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# Thermohaline Fronts and Baroclinic Flow in the Argentine Basin During the Austral Spring of 1984

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Thermohaline fronts, structure, and baroclinic flow in the central Argentine basin are investigated on the basis of a 1984 field experiment. The Brazil Current, after initial overshoot, meanders northeastward toward subtropical latitudes with speeds of the order of 0.3 m s$^{-1}$. The meanders have a wavelength of about 400 km and an amplitude of 200 km. Brazil Current signatures, as expressed by dynamic height, are recognizable to depths of several kilometers. The Brazil and Antarctic Circumpolar currents do not meet in the central Argentine basin to form common eastward flow, as was expressed in classical descriptions, but instead diverge sharply near 42°W. This is seen also in the trajectories of satellite-tracked drifters. The region between the currents is marked by cyclonic and anticyclonic eddies. Strong thermohaline fronts accompany the boundaries of these currents. The Brazil Current and subantarctic fronts are well separated in the central basin. Brazil Current density fronts are deep and extend from the surface to 3000 m, while the associated temperature and salinity fronts are intermittent over this depth interval. Temperature fronts virtually vanish at the interface between the Antarctic Intermediate Water and the North Atlantic Deep Water. Salinity fronts reverse their polarity beneath the core of the former. At depths between 3000 and 4000 m, abyssal temperature and salinity fronts are observed which are largely density compensating. At the subantarctic and cold core eddy fronts, horizontal temperature and salinity gradients in the upper mixed layer compensate each other in such a way that no density front is found. Deep subpycnocline mixed layers occur in the poleward lobes of the Brazil Current during austral spring, suggestive of previous winter convection.

## INTRODUCTION

The large-scale circulation and basic thermohaline structure in the mid-latitude South Atlantic have been known since the pioneering works of *Wüst* [1935], *Defant* [1936, 1941], and *Deacon* [1937], recently reevaluated and updated by *Reid et al.* [1977], *Gordon* [1981], and *Gordon and Molinelli* [1982]. The picture that emerges is one of great complexity, involving a large anticyclonic gyre with western and eastern boundary currents and their seaward extensions, Antarctic circumpolar flow, flow along density surfaces of water masses originating in high latitudes of the North and South Atlantic as well as in the Pacific, and local intrusions from the Indian Ocean. Interactions among and instabilities of the large-scale flows give rise to prominent secondary features such as fronts and eddies that have been known to exist since the early days of hydrographic exploration [*Brennecke*, 1921], though not in any detail.

The classical view of the upper layer circulation in the mid-latitude South Atlantic is shown in Figure 1, based upon *Schott* [1943]. According to this view, the large-scale circulation is dominated by the warm and saline Brazil Current and its seaward extension in the west, the cool and less saline Benguela Current and its seaward continuation in the east, the southeast trade wind current in the north, and the Antarctic Circumpolar Current in the south, with the cold and low-salinity Falkland (Malvinas) Current representing a branch of the latter. A closer look at the figure suggests recirculation regions for both the Brazil and the Benguela currents and reveals the existence of three current confluence zones, which will be called here, from north to south, the subtropical, subantarctic, and Antarctic polar zones. These confluence zones are favorable for the formation of fronts. The strongest thermohaline fronts occur at the confluence of the warm and salty Brazil current with the cold and low-salinity Falkland Current and between the Brazil Current extension and the Antarctic Circumpolar Current. Figure 1, which represents an average of ship drift measurements over many years, suggests that the latter confluence extends halfway across the South Atlantic; it will be shown below, however, that on quasi-synoptic time scales the two currents do not flow side by side but separate near 42°W, with the Brazil Current extension returning to subtropical latitudes.

The mesoscale flow field and thermohaline structure of the mid-latitude South Atlantic remained unresolved until the advent of modern electronic profilers and satellite imaging techniques. The picture is still sketchy, but some details are starting to emerge from a combination of techniques. Analysis of satellite infrared images [*Legeckis and Gordon*, 1982], satellite altimeter data [*Cheney et al.*, 1983], and buoy trajectories (D. B. Olson, personal communication, 1985) indicates the presence of strong mesoscale variability in the southwestern part out to about longitude 40°W and in the region of the Antarctic Circumpolar Current. The large and mesoscale flow patterns appear to be linked. The Brazil Current on the satellite images does not resemble the broad southward flow of the classical picture (Figure 1) but rather represents a narrow jet-like flow with predominant wavelike perturbations along its flanks. The mesoscale perturbations have a wavelength of a few hundred kilometers and change with time. Some of the perturbations develop narrow necks with one or two vortices at the end, become unstable, separate from the parent stream, and develop into warm core eddies and rings, predominantly elliptical in shape with axes of the order of 100–200 km and propagation speeds of 0.1–0.2 m s$^{-1}$. The Falkland Current likewise does not resemble the broad northward flow suggested in Figure 1 but appears to be much narrower, of the order of 100 km, with large meander type perturbations on its periphery, some of which develop instabilities, break off, and drift away in the form of cold core eddies. Ring and eddy formations have been observed also in the Antarctic Circumpolar Current [*Joyce et al.*, 1981] in Drake Pasage. It is not surprising to find, therefore, that infrared images of the confluence zones between the Brazil and Falkland currents [*Legeckis*, 1978; *Legeckis and Gordon*, 1982] show a multitude of thermal phenomena in various stages of development and



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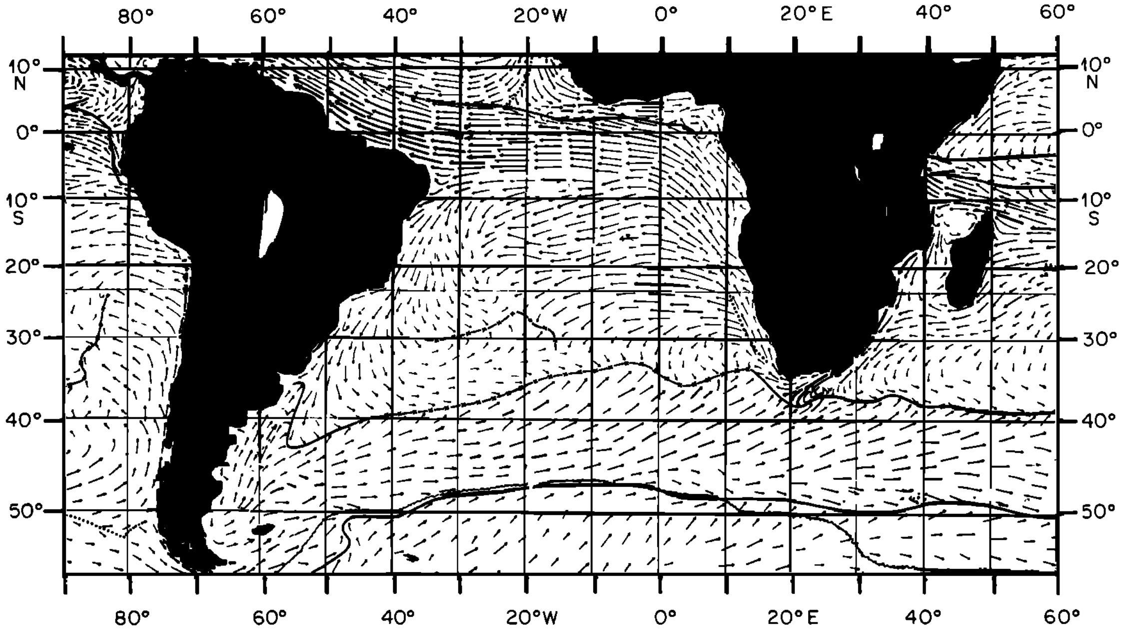


Fig. 1. Surface currents in the South Atlantic Ocean according to *Schott* [1943]. Solid lines indicate well-defined current convergences; dotted lines indicate less well defined convergences.

decay, such as meandering fronts, single and double vortices, eddies, and long filamentlike structures. The larger features seen on infrared images can often be verified by shipboard hydrographic measurements, but it is difficult to prove the existence of thin filamentlike structures by conventional shipboard surveys because of the small cross-filament scales and the high temporal variability.

The mesoscale flow field and thermohaline structure associated with the confluence zone between the seaward extension of the Brazil Current and the Antarctic Circumpolar Current are much less known. There is common agreement from historical and recent hydrographic surveys and from analysis of satellite infrared images that the Brazil Current flows southwestward along the continental margin of South America to about 38°S, where it leaves the margin, turns southeastward, and makes a large anticyclonic loop with a poleward apex lying between 42° and 49°S before turning northeastward near longitude of 50°W [*Legeckis and Gordon*, 1982]. Where the Brazil Current goes from there, whether or not it impinges on the Antarctic Circumpolar Current and over what distance, and whether or not the two currents continue to shed as many energetic eddies as they shed farther to the west are largely unknown. Infrared satellite imagery is of little help in this region because of persistent cloudiness. Sparse historical data hint at generally northeastward and eastward flow of both currents [*Reid et al.*, 1977; *Gordon*, 1981] but do not permit one to determine mesoscale features. There is evidence from satellite data, however, of a sharp decrease in sea height variability between 50°W and 35°W, which is suggestive of an eastward decrease of eddy energy [*Cheney et al.*, 1983; *Gordon et al.*, 1983], perhaps as the result of a weakening of the Brazil Current as it penetrates into the interior of the South Atlantic beyond the retroflection region.

During the austral spring of 1984 a major effort was made to study the Brazil Current and its seaward extension. Forming part of a larger Southern Oceans Program, this was a multi-investigator experiment involving many institutions with scientific interests spanning the spectrum from eddies associated with the Brazil Current overshoot to the Brazil Current recirculation gyre and satellite-tracked drifter trajectories.

This paper focuses on mesoscale aspects of oceanic fronts and eddies associated with the Brazil Current extension and the Antarctic Circumpolar Current in the region east of 50°W. Particular emphasis will be placed on the three-dimensional thermohaline structure and on the associated baroclinic flow field. Knowledge of the three-dimensional thermohaline structure permits one to determine the shape and depth variations of the fronts more accurately than has been possible hitherto and to ascertain whether the Brazil Current extension and subantarctic fronts are separate or form a common front. Knowledge of the baroclinic flow field is important in understanding frontal dynamics and assessing the differences between baroclinic and actual flow patterns derived from satellite tracking of buoys [*Kirwan et al.*, 1978].

## FIELD MEASUREMENTS AND DATA REDUCTION

To investigate the three-dimensional thermohaline structure of the Brazil Current and the subantarctic fronts in the area east of the Brazil Current retroflection, the R/V *Thomas Washington* on leg 8 of the Marathon Expedition occupied a regularly spaced station grid between 36°–42°S and 40°–42°W, as is shown in Figure 2. Stations were taken at intervals of 20′ latitude, 30′ longitude, yielding a mesh of approximately 37 km by 43 km. In addition, two long station lines were occupied between Montevideo, Uruguay, and the working area, where expendable bathythermographs XBTs were dropped at 30 km (outgoing) and 15 km (returning) intervals to resolve the eddy structure in the region of the Brazil Current.

The chief instrument deployed on the cruise was the Neil Brown conductivity-temperature-pressure probe, commonly known as the CTD. In the working area, the CTD was lowered from the surface to 1500 dbar with every third station on alternating north-south lines extending to the bottom; this allowed one to resolve the deep structure on a roughly 111 km by 86 km grid. The CTD output was in digital form and was calibrated against Rosette sampler information. The data were averaged over 2-dbar blocks, and these regularly spaced data formed the basis for all subsequent calculations. All variables derived from the pressure, temperature, and salinity were com-

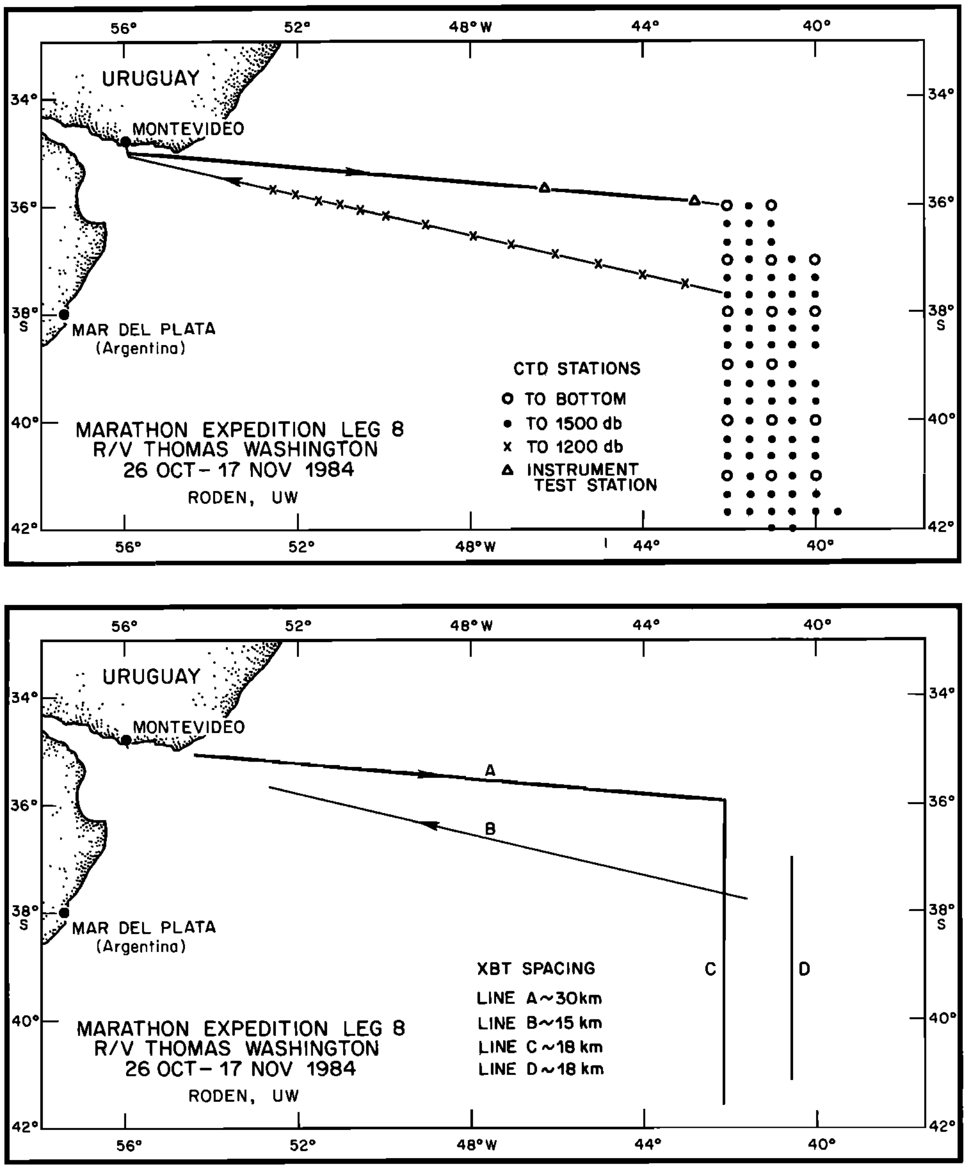


Fig. 2. Ship's track and position of CTD stations and XBT lines during the field survey in the austral spring of 1984.

puted utilizing the new international equation of state, (EOS 80) for seawater [*Gill*, 1982; *Fofonoff*, 1985]. The Väisälä frequency was computed from the vertical density gradient and the compressibility term [*Eckart*, 1960].

