the noise level of the 1500-dbar referenced geostrophic calculations. However, in consideration of the water mass properties, the South Atlantic Current cannot be the local source of the Benguela Current, and a circulation link between the South Atlantic and the Indian Ocean is required.

6. DISCUSSION

The SAVE leg 4 CTD and tracer data provide strong evidence that there is significant exchange of Atlantic and Indian Ocean thermocline and AAIW water within the interocean conduit south of Africa. About two thirds of the water in the 9°–14°C thermocline stratum, and presumably of the warmer than 14°C near surface water, is derived from the Indian Ocean. Half of the lower thermocline and AAIW water is drawn from the Indian Ocean. Part of the South Atlantic thermocline water and AAIW must pass into the Indian Ocean. At depths greater than that of AAIW there appears to be no water mass linkage between the Atlantic and Indian circulation gyres. The combination of a large meridional gradient of CFM (and other parameters) across stations 211 and 212 from 200-m depth to near 1500 m at the 3°C isotherm (Figures 2*d* and 5*c*) with the change of geostrophic current direction at station 211 (Figure 3) argue that the spread of water properties at the intermediate and thermocline water represent primarily an advective feature.

6.1. *South Atlantic–Indian Ocean Circulation Loop*

What happens to the South Atlantic Central Water once in the Indian Ocean? The distribution of water mass properties within the Indian Ocean thermocline and AAIW suggests a spreading pattern.

The 10°E and 40°E hydrographic sections of *Gordon and Molinelli* [1982, sections II–III, Plates 118–133] reveal an eastward flowing (relative to a deep reference level) layer of 9°–14°C water immediately south of the Agulhas Return Current. Within the Indian Ocean, temperature and salinity distributions at 200 m [*Gordon and Molinelli*, 1982, Plates 11 and 28] show that the 9°–14°C band, along with higher oxygen concentration, expands northward to the east of 70°E. The surface and 500 dbar (relative to 3000-dbar level) dynamic topography maps of the Indian Ocean given by *Wyrtki* [1971, Plates 388 and 389] indicate that 70°E marks the eastern boundary of a small but rather energetic anticyclonic "recirculation" gyre supporting the bulk of the Agulhas Current [*Gordon et al.*, 1987] and thus delineates northward geostrophic flow.

The 30°S zonal sections presented by *Wyrtki* [1971, Plates 415–427] show a thick lense of near 11°C water in the 80°–85°E sector, accompanied by an oxygen maximum. The oxygen maximum appears on the *Atlantis* cruise 15, 1965, section at 82°E. The 11°C thermostad accompanied by high oxygen (also see the western Indian Ocean GEOSECS section shown by *Spencer et al.* [1982]) is a remnant of a subantarctic winter mixed layer [*Colborn*, 1975], which *McCartney* [1977] refers to as the Subantarctic Mode Water (SAMW). McCartney proposes that it is part of a subantarctic circumpolar feature beginning with 14°C thermostad water of the Argentine Basin. This band becomes colder and denser, by contact with the winter atmosphere, as it progresses eastward around Antarctica. At various sites part of the flow is injected as a pycnostad into the thermocline. Consistent with this picture, the SAVE 4 data suggest that the SACW feeds the 11°C SAMW of the central Indian Ocean.

At the AAIW layer, the *Wyrtki* [1971] and *Gordon and Molinelli* [1982] atlas plates indicate more northern spreading of the salinity minimum water east of 60°E with a secondary northern extension between 40° and 50°E (a response to the Madagascar Ridge). R. Fine (personal communication, July 1991) concludes on the basis of CFM data collected along an Indian Ocean section at 32°S that most recently ventilated AAIW circulates in a compact anticyclonic gyre west of 75°E.

