Deep-Sea Research, Vol. 36, No. 3, pp. 359–384, 1989.
Printed in Great Britain.

0198–0149/89 $3.00 + 0.00

Brazil–Malvinas Confluence—1984

ARNOLD L. GORDON*

(*Received* 5 *April* 1988; *in revised form* 15 *September* 1988; *accepted* 21 *September* 1988)

Abstract—The Brazil–Malvinas (Falkland) Confluence is marked by a complex array of strongly contrasting water types. In October 1984 two large poleward meanders of South Atlantic thermocline water, separated by a cold-core cyclonic eddy near 40°S and 50°W, were observed west of 46°W. The western feature extended further south, to 43°S, with a geostrophic volume transport for the upper 1500 decibars (db) relative to 1500 db of $22.5 \times 10^6\ m^3\ s^{-1}$. The branch to the east has a somewhat weaker baroclinic structure, though it is associated with warmer and more saline surface water. The warmer temperature reflects less atmospheric cooling than experienced within the western branch, which is exposed directly to the cold prevailing westerlies. The western branch is capped by a low salinity layer, the origin of which appears to be a mixture of continental shelf water with surface water from the Brazil Current. Near 39–40°S the surface water at the Confluence front is of very low salinity, yet too warm to be subantarctic water carried in with the Malvinas Current. It is likely that it represents warm river plume water from the Rio de la Plata, that has "folded-over" the northern tip of the cyclonic trough formed by the Malvinas Current and its return to the south. At depth the most concentrated North Atlantic Deep Water is associated with the western branch. This feature continues flowing south, below the Malvinas Current, indicating that the western boundary separation at depth need not be coherent with the thermocline separation position.

South of the western branch are two warm-core eddies; the northern eddy is in the process of separation while the southern eddy has been separated for a period of 2–3 months and has undergone thermohaline modification by the late winter atmosphere. These modified warm-core eddies may not re-coalesce with the main thermocline and hence represent a significant salt flux into the subantarctic zone of the South Atlantic.

INTRODUCTION

THE Brazil Current and the Malvinas (also referred to as Falkland) Current converge along the continental margins of South America roughly within the latitude band 35°S and 40°S. They then flow seaward in a complex pattern of meanders and eddies, with the warm water of the Brazil Current foming a quasi-stationary poleward meander. This feature is referred to as the Brazil–Malvinas or Falkland Confluence (e.g. OLSON *et al.*, 1988).

The thermohaline structure of the Brazil–Malvinas Confluence was studied from the R.V. *Thomas Washington* cruise Marathon 7 in October 1984 (Fig. 1). In November 1984 the area east of the Confluence was investigated during *Thomas Washington* cruise Marathon 8 (RODEN, 1986) and in December 1984 on *Thomas Washington* cruise Marathon 9 the area to the north was surveyed by McCartney.

The series of CTD and XBT observations along 38°S obtained during Marathon 7 (Fig. 2) duplicate an *Atlantis* II cruise 107-3 section obtained in December 1979

* Lamont Doherty Geological Observatory and Department of Geological Sciences, Columbia University, Palisades, NY 10964, U.S.A.

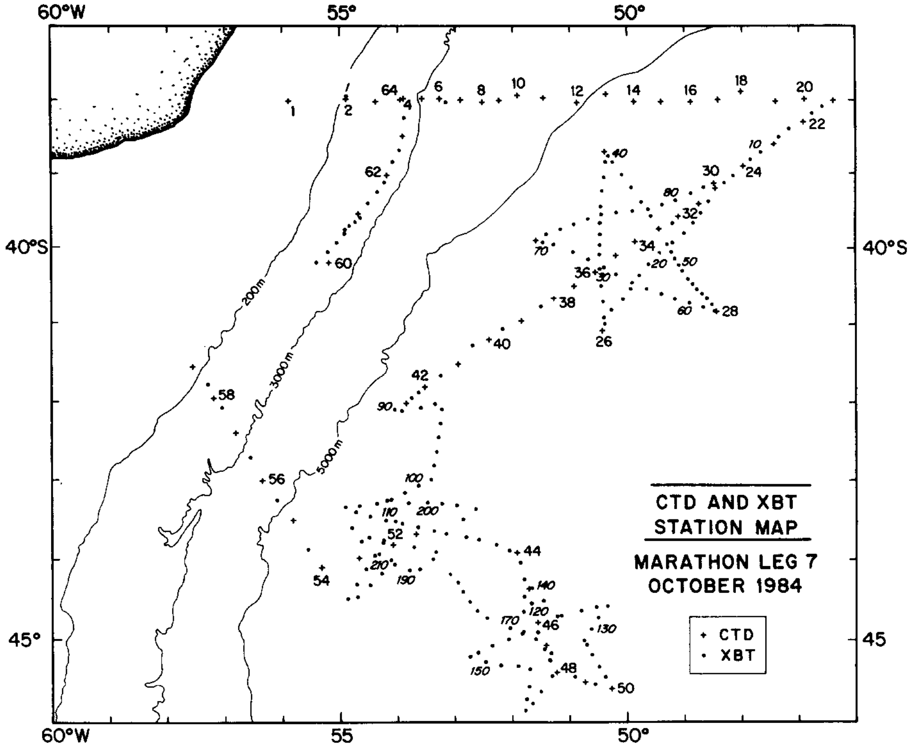

Fig. 2. The array of CTD stations and XBT observations obtained during Marathon cruise 7.

(GORDON, 1981), enabling inspection of time variability of the water mass properties. The observations south of 38°S were designed to study the thermohaline structure of two warm eddies and one cold eddy, which were monitored from satellite during the cruise, as well as the cold water intrusion associated with the Malvinas Current over the continental slope. The "star" patterns over two of the eddies were followed as a time-efficient survey of eddy features. The irregular pattern over the warm eddy near 44°S and 54°W resulted from the collision of an attempted star pattern with a storm. The surveyed eddies are named for reference: the anticyclonic warm-core eddies are referred to as Asp and Anthony; the cyclonic cold-core eddy is named Cleopatra.

SURFACE WATER

Temperature and salinity

The surface water ranges in temperature from 7 to 18°C (Fig. 3a) and in salinity from 33.6 to 36.0 (Fig. 3b), an extraordinary range considering the rather limited area of the survey. The sharp contrast results from the advection of water from two very different oceanic regimes: the subtropical water introduced by the Brazil Current and the subantarctic water of the Malvinas Current. Within the Confluence these waters are vigorously stirred and mixed, with further modification as they interact with the atmosphere.

The surface temperature and salinity patterns reveal two poleward projections of warm water, separated by the cold/fresher core of Cleopatra. The eastern branch is

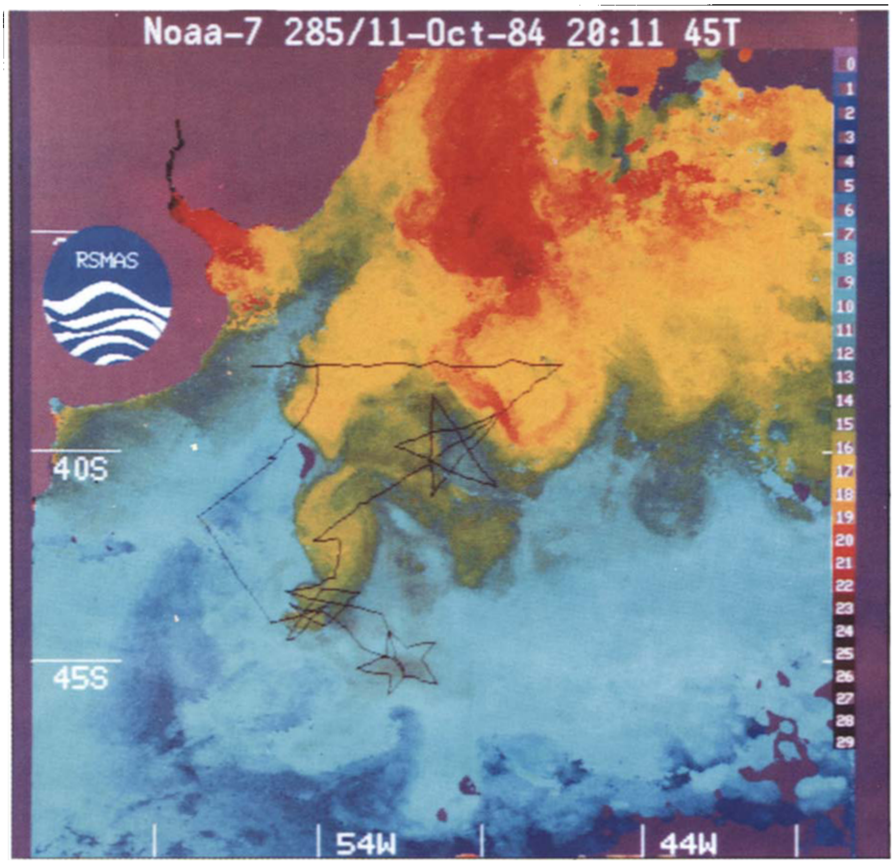

Fig. 1. The cruise track of *Thomas Washington* Marathon cruise 7, October 1984, superimposed on a satellite derived infra-red image (provided by the satellite facility at RSMAS, University of Miami, R. Evans).