## THE BRAZIL CURRENT DURING THE AUSTRAL SPRING OF 1984

### *As Seen by Satellite*

A synoptic view of the Brazil Current and its confluence with the Falkland Current on October 31, 1984, based on NOAA 7 infrared imagery, is shown in Figure 3, where the solid line indicates the track of the R/V *Thomas Washington* en route to the working area. The Brazil Current is indicated by very wam (WW) and warm (W) water, and the Falkland Current is indicated by cold (C) and very cold (CC) water. White areas indicate a mixture of the warm and cold water masses. It is seen that the Brazil and Falkland currents interleave in a complicated wavy fashion, with several eddies present. In agreement with earlier satellite studies [*Johnson and Norris*, 1977; *Legeckis and Gordon*, 1982], the western boundary of the Brazil Current is well defined and occurs near 50°W between 30°S and 38°S. A narrow tongue of very warm water, about 50 km wide, extends southward along the continental margin off Brazil and Uruguay; this tongue has a very rugged boundary perhaps due to instabilities and eddies developing on the jetlike current [*Holland et al.*, 1983]. The eastern boundary of the Brazil Current is more diffuse and is characterized by large meanders, of which two (marked W) are visible in the satellite image. The main branch of the Falkland Current extends northeastward in a fingerlike fashion off the South American coast to about 35°S; a second cold intrusion is present near 53°W. The warm water in the Rio de la Plata estuary is a seasonal phenomenon and represents a mixture of river runoff, subantarctic water carried north by the Falkland Current, and South Atlantic Central Water carried south by the Brazil Current. The thermal contrasts are strongest in austral winter and spring and diminish toward summer.

### *As Seen by the Depth of the 8°C Isotherm*

The Brazil Current south of 35°S represents an intrusion of warm water into a cooler environment. The depth of the 8°C

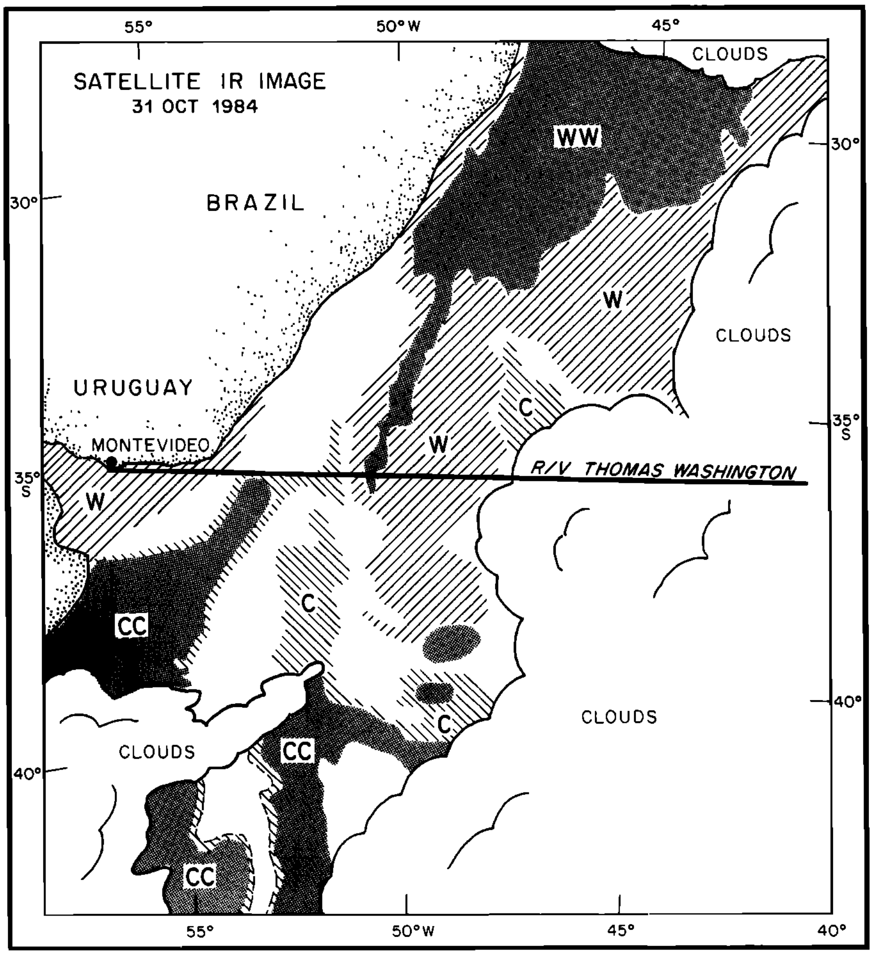


Fig. 3. Satellite infrared image of the Brazil and Falkland current confluence zone, obtained by NOAA-7 satellite (courtesy of National Environmental Satellite Service (1984)). Water temperatures are shaded as follows: WW, very warm; W, warm; C, cold; CC, very cold.

isotherm changes rapidly along the boundaries of this intrusion and can be used to delineate this current roughly. Conditions during the austral spring of 1984 are shown in Figure 4 and are based on joint findings by A. Gordon (personal communication, 1984) and the author. The Brazil Current, here indicated where the depth of the 8°C isotherm exceeds 500 m (shaded areas), flows southward to about 43°S then meanders back toward subtropical latitudes. Three meanders are seen, centered at longitudes 42°W, 47°W, and 53°W. The meanders have a "wavelength" of 400–500 km and a "wave amplitude" of roughly 200 km. Three large warm core anticyclonic eddies and three to four cold core cyclonic eddies occur in the vicinity of the Brazil Current return flow. The meander near 42°W appears to be near detachment to form a warm core eddy.

Meanders and eddies of the dimensions and types associated with the Brazil Current are common in the ocean. They have been found not only in conjunction with western boundary currents and their seaward extensions such as the Gulf Stream [*Olson and Spence*, 1978; *Olson*, 1980; *Richardson*, 1983], the Kuroshio Current [*Kitano*, 1975; *Kawai*, 1972], the Agulhas Current [*Grundlingh*, 1978], and the Somali Current [*Swallow*, 1983] but also at mid-oceanic subtropical fronts in the Pacific [*Roden*, 1981] and the Atlantic [*Kase et al.*, 1985]. Their widespread occurrence points toward basic instability mechanisms associated with strongly sheared mean flows in a horizontally and vertically stratified medium [*Pedlosky*, 1979; *Holland et al.*, 1983]. Whether the instabilities are of the baroclinic, barotropic, or mixed type is difficult to generalize; realistic parameter numerical models of the Gulf Stream favor mixed instability (*Holland and Haidvogel*, 1980].

### *Mesoscale Variability Across the Brazil Current and its Seaward Extension*

The vertical temperature structure in the upper 700 m is shown in two highly resolved XBT sections taken about 3

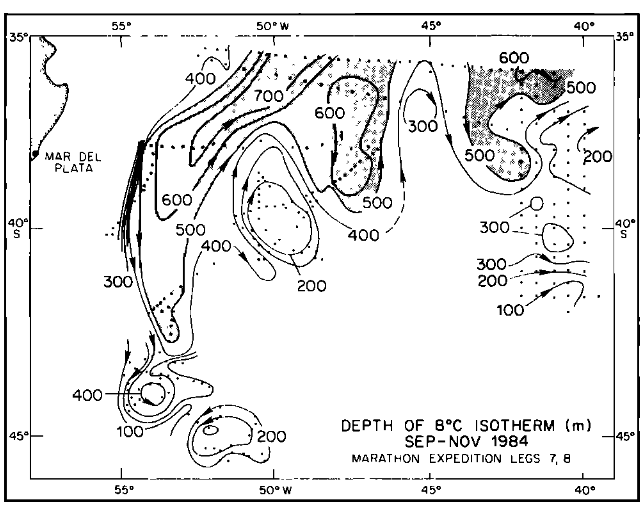


Fig. 4. Depth of the 8°C isotherm in the Argentine basin during the austral spring of 1984. The contours between 38°S–46°S and 46°W–56°W were kindly furnished by A. Gordon. Shading indicates Brazil Current water; arrows indicate the flow direction.

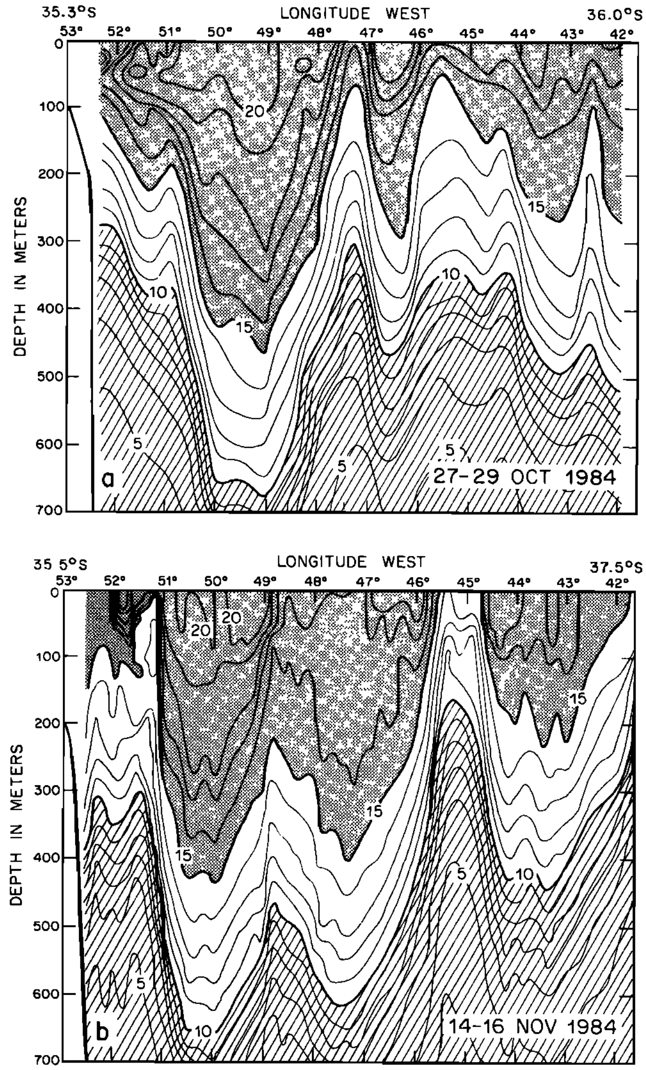


Fig. 5. Thermal structure along two sections through the meandering Brazil Current, as determined by closely spaced XBTs. Sampling intervals were (*a*) 30 km and (*b*) 15 km.

weeks apart (Figures 5*a* and 5*b*). The wavy temperature structure results from a cut through a meandering and eddy-shedding Brazil Current, as is indicated in Figure 4. Three large warm water lobes stand out, of which the westernmost, near 50°W, extends the deepest and represents the first anticyclonic loop of the initial Brazil Current overshoot and retroflection, which is almost always present in the vicinity of this longitude [*Legeckis and Gordon*, 1982]. Subsequent warm water lobes extend to lesser depths, and their core temperatures are lower, indicating mixing with surrounding cooler water. Strong thermal fronts bound the Brazil Current and its seaward extension. These fronts reach below 700 m and, for a sampling interval of 15 km, have maximum gradients of 4°C/15 km, or about 1°C/3.7 km. Locally, much stronger gradients can occur; *Johnson and Norris* [1977] analyzed very-high-resolution infrared imagery from the Skylab mission and found that at the boundary between the Brazil and Falkland currents, the surface temperature gradient was 1°C/67 m. The lifetime of such instantaneous gradients is likely to be short, however, because of the high time variability associated with short spatial scales, and they cannot be studied by conventional shipboard techniques.