6.2. *Conceptual Model of South Atlantic–Indian Ocean Circulation Loop*

SAVE 4 results have far-reaching implications regarding interocean water mass exchange. What is presented below is an eclectic or a conceptual model of the interocean circula-

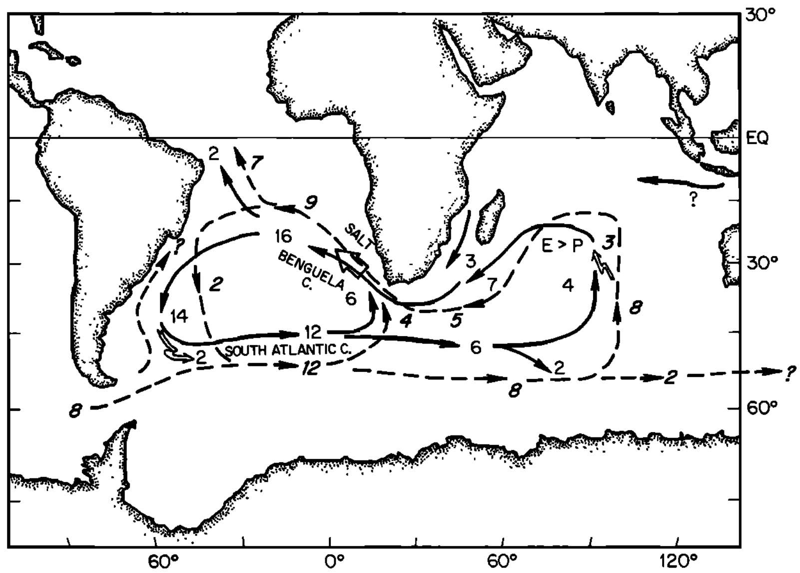

Fig. 9. Schematic representation of the Indian Ocean and South Atlantic interocean circulation pattern. The volume geostrophic transport values are relative to 1500 dbar and are rounded to the nearest whole number (from Table 1). The transport numbers are given in sverdrups (1 Sv = 10^6 m^3 s^{-1}). The solid arrows represent thermocline (warmer than 9°C) transport; the dashed lines represent flow of water colder than 9°C but shallower than 1500 dbar, marking the lower thermocline and Antarctic Intermediate Water.

tion pattern that can give rise to the SAVE 4 findings (Figure 9). Circulation gyres and their transports which are confined within an ocean (e.g., the Agulhas Retroflection) are not explicitly included. The transport values are consistent with the SAVE leg 4 water mass analysis and geostrophic transports, the adjusted geostrophic circulation pattern presented by *Reid* [1989], and the general requirement of thermocline upwelling and transfer between subtropical and subantarctic regimes (all of which are discussed within the preceding text). The volume geostrophic transport values given in Figure 9 are relative to 1500 dbar and are rounded to the nearest whole number. In the following discussion the transport numbers with the notation "L" are approximations that help close the loop; the notation "G" represents numbers that are derived from this study (Table 1).

For thermocline water warmer than 9°C, the following circulation is proposed.

1. Thermocline water flows northward within the Benguela Current (16 Sv (G)). Based on the CFM data, approximately 65% or 10 Sv (G) of this transport is derived from the Indian Ocean with the rest (6 Sv (G)) derived from direct incorporation of South Atlantic water into the Benguela Current. The thermocline water flows westward across the South Atlantic within the northern limb of the subtropical gyre. Most of it (14 Sv (L)) merges with the southward flowing thermocline water within the Brazil Current [*Gordon*, 1989; *Reid*, 1989]. A minor amount, 2 Sv (L) is available to pass into the North Brazil Coastal Current. *Reid* [1989] shows streamlines of adjusted geostrophic flow turning northward near 10°S at the South American boundary.

2. Much of the thermocline water (12 Sv (G)) returns to the east flowing with the South Atlantic Current, the polar limb of the subtropical gyre. The reduction from 14 Sv of thermocline water flowing in the Brazil Current to 12 Sv of thermocline water within the South Atlantic Current may be accounted for by 2 Sv (L) converted to less than 9°C water as a result of atmospheric cooling. The concept of cooling of thermocline water trapped within Brazil Current warm core eddies in the Argentine Basin representing injection of subtropical salt into the subpolar regime is discussed by *Gordon* [1989].

3. About half (6 Sv (G)) of the 12 Sv of thermocline water flowing eastward in the South Atlantic current turns directly into the Benguela Current. The rest (6 Sv (G)) continues to flow eastward, passing into the Indian Ocean by a route south of the Agulhas Return Current.