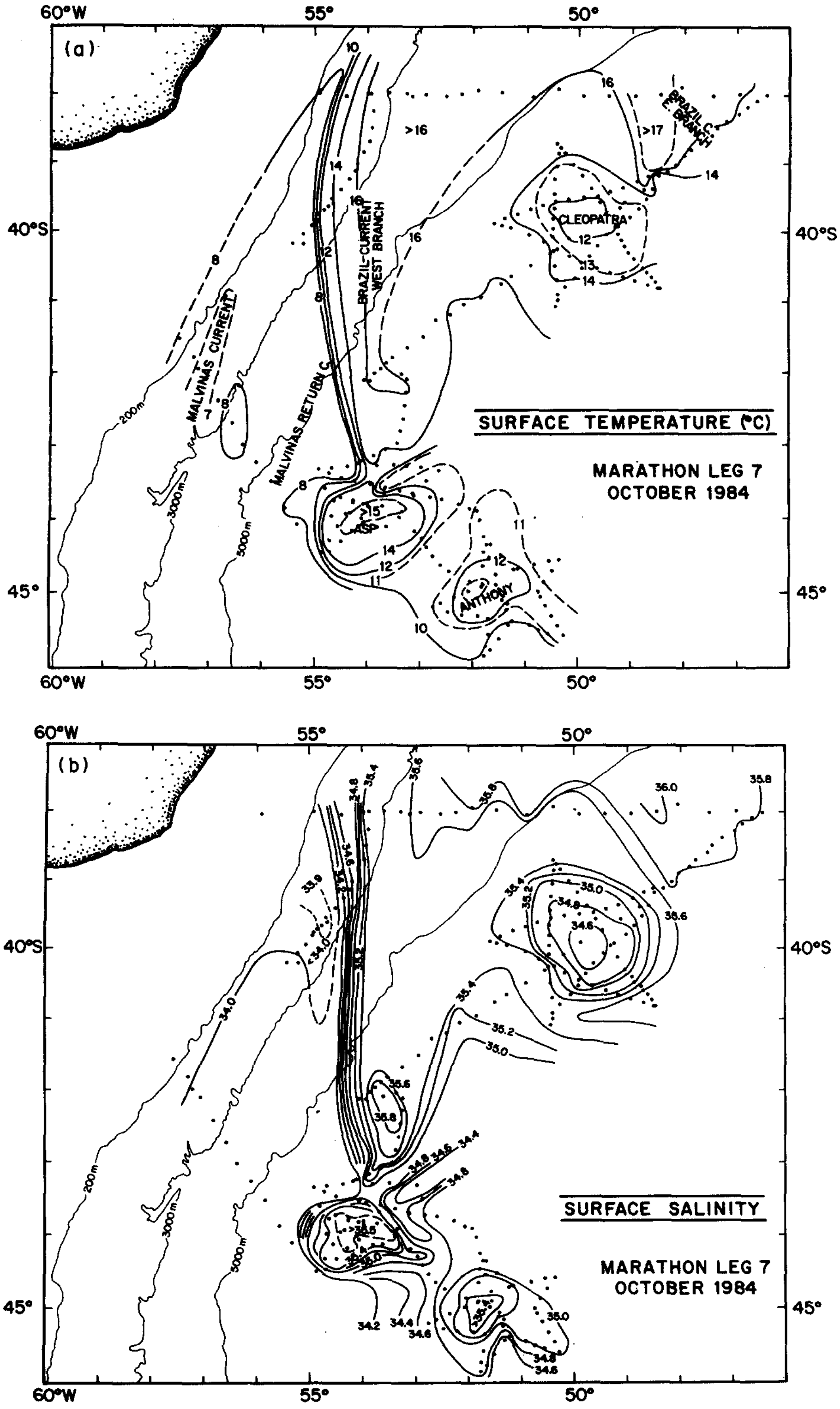

Fig. 3. (a) Surface temperature as measured at the CTD stations and XBT observations, shown in Fig. 2. (b) Surface salinity as measured at the CTD stations and XBT observations, shown in Fig. 2.

warmer and saltier within the surface layer. The appearance of the surface water patterns suggests that the primary flow of Brazil Current water feeds the eastern branch, i.e. the Brazil Current separates from the continental margin near 35°S (OLSON *et al.*, 1988). However, caution is suggested in that this may only be a surface feature, not totally coincident with the deeper circulation, as discussed below. The cooler surface water of the west branch may be induced as the prevailing southwesterlies, blowing from the continent and from a much colder water surface, force large ocean heat loss from the first encounter with the warm Brazil Current water. Additionally, low salinity surface water introduced by the Malvinas Current may spread across the Confluence front, perhaps in response to wind events.

The eddy features are clearly brought out in the surface water characteristics. Asp has a core temperature/salinity of about 15°C/35.5; Anthony with 13°C/35.4; and Cleopatra with 12°C/34.6.

The two end-members of the surface water temperature/salinity plot (Fig. 4) are introduced by the warm salty Brazil Current and the cold fresher Malvinas Current. Mixing of these end-members is not expected to be fully conservative, in that during the 1 month cruise, both end-members would be expected to be altered by heat/fresh water exchange with the atmosphere. During October the cold subantarctic surface water is expected to warm. HÖFLICH (1984) determined a September and October heat flux into the ocean of 62 and 119 W m^{-2}, respectively, for the 9–10°C surface temperature characteristic of the Malvinas regime within the area 40–45°S and 55–65°W. The warm subtropical surface water would cool, particularly that trapped within the eddies at higher latitude. GREENGROVE (1986), modeling warm subtropical water exposed to the same atmospheric conditions as used by Höflich, finds a September and October oceanic

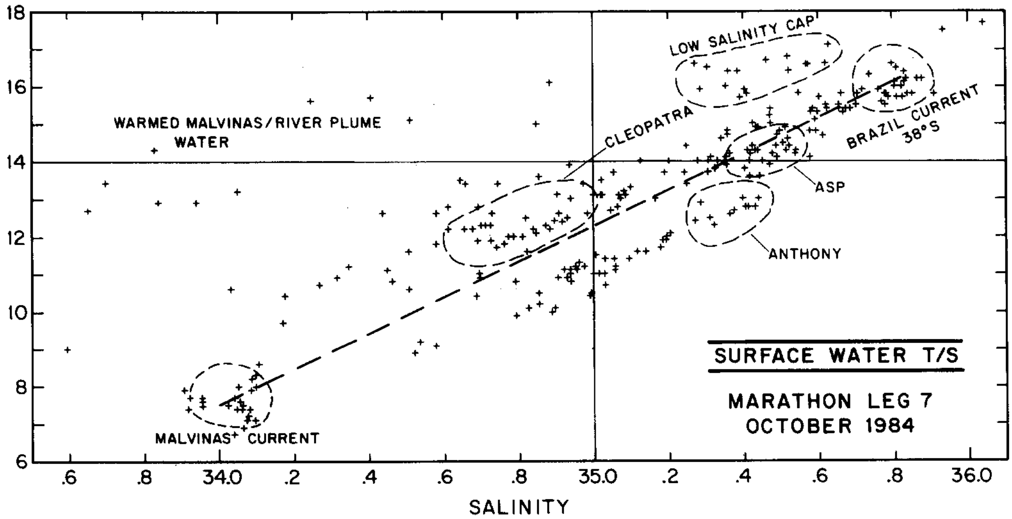

Fig. 4. Surface water temperature/salinity relationship at the CTD stations and XBT observations. The heavy dashed line represents the mixing curve for the two end-members: the warm salty Brazil Current surface water at 38°S and the cold, fresher surface water of the Malvinas Current. The thinner dashed lines envelop the temperature and salinity range of the three eddies and low salinity surface feature observed over the western branch of the Brazil Current poleward protrusion.

heat loss of 125 and 25 W m^{-2}, respectively. Late winter to early spring warming of the characteristic 50 m mixed layer for the subantarctic water would be 1–2°C per month, while cooling of the 200 m mixed layer of the subtropical water would proceed at a rate of 0.23°C per month.

The 14–15°C surface water within Asp falls only slightly to the cold side of the mixing curve; Cleopatra is displaced approximately +1°C from the mixing curve and Anthony is about 1.5°C cooler. The surface water within the bulk of the poleward meander of subtropical water exterior to the warm eddy cores, falls about 1°C colder than the mixing curve (in the 34.8–35.2 range). The surface water temperatures suggest that both Asp and Cleopatra were in the area about 1 month, while Anthony was exposed to the cold atmosphere for a longer period. Comparison of Anthony's thermal stratification to that of Asp, indicates a relative heat deficit of 1.86×10^9 J m^{-2}. Using the results of GREENGROVE (1986), Anthony had to be exposed to the winter atmosphere since late July or early August 1984, and was in the confluence region for about 2.5 months at the time of the *Thomas Washington* observations. This does not necessarily correspond to the separation date of the Anthony from the main body of the thermocline. For example, Asp, which is still attached to the thermocline, exhibits some modification relative to the linear mixing curve.

The surface water T/S plot (Fig. 4) shows very low salinity points (<34.2) falling well above (warmer than) the mixing line. These points are located along the Confluence front, between 39 and 40°S near 55°W (Sta. 61 is within this feature, see area "A" in Fig. 5). It is proposed that these points represent continental shelf water that has been advected to the north by the coastal segment of the Malvinas Current and has warmed (but still cooler than the Brazil Current surface water) before returning to the south within the Malvinas Return Current.

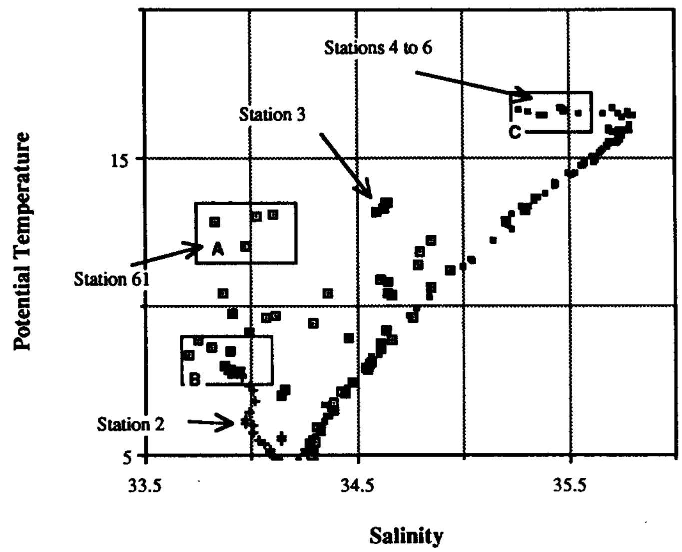

Fig. 5. Potential temperature/salinity relationship of select stations along the Confluence front and western branch of the Brazil Current at 38°S. Station 61 near 40°S falls within the very low salinity surface water at the Confluence front. Boxes A, B and C are discussed in the text.

The shelf water is diluted with river water, particularly with the relatively warm outflow from the Rio de la Plata (which carries the runoff of the Rio Paraná and Rio Uruguay; Fig. 1 shows the northward spreading of the relatively warm Rio de la Plata plume). The river water signature folds back to the south around the cyclonic circulation of the Malvinas Current, to form elongated cells of low salinity water along the Confluence. This phenomena is analogous to a cold, low salinity filament of shelf and river water of 100 m thickness aligned along the west edge of the Gulf Stream (FORD *et al.*, 1952). The sea surface dynamic height relief, discussed below, reveals that the baroclinic front of the Confluence in October 1984 coincides with the surface water thermal front. The surface water salinity front is located to the east, well within the strong southward-flowing current marked by the strongly baroclinic thermocline structure.