A remarkable cold core eddy, about 100 km across, occurred near 37°S, 45°W (Figure 5*b*). It consisted of subantarctic water and was discolored by numerous reddish brown patches. The temperature, salinity, and density differences inside (station 91) and outside (stations 90 and 92) this eddy are shown in Figure 6, which is based on CTD observations. Temperature differences as large as 6°C and salinity differences up to 1.2‰ were observed in the upper 400 m, with diminishing contrasts below. Density differences were small in the upper 50 m, indicating a large degree of compensation of the horizontal temperature and salinity gradients, then increased to a maximum of 0.4 kg m$^{-3}$ between 200 and 400 m, then diminished again toward greater depths. The near compensation of density differences in the top layer is indicative of the influence of surface heat and salt fluxes. Cooling of warm, high-salinity water of subtropical origin and warming of cold, low-salinity water of subantarctic origin leads to an inherent decrease in density contrast. Because the surface heat and salt fluxes are most pronounced in the layer atop the seasonal pycnocline, the density compensation is largely limited to this layer. Below the seasonal pycnocline, other processes such as

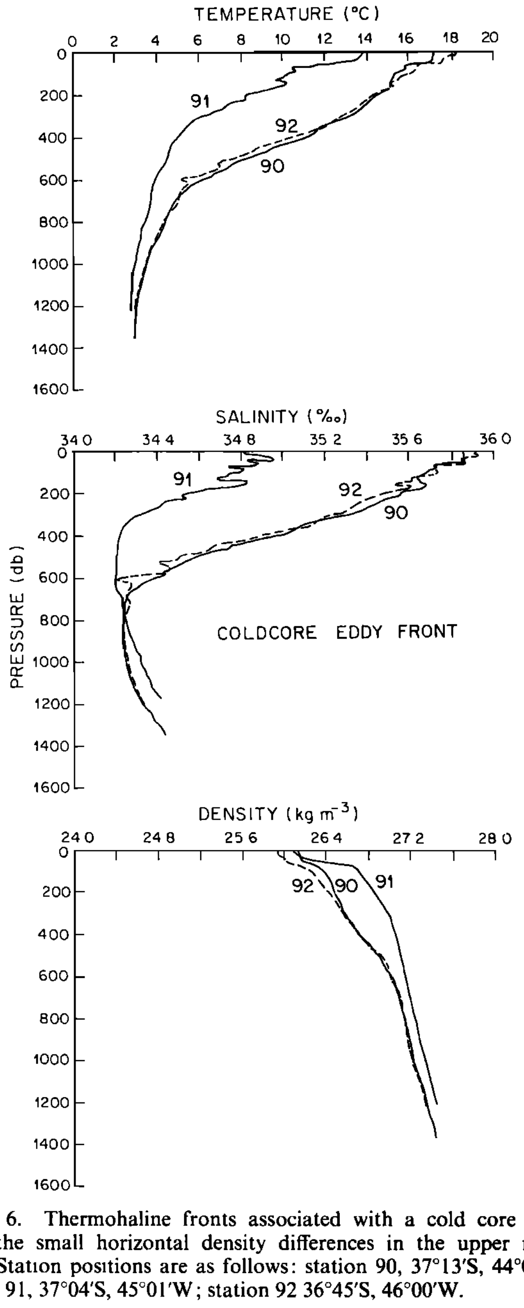


Fig. 6. Thermohaline fronts associated with a cold core eddy. Note the small horizontal density differences in the upper mixed layer. Station positions are as follows: station 90, 37°13′S, 44°01′W; station 91, 37°04′S, 45°01′W; station 92 36°45′S, 46°00′W.

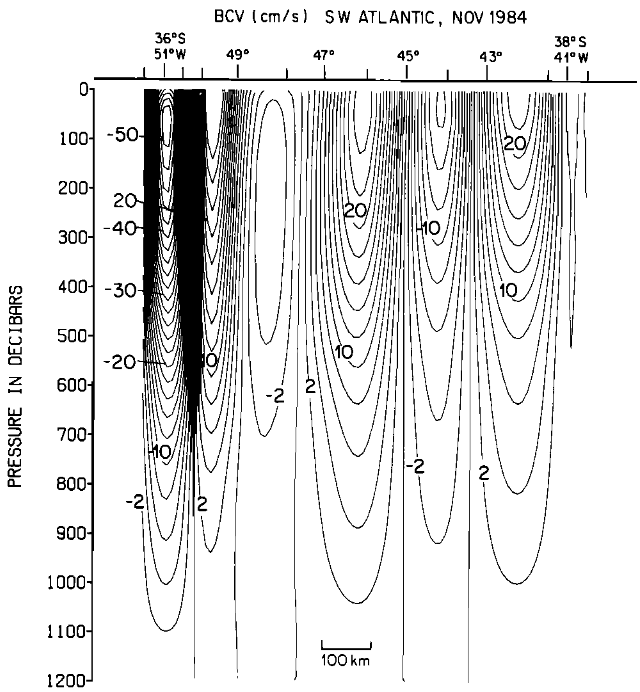


Fig. 7. Baroclinic flow in centimeters per second in a zonal section across the meandering Brazil Current. Positive values are northward.

mixing and diffusion are active at the boundaries of the eddy. These processes appear to be less efficient than the surface heat and salt fluxes in reducing the density contrast. An independent confirmation of the subantarctic origin of this cold core cyclonic eddy came from an analysis of the discolored water found therein; it contained species of the subantarctic copepods *Neocalanus* and *Calanoides* (S. Moore, personal communication, 1984).

The mesoscale baroclinic flow structure in the region of the Brazil Current and its seaward extension is shown in Figure 7, which indicates the north-northeastward and south-southwestward components relative to 1200 dbar. As can be expected from a cut through a meandering and eddy-shedding current, the structure is dominated by alternating bands of southward and northward flow. These bands are 100–200 km wide and are vertically coherent in the upper kilometer. The two westernmost bands represent the anticyclonic loop of the Brazil Current retroflection (Figure 4). The southward setting branch of the Brazil Current is about 100 km wide and has maximum speeds of more than 0.5 m $s^{-1}$, which occur at depths between 50 dbar and 125 dbar. The northward setting branch is of the same width, but the speeds are weaker, not exceeding 0.27 m $s^{-1}$. Both horizontal and vertical shears are large in the retroflection loop, the former reaching $10^{-5}$ $s^{-1}$ and the latter $2 \times 10^{-3}$ $s^{-1}$, on the basis of station spacing of 45 km. The pair of northward and southward flows near 45°W is a cut through the cyclonic cold core eddy discussed above. The eddy has deep roots extending down to 1000 dbar. The peripheral speeds, based on CTD sampling at 90-km intervals, reach 0.25 m $s^{-1}$ and are stronger on the westward side. These peripheral speeds are likely to be an underestimate; XBT sampling at 15-km intervals (Figure 5*b*) gives thermal slopes that are comparable to those observed in the retroflection area, where speeds exceed 0.5 m $s^{-1}$.

The vertical baroclinic flow structure observed in the Brazil Current region is similar to that found in other regions of western boundary currents and their seaward extensions. *Roden* [1984*a*] observed that in the area of the Kuroshio extension, the widths of the bands of unidirectional flow were of the order of 200 km, that they were vertically coherent in the upper kilometer, and that maximum speeds were about 0.6 m $s^{-1}$. Gulf Stream eddies and rings have similar dimensions and vertical coherency [*Richardson*, 1983].

## DYNAMIC HEIGHT AND BAROCLINIC FLOW IN THE CENTRAL PART OF THE ARGENTINE BASIN

### *Dynamic Height*

High-resolution dynamic height topographies relative to 1500 dbar, based on a 37 km by 43 km sampling grid, are shown in Figure 8. Two baroclinic currents, clearly separated from each other, stand out. The northern one represents the meandering Brazil Current return flow, and the southern one

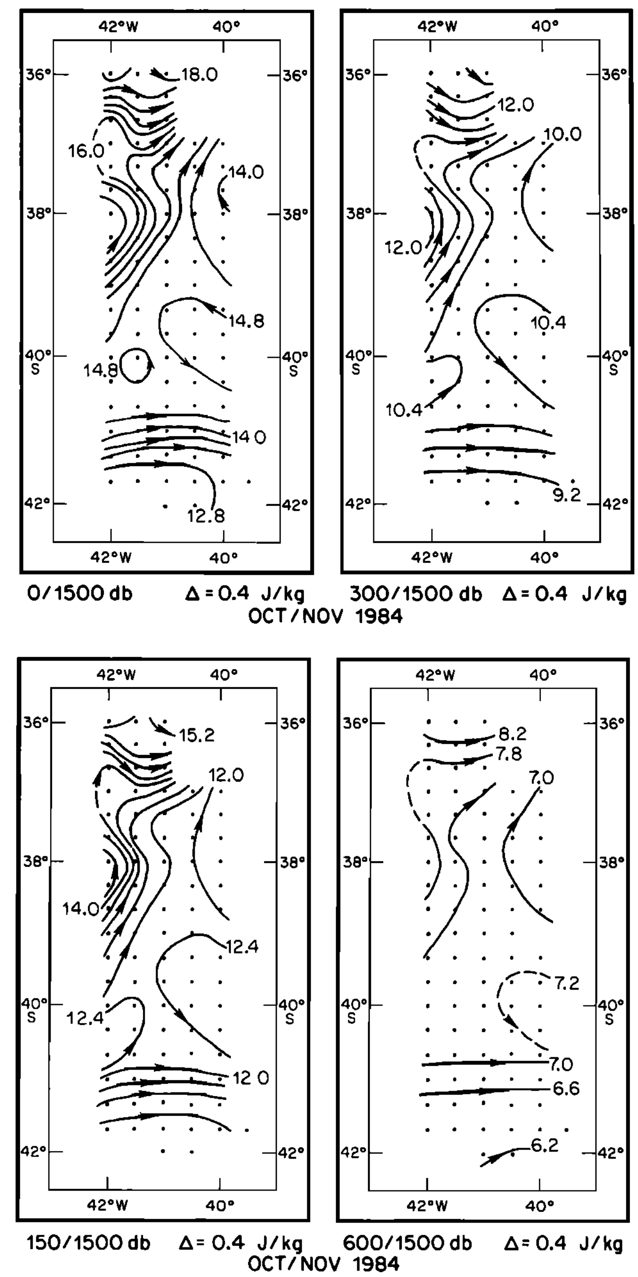


Fig. 8. Baroclinic flow relative to 1500 dbar in the central Argentine basin. Dots indicate station positions, and arrows indicate the direction of flow.

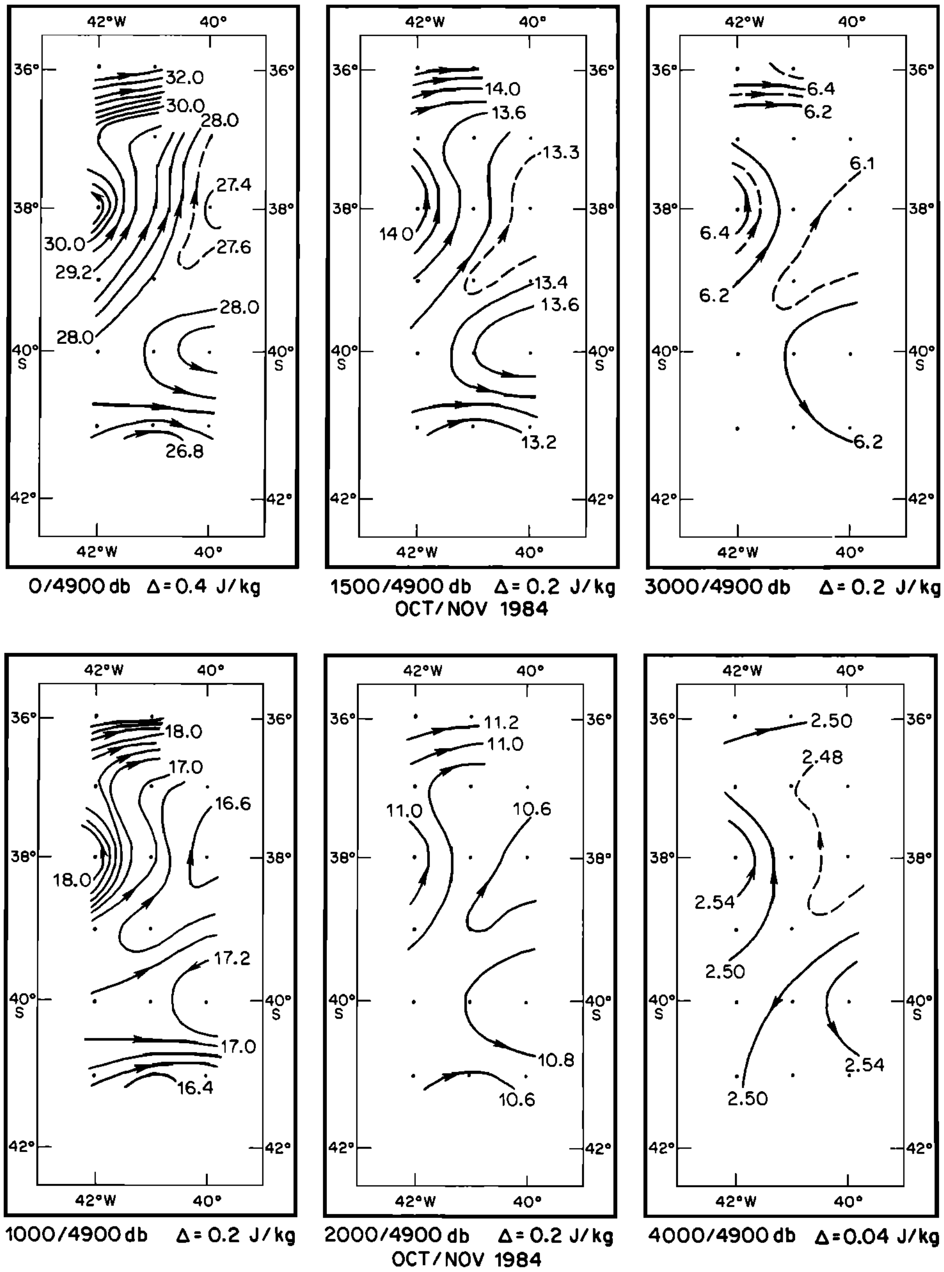


Fig. 9. Baroclinic flow relative to 4900 dbar in the central Argentine basin. Dots indicate station positions, and arrows indicate the direction of flow.

indicates a branch of the Antarctic Circumpolar Current. Both cyclonic and anticyclonic eddies occupy the region between these currents. The currents and eddies are vertically coherent in the upper 600 dbar, though their strength diminishes as the pressure increases. Typical surface speeds vary between 0.2 and 0.3 m $s^{-1}$, with about half the strength observed at 600 dbar.