4. In the Indian Ocean the Atlantic thermocline water is exposed to the subpolar atmosphere, and cooling ensues, transferring additional thermocline water to the layers colder than 9°C (as a "working" number a value of 2 Sv (L) is used for this conversion). The South Atlantic thermocline water remaining in the 9°–14°C layer (4 Sv (L)) folds into the Indian Ocean subtropical gyre, primarily as 11°C SAMW near 80°E.

5. The Atlantic thermocline water embedded within the Indian Ocean thermocline (4 Sv (L)) returns to the South Atlantic within the Agulhas recirculation gyre to close the loop. Warming of this water within the Indian Ocean is expected. As 10 Sv (G) of Indian Ocean thermocline water is required to close the loop with the Benguela Current, an additional 6 Sv (L) must be derived from other sources. There are two possibilities: upwelling water from the colder than 9°C layer, and water drawn from the tropical Indian Ocean. An equal split is suggested, 3 Sv (L) of upwelling (using an area for the Agulhas recirculation gyre of 10×10^6 km^2 determined from *Wyrtki*'s [1971] 500/3000 dbar dynamic topography, 3 Sv amounts to an upwelling rate of 3×10^{-5} cm s^{-1}) and 3 Sv (L) from the tropics. The 3 Sv (L) from the Indian Ocean tropics (with reduced CFM concentrations) represent that portion of the transfer of warm surface water from the tropical Pacific through the Indonesian seas which passes into the Atlantic. A greater portion of the Pacific to Indian interocean transport may be expected to pass directly back to the Pacific by a purely Indian Ocean route embedded within the Agulhas Return Current.

For lower thermocline and AAIW water (colder than 9°C but shallower than 1500 dbar, the following circulation is proposed.

1. The Benguela Current carries 9 Sv (G) of lower thermocline and AAIW water. Following the roughly 50/50 ratio of South Atlantic to Indian Ocean water properties suggested by the SAVE 4 data, approximately 5 Sv (G) are derived from the Indian Ocean and 4 Sv (G) are injected directly from the South Atlantic Current.

2. It is proposed that most of this water (7 Sv (L)) passes to lower latitudes of the South Atlantic. This is consistent with the adjusted circulation pattern presented by *Reid* [1989, Figure 17], which shows the geostrophic streamlines turning into a large cyclonic gyre in the tropical South Atlantic (also see *Gordon and Bosley*, [1991]). It is suggested that within this feature and in the equatorial regime there is significant transfer of AAIW into the thermocline which may account for the abundance of South Atlantic thermocline water passing northward within the Straits of Florida [*Schmitz and Richardson*, 1991].

3. There are 12 Sv (G) of lower thermocline and AAIW flowing eastward within the South Atlantic Current. The freshness of the AAIW suggests that most of this water must be derived from the Pacific Ocean, through the Drake Passage. However, some injection of thermocline water into this layer is expected from the Brazil Current. To be consistent with the "warmer than 9°C" transport pattern, it is assumed that 2 Sv (L) is derived from cooled thermocline water. Additionally, 2 Sv (L) of colder than 9°C water is assumed to be recirculated from Benguela Current, leaving room for 8 Sv (L) of new AAIW; it is noted that these proportions yield the observed AAIW salinity at 10°W.

4. About one third of lower thermocline and AAIW transport within the South Atlantic Current (4 Sv (G)) turns into the Benguela Current at the Agulhas Retroflection.

5. The rest of the lower thermocline and AAIW transport (8 Sv (G)) flows in the Indian Ocean, with 6 Sv (L) folding into the Indian Ocean Agulhas recirculation gyre and 2 Sv (L) passing to the east. Consistent with the thermocline transport schematic, there is an influx of 2 Sv (L) of cooled thermocline water into the lower thermocline and AAIW layer.

6. Part (3 Sv (L)) of the colder than 9°C water that enters the Indian Ocean upwells into the greater than 9°C stratum (see discussion in point 5 of the thermocline transport discussion above).

7. Much of the colder than 9°C water flowing into the southwestern Indian Ocean returns to the South Atlantic as somewhat saltier (Figure 5*a*) water (5 Sv (G)); it mixes with the 4 Sv (G) injected directly at the Agulhas Retroflection region to yield a 9 Sv (G) transport of water colder than 9°C within the Benguela Current.