The complexity of the surface temperature patterns revealed by the i.r. images suggests that this return flow of warmed Malvinas Current water and/or mixtures of subantarctic water with river water is not continuous, but rather occurs with filaments and eddies. The *Thomas Washington* data along 38°S do not reveal the warm, very low salinity surface water feature seen at 39°S, though at 38°S there is a warm, slightly fresher surface water cap over the thermocline structure.

In addition to the direct input of river water along the Confluence front, there is a regional low salinity surface water cap commonly observed throughout the western part of the Brazil Current (GORDON, 1981). This is shown within the *Thomas Washington* data by the scatter of surface water T/S points within the high salinity range (>35.2), slightly warmer than the mixing curve (also seen in the 38°S salinity section, discussed below). An example of the low salinity surface water feature can be seen in Stas 2–6 aligned along 38°S across the Confluence (Fig. 5): Sta. 2 is within the Malvinas Current (area "B" in Fig. 5); Sta. 3 is near the front and Stas 4–6 (area C in Fig. 5) are within the subtropical regime.

The widespread low salinity cap over the western branch may be induced by mixing of thermocline water with river outflow or heavy coastal precipitation north of the Confluence region. The high temperature of the low salinity cap at Stas 4–6 suggests that the admixture forms well north of the Confluence site. While there are no major rivers flowing into the Atlantic between 25 and 35°S, BAUMGARTNER and REICHEL (1975; their Plates 19 and 22) show great excess of fresh water input to the coastal region (continental and oceanic) south of Cabo Fio extending to Uruguay. Additionally, much of the Mar de la Plata plume may spread northward along the continental shelf before "diffusing" eastward over the thermocline. The low salinity cap is not observed within the eastern branch of the Brazil Current, which may be fed by a more offshore component of the Brazil Current, less contaminated with river outflow. Thus, the low salinity filaments along the Confluence front are derived directly from the river discharge from Mar de la Plata, whilc the regional depression of surface salinity east of the front is derived from a more extensive coastal region input.

BLANC *et al.* (1983) report a weak exponential relationship between surface temperature and mixed-layer depth within the Confluence region, with distinct difference between the subtropical (Brazil Current) and subantarctic (Malvinas Current) regimes. The mixed layer tends to be slightly deeper for warmer temperatures within the subtropical regime, whereas it is slightly shallower for warmer temperatures within the subantarctic regime. While the early spring season *Thomas Washington* data do reveal somewhat deeper mixed layers coupled to warmer surface water, it is an ambiguous relationship. However, an improved relation can be found by inspecting the winter remnant mixed layer. It is noted that the subtropical water column often has a thin mixed layer (tens of meters) cap above a thicker, slightly cooler homogeneous layer. This double mixed layer configuration is considered to represent the initiation of the seasonal mixed layer over the remnant winter mixed layer. The relationship of the surface water temperature and salinity to the thickness of the winter remnant mixed layer of the subtropical regime is more significant (Fig. 6a,b). The stronger correlation lies with surface salinity, with a correlation coefficient of $R = 0.73$ vs 0.64 for surface temperature; higher surface salinity is positively correlated to the deeper winter mixed layer.

As Blanc *et al.* (1983) point out, an exact functional relationship between mixed-layer depth and surface temperature could not be found. However, it is likely that a reasonably useful relation can be derived between surface salinity and winter mixed-layer depth for the subtropical regime. This indicates that the low salinity input from the margins supresses the full development of the winter mixed layer within the thermocline; the sea

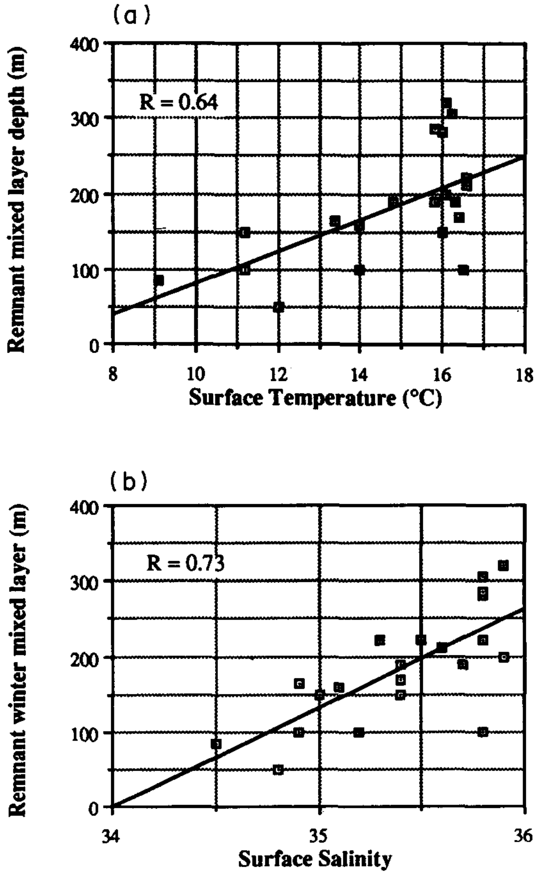

Fig. 6. (a) The depth of the winter remnant mixed layer within the thermocline regime vs surface temperature. (b) The depth of the winter remnant mixed layer within the thermocline regime vs surface salinity.

surface temperature criteria is not enough to parameterize the winter mixed-layer thickness.

Sea surface dynamic topography

A more complete view of the sea surface dynamic topography relative to a deep reference surface can be derived from the combination of CTD and XBT data (Fig. 7). The relationship of the 8°C isotherm depth (or any mid-thermocline isotherm) to the 0/1500 dynamic height anomaly is linear, with a coefficient of correlation of 0.98, with 81% of the data points falling within 0.05 dyn m of the straight line fit value. This is essentially an expression of the dominance of the thermocline baroclinicity over that of the deeper water, i.e. to a good approximation the thermocline regimes represent a two-layer system.

The Brazil Current poleward meanders are best defined as the pattern given by the 1.6 dyn m isopleth. In this way the Brazil Current feature is bisected by a large cyclonic cold-core eddy, Cleopatra. A secondary poleward meander and cyclonic eddy is seen just west of Cleopatra. Sea level within the crest of the western branch of the Brazil Current meander stands 0.83 dyn m above that of the Malvinas Current, defining the maximum relief of the region, somewhat greater than the 0.78 dyn m found during the *Atlantic* II 107–3 1979/80 cruise in the same area (GORDON and GREENGROVE, 1986, adjusting the

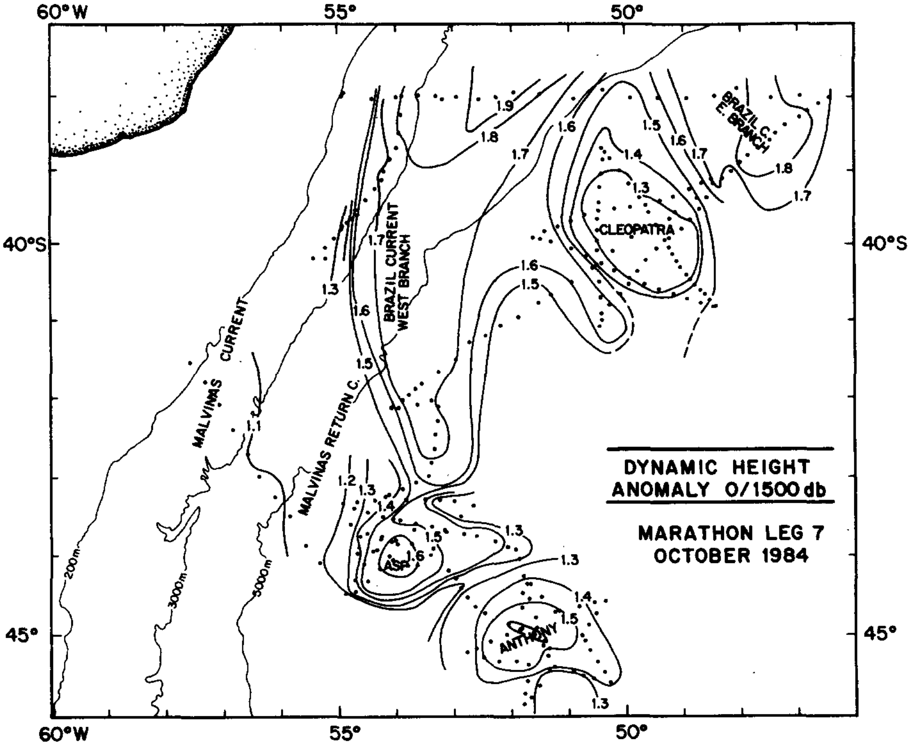

Fig. 7. Sea surface anomaly of dynamic height relative to 1500 db. The XBT data is used in the construction of this map by using a near linear relationship of the depth of the 8°C isotherm to the 0/1500 dynamic height.

0/1400 db values given in that paper to 0/1500 db). The east branch of the Brazil Current meander has a crest dynamic height about 0.10 dyn m less than the west branch, although it carries warmer, saltier surface water. RODEN (1986) dicusses a third meander further east, centered at 42–43°W. The three branches reveal a wave-like structure of the Brazil Current's seaward extension, with a wavelength of 400–500 km with an amplitude of 200 km (not including the secondary feature west of Cleopatra).

Expressed in dynamic height anomaly values of the sea surface relative to 1500 m: Cleopatra center is 0.27 dyn m below the values at the points of the star pattern; Asp is 0.27 dyn m above the sea surface at its edges and Anthony is 0.22 dyn m above the points of its star pattern. The maximum geostrophic velocity and radial locations are as follows: 50 cm s^{-1} at 135 km for Cleopatra; 78 cm s^{-1} at 70 km for Asp and 35 cm s^{-1} at 55 km for Anthony. The characteristic 0/1500 geostrophic volume transports, based on the CTD station data, are roughly 24 × 10^6 m^3 s^{-1} (24 Sv), 21 and 12 Sv, respectively.