The sea surface elevation differences across the major topographic features, obtained by dividing the dynamic height differences by the acceleration of gravity, vary between 0.2 and 0.4 m over distances of 100 km. Such elevation differences can be measured by satellite altimeter [*Cheney et al.*, 1983], and it is hoped that in the future, time variations of the Brazil and subantarctic currents can be monitored in this manner.

Lower-resolution dynamic height topographies relative to 4900 dbar, based on a 110 km by 100 km sampling grid, are shown in Figure 9 in order to bring out the flow patterns at intermediate and great depths. Increasing the reference pressure level and decreasing the resolution does not change significantly the patterns of surface flow. These patterns are essentially the same in the upper 2000 dbar, characterized by a northeastward meandering Brazil Current, an eastward flowing Antarctic Circumpolar Current, and two oppositely rotating eddies in between. Between 2000 and 4000 dbar the Brazil current in the two eddies are still in evidence, but the Antarctic Circumpolar Current has disappeared or, conceivably, shifted its axis poleward, out of the region investigated. The baroclinic flow speeds decrease rapidly with pressure. At 1500 dbar the speed is typically one quarter of the value observed at the surface, at 3000 dbar it is one tenth of the surface value.

The findings reported above contradict the classical notion (Figure 1) of a common confluence line between the Brazil and Antarctic Circumpolar currents extending across most of the South Atlantic. To the extent that the Falkland Current is a

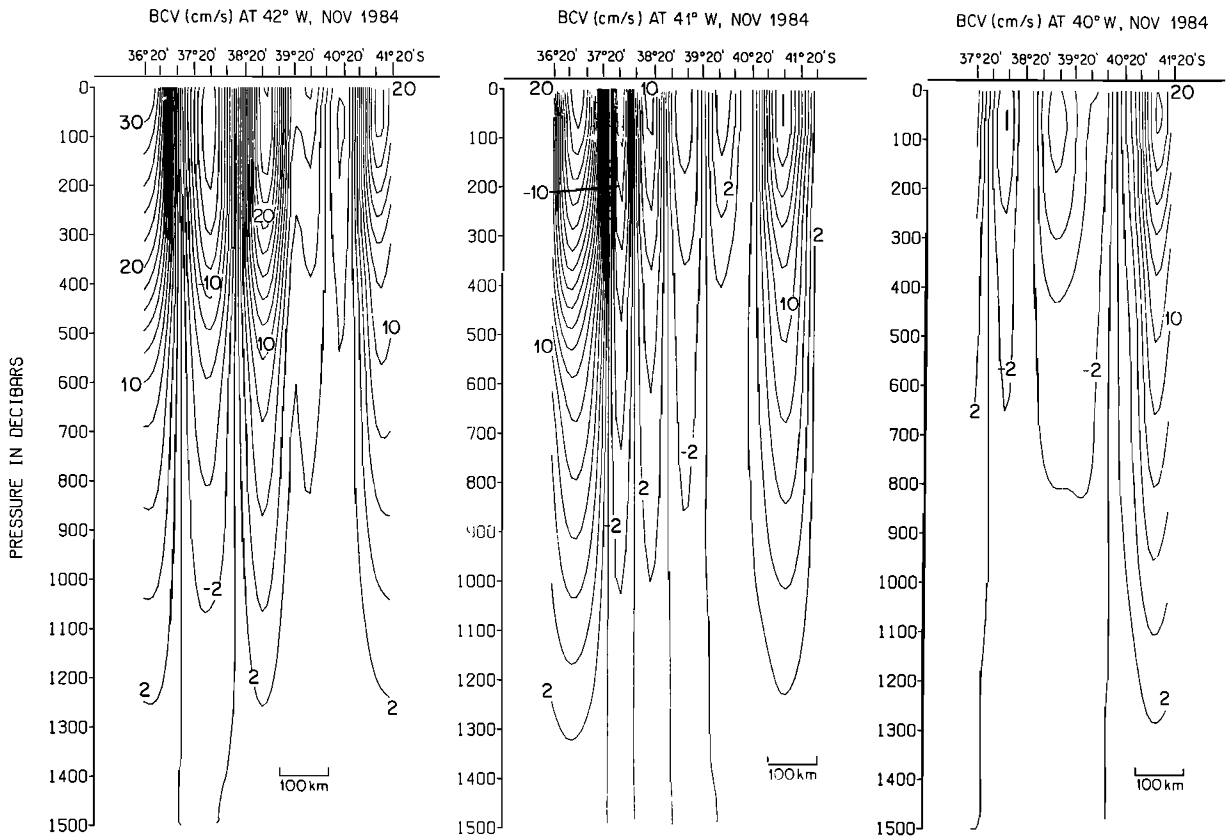


Fig. 10. Meridional component of baroclinic flow relative to 1500 dbar in the central Argentine basin. Positive values are northward.

branch of the Antarctic Circumpolar Current, such a confluence takes place close to the continental margin of South America out to about 50°W [*Legeckis and Gordon*, 1982]; in the central part of the Argentine basin, however, the Brazil and Antarctic Circumpolar currents are clearly separated and diverging. The area between appears to be occupied by eddies of both subtropical and subantarctic origin.

### *Vertical Structure of Baroclinic Flow*

Meridional sections of the eastward component of baroclinic flow, relative to 1500 dbar, are shown in Figure 10. As can be expected from cuts through meandering currents and through eddies, the structure is dominated by mesoscale cells of eastward and westward flow, about 100–200 km wide, and by strong vertical and horizontal shear. The structure varies from longitude to longitude, though a few common features stand out. The roots of the Brazil and Antarctic Circumpolar currents are deep, with the 0.1 m $s^{-1}$ isotach extending to 600 dbar. Maximum speeds of the eastward components are of comparable magnitude, 0.3 m $s^{-1}$ and 0.2 m $s^{-1}$, respectively. The roots of the eddies in the region investigated are shallower, with the 0.1 m $s^{-1}$ isotach occurring above 200 dbar. The Brazil and Antarctic Circumpolar currents have comparable vertical shear, up to $5 \times 10^{-4}$ $s^{-1}$. Horizontal shears in the Brazil Current reach $10^{-5}$ $s^{-1}$ and are stronger than those in the Antarctic Circumpolar Current.

The change of speed and direction of baroclinic flow, relative to 4900 dbar, with pressure are given in Table 1. Both

TABLE 1. Variability of Baroclinic Flow With Pressure in the Central Argentine Basin

| | 37°S, 41°W | | | | 38°S, 41°W | | | | 40°S, 41°W | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *p*, dbar | *u*, cm $s^{-1}$ | *v*, cm $s^{-1}$ | *w*, cm $s^{-1}$ | $\phi$, deg | *u*, cm $s^{-1}$ | *v*, cm $s^{-1}$ | *w*, cm $s^{-1}$ | $\phi$, deg | *u*, cm $s^{-1}$ | *v*, cm $s^{-1}$ | *w*, cm $s^{-1}$ | $\phi$, deg |
| 1 | 18.7 | 11.8 | 22.0 | 57 | 4.8 | 24.2 | 24.6 | 11 | 5.4 | −5.4 | 7.7 | 134 |
| 150 | 17.4 | 10.8 | 20.5 | 58 | 4.3 | 22.6 | 23.0 | 10 | 4.6 | −5.0 | 6.8 | 137 |
| 300 | 15.7 | 8.8 | 18.0 | 60 | 3.8 | 19.2 | 19.6 | 11 | 3.3 | −4.7 | 5.8 | 144 |
| 600 | 10.1 | 5.9 | 11.7 | 59 | 2.4 | 12.7 | 12.9 | 10 | 2.2 | −4.0 | 4.6 | 150 |
| 1000 | 7.4 | 4.0 | 8.4 | 61 | 1.6 | 9.1 | 9.2 | 9 | 1.4 | −3.3 | 3.6 | 153 |
| 1500 | 4.7 | 1.9 | 5.0 | 67 | 0.8 | 5.5 | 5.6 | 8 | 0.6 | −2.5 | 2.6 | 166 |
| 2000 | 3.3 | 0.8 | 3.4 | 75 | 0.4 | 3.8 | 3.8 | 5 | 0.2 | −2.0 | 2.0 | 172 |
| 2500 | 2.5 | 0.4 | 2.6 | 83 | 0.2 | 2.8 | 2.8 | 3 | 0.0 | −1.7 | 1.7 | 179 |
| 3000 | 1.8 | 0.2 | 1.8 | 83 | −0.0 | 2.1 | 2.1 | 358 | −0.1 | −1.2 | 1.2 | 184 |
| 3500 | 0.8 | 0.0 | 0.8 | 86 | −0.2 | 1.2 | 1.2 | 351 | −0.2 | −0.7 | 0.7 | 196 |
| 4000 | 0.1 | 0.0 | 0.1 | 86 | −0.2 | 0.5 | 0.6 | 342 | −0.1 | −0.3 | 0.3 | 205 |
| 4500 | −0.0 | −0.0 | 0.0 | 251 | −0.1 | 0.1 | 0.1 | 331 | −0.1 | −0.1 | −0.1 | 210 |

Parameters are as follows *p*, pressure; *u*, eastward component; *v*, northward component; *w*, speed; and $\phi$, direction. Speeds have been rounded to the nearest tenth.

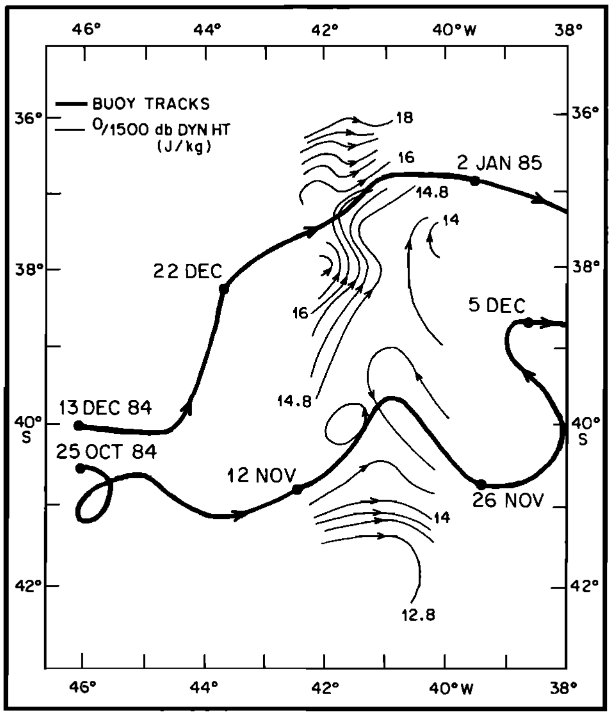


Fig. 11. Trajectories of satellite tracked drifters (A. Gordon and D. Olson, personal communication, 1985) superposed upon the 0/1500 dbar dynamic height field observed during the austral spring of 1984.

clockwise turning and counterclockwise turning of currents are observed. At 37°S, 41°W the current turns clockwise. The total directional change between the sea surface and 4000 dbar is 29°, from 47° to 86°. Below 4000 dbar the current has a 251° heading, suggestive of west-southwestward abyssal flow. At 38°S, 41°W the total directional change in the upper 4000 dbar is also 29°, but counterclockwise, from 11° to 342°. Here the abyssal flow below 4000 dbar has a northwestward component. At 40°S, 41°W the rotation with pressure is again clockwise, from 134° at the sea surface to 205° at 4000 dbar. At this location the abyssal flow has a southwestward direction. In all examples given, the current speeds decrease monotonically with pressure.

The findings indicate that the flow in the central part of the Argentine basin is complex and dominated by mesoscale features which extend to great depths. There is, from these data, little evidence of coherent large-scale differential meridional motion as envisioned in the classical works of *Wüst* [1935] and *Defant* [1941]. If such flow does indeed occur, it either is masked by the presence of the energetic mesoscale field, occurs in regions other than the central part of the Argentine basin, or is not in geostrophic balance. *Reid et al.* [1977] found by short-period direct current measurements near the continental margin of South America poleward deep water flow and equatorward abyssal flow, in agreement with classical conceptions, but it is not known how far into the interior of the Argentine basin these findings can be extrapolated.

### *Relationship Between Baroclinic Flow and Satellite-Tracked Drifters*

Large-scale studies of the southern ocean circulation by satellite-tracked drifters [*Hofmann*, 1985] have shown that the drifter tracks are not distributed uniformly over the temperate latitude band but are clustered in narrow zones, centered on the mean positions of the subtropical, Subantarctic, and Antarctic polar fronts. Because many fronts are regions of enhanced baroclinic flow, a qualitative relationship can be expected between the drifter trajectories and the baroclinic flow, at least in the statistical mean sense [*Kirwan et al.*, 1978].