6.3. *Relationship to Global Thermohaline Circulation*

With 25.4 Sv entering from the Indian and 23.0 Sv leaving the Atlantic within the upper 1500 m, there would seem to be only 2.4 Sv, essentially a "noise level" transport, available to compensate Atlantic export at deeper layers (i.e., NADW, within the vertical plane). This rather insignificant imbalance in the interocean exchange transport might lead one to abandon the suggestion that part of the Indian Ocean inflow to the Atlantic is compensated at a deeper level by North Atlantic Deep Water [*Gordon*, 1985, 1986]. However, not all of the 23-Sv South Atlantic Current transport within the upper 1500 m is derived from the South Atlantic. The proposed transport pattern (Figure 9) includes 8 Sv AAIW of inflow from the Drake Passage, 3 Sv thermocline inflow from the Indonesian seas to balance the 7 Sv (colder than 9°C) and 2 Sv (warmer than 9°C) export to the northern Atlantic presumably to balance Atlantic outflow of NADW, plus the 2-Sv loss of colder than 9°C to the eastern Indian Ocean. As Atlantic export of NADW is estimated as 12 Sv (*Gordon* [1986] assumes that 5 Sv of the 17-Sv total production of NADW upwells within the Atlantic basin before export to the other oceans) the thermocline and AAIW compensating flow of 9 Sv is in principle sufficient to balance NADW export.

Rintoul [1991], applying inverse methods to a grid of International Geophysical Year (late 1950s) with more recent, higher-quality oceanographic sections that effectively boxes in the South Atlantic from the Indian and Pacific oceans, finds a more or less equal split of thermocline to intermediate water balancing NADW export across 32°S. However, the thermocline water is generated from local warming of upwelled intermediate water in the South Atlantic south of 32°S rather than drawn from the Indian Ocean. The general need for South Atlantic upwelling of AAIW into the thermocline is well documented by the study of *Schmitz and Richardson* [1991]. Examining the water mass flux through the Straits of Florida, they find significant flux within the South Atlantic thermocline water. As was suggested in the preceding section the bulk of conversion of AAIW to thermocline water may occur in the cyclonic gyre of the tropical South Atlantic, north of the 32°S section used by Rintoul.

The SAVE 4 data suggest that the AAIW of the subtropical South Atlantic enters the Atlantic with the Benguela Current and that as much as half of this water is injected into the South Atlantic from the Indian Ocean. As the Indian Ocean component is drawn from AAIW within the South Atlantic Current, passing into the Indian Ocean south of the Agulhas Retroflection, the Indian Ocean input at the AAIW levels would not "show up" in the Rintoul transport figures. The SAVE 4 data also indicate that while significant amounts of Indian Ocean thermocline water are carried into the South Atlantic, most of it passes back to the Indian on an approximate horizontal plane (the possibility of which is considered by *Gordon* [1985]). This is not in violation of Rintoul's results, as apparently little of this water "stays" north of 32°S as part of the global (vertical plane) thermohaline circulation cell.

The interocean exchange circulation pattern (Figure 9) suggests that the bulk of the Atlantic export of NADW is balanced by lower thermocline water and AAIW. However, the dominant cold water path follows a rather unexpected course: rather than follow a route along the western boundary of the South Atlantic, the bulk of AAIW may first pass across the South Atlantic and through the southwest Indian Ocean before spreading northward in the subtropical South Atlantic Ocean. During the Indian sojourn the AAIW is increased in salinity by at least 0.15 ppt over the salinity near 10°W and by 0.25 ppt over the initial characteristics of AAIW in the Argentine Basin [*Piola and Gordon*, 1989]. Furthermore, the AAIW once in the Atlantic Ocean may receive additional salt from the SACW. Owing to the injection of salty IOCW, the South Atlantic thermocline is expected to be saltier than would be expected if the Benguela Current were fully supplied by the South Atlantic Current, with no Indian Ocean thermocline link. The salt-enhanced SACW would increase the susceptibility of the South Atlantic to salt finger processes that greatly strengthen vertical mixing and the downward cascading of salt to the intermediate layers [*Schmitt*, 1981; *Greengrove and Rennie*, 1991]. Therefore the AAIW salinity is enhanced in two ways: by picking up extra salt in the southwest Indian Ocean and then by receiving, through vertical mixing within the South Atlantic, additional Indian Ocean salt from the thermocline.