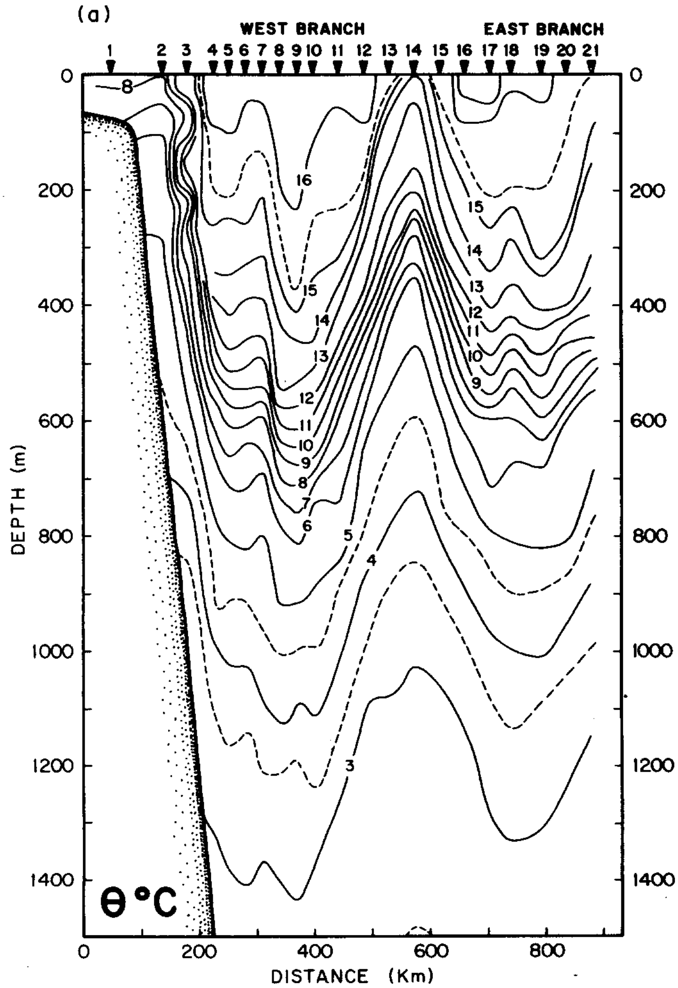

Fig. 8a.

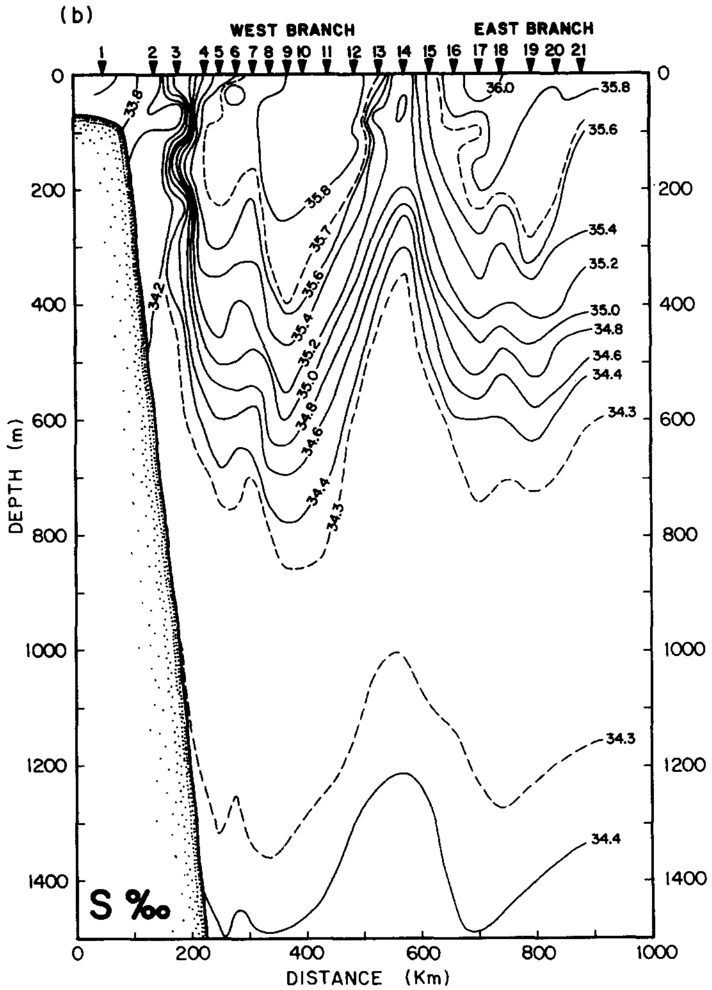

Fig. 8. (a,b) Potential temperature and salinity section along 38°S, surface to 1500 db.

38°S SECTION

Thermohaline structure

The potential temperature and salinity stratification along 38°S (Fig. 8a,b) reveals the large depth change of isopleths associated with the baroclinic circulation. The west and east branch of the Brazil Current poleward meander is a dominant feature. The thermocline is most intense between the 7 and 13°C isotherm. The relaxation of the vertical gradient at warmer temperatures is a consequence of the winter mixed layers. This "thermostad" marks the warmest end-member of Subantarctic Mode Water (McCARTNEY, 1977). The thick low salinity band below the thermocline is the complex array of Antarctic Intermediate Water (AAIW) and coldest variety of the Subantarctic Mode Water (SAMW; PIOLA and GORDON, 1989).

The west wall of the Brazil Current, sharply defined between Stas 2 and 4, is within 70 km of the continental slope. The wave-like form of the isopleths at Sta. 3 is a reflection of fine structures revealed by the CTD. The 1984 position is 127 km west of the Brazil Current axis observed in the December 1979/January 1980 cruise of the *Atlantis* II (GORDON, 1981). GARZOLI and BIANCHI (1987), using an 8 month time series data set (November 1984 to the end of June 1985) from two inverted echo sounders, also observe oscillations of the thermal front associated with the baroclinic expression of the Brazil Current. GARZOLI and GARRAFO (1989) discuss the extension of the inverted echo sounders time series at the same sites plus an additional site, from June 1985 to March 1986. They find zonal oscillations of 100 km amplitude at the annual period. These are coupled to meridional shifts in the northward penetration of the Malvinas Current.

The full depth section along 38°S of the *Thomas Washington* (Fig. 9a,b) reveals some changes within the deep and bottom stratification relative to that found during the *Atlantis* II cruise (Fig. 10a,b). In 1979/80 the Brazil Current axis was situated over the continental rise rather than over the upper slope as was the case in 1984. In 1984 the deep boundary flow (the steeper slope of the isopleths in the 1000–4000 m interval) was displaced eastward of the thermocline expression of the Brazil Current. The displacement in both realizations was about the same, 100 km displacement relative to the sea surface position, at the 3000 m level. The entire water mass "layer-cake" structure of the South Atlantic deep western boundary current was shifted west in 1984 relative to the 1979/80 condition. While this argues for some unity in the dynamics of the various parts of the "layer cake", there are also depth-dependent changes, as discussed below, namely

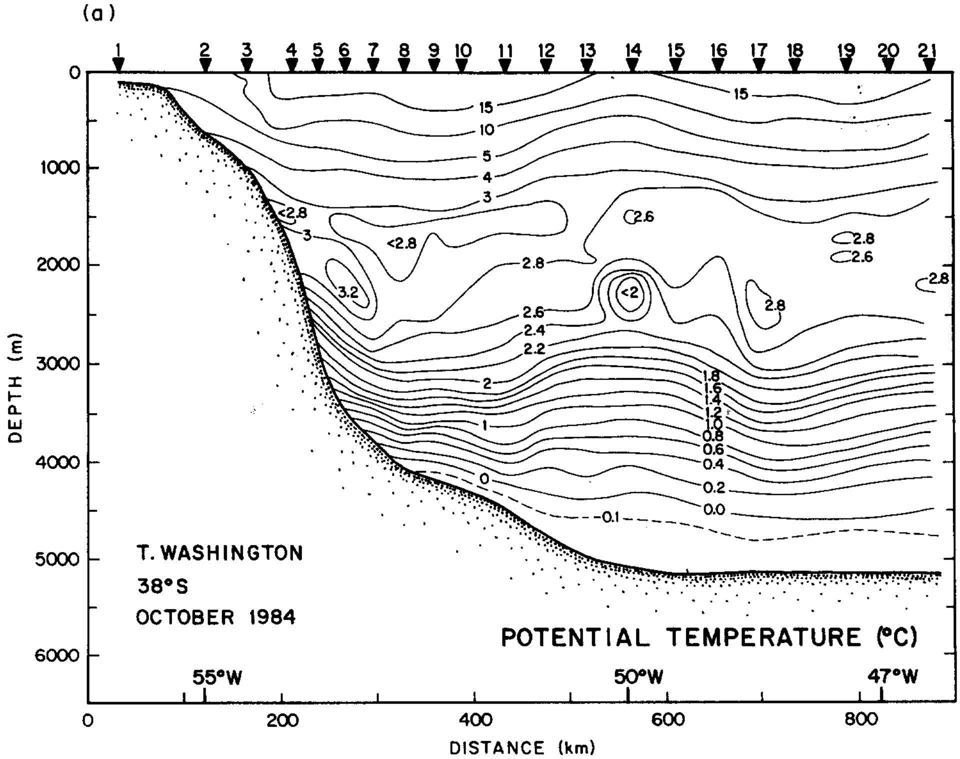

Fig. 9a.

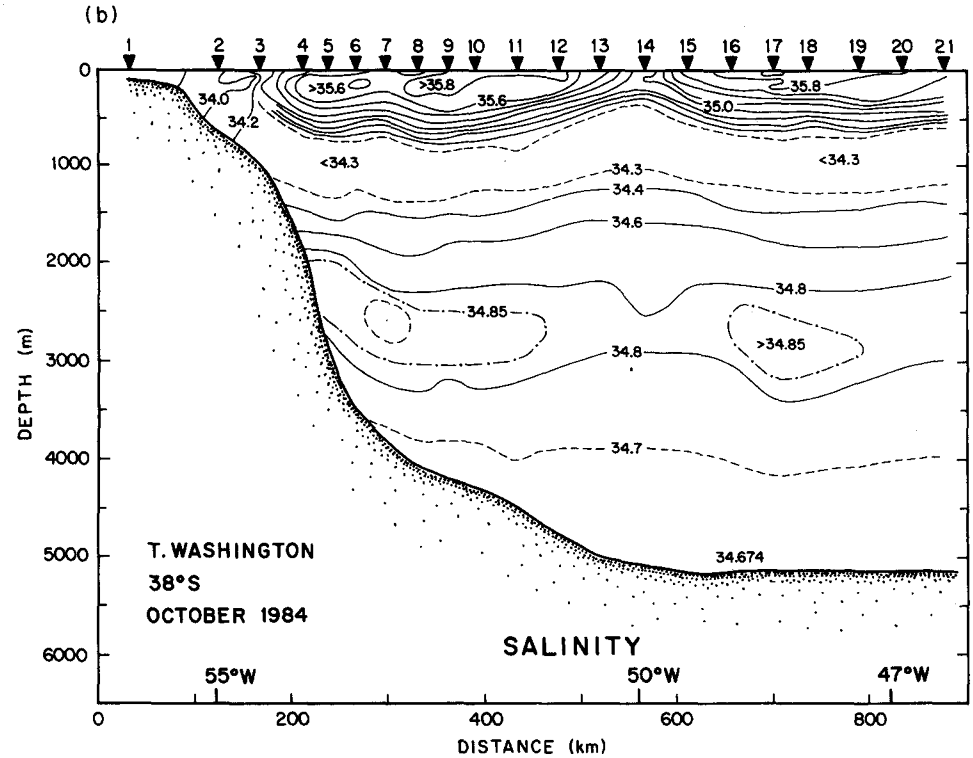

Fig. 9. (a,b) Potential temperature and salinity section along 38°S, surface to the sea floor.

the North Atlantic Deep Water (NADW) flows south passing below the Malvinas Current.

