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Deep jets in the equatorial Atlantic Ocean

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Abstract. Deep velocity profiles taken in the equatorial Atlantic Ocean show equatorially trapped deep jets with similar features to those of the Indian and Pacific Oceans: a zonal velocity of the order of 10 to 20 cm s^{-1} and a meridional scale of 1°. In the Pacific and Indian Oceans the zonal extent of the jets is at least 15° of longitude. Owing to the lack of synoptic measurements, we have no information on the zonal scale in the Atlantic Ocean, but we present here zonal velocity profiles, made at a 16-month interval, that have identical baroclinic structure in the western (35°W) and central basin (13°W). The Atlantic jets have a vertical scale larger (400-600 m) than those observed in the Pacific Ocean (250-400 m). Our measurements confirm the opposite directions of the jets for different seasons in the Atlantic Ocean. Furthermore, for a given season, the vertical profiles of zonal velocity at 35°W-0° are astonishingly similar at a 5-year interval. As in the Pacific and Indian Oceans, the jets are embedded in a large-vertical-scale current that changes direction with time. The few profiles available in the equatorial Atlantic Ocean suggest a seasonal reversal of the jets, but neither this nor the temporal variability of the large-scale current has been adequately resolved.

1. Introduction

This paper describes new deep velocity measurements made in the western and the central equatorial Atlantic Ocean. These top to bottom velocity profiles show the presence of equatorially trapped deep jets between 300 and 2500 m depth.

To our knowledge, the very first direct observations of deep equatorial jets are reported by *Rual* [1969] in the western Pacific, at 170°E; but the measurements were made only between 1000 and 1500 m and were relative to 1500 m, so there was no indication that the two westward jets within that depth range were actually part of a larger stack of regularly spaced eastward and westward extrema. The first observations of a complete stack of jets were the full-depth equatorial current profiles in the Indian Ocean by *Luyten and Swallow* [1976]. Their meridional, zonal, and temporal scales were then discussed by *Ponte and Luyten* [1990]. In the equatorial Pacific Ocean the jets were described by *Hayes and Milburn* [1980], *Eriksen* [1981], *Leetmaa and Spain* [1981], and *Firing* [1987]. In the Atlantic Ocean the presence of the jets has been inferred by *Eriksen* [1982] from geostrophic computation, and two profiles of direct velocity measurements have recently confirmed that analysis [*Ponte et al.*, 1990; *Böning and Schott*, 1993]. The measurements in the Pacific and Indian Oceans enabled the most complete description of the jets. The equatorial jets have similar characteristics in both oceans: the zonal velocity amplitude is ~10-20 cm s^{-1}, the jets are equatorially trapped between 1°N and 1°S, their vertical scale is about 300-400 m (from maximum to maximum), and they are zonally coherent over the maximum extent of the measurements (10° to 15° of longitude). Furthermore, *Firing* [1987] and *Ponte and Luyten* [1990] report that the jets are superimposed on a large-scale, linear, vertical shear. At present, the only published measurements showing a reversal of the jets originate from the Atlantic Ocean [*Böning and Schott*, 1993]. In the equatorial Pacific Ocean the longest time series of deep equatorial velocity profiles ever realized (16 months) did not show any reversal of the jets [*Firing*, 1987]. However, recently, jets with opposite direction have been observed in the western Pacific, at 150°W, between June and January (E.Firing, personal communication, 1998). To our knowledge, no such observation was made in the Indian Ocean, but measurements are not adequate to exclude such behavior. In Figure 1, redrawn from *Böning and Schott* [1993], jets of vertical extent of ~300 m are seen with maximum amplitude at 750, 950, 1300, and 1800 m depth. The reversal of the current associated with these jets and the large-scale flow in which they are embedded are visible from the two profiles taken in January 1989 and June 1991. As the two profiles were made in two opposite seasons, the hypothesis of a seasonal variability has been put forward, although they were sampled at a 2-year interval. Using a high-resolution model of the equatorial Atlantic Ocean forced by the wind, *Böning and Schott* [1993] showed that the simulated deep currents oscillate at an annual period. It must be noted that the model creates deep currents with a larger vertical