The more salt that can be obtained from the evaporative Indian Ocean, the less is the burden on the atmosphere over the Atlantic to transfer water vapor to a neighboring ocean basin as required to maintain a salty northern Atlantic with an energetic production of NADW. Additionally, the Indian Ocean inflow boosts the initial salinity of the upper limb of the NADW-driven thermohaline "conveyor belt" in the South Atlantic Ocean, so a given intensity of atmospheric processes results in a saltier northern product.

What the salinity of the Atlantic would be if the Indian Ocean salt link were severed may best be studied with general circulation models, but a simple estimation may be made as follows. If the Atlantic water balance with the atmosphere remains constant and AAIW is the chief feed for sinking NADW, a linear relationship of northern North Atlantic upper layer salinity to AAIW salinity at the equator is expected. It is conjectured in this study that a significant part of the salinity increase of AAIW at the equator relative to its initial Drake Passage characteristics (amounting to 0.4–0.5 ppt) is derived from Indian Ocean salt: 0.1–0.2 ppt picked up by the AAIW in the southwest Indian Ocean and at least that amount transferred by mixing with the Indian Ocean salt-enhanced South Atlantic thermocline. Thus with the Indian Ocean link the North Atlantic upper layer salinity could be as much as 0.2–0.4 ppt saltier relative to what it would be if Indian Ocean link with the South Atlantic were severed. Presumably this would be reflected in NADW salinity and perhaps production rates. Thus is it natural to ask, might introduction of Indian Ocean salt precondition the North Atlantic for deep convection? Once the "pump is primed," a network of powerful positive feedback mechanisms involving the coupled ocean-atmosphere system would invigorate the thermohaline circulation and saltiness of the North Atlantic Ocean. Conversely, if the Indian Ocean salt input were severed, might the NADW thermohaline cell run down? The rather tenuous interocean circulation link around the southern rim of Africa might be a significant choke point within the global thermohaline circulation. *Stocker and Wright* [1991] point out that the present-day thermohaline circulation is very sensitive to changes in the surface water budget. They have in mind changes in the Atlantic to Pacific basin freshwater flux by the atmosphere, but might varied access of the Indian Ocean water to the Atlantic have a similar effect?

6.4. *Stability of the Indian–South Atlantic Link*

The probable sporadic nature of the Agulhas inflow and low-frequency variability of thermohaline circulation should discourage the assumption that the SAVE data of December 1989 and January 1990 can be viewed as a steady state condition. It is possible that at times the South Atlantic Current does fold completely into the Benguela Current, essentially decoupling the subtropical gyres of the Indian and South Atlantic oceans. At other times the gyres are well linked, as was the situation during SAVE 4 expedition in early 1990. However, the regional CFM-11 distribution within the South Atlantic thermocline during the 1987–1990 SAVE cruises suggests that the linkage of the South Atlantic and Indian Ocean thermoclines may be more climatically persistent. A plot of the CFM-11 on the σ_0 surface 26.75 (Figure 10), passing through the central region of the 9°–14°C stratum, reveals that high CFM-11 (greater than 2) is confined to the region south of 35°S. Within the central and westward flowing limb of the South Atlantic subtropical gyre, roughly north of 33°S, the CFM concentrations are low. There are appears to be no intrusions of high CFM from the south. Since it takes about 3 years for Agulhas eddies to migrate across the entire South Atlantic [*Gordon and Haxby*, 1990], it appears that for at least the late 1980s the South Atlantic and Indian Ocean thermoclines were well linked.