Potential temperature vs salinity

Various property:property relationships from previous data sets have been discussed elsewhere (REID *et al.*, 1977; GREENGROVE, 1986). The potential temperature/salinity relationship observed during the *Thomas Washington* cruise is briefly discussed below to bring out specific circulation and mixed features.

The potential temperature/salinity (θ/S) relation for the *Thomas Washington* data set along 38°S (Fig. 11) reveals the broad arc of the thermocline θ/S expression, with a density ratio $[(\alpha/\beta)\Delta T/\Delta S]$ of 1.5–1.6, less than the regional value of 2.0 for the South Atlantic thermocline (GORDON, 1981). The salinity minimum cores of the AAIW and SAMW are discussed by PIOLA and GORDON (1989). The only special points that need be made here are related to the deep water.

The NADW water is more concentrated (saltier) within the western branch of the Brazil Current, primarily at Stas 6 and 7. Therefore, while the surface water temperature suggests a separation of the Brazil Current further north feeding the eastern branch, the deep water apparently continues to flow south in closer proximity to the continental slope. Furthermore, NADW with concentration identical to that at Stas 6 and 7, is also observed at Sta. 56 (43°S; see Fig. 14), within the trough formed by the Malvinas and the

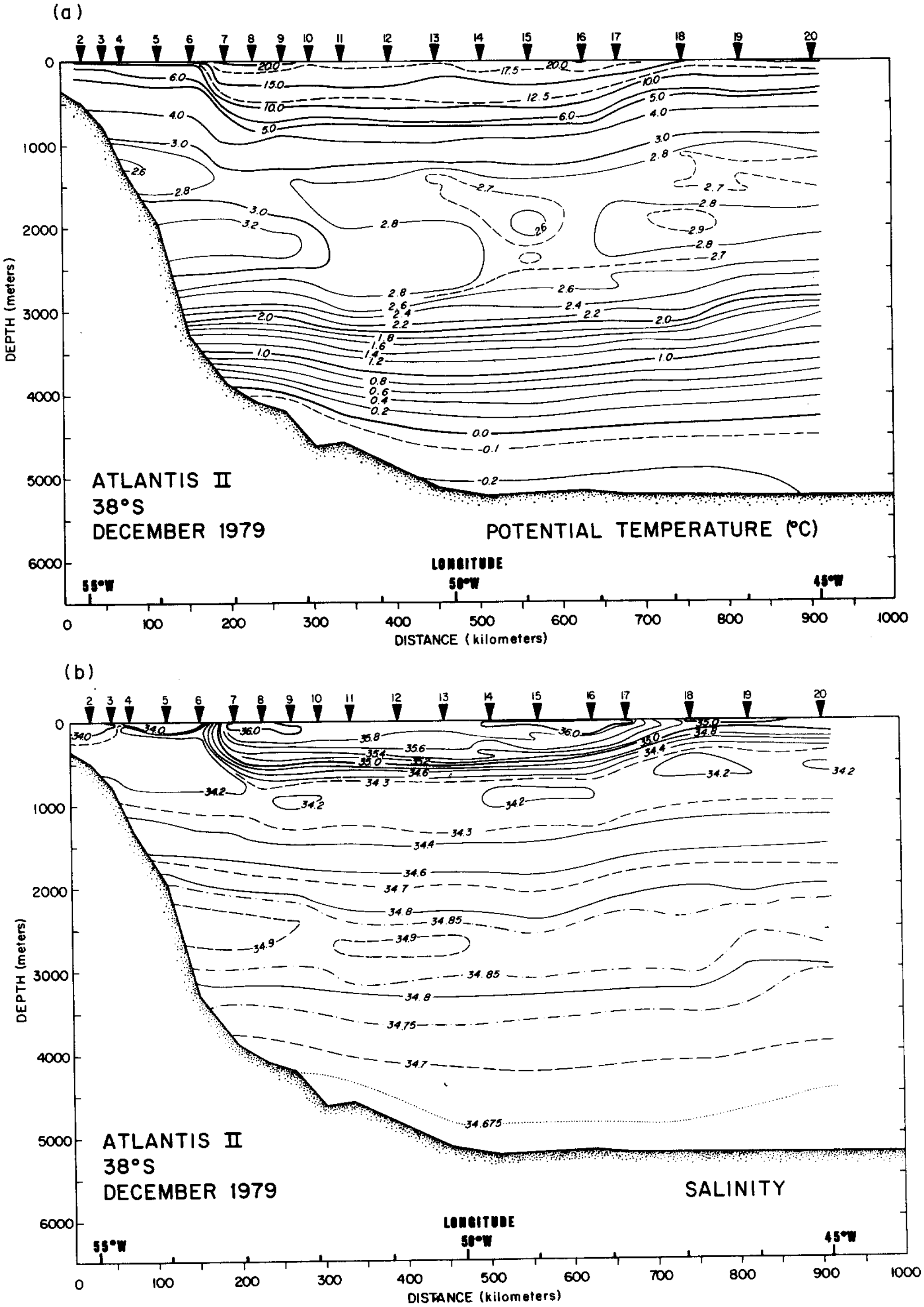

Fig. 10. (a,b) *Atlantis* II potential temperature and salinity section along 38°S, surface to the sea floor.

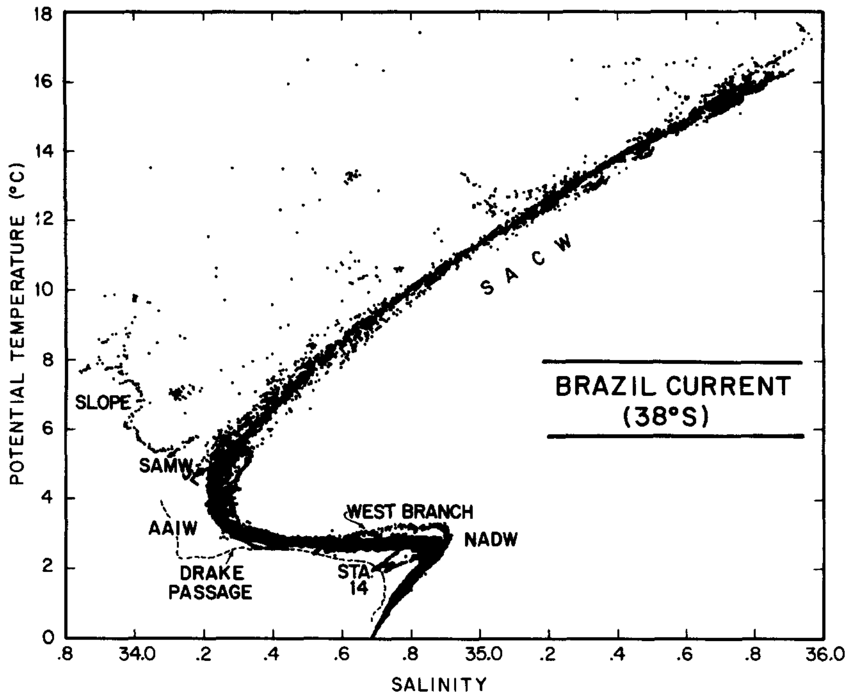

Fig. 11. Potential temperature vs salinity for the Marathon 7 stations along 38°S.

Malvinas Return Currents. This is south of the main thermocline separation marking the western branch. Therefore, the separation point of the southward-flowing western boundary current occurs at different latitudes for different depths.

At Sta. 14, between the two branches of thermocline water, marking the northern edge of the cold eddy Cleopatra, is a 500 m thick low salinity anomaly near the sigma-2 37.0 isopycnal (also see Fig. 9a). At its lowest salinity this feature is similar to the deep water within the northern Drake Passage. The *Thomas Washington* stations across the Malvinas Current further south extended to only 1500 m and did not sample the deep water characteristics, but comparison of *Thomas Washington* Sta. 14 with select stations from the AII (see Fig. 5 of Gordon, 1981) indicates, as expected, that the Malvinas Current links the northern Drake Passage water masses with the Confluence region.

The fine structure associated with the low salinity feature at Sta. 14 reveals significant stirring of NADW with Pacific-derived deep water. Stirring of these contrasting water types is found throughout the Argentine basin (Georgi, 1981). Apparently the eddies with thermocline expressions participate in this deep stirring process. It is noted that the local density ratio (at 2000 db) at the top boundary of the low salinity intrusion is only 1.08 (nearly neutral stability), most conducive to vigorous salt-finger mixing (Schmitt, 1981); a life time measured in months is expected.