To determine whether the separation of the Brazil and Antarctic circumpolar currents in the central part of the Argentine basin, as suggested by the 0/1500 dbar dynamic height topography, could be verified independently, A. Gordon and D. Olson (personal communication, 1985) kindly provided the author with two satellite-tracked drifter trajectories that passed through this area. The results are shown in Figure 11. The southern buoy closely followed the northern edge of the Antarctic Circumpolar Current at about the same time the CTD survey was taken. The northern buoy, which traversed the area about a month and a half later, appeared to follow the Brazil Current return flow. The trajectories, which were close together to 44°W, separated near 42°W, as the dynamic height topography indicated, and then approached each other again near 38°W. The agreement between trajectories and baroclinic flow stream lines is suggestive rather than conclusive evidence for current separation, because the two need not coincide perfectly when the flow is time variable.

## THREE-DIMENSIONAL THERMOHALINE STRUCTURE OF THE BRAZIL CURRENT AND SUBANTARCTIC FRONTS IN THE CENTRAL PART OF THE ARGENTINE BASIN

### *Frontal Nomenclature*

No universally accepted nomenclature for South Atlantic frontal features exists. Thus the separation between the warm subtropical water and the cold subantarctic water has been called variously "subtropical convergence" [*Deacon*, 1937] and "subantarctic front" [*McCartney*, 1977], sometimes modified by the word "zone" to emphasize the finite width of the separation. The term "subtropical convergence" is somewhat ambiguous, however, because it does not differentiate between convergence of deep boundary currents and that of shallow Ekman drifts, both of which can produce fronts in subtropical latitudes at widely different locations.

For present purposes it is useful to distinguish between transition zones, frontal zones, and individual fronts. The subtropic-subantarctic transition zone of the South Atlantic is a large-scale upper ocean feature of primary thermohaline gradients established between the subtropical source water region (where net downward heat and salt fluxes predominate) and the subpolar source water region (where net heat and salt fluxes are predominantly upward). Interaction of spatially variable large-scale flow with the primary thermohaline gradients leads to intensification of these gradients in geographically preferred regions. Thus the change from warm, salty subtropical water to cool, less saline subpolar water is not gradual but occurs rather abruptly near the northern and southern limits of the transition zone. These regions of rapid change will be called frontal zones. In the central Argentine basin there are two main frontal zones. The first is associated with the poleward boundary of the Brazil Current and its seaward extension and will be called the Brazil Current frontal zone. The second is related to the equatorward boundary of the Antarctic Circumpolar Current (Figure 1) and will be designated as the subantarctic frontal zone. In each frontal zone, one or several fronts and frontal eddies occur. The fronts are often sharp, convoluted, and of mesoscale dimensions. Naming individual fronts in frontal zones is rarely meaningful, except when the frontal zone contains a single dominant front or when dealing with a climatological mean front. In such cases

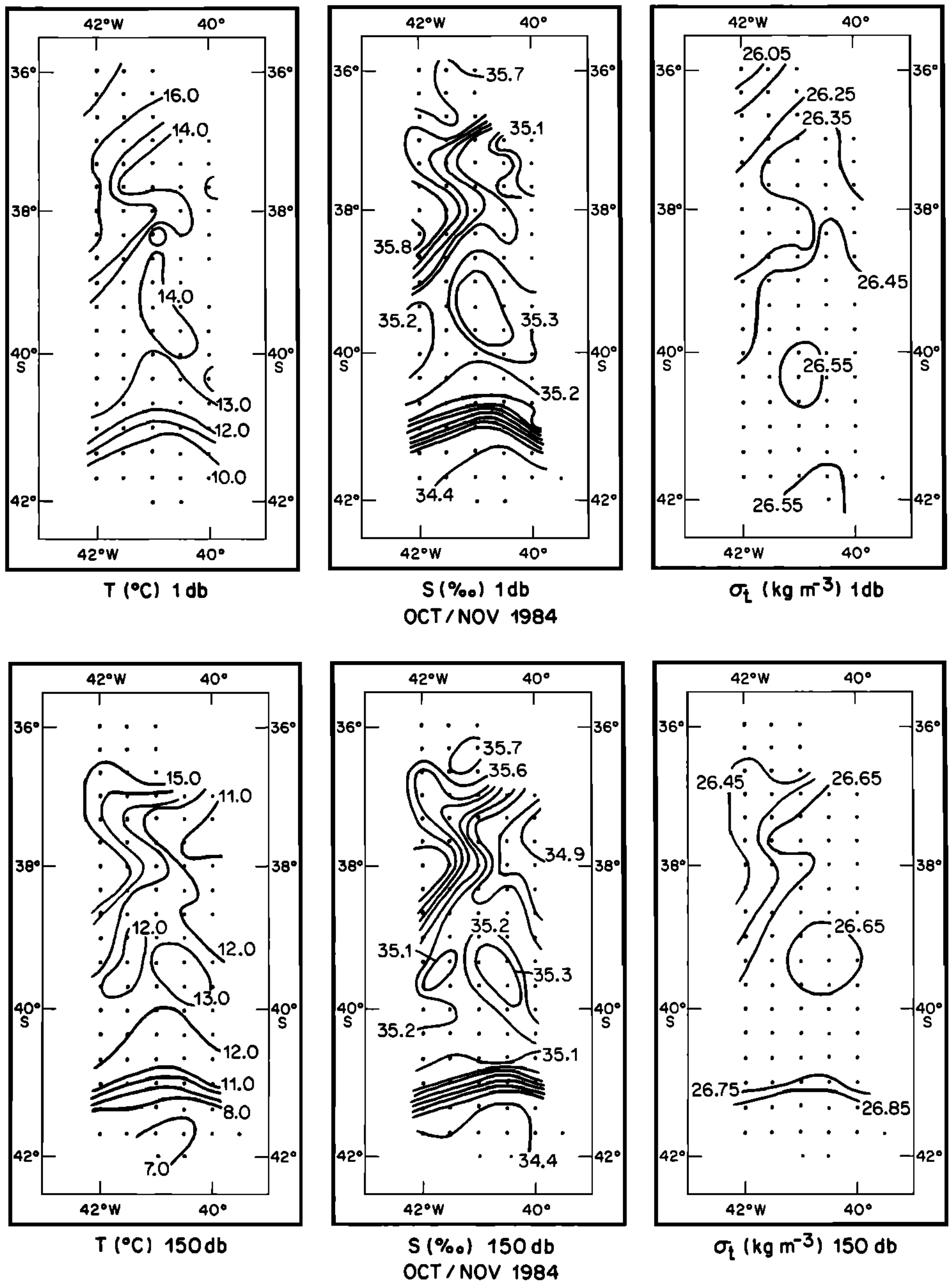


Fig. 12. Horizontal temperature, salinity, and density structure at 1 and 150 dbar.

the front will be named Brazil Current front or subantarctic front, as appropriate.

In the climatological mean sense, the Brazil Current front is characterized by sharp thermohaline gradients in the upper 500 m, by a rapid poleward decrease in the depth of the salinity minimum (from about 1000 m to 700 m), and by large vertical shear of the horizontal geostrophic flow throughout the upper layer. The Brazil Current front can be traced approximately by the positions of the 10°C isotherm and the 34.8‰ isohaline, which are embedded in the front between 300 m and 500 m [*Gordon and Molinelli*, 1982].

The definition of the climatological mean of the subantarctic front is more difficult, and no unanimous agreement exists on the subject. The approach taken here is to define the front in terms of its characteristics in the upper layer, in which they are best developed. When this is done, it is found that the distinguishing features are (1) the absence of significant vertical shear of horizontal geostrophic flow in the upper mixed layer, due to density-compensating horizontal thermohaline gradients; (2) the outcrop or near outcrop of the 10°C isotherm and 34.8‰ isohaline usually embedded in the front; (3) the appearance of a low-salinity top layer and of temperature inversions on the poleward side of the front (the two events are related: because of hydrostatic stability reasons, large temperature inversions can occur only in a well-developed subpolar halocline, in which salinity increases with depth); and (4) the appearance of subsurface isopycnal layers as a result of previous winter convection on the equatorward side of the front [*McCartney*, 1977].

The definition of the climatological mean of the subantarctic front used here is consistent with that of the subarctic front of the North Pacific [*Roden*, 1975, 1977] and is in agreement with the modern notion of subantarctic and subarctic mode water formation along the equatorward boundaries of these

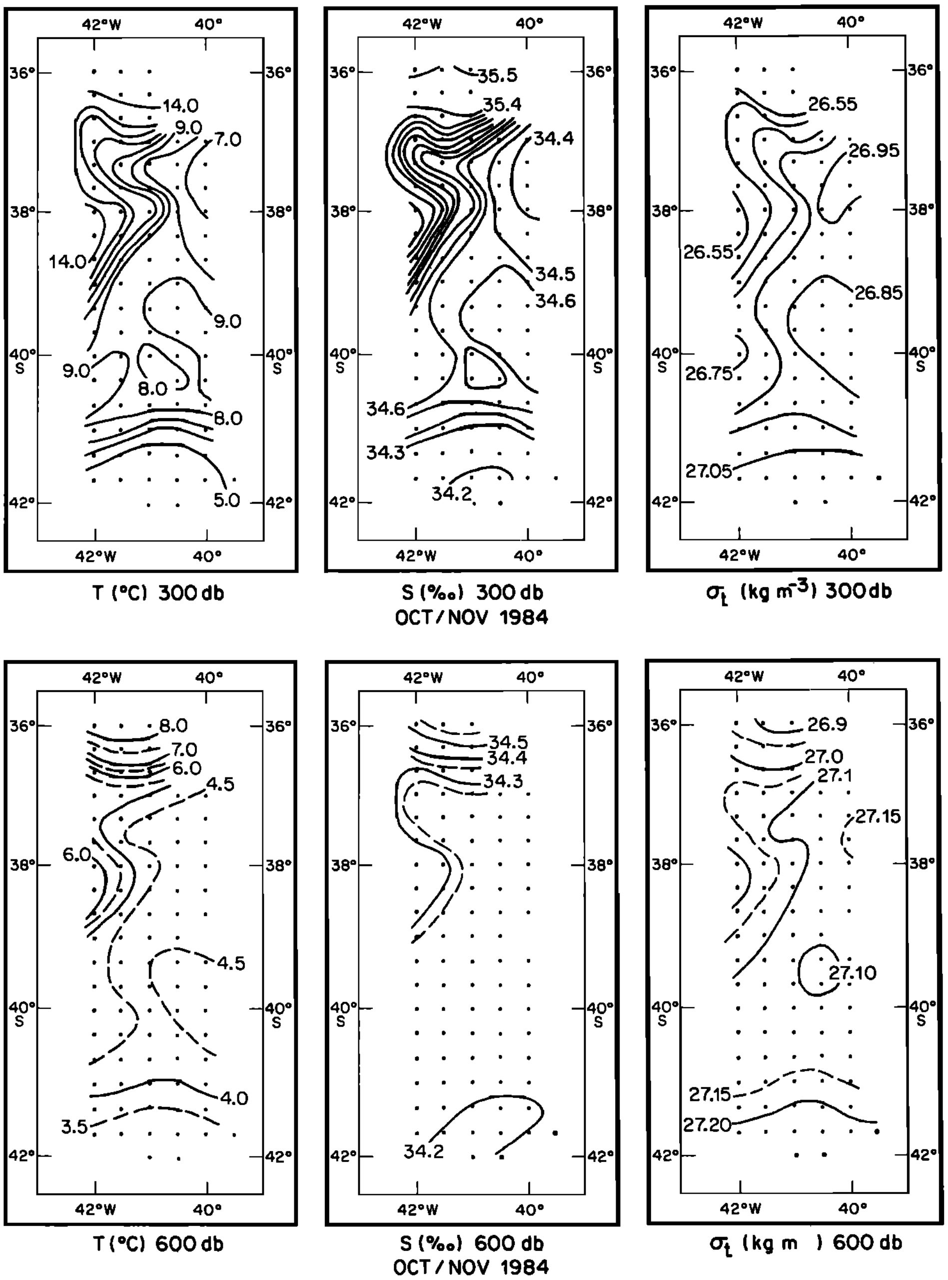


Fig. 13. Horizontal temperature, salinity, and density structure at 300 and 600 dbar.

subpolar fronts [*McCartney*, 1977; *Keffer*, 1985]. Other definitions of the subantarctic front have been used, based on characteristics of property differences over the entire water column rather than in the upper layer. While these definitions are useful in describing local fronts observed in regions such as Drake Passage [*Nowlin and Clifford*, 1982; *Sievers and Nowlin*, 1984], it is felt that for oceanwide scales and for comparison of similar fronts in other oceans it is better to define the subantarctic front in terms of well-developed and easily traceable upper layer characteristics such as those outlined above. Because the geographic location of the subantarctic front depends upon its definition, care should be used when comparing positions reported in the literature until standardization of terminology is achieved.