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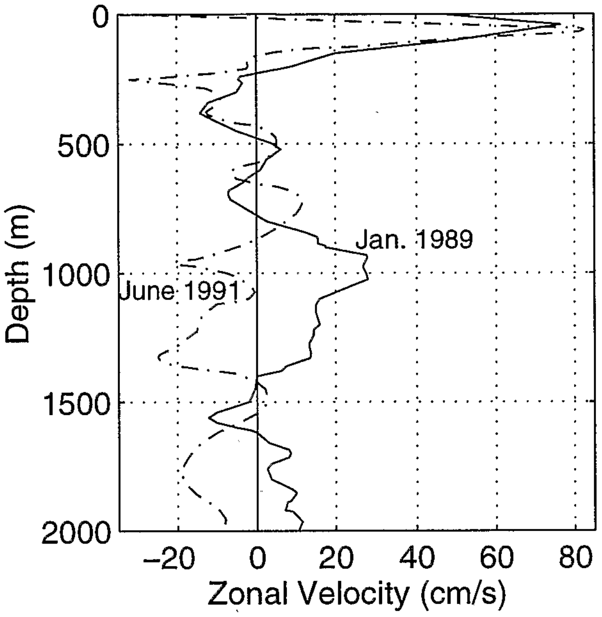

Figure 1. Depth profile of the zonal component of velocity, in cm s^{-1}, at 0°-30°W, in January 1989 [*Ponte et al.*, 1990] and in June 1991 [*Böning and Schott*, 1993] (redrawn from Figure 2 of *Böning and Schott* [1993]).

scale than the stacked jets observed in the ocean. *Richardson and Schmitz* [1993], using SOFAR floats in the equatorial Atlantic Ocean, observed a westward reversal of the current at 1800 m depth after 18 months, but this "period" has to be taken with caution, as the float trajectories have been averaged in a 5° latitude wide box centered on the equator, much wider than the meridional scale of the jets reported in the Pacific and Indian Oceans.

The deep jets in the equatorial Atlantic Ocean could play a key role in the interhemispheric exchange of heat and mass. *Richardson and Schmitz* [1993] began to explore the connection between the Deep Western Boundary Current, which flows southward between 1000 and 4000 m along the American continental slope, and the equatorial current system. They suggest that the eastward equatorial tongue of chlorofluorocarbon F-11 observed at 1700 m by *Weiss et al.* [1985] (see also *Andrié et al.* [1998]) is the result of a branching of the Deep Western Boundary Current (DWBC) at the equator. *Richardson and Schmitz* [1993, p.8384] suggest that "the equatorial current system acts as a temporary reservoir for the DWBC water," but we note that the vertical scale of the jets is an order of magnitude smaller than the vertical scale of the Deep Western Boundary Current. This scale mismatch, together with the observed reversals of the jets, indicates that the jets are not the part of the equatorial current system that is most directly connected to the Deep Western Boundary Current system.

The new deep velocity profiles presented in this paper show, for the first time, the existence of deep jets in the middle of the basin, resolve their meridional scale, and confirm the reversal of the deep currents already observed by *Böning and Schott* [1993].

The paper is organized as follows. In section 2 we present the data, then we describe the vertical, zonal, meridional, and temporal scales of the deep jets in section 3. We summarize and discuss the results in section 4.

2. Data

The deep velocity measurements presented in this paper were acquired during the Romanche 3, Cither 1, and Etambot 2 cruises using a Pegasus profiler [*Spain et al.*, 1981], or a lowered acoustic Doppler current profiler attached to a rosette (LADCP).

During Cither 1, in January-March 1993, seven Pegasus velocity profiles were made in the western equatorial Atlantic Ocean along 35°W (Figure 2). The processing of the raw data was done at the Institut für Meereskunde, Universität Kiel. Downcast and upcast have been averaged and subsampled every 10 m. The errors on the measurements rarely exceed 10% of the velocity at the surface, 5% for the intermediate layers (where the stratification is maximum), and 2% in the deep waters [*Colin et al.*, 1994].