Geostrophic velocity transport

The maximum poleward geostrophic velocity of 61 cm s^{-1} relative to 1000 db, the deepest common pressure surface of the station pair, occurs between *Thomas Washington* Stas 3 and 4 (Fig. 12). No significant northward flow is found westward of these

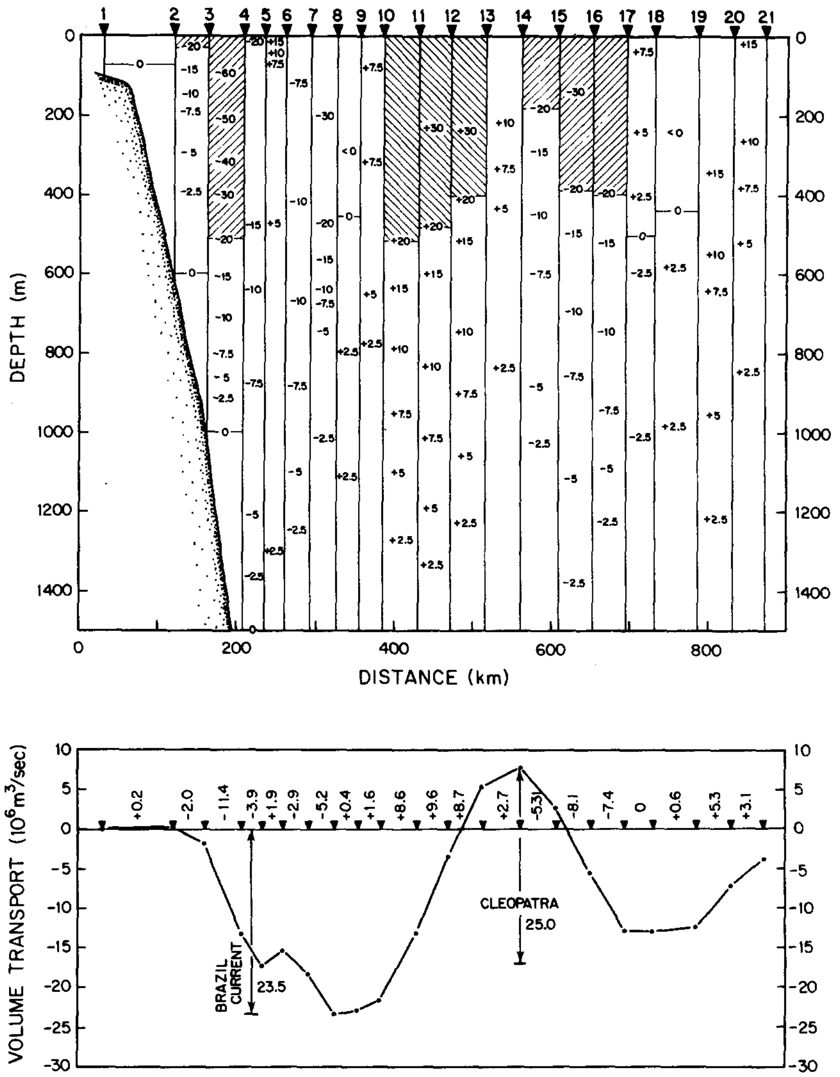

Fig. 12. Geostrophic velocity (upper panel) and accumulated volume transport (lower panel) for the upper 1500 db relative to 1500 db across 38°S.

stations. The *Atlantis* II section (Gordon and Greengrove, 1986) shows a "wedge" of Malvinas Current water west of the Brazil Current axis. Thus a more southern continental slope separation point for the Malvinas Current accompanies the more western position of the Brazil Current during the *Thomas Washington* cruise, relative to the AII cruise. The surface geostrophic velocity (poleward component) associated with Cleopatra is approximately 36 cm s^{-1}.

The geostrophic volume transport relative to 1500 db (or the commonest deepest depth) between Stas 3 and 8, which marks the boundaries of the western branch of the Brazil Current, is 21.5×10^6 m^3 s^{-1} (21.5 Sv). The poleward flow between Stas 2 and 3 occurs within the frontal separation of the Brazil and Malvinas Current and hence cannot be attributed totally to the subtropical water of the Brazil Current. Using 50% of the transport between these stations would only boost the transport to 22.5 Sv, not significant. Further adjustment can be made by not crediting the low salinity fine structure observed within Sta. 3 to the subtropical water of the Brazil Current, but this is a secondary consideration.

The geostrophic volume transport relative to 1500 db between Stas 14 and 17, which mark the poleward-flowing limb of the eastern branch, is 20.8 Sv.

The *Atlantis* II section along 38°S yields a geostrophic transport relative to 1400 db of 19.0 Sv (GORDON and GREENGROVE, 1986). Since the geostrophic shear below 1000 db is small (GORDON and GREENGROVE, 1986, their Table 2) the *Thomas Washington* transport expressed relative to 1400 db changes only slightly, 21.5 Sv. Thus the Brazil Current transport may be slightly greater for the 1984 *Thomas Washington* data set than for the 1979 *Atlantis* II data, a variability that may be related to the more western position of the Brazil Current axis. However, the uncertainty associated with the reference level does not allow emphasis of this point.

EVANS and MASCARENHAS (personal communication) find a geostrophic transport for the upper 800 m of 17 Sv at 31°S. This value is referenced to direct current measurements from the *Pegasus* profiler. The transport of the upper 800 m for the *Thomas Washington* stations relative to 1500 db or the sea floor, is 20 Sv. The increased transport of the Brazil Current from 31 to 38°S amounts to only 0.003 Sv/100 km. The main growth of the Brazil Current seems to occur between Cabo Frio (24°S) and 31°S, as pointed out by Evans and Mascarenhas. Thus the northern boundary of a baroclinic re-circulation cell proposed by Gordon and Greengrove would lie between 24 and 31°S. However, due to the uncertainty of the reference level and that the re-circulation cell of the Brazil Current may be strongly barotropic as is the Gulf Stream cell (e.g. NIILER, 1986), it is evident that further definition of Brazil Current transport requires direct current measurements.

THE EDDIES; THERMOHALINE STRUCTURE AND ALTERATION

Cleopatra

Cleopatra is centered at Sta. 34 (Fig. 13a,b) with a second crest in the thermocline at Sta. 39. The latter feature corresponds to lower surface water temperature revealed in the i.r. image (Fig. 1). The θ/S characteristics (Fig. 14) of the salinity minimum at Cleopatra's core are similar to subantarctic water of the Malvinas Current. Above the 5°C isotherm subtropical water penetrated into the eddy center. Stations 30 and 38 within the eddy rim have surprisingly high salinity in the 4–8°C range, even in comparison to the 38°S section. High salinity within this stratum clearly reveals a northern origin, carried into the Confluence region by the Brazil Current. The NADW at Cleopatra's core and rim is lower in salinity than observed along the 38°S section and within the Malvinas Return Current, though still well above the salinity of Pacific deep water entering the Argentine Basin within the Antarctic Circumpolar Current. The only exception is at Sta. 14 where concentrated Pacific deep water is observed (discussed above).

Cleopatra is composed of a complex array of filaments and fine structure primarily of southern origin water types, though northern water is stirred into the eddy circulation, particularly along the rim. LEGECKIS and GORDON (1982) suggest that the position near 40°S and 50°W is frequently favored by a large cyclonic eddy, which forms the trough of the multiple Brazil Current extension. The thermohaline structure observed in October 1984 may represent a commonly occurring configuration.

Asp and Anthony

The two warm eddies, Asp and Anthony, appear as two relatively shallow lens of thermocline water floating on a thick layer of AAIW/SAMW (Fig. 15a,b). Anthony is colder and fresher with a deeper reaching core than Asp. The mixed layer at Anthony is homogeneous to about 200 m. Asp's surface layer is similar to the western branch of the Brazil Current, in that it is lower in salinity and slightly cooler than the water immediately below it. As discussed above, Asp appears to be still linked to the main volume of the thermocline, and has not yet been significantly altered by the colder atmosphere. Anthony on the other hand has been separated for a longer period, and has been modified. As discussed above, Anthony has a heat deficit relative to Asp of

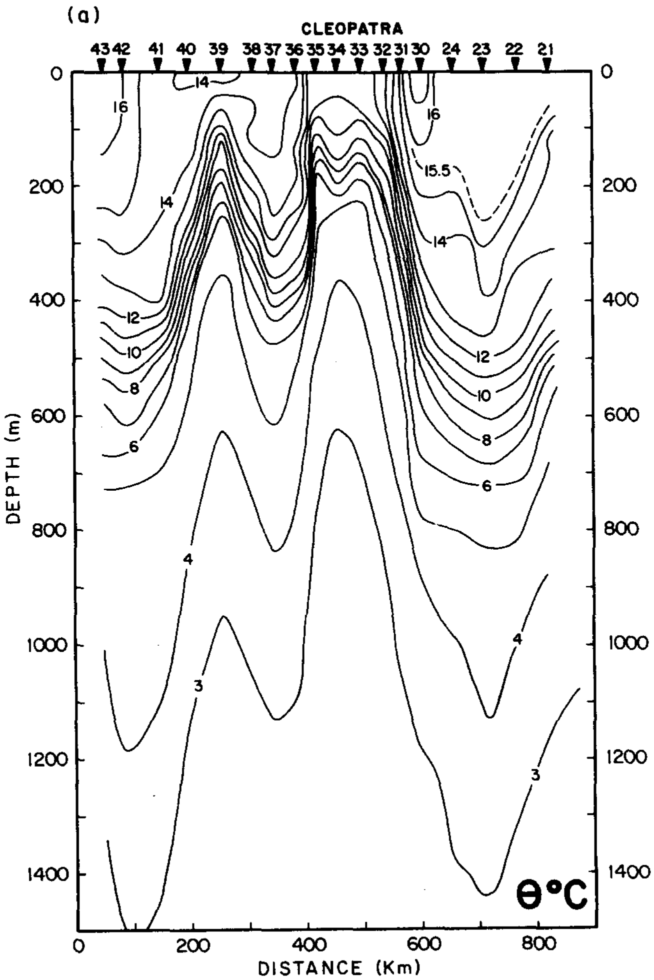

Fig. 13a.

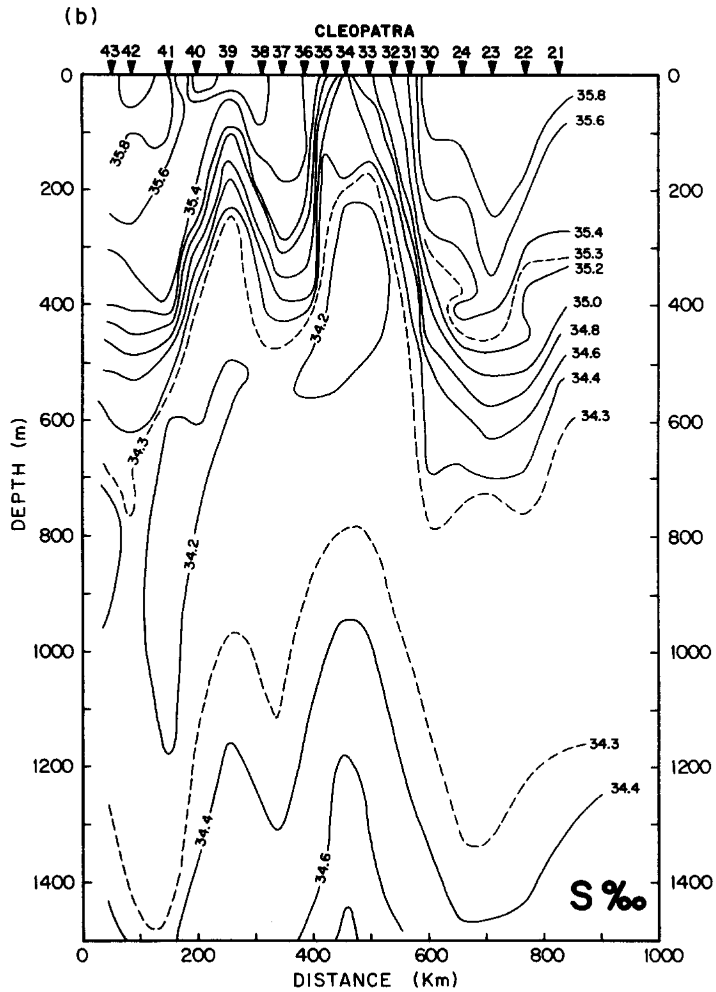

Fig. 13. (a,b) Potential temperature and salinity sections across the cold-core cyclonic eddy, Cleopatra.