### *Horizontal Structure*

Temperature, salinity, and density distributions in the upper 4900 dbar are shown in Figures 12–14. A 37 km by 43 km sampling grid was used down to 1500 dbar, and a 110 km by 100 km grid was used below. Two fronts stand out in the upper 1500 dbar, well separated from each other. The front meandering northeastward from 39°S toward subtropical latitudes is the Brazil Current front. The zonally oriented front near 41°S is the subantarctic front. Though only a short section of this front is shown here, it is known from the sharp gradients near 200 m to be an oceanwide feature [*McCartney*, 1977]. The two fronts have rather different physical characteristics. The Brazil Current front, like western boundary current fronts elsewhere, is deep and recognizable to at least 3000 dbar. The subantarctic front is shallower, and the gradients become weak below 1500 dbar. At the Brazil Current front the strong horizontal thermohaline gradients are almost always accompanied by strong horizontal density gradients in the upper mixed layer. At the subantarctic front the temperature and salinity fronts in the mixed layer compensate each other in such a way that no density front occurs. At the Brazil

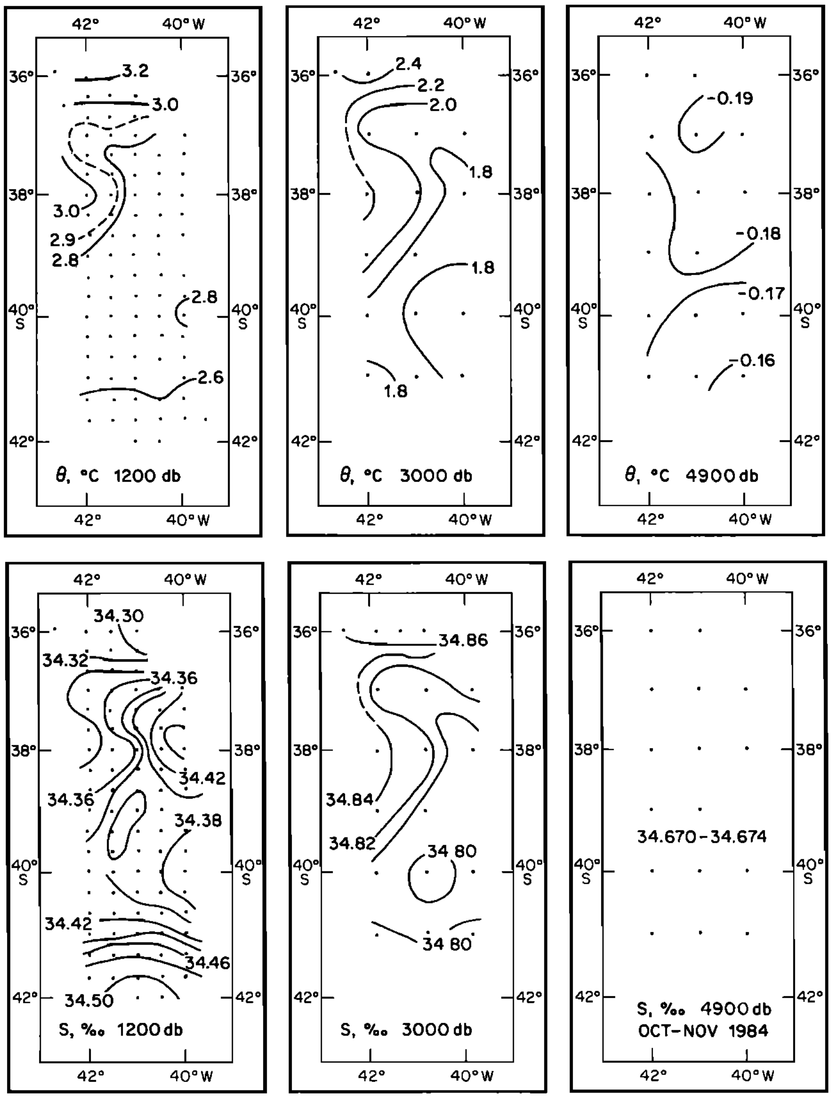


Fig. 14. Horizontal potential temperature and salinity structure at 1200, 3000, and 4900 dbar.

Current front, cross-frontal thermohaline gradients are generally largest at subsurface depths; at the subantarctic front they occur at the surface.

In the central part of the Argentine basin, the temperature, salinity, and density fronts are not always coincident at given pressure levels, nor do all the thermohaline fronts keep their polarity throughout the water column. In the Brazil Current region the temperature front has the same sign down to 3000 dbar, while the salinity front reverses its polarity twice over this pressure interval. Above the subantarctic salinity minimum, lower salinities are found on the poleward side. Between this minimum and the underlying salinity maximum, higher salinities occur on the poleward side. Below the maximum, salinities again decrease poleward. At pressures where the horizontal salinity gradients change sign, the salinity front vanishes altogether. The reversal of polarity of the salinity front is indicative of vertical motion. The relatively fresh subantarctic water not only moves northward but also sinks. The salty North Atlantic Deep Water moves southward and rises. Thus on a constant pressure surface the salinity gradient in the upper layer (say, 150 dbar) will be opposite in sign to that in the intermediate layer (1200 dbar) but of the same sign as that in the deep water (3000 dbar).

The thermohaline fronts in the central Argentine basin do not appear to extend much below 3500 dbar. At 4900 dbar (the greatest common pressure for all the deep stations) no fronts are evident. Instead, the potential temperature distribution suggests eddylike patterns with the coldest temperatures in the northeast. These findings are in qualitative agreement with *Georgi's* [1981] conclusions on the bottom waters in the southwestern South Atlantic.

### *Vertical Profiles*

Basic vertical profiles of temperature, salinity, and density in the Brazil Current extension area are shown in Figure 15. Warm and saline water of subtropical origin is found in the upper 600 dbar. Beneath it lies rather cool and low salinity Antarctic Intermediate Water, marked by a pronounced salinity minimum near 900 dbar. This water is believed to originate in the region of the subantarctic front by winter convection and mixing [*McCartney*, 1977, 1982] and by sinking of surface waters near the polar front [*Piola and Georgi*, 1981]. Beneath the Antarctic Intermediate Water the outstanding feature is a 1000-m-thick layer in which the mean vertical temperature gradient is small, while the mean vertical salinity gradient is strongly negative. Numerous small temperature inversions occur in the deep halocline. which is hydrostatically stable. The complex thermohaline structure in this layer may result

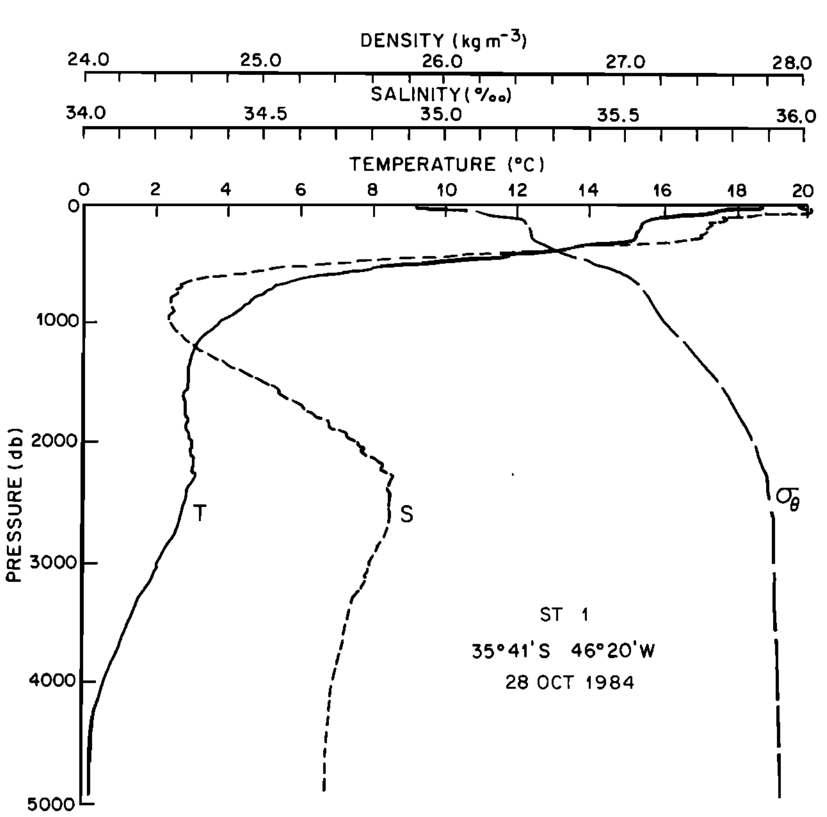


Fig. 15. Vertical profiles of temperature, salinity, and density in the region of the Brazil Current.

from the interfacing of different water masses of widely differing salinity but of similar temperature, involving Antarctic Intermediate Water, Antarctic Circumpolar Water, and North Atlantic Deep Water [*Reid et al.*, 1977; *Warren*, 1981]. The core of the latter can be recognized by a distinct salinity and weaker temperature maximum near 2300 dbar. From there to the bottom, both temperatures and salinities decrease.

The shape of the profiles and the position of the extrema change as one proceeds from the Brazil Current region poleward, with the sharpest changes observed in frontal areas. Across the Brazil Current front (Figure 16, left) there is a sharp decrease in the thickness of the warm and salty surface layer, and the salinity minimum rises from 900 dbar to 600 dbar over a distance of 100 km. Across the subantarctic front (Figure 16, right), there is a 4°C temperature drop and a 0.8‰ salinity drop over 100 km, and the salinity minimum almost disappears. In the center of this front, at 41°S, large salinity and temperature inversions occur at the base of the upper mixed layer, near 100 dbar. These inversions are suggestive of overrunning of cold, low-salinity surface water over warmer, more saline subsurface water, probably as a result of northward Ekman drift superposed on deeper eastward baroclinic flow associated with the Antarctic Circumpolar Current.

### *Meridional Sections*

Meridional temperature, salinity, and density sections in the upper 1500 dbar are shown in Figures 17 and 18. As can be expected from cuts through meandering, eddy-shedding currents, multiple fronts appear, giving the impression of a continuous frontal zone between 36°S and 42°S. A closer examination of the structure reveals that the three fronts on the left at 42°W are Brazil Current fronts, recognizable by warm ($T > 10$°C) and salty ($S > 35$‰) water at 500 dbar, while the front on the right is the subantarctic front, which can be recognized by the surfacing of the embedded 10°C isotherm and the 34.8‰ isohaline.

The Brazil Current fronts are strongest between 100 and 700 dbar, where cross-frontal thermohaline differences reach 4°C and 0.5‰. A pronounced well-mixed layer, 100 km wide and about 200 m deep, with temperatures of about 15.3°C and salinities of 35.7‰, occurs near 38°S, 42°W. This uniform layer with a density of 26.5 kg m$^{-3}$ ($\sigma_t$ units) may have formed in the previous winter by cooling of warm saline surface water of subtropical origin, with subsequent convection and mixing. During the following spring warming, a shallow pycnocline developed to cap off the well-mixed layer. Such winter convection in warm and salty rings and eddies has been studied in the Gulf Stream region and found to be effective in thermocline ventilation and in the formation of mesoscale lenses [*Schmitt and Olson*, 1985].

The meridional structure varies strongly from longitude to longitude even over short distances. At 40°W, only 200 km to the east, the structure looks different because the Brazil Current and its associated frontal system have meandered north of the investigated area. Consequently, the dominant front is the subantarctic front near 41°S, which is strongest in the upper 300 dbar. Here cross-frontal thermohaline differences reach 5°C and 0.8‰. In the upper 100 dbar the temperature and salinity differences compensate each other so that no density front is formed. Apparently, only slight cooling and freshening of diluted subtropical water and slight warming and "salting" of subantarctic water are sufficient to eliminate the horizontal density contrast while keeping the horizontal temperature and salinity contrasts largely intact. Because the surface heat and salt fluxes do not significantly penetrate beyond the upper mixed layer, such compensation is not observed below 100 dbar. In addition to the dominant subantarctic front, shallow secondary fronts associated with cold and warm

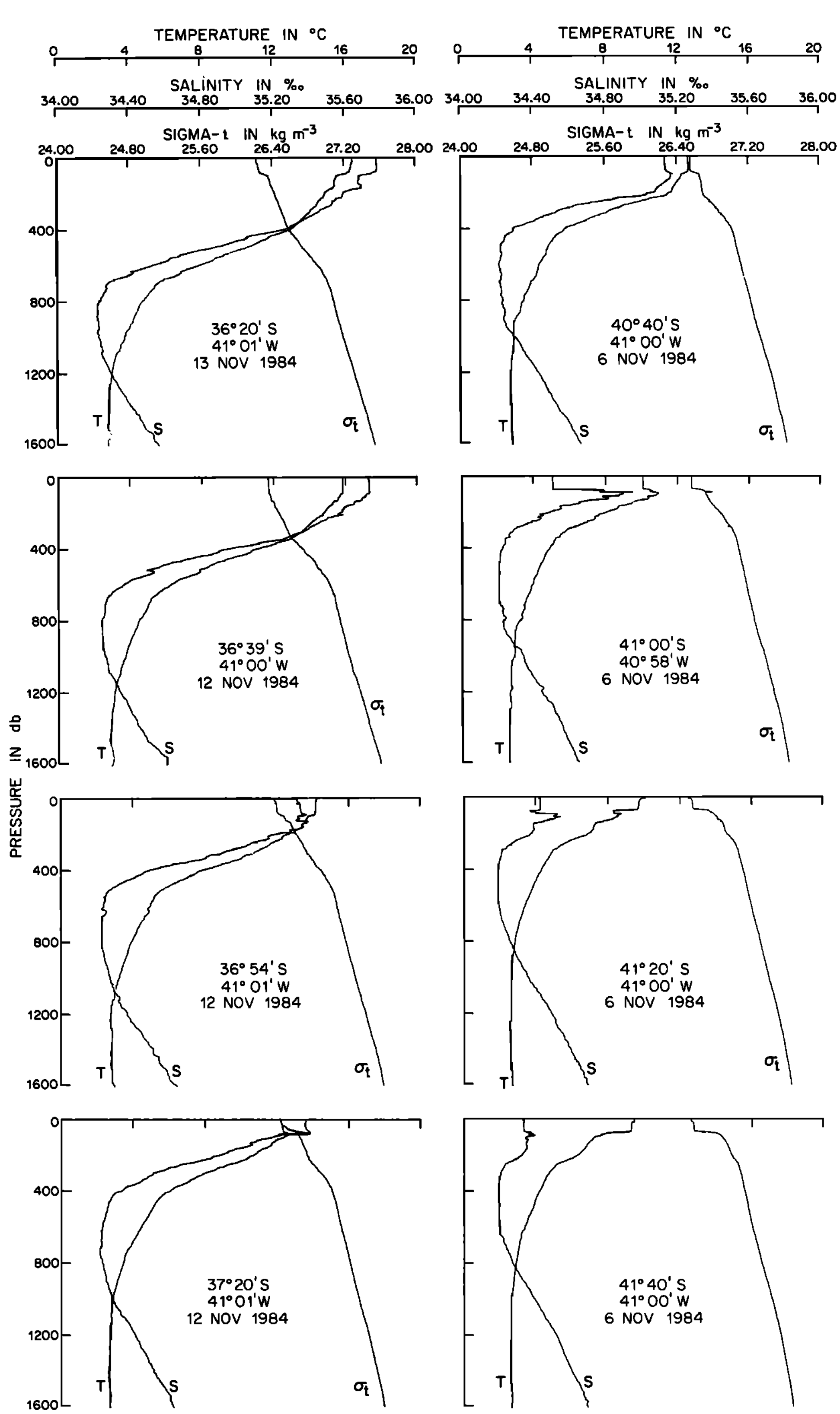


Fig. 16. Change of vertical profiles of temperature, salinity, and density across (left) the Brazil Current and (right) the subantarctic fronts.

core eddies are found. Like the primary front, these secondary fronts have density-compensating temperature and salinity gradients in the upper mixed layer.