7. CONCLUSIONS

Water mass analysis of the SAVE 4 data indicates that rather than folding into the Benguela Current, much of the thermocline and Antarctic Intermediate Water of the South Atlantic Current flows into the Indian Ocean by a route immediately south of the Agulhas Retroflection. The linking of the subtropical gyres of the South Atlantic and Indian Oceans is completed by a flow of Indian Ocean water into the Benguela Current. Approximately 65% of the Benguela Current thermocline and perhaps as much as 50% of the intermediate water is derived from the Indian Ocean. The remaining water is derived from the South Atlantic and is injected into the Benguela Current at the western end of the Agulhas Retroflection, presumably during the frequent eddy-shedding episodes. These results are in agreement with those of *Gordon et al.* [1987], whose geostrophic transport analysis of the Agulhas retroflection region finds that within the upper 1500 m (relative to 1500 dbar) between the African mainland and an Agulhas eddy offshore of Cape Town, 10 Sv of Indian Ocean water combines with 5 Sv of South Atlantic water to flow into the Benguela Current.

A conceptual model for interocean circulation of thermocline and intermediate water is proposed (Figure 9). The main supply of upper layer water crossing the Atlantic equator, compensating for Atlantic export of NADW, is drawn from AAIW. The route followed by this stratum is not along the western boundary of the South Atlantic but rather is part of the general upper layer circulation pattern, which includes a loop into the southwestern Indian Ocean. In the Indian Ocean, excess salt is introduced to the AAIW. Salt is also introduced to the South Atlantic AAIW layer from the South Atlantic Central Water. SACW with elevated salinity (relative to what its salinity would be if the South Atlantic Current fully supplied the Benguela Current) due to the Indian Ocean input mixes into the AAIW. The interocean link allows the evaporative Indian Ocean to boost the salinity of the Atlantic Ocean and presumably its corresponding susceptibility to NADW formation. Severing of the Indian Ocean and South Atlantic interchange at the thermocline and AAIW levels would lower the salinity of the

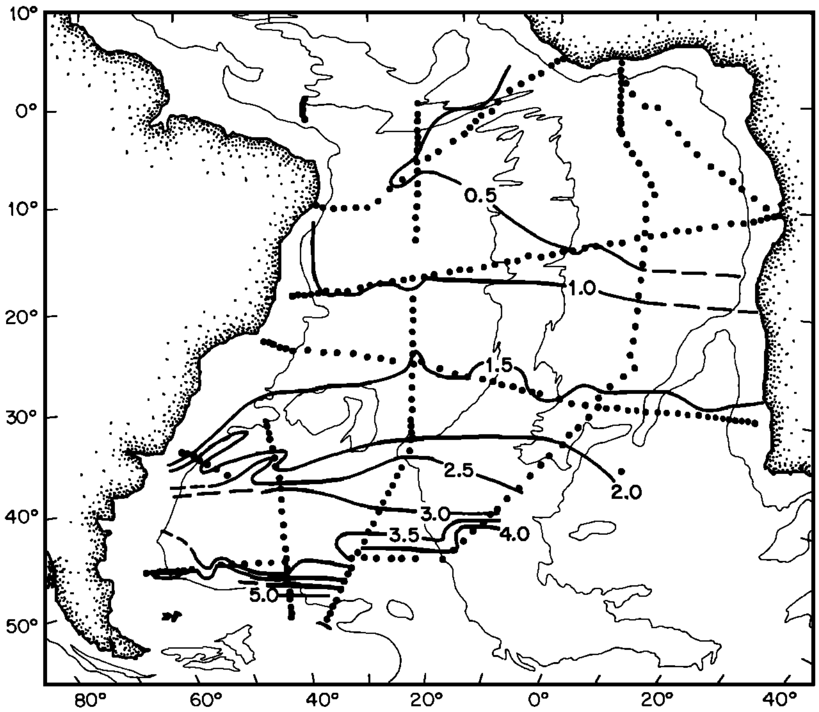

Fig. 10. CFM-11 concentration on the σ_0 = 26.75 surface. This surface falls within the 9°–14°C stratum of the midthermocline.

Atlantic Ocean and might have an attenuating influence on the Atlantic thermohaline conveyor belt.

Acknowledgments. A.L.G. was supported by grants ONR N00014-90-J-1233 and NSF OCE-86-13325; W.S., grant NSF OCE-86-13327; and R.F.W., grant NSF OCE-86-13321. Lamont-Doherty Geological Observatory contribution 4887.

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(Received September 27, 1991;
accepted January 10, 1992.)