1.86×10^9 J m^{-2}, suggesting separation from the Brazil Current after late July or early August.

In θ/S space (Fig. 16) there are significant differences: Asp follows the θ/S relation of the thermocline observed along 38°S, while Anthony is 0.1 higher in salinity for water warmer than 8.8°C (near a depth of 380 m at Sta. 47 marking the center of Anthony). GORDON (1981) describes similar features within mixed layers and subsurface intrusions observed by the *Atlantis* II. He attributes these anomalous saline features to winter cooling with insufficient precipitation to maintain the mixed-layer θ/S point along the initial thermocline θ/S curve. The saline mixed layer induces a low density ratio at its base and it is expected that vertical mixing is accelerated by salt-finger activity (SCHMITT, 1981). The mean density ratio within the thermocline core of Anthony is 1.5 vs a value of 1.6 at Asp. However, within the lower 20 m of the positive salinity anomaly the density

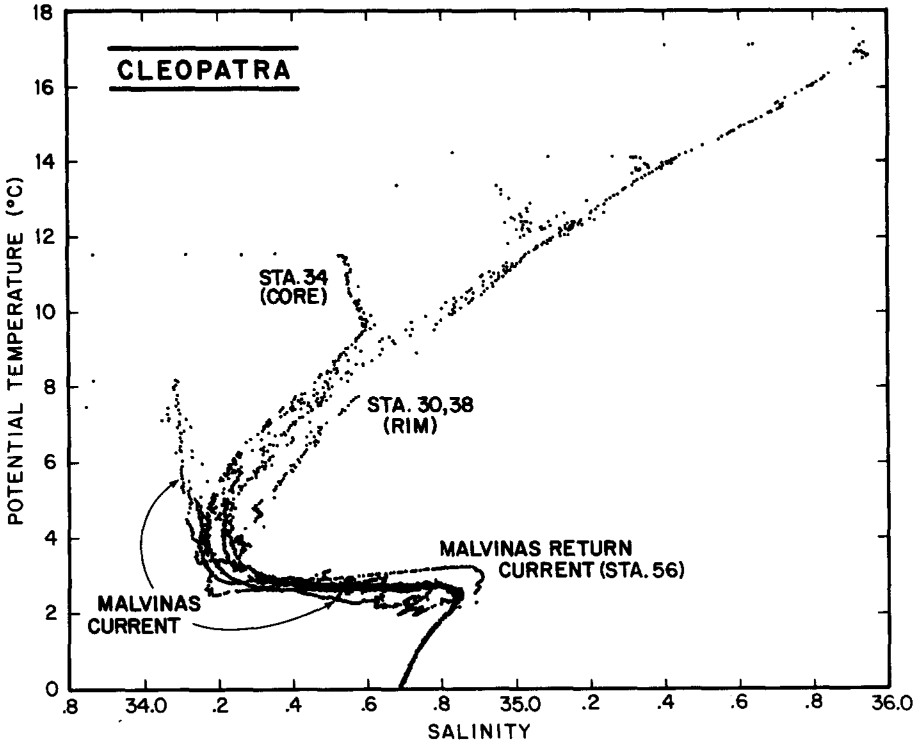

Fig. 14. Potential temperature vs salinity relationship for select stations within the cold-core eddy Cleopatra. Station 57 (43°S) within the Malvinas Current is included for reference and is referred to in regard to the relatively concentrated form of North Atlantic Deep Water found below the Malvinas Current.

ratio falls to 1.38 at Sta. 47. This indicates that salt transfer to the lower layer would be concentrated in a thin slab at the base of the positive salinity anomaly. In this way the salt-finger susceptible base migrates upward, eventually wiping out the salty anomaly.

Legeckis and Gordon (1982) show that warm eddies spawned at the Confluence drift to the southeast without re-coalescing with the main thermocline as is the case for the Gulf Stream counterparts. These eddies are expected to cool and become increasingly unstable to salt fingers (Greengrove, 1986). Their salt eventually mixes downward into the AAIW/SAMW stratum. Are these "run-away" eddies important to the salt balance of the subantarctic zone?

Assuming these "run-away" eddies are similar to Asp, essentially pieces of the South Atlantic thermocline, their water mass properties are: circular features with a radius of 100 km, extending to a depth of 400 m, with a mean salinity of 35.0, about 0.7 above that of the AAIW/SAMW stratum. Each eddy would deliver 9.034×10^{15} g or 0.1294 g cm^{-2} per eddy of excess salt to the subantarctic region (the 40–50°S belt, noting that the Antarctic Polar Front in the South Atlantic is near 49°S). The excess precipitation within that belt amounts to 20 cm y^{-1} (Baumgartner and Reichel, 1975). Each eddy would supply enough salt to convert 3.8 cm of the annual excess precipitation into subantarctic surface water, about 34.3.

The number of eddies produced each year that blend into the subantarctic zone is not known, though an estimation can be made, if only to make a first order assessment of the potential salt flux. The growth of the Brazil Current poleward meander seems to have a 2 month period (Garzoli and Garraffo, in press). This is supported by the *Thomas Washington* observations: as discussed above, Anthony has been undergoing thermohaline alteration for a period of 2.5 months, but its actual separation was probably more recent. If each poleward event produces one eddy [the i.r. images discussed by Legeckis and Gordon (1982) suggest that one or two eddies may be produced for each poleward event] there would be at least six eddies per year. If all of these eddies eventually contribute excess salt to the subantarctic zone, it would compensate the total excess precipitation. However, not all eddies may be absorbed into the subantarctic zone, since the winter-cooled eddy water may re-enter the thermocline below the sea surface

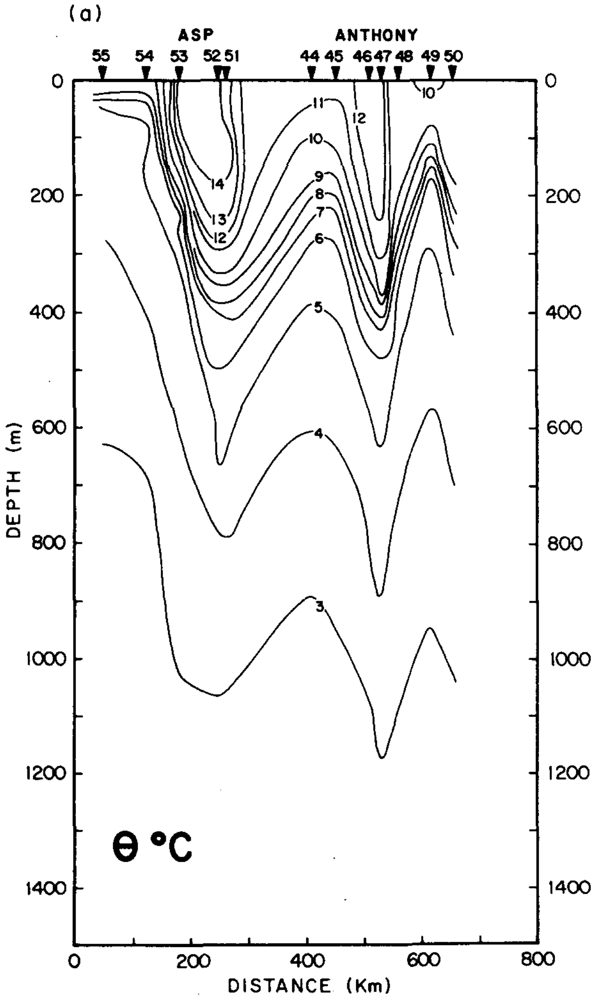

Fig. 15a.

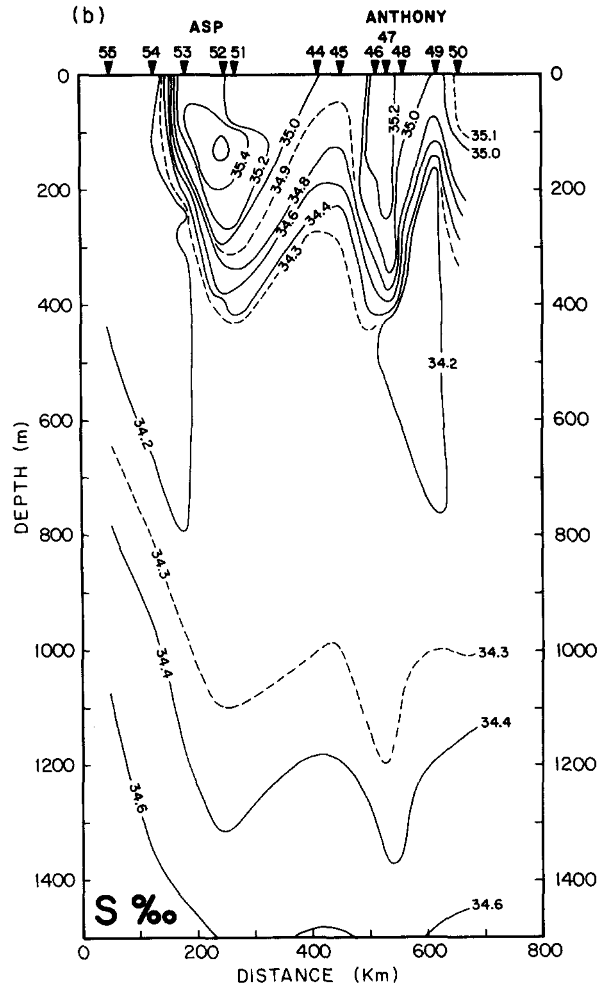

Fig. 15. (a,b) Potential temperature and salinity sections across the warm eddies, Asp and Anthony.