### *Zonal Sections*

Zonal temperature, salinity, density, and sound speed sections extending from the continental margin off Rio de la Plata to the central Argentine basin are shown in Figures 19 and 20. The sections pass through the meandering Brazil Current (flanking the warm core lobes near 50°W, 47°W, and 43°W) and two cold core eddies centered at 45°W and 40°W (see Figure 4). The thermohaline structure is highly complex and is marked by deep fronts as well as by a thick subpycnocline mixed layer. At 52°W a cool and low-salinity mixture of

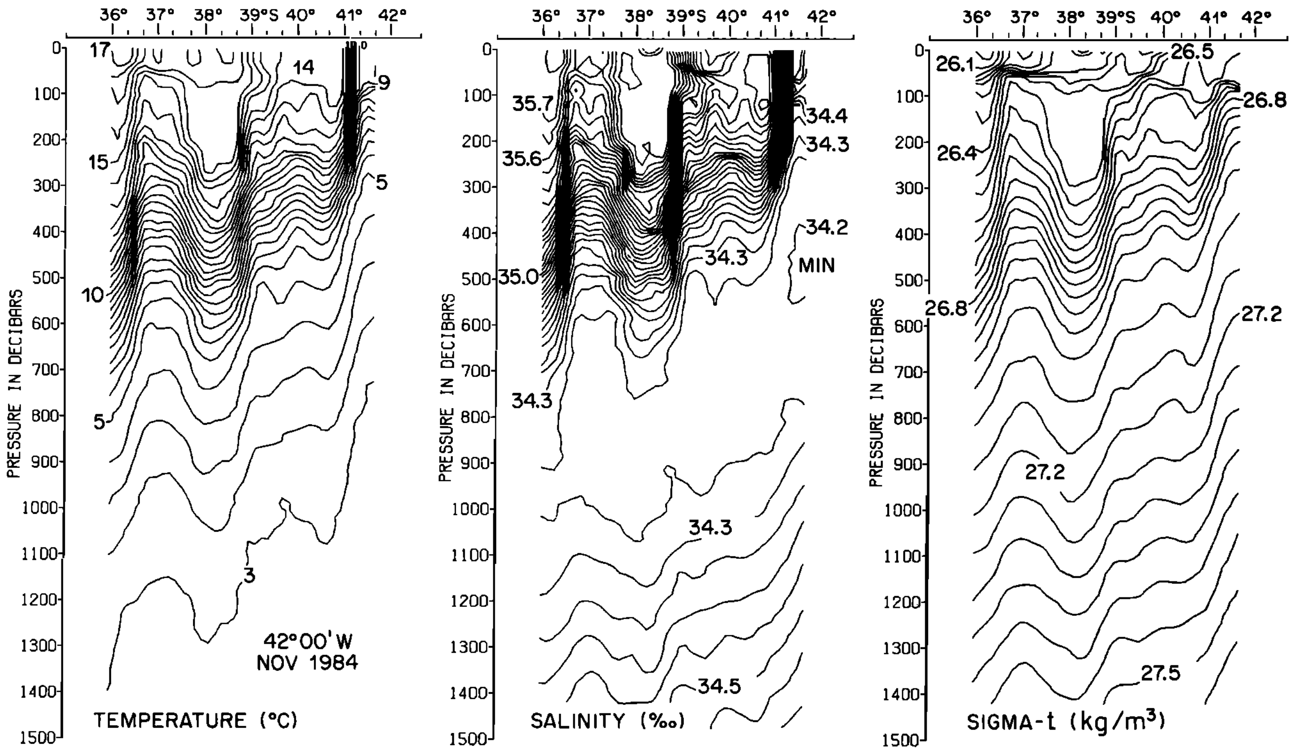


Fig. 17. Meridional temperature, salinity, and density structure along 42°W.

Rio de la Plata water with Malvinas shelf water overrides the cold, more saline water carried north by the Falkland Current, both of which impinge on the deep, warm, and saline, southward moving Brazil Current. The resulting fronts are very sharp, especially near the surface and between 300 dbar and 700 dbar. In the intervening range between 100 dbar and 300 dbar frontal intensities are weaker, perhaps because of increased mixing near the shelf break. As was observed previously by *Gordon* [1981] and *Legeckis and Gordon* [1982], the strongest fronts occur on the western side of the Brazil Current and where the Brazil Current return flow impinges on eddies containing water of subantarctic origin. Such a cold core eddy is found near 45°W. It is about 100 km across and has temperatures and salinities which are up to 6°C and 1.2‰ less than those found in the surrounding environment. The associated temperature and salinity fronts extend to the sea surface, but there is no surface density front.

A noteworthy subpycnocline temperature- and density-

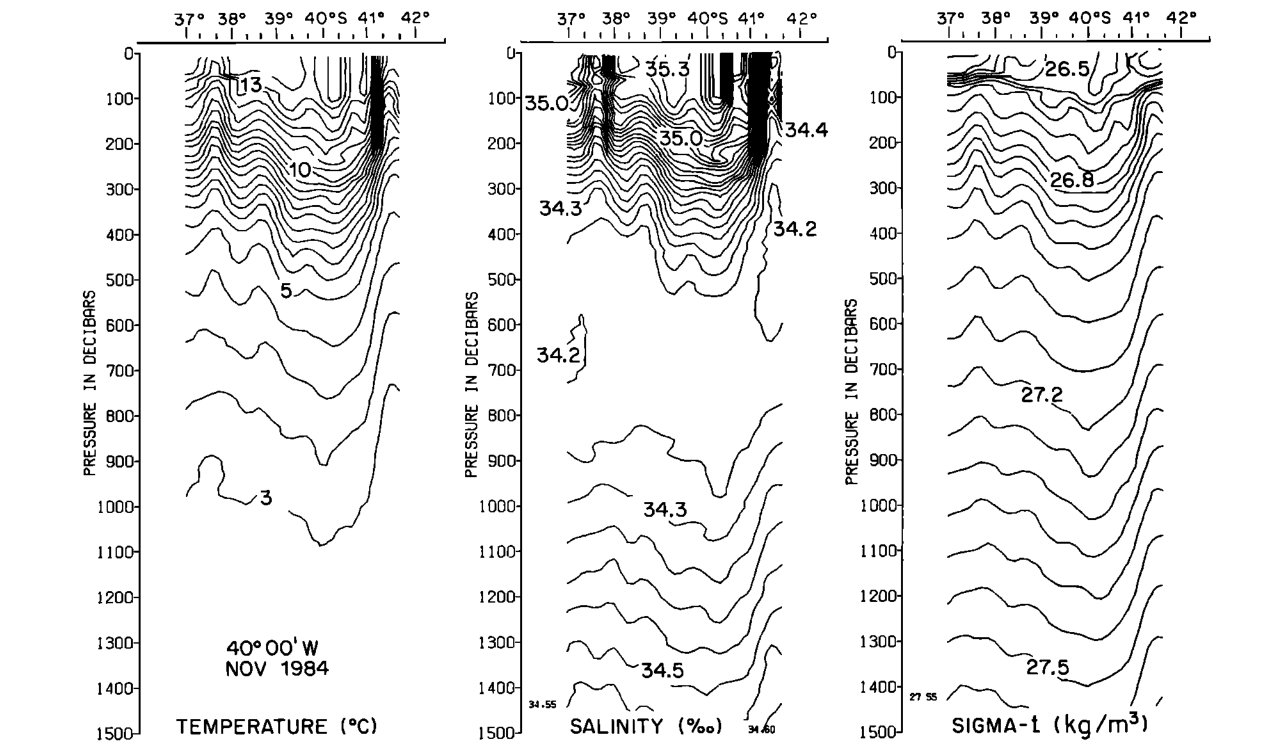


Fig. 18. Meridional temperature, salinity, and density structure along 40°W.

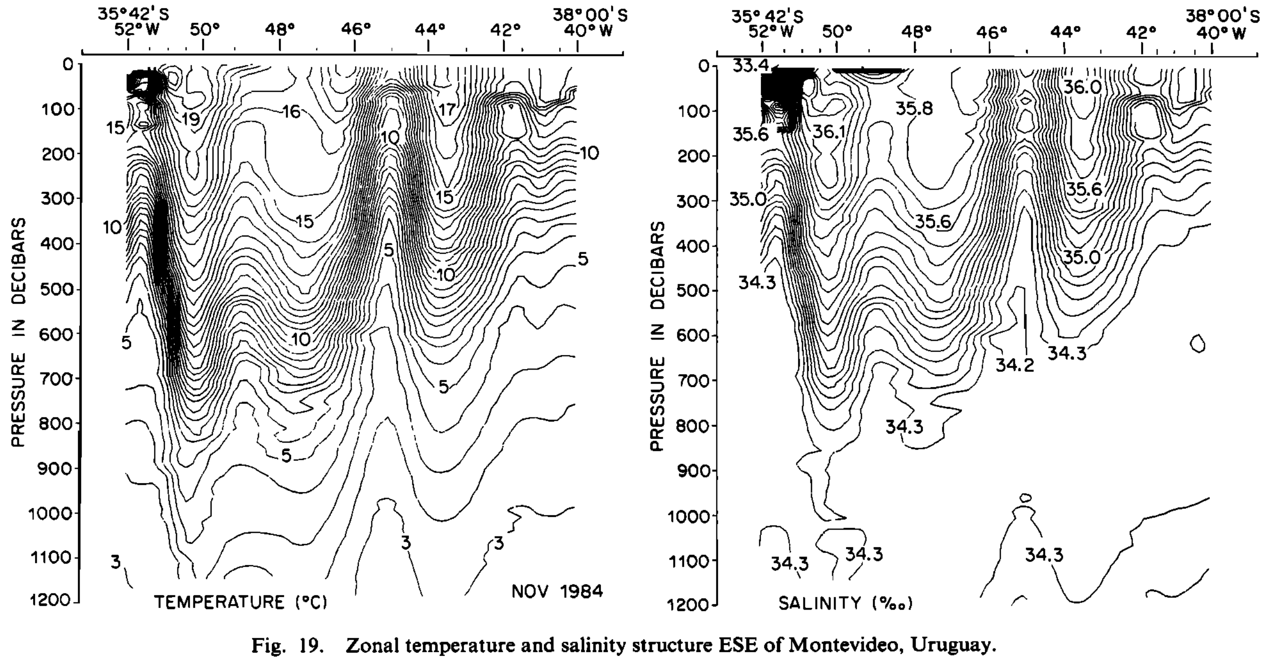


Fig. 19. Zonal temperature and salinity structure ESE of Montevideo, Uruguay.

mixed layer occurs near 48°W, between 100 dbar and 300 dbar, with the accompanying salinity-mixed layer extending to the surface. The high temperatures ($T > 15°C$) and salinities ($S > 35.8‰$) in this layer suggest that it is a remnant of previous winter convection and mixing of a poleward lobe of Brazil Current water. Subsequent spring warming has created a shallow seasonal thermocline and pycnocline but has not affected the vertical salinity structure.

The sound speed structure in the upper 500 dbar resembles the temperature structure, as is expected. Sound speed differences across the Brazil Current front and across the cold core eddy front reach 30 m s$^{-1}$. The sound speed structure below 500 dbar varies from the temperature structure in cold core eddies; here, the Sofar channel axis lies at about 600 dbar, as opposed to 900–1100 dbar in the region of the Brazil Current.