Twenty-six LADCP profiles were made in October-November 1994, in the central equatorial Atlantic Ocean

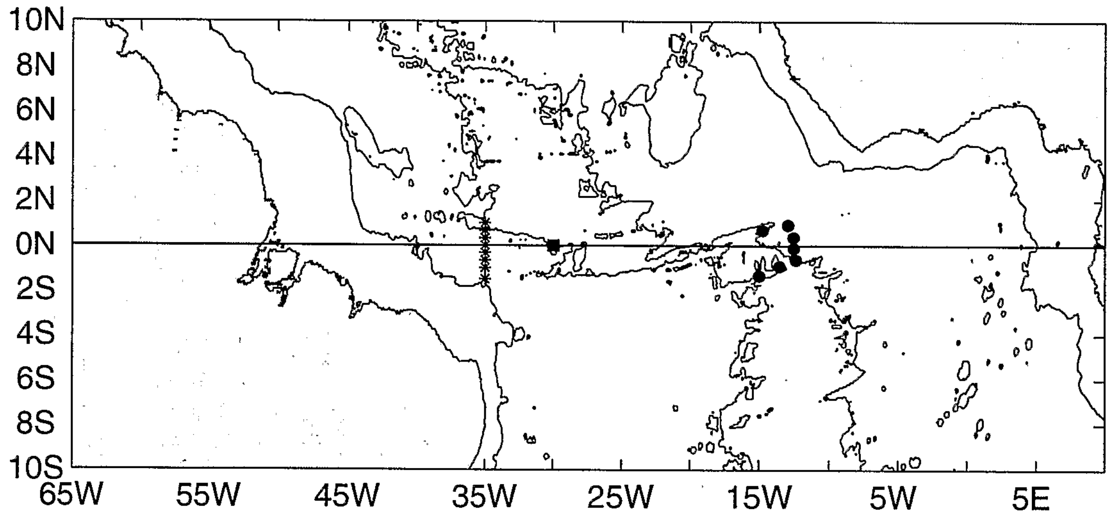

Figure 2. Position of the velocity profiles. Symbols denote the following : asterisks, Cither 1 and Etambot 2 profiles; circles, Romanche 3 profiles; and squares, *Ponte et al.* [1990] and *Böning and Schott* [1993] profiles.