(Gordon, 1981). However, even with this factor, poleward eddy flux of salt, and probably heat, must be considered as a potent source for subantarctic zone salt and heat. The salt delivered to the subantarctic may re-enter the South Atlantic within the AAIW layer and not necessarily be advected to the Indian Ocean via the Antarctic Circumpolar Current. In addition, since the salt is introduced within cells and not immediately spread throughout the subantarctic zone it is feasible that the eddies actively contribute to water mass modification.

CONCLUSIONS

The *Thomas Washington* Marathon cruise 7 data set, obtained in October 1984 within the Brazil–Malvinas Confluence region, reveals the expected complex array of contrast-

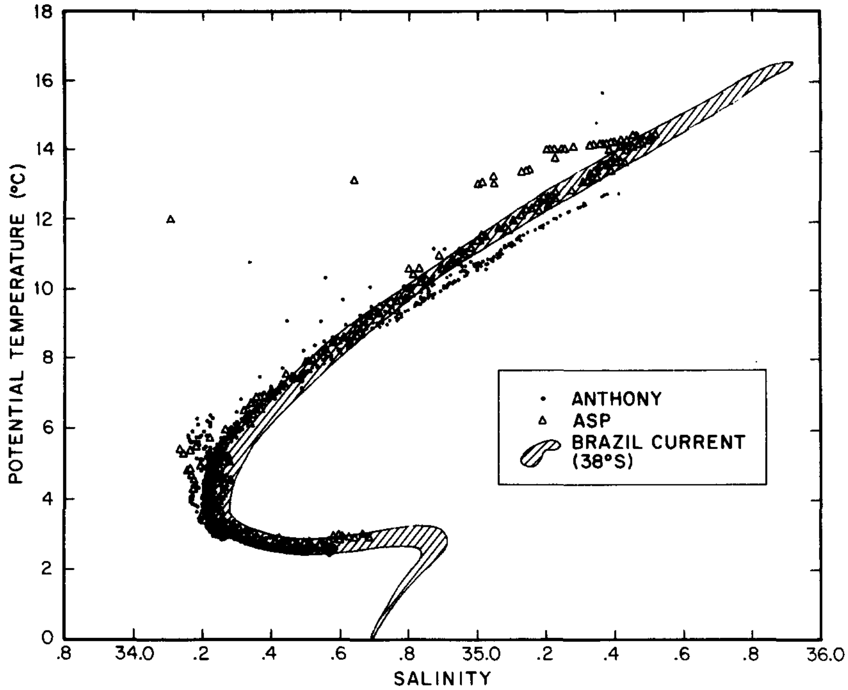

Fig. 16. Potential temperature vs salinity for the two warm eddies, Asp and Anthony.

ing water masses, amid strong baroclinic currents and eddies. A number of features, not seen or not discussed in regard to earlier data sets, are presented in this study. These are:

Surface water

Two poleward protrusions of relatively warm salty surface water reveal a wave-like pattern of the Brazil Current after separation. These branches are bisected near 40°S and 50°W by a large cold-core eddy (Cleopatra). At the poleward end of the western branch are two warm-core eddies (Asp and Anthony).

The western branch has a thin cap (<50 m) of cooler, low salinity water relative to the thermocline θ/S curve. This feature represents infiltration of coastal water into subtropical surface water of the Brazil Current. Along the front formed by the Brazil and Malvinas Confluence, is a band of very low salinity surface water. This water may be a direct remnant of the Rio de la Plata plume. The eastern branch observed during Marathon cruise 7, lacks the slightly cooler low salinity cap. It is likely that the surface water within this branch is derived from offshore thermocline water and is not contaminated by river outflow. The winter mixed-layer thickness within the thermocline regime may be significantly suppressed by the introduction of the low salinity input from the margins.

Baroclinicity

Sea level relative to 1500 db within the western branch stands 0.83 dyn m (about 0.10 dyn m greater than the eastern branch) above that of the Malvinas Current. RODEN (1986), during Marathon cruise 8, measured a third meander further east, centered at

42–43°W. The three branches reveal a wave-like structure of the Brazil Current's seaward extension, with a wavelength of 400–500 km with an amplitude of 200 km.

The geostrophic volume transport of the Brazil Current relative to 1500 db within the western branch amounts to $22.5 \times 10^6\ m^3\ s^{-1}$, about 10% above the transport obtained from the 1979 data. A more western position also occurs within the deep water, preserving the slope of the axis of maximum velocity with depth as determined with the *Atlantis* II data set.

Western boundary current separation

The separation of the Brazil Current is a function of depth. Surface water which feeds the warmer more saline eastern branch may separate near 35°S, while the main thermocline separates near 38°S to form the western branch. At greater depths the separation of the poleward-flowing western boundary current is still further south, as there is relatively concentrated NADW under the Malvinas Current. This raises the question, should the NADW layer be included in the Brazil Current transport, i.e. is it part of the same dynamical feature?

Cleopatra

Sea level in Cleopatra's center is 0.27 dyn m (relative to 1500 db) below the values at the points of the star pattern; with characteristic 0/1500 geostrophic volume transports of $24 \times 10^6\ m^3\ s^{-1}$. The θ/S characteristics of Cleopatra show that at its core the water is similar to subantarctic water of the Malvinas Current, though some thermocline water has mixed into the eddy center above a temperature of 5°C. At Sta. 14 concentrated Pacific deep water is observed as a 500 m thick low salinity anomaly, near the sigma-2 37.0 isopycnal at 2000 m. Also included within the dynamical feature of Cleopatra are filaments of NADW, attesting to the importance of these eddies as water mass stirring agents.

Asp and Anthony

Asp is 0.27 dyn m (relative to 1500 db) above the sea surface at its edges and Anthony is 0.22 dyn m above sea level at its edges. Their 0/1500 db geostrophic volume transports are 21 and $12 \times 10^6\ m^3\ s^{-1}$, respectively. In θ/S space there are significant differences between the two warm eddies: Asp follows the θ/S relation of the thermocline observed along 38°S, while Anthony is 0.1 higher in salinity (measured along isothermal surfaces) for water warmer than 8.8°C. The thermohaline alteration of the core water of Anthony is forced by winter cooling and evaporation, creating a water column susceptible to salt-finger mixing. The high salinity anomaly is mixed downward into the low salinity intermediate water layer.

Salt flux into the subantarctic

As warm eddies spawned at the Confluence and drift to the southeast, they cool and their salt ultimately mixes with the aid of salt-finger activity, into the subantarctic water. These "run-away" thermocline eddies may represent a significant source of salt and perhaps heat for the antarctic zone. Their impact depends on their annual production; reasonable assumptions suggest that the majority of the excess precipitation into the subantarctic zone (40–50°S) could be balanced by these eddies.

Acknowledgements—The work was funded by ONR N0001 4-87-K-0204. Bruce Huber was in charge of the data collection and processing, and of great value in discussions of the analysis. Lamont-Doherty Contribution no. 4401.

REFERENCES

BAUMGARTNER A. and E. REICHEL (1975) *The World water balance.* Elsevier, New York, 179 pp.

BLANC S., G. GOÑI and J. NOVARINI (1983) Surface mixed layer temperature and layer depth in water off the Argentinian coast. *Journal of Geophysical Research.* **88**, 5987-5996.

FORD W. L., J. R. LONGARD and R. E. BANKS (1952) On the nature, occurrence and origin of cold low salinity water along the edge of the Gulf Stream. *Journal of Marine Research,* **11**, 281–293.

GARZOLI S. L. and A. BIANCHI (1987) Time-space variability of the local dynamics of the Malvinas–Brazil Confluence as revealed by inverted echo sounders. *Journal of Geophysical Research,* **92**, 1914–1922.

GARZOLI S. L. and Z. GARRAFFO (1989) Transport, frontal motions and eddies at the Brazil–Malvinas Confluence. *Deep-Sea Research,* in press.

GEORGI D. (1981) On the relationship between the large-scale property variations and fine structure in the circumpolar deep water. *Journal of Geophysical Research,* **86**, 6556–6566.

GORDON A. L. (1981) South Atlantic thermocline ventilation. *Deep-Sea Research,* **28**, 1239–1264.

GORDON A. L. and C. L. GREENGROVE (1986) Geostrophic circulation of the Brazil–Falkland confluence. *Deep-Sea Research,* **33**, 573–585.

GREENGROVE C. L. (1986) Thermohaline alterations of the South Atlantic pycnocline. Ph.D thesis, Columbia University, New York, 211 pp.

HÖFLICH O. (1984) Climate of the South Atlantic. In: *Climate of the oceans,* Ch. 1, H. VAN LOON, editor, Elsevier, Amsterdam, pp. 1–191.

LEGECKIS R. and A. GORDON (1982) Satellite observations of the Brazil and Falkland Currents—1975 to 1976 and 1978. *Deep-Sea Research,* **29**, 375–401.

MCCARTNEY M. S. (1977) Subantarctic Mode Water. In: *A voyage of Discovery,* M. ANGEL, editor, Supplement to *Deep-Sea Research,* **24**, 103–119.

NIILER P. P. (1986) The observational basis for large scale circulation. In: *General circulation of the ocean,* ABARBANEL and YOUNG, editors, Springer-Verlag, Berlin, pp. 1–54.

OLSON D., G. P. PODESTA, R. H. EVANS and O. BROWN (1988) Temporal variations in the separation of Brazil and Malvinas Currents. *Deep-Sea Research,* **35**, 1971–1990.

PIOLA A. R. and A. L. GORDON (1989) Intermediate water in the southwest South Atlantic. *Deep-Sea Research,* **36**, 1–16.

REID J. L., Jr, W. D. NOWLIN Jr and W. C. PATZERT (1977) On the characteristics and circulation of the southwestern Atlantic Ocean. *Journal of Physical Oceanography,* **7**, 62–91.

RODEN G. I. (1986) Thermohaline fronts and baroclinic flow in the Argentine Basin during the austral spring of 1984. *Journal of Geophysical Research,* **91**, 5075–5093.

SCHMITT R. W. (1981) Form of the temperature–salinity relationship in central water: evidence for double diffusive mixing. *Journal of Physical Oceanography,* **11**, 1015–1026.