*Deep Structure*

The thermohaline structure between 800 dbar and the bottom is shown in Figure 21 and is based on a horizontal station spacing of 110 km. A rather fine vertical contour interval has been chosen to bring out the salient features. The deep density structure is comparatively simple, showing stable stratification and the presence of three fronts in the upper 2000 dbar that are associated with Brazil Current meanders. Below 3000 dbar the vertical density gradients are very small. In contrast, the deep temperature and salinity structures are highly complex. Thermal fine structure occurs between 1200 dbar and 2200 dbar, and haline fine structure occurs between 2000 dbar and 3000 dbar. Note that the regions of temperature and salinity fine structure are mostly nonoverlapping,

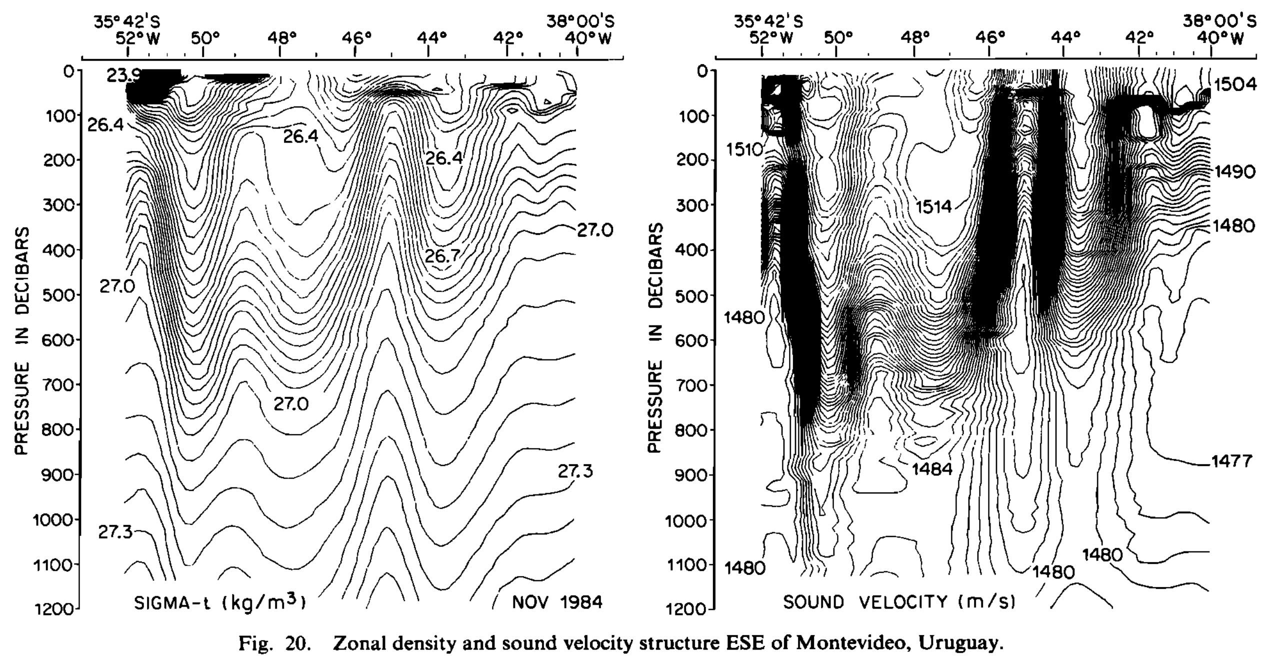


Fig. 20. Zonal density and sound velocity structure ESE of Montevideo, Uruguay.

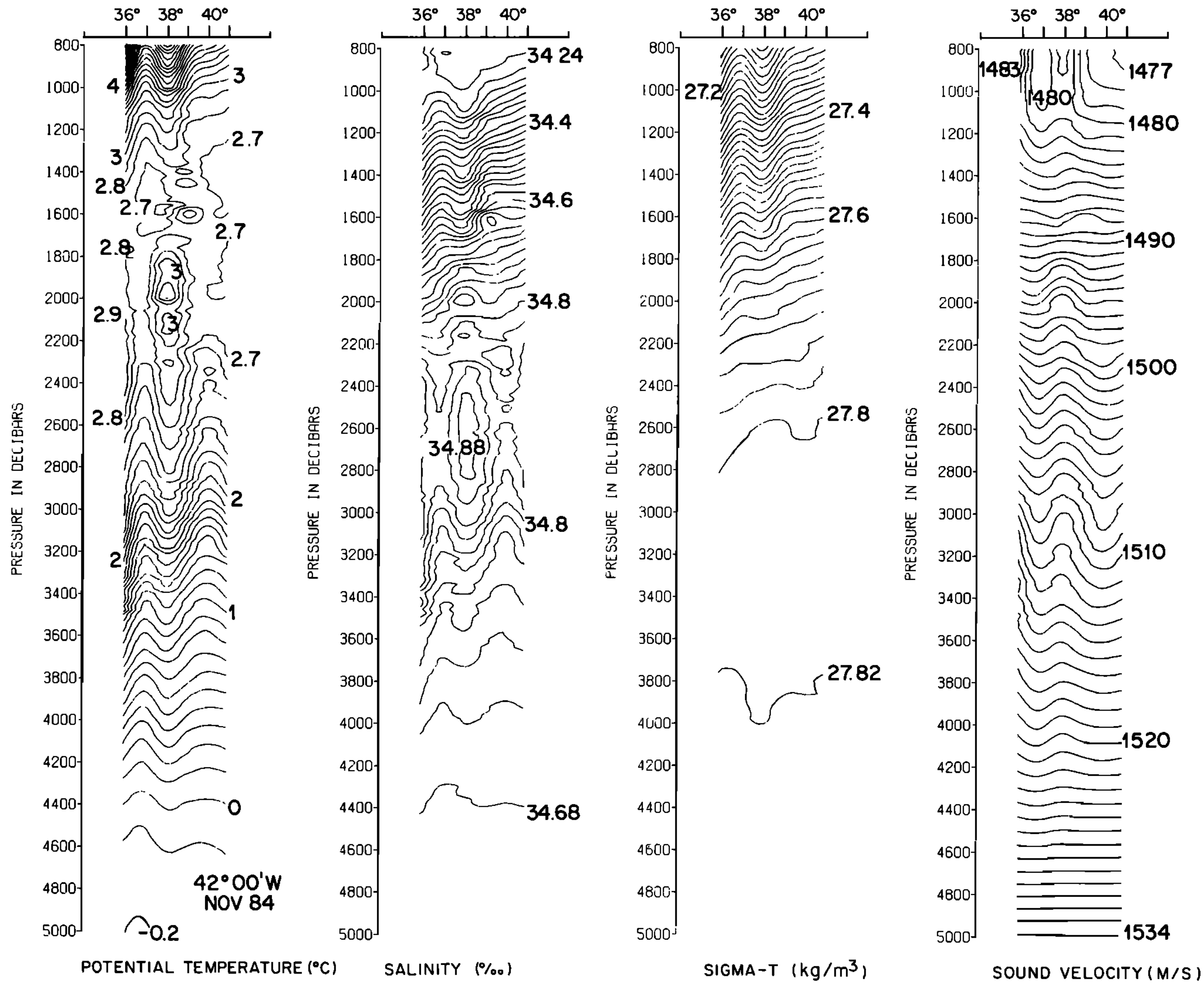


Fig. 21. Deep potential temperature, salinity, density, and sound speed structure in the central Argentine basin.

the former occurring principally in the halocline and the latter mainly in the abyssal thermocline; neither fine structure is reflected in the density field.

The deep temperature and salinity fronts are vertically intermittent. Thermal fronts are well defined in the upper 1400 dbar and then again between 2200 dbar and 4400 dbar. In the thermal fine structure region between, the fronts are weak, and if they occur, they are of small vertical extent. Haline fronts reverse their polarity twice between surface and bottom. In the layer above the salinity minimum, the lower salinity lies on the poleward side. In the salinity minimum between about 600 dbar and 1000 dbar, the fronts effectively vanish. Between 1000 dbar and 2000 dbar salinities increase poleward. In the fine structure region between 2000 dbar and 3000 dbar, the fronts are weak. Between 3000 dbar and 4000 dbar, salinities again decrease poleward. Note that the abyssal temperature and salinity fronts are largely density compensating in the 2800-dbar to 3800-dbar range.

The deep sound speed fronts are also vertically intermittent, being well defined in the upper 1200 dbar and then again between 2200 and 4200 dbar. The deep sound speed structure bears little resemblance to the deep temperature and salinity structure. Closed isosones do not occur, and the slopes and curvatures of the isosones are opposite to those of the isotherms and isohalines. Below 4200 dbar, the isosones are essentially horizontal, meaning that the pressure effect on sound speed is so large that minor temperature and salinity perturbations do not change its value measurably. Similar conditions of abyssal sound speed structure exist in the North Pacific [*Roden*, 1984*b*].

## CONCLUSIONS AND DISCUSSION

The following conclusions can be drawn from an analysis of high-resolution hydrographic data in the central Argentine basin:

1. The thermohaline structure is dominated by mesoscale features associated with the Brazil Current and the Antarctic Circumpolar Current.

2. The Brazil Current, after initial retroflection, meanders northeastward toward subtropical latitudes, with speeds of the order of 0.3 m $s^{-1}$. The meander wavelength is about 400 km, and the meander amplitude is about 200 km.

3. The Brazil Current signatures, as expressed by relative dynamic height, are recognizable to depths of 4000 m.

4. The Brazil and Antarctic Circumpolar currents do not merge to form common eastward flow, as was envisioned in classical descriptions (Figure 1). Instead, these currents strongly diverge near 42°W (Figure 8). The current divergence is suggested also by the track of satellite drifters.

5. The region between the Brazil and Antarctic Circumpolar currents is marked by both cyclonic and anticyclonic eddies, the signatures of which extend to great depths.

6. Strong thermohaline fronts accompany the boundaries of the Brazil and the Antarctic Circumpolar currents. The vertical structure of these fronts is highly complex. Temperature, salinity, and density fronts need not be present simultaneously, nor do they penetrate to the same depths.

7. At the subantarctic front and fronts associated with cold core eddies, the compensation of the horizontal temperature and salinity gradients in the upper mixed layer is so complete that no density front is observed. This implies absence of vertical shear of horizontal geostrophic flow in this layer.

8. Temperature and salinity fronts below the upper mixed layer are vertically intermittent, while density fronts are not. The former become very weak in regions of small mean vertical temperature and salinity gradients and intensify again below, where these gradients become larger, suggesting that the fronts are formed by differential vertical advection.

9. Deep subpycnocline mixed layers occur in the poleward lobes of the Brazil Current return flow. This is suggestive of previous winter convection induced by cooling high-salinity water of subtropical origin and subsequent spring warming.

The thermohaline structure and circulation in the Argentine basin is more complex than was envisioned by the early investigators [*Wüst*, 1935; Deacon, 1937]. Instead of smoothly converging flow between the Brazil Current extension and the Antarctic Circumpolar Current, one finds these currents to be meanderlike and well separated from each other by an eddy field. In place of a single thermohaline front between these currents spanning much of the South Atlantic, one encounters two convoluted fronts following the boundaries of the respective currents, as well as frontal eddies. Instead of coincident temperature, salinity, and density fronts extending to a common depth, one observes thermohaline fronts that are vertically intermittent and density compensating at the top. The dominance of such complex mesoscale flow features and frontal structures in the Argentine basin is in agreement with observations from other western boundary current regions such as the Kuroshio [*Kawai*, 1972; *Roden*, 1975], the Agulhas [*Grundlingh*, 1978; *Lutjeharms*, 1981], and the Gulf Stream (*Olson*, 1980; *Richardson*, 1983; *Watts*, 1983].

While the Kuroshio Current, the Agulhas Current, and the Gulf Stream are readily defined by their deep signatures and large transports, no unanimous agreement yet exists as to what constitutes the Brazil Current. From a classical point of view, this current was regarded as the southward flowing branch of the South Atlantic anticyclonic gyre, which carries warm and saline water of subtropical origin poleward along the continental margin of South America [*Sverdrup et al.*, 1942]. This definition, based on water mass characteristics, confines the current to the upper ocean because no subtropical water is found below about 1000 m. Even the existence of a steady and coherent Brazil Current has been questioned in some parts of its previously surmised domain. *Fu* [1981], applying inverse methods to sparse and nonsynoptic data, finds no Brazil Current equatorward of 25°S. *Reid et al.* [1977] find the anticyclonic gyre to be compressed against the western boundary at intermediate and greater depths, and they believe that its southward flowing branch is of different origin above and below 1000 m because of different water mass characteristics.

The position taken here is to define the Brazil Current in terms of baroclinic flow rather than water mass characteristics. High-resolution investigations in the central Argentine basin indicate that the dynamic height patterns associated with the Brazil Current are vertically coherent in the upper 4000 dbar. This suggests that the Brazil Current, though much diminished in strength, extends to great depths, in common with other western boundary currents. When so defined, the Brazil Current still can be regarded as a branch of the South Atlantic anticyclonic gyre, but it no longer is vertically restricted by upper ocean water mass characteristics.

Several unresolved problems remain. The growth rates of the current meanders and the lifetimes and migrations of cold and warm core eddies in the central Argentine basin are not known. Satellite observations in the western part of this basin have shown that the first Brazil Current meander expands and contracts in a north-south direction by as much as 400 km over a time period of a month and that the lifetime of mesoscale eddies is several weeks [*Legeckis and Gordon*, 1982]. There is reason to believe that the meanders and eddies in the central basin vary similarly with time. Judging from satellite altimeter information [*Cheney et al.*, 1983], the amplitude of the variability appears to be less here than in the west. There is a need also to determine how the variability in time and space varies with depth.

The processes leading to the formation of deep mixed layers in the vicinity of the Brazil Current and subantarctic fronts and in drifting eddies need to be investigated more fully, because they have important consequences for thermocline ventilation and the spreading of intermediate water masses. As previous investigations have shown, a combination of convection, wind stirring, and Ekman pumping is an effective means of mode water formation and its spreading into the interior of the ocean [*McCartney*, 1977; *Rhines and Young*, 1982; *Talley*, 1985]. It is not known whether the primary mode of these processes is intermittent and occurs during favorable oceanic and meteorological events (such as polar air sweeps across the poleward reaches of the Brazil Current or drift of warm and saline eddies to high latitudes) or whether it occurs in a more continuous fashion during the winter season.

The barotropic flow patterns in the Argentine basin are virtually unknown. A few short-period current measurements at two mooring sites in the northernmost part of the basin indicate large temporal variability in speed and direction [*Reid et al.*, 1977]. Abyssal velocities averaged over several weeks are of the order of 0.05 m s$^{-1}$, which is higher than the computed baroclinic flow at these depths. Until long-period current measurements of the order of a few years and quasi-Lagrangian drifter results become available, the abyssal flow will remain largely conjectural.

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