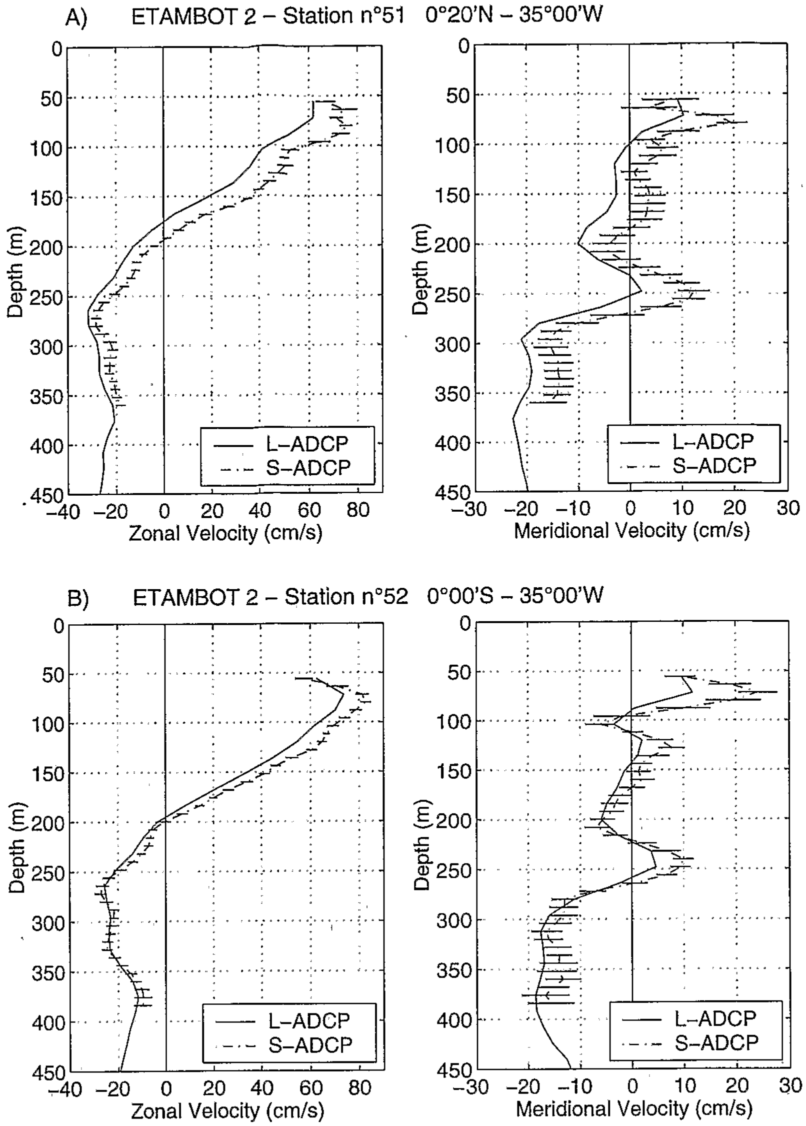

Figure 3. Zonal and meridional components of velocity in cm s^{-1}. Comparison between lowered acoustic Doppler current profiler (LADCP) (solid line) and ship-mounted acoustic Doppler current profiler (SADCP) (dashed line) measurements, for (a) station 51 at 0°20'N-35°W on April 29, 1996, and (b) station 52 at 0°-35°W on April 29, 1996. The SADCP velocity profile is the average over the duration of the conductivity-temperature-depth (CTD) station (about 3 hours). The small horizontal lines superimposed on the SADCP profiles are the standard deviation around the mean.

(1°30'S-1°N, 12°W-16°W) during the Romanche 3 cruise [*Mercier*, 1997] (Figure 2). Eighty-nine LADCP profiles were made in April-May 1996, in the western equatorial Atlantic Ocean (5°S-7°30'N, 35°W-53°W) during the Etambot 2 cruise [*Chuchla et al.*, 1997] (Figure 2). During both Romanche 3 and Etambot 2 cruises the LADCP was a broadband 150-kHz instrument manufactured by RD Instruments. Data have been processed following the method described by *Fischer and Visbeck* [1993]. The nominal thickness of a measurement cell was 16 m. As the LADCP had no pressure sensor, the depth of each cell was computed by integrating the vertical velocity measurements over the downcast and upcast. At the end of the integration the calculated depth should be equal to the known depth of the conductivity-temperature-depth (CTD) package at the surface. If this is not the case, the error is corrected by linearly distributing the difference between the two depths over the upcast and downcast. For the Etambot 2 equatorial stations the mean error was equal to 35 m (standard deviation equal to 30 m) with a maximum error of 82 m found at station 49 and a minimum error equal to 3 m at station 50. The precision of the LADCP measurements is difficult to evaluate. The error in the vertically averaged current, using Global Positionning System (GPS) measurements, was estimated as about 1 cm s^{-1} [*Fischer and Visbeck*, 1993]. *Fischer and Visbeck* [1993] indicated that the main source of uncertainty in velocity at any given depth came from errors in the estimation of the vertical shear and that the editing part of the treatment is essential. During the Etambot 2 cruise an independent velocity measurement came from the ship-mounted ADCP (SADCP) that extended to 300 m depth. The SADCP profiles have been systematically compared to the LADCP ones in order to detect any bias in the measurements. Figure 3 displays the comparison of profiles at 0°20'N-35°W (station 51) and 0°-35°W (station 52). The vertical shears obtained by the two methods are quite comparable. The maximal velocity difference is observed in the surface layer with values as large as 10-20 cm s^{-1}, above 150 m. Below 200 m the difference between the two types of measurement is close to zero for the equatorial station (Figure 3b), while there is a bias of 5 cm s^{-1} for the 0°20'N profile (Figure 3a). Those figures are representative of the comparisons made for the 89 profiles of the Etambot 2 cruise.

3. Description of the Deep Jets

3.1. Vertical Scale

The LADCP zonal velocity profile obtained at the equator-35°W, during the Etambot 2 cruise on April 29, 1996, displays a complex vertical structure with alternating minima and maxima of velocity (Figure 4). The strong eastward flowing current at 80 m depth is the Equatorial Undercurrent. The westward flowing current just below it is the Equatorial Intermediate Current. Using LADCP measurements along 35°W, *Schott et al.* [1995] observed that the westward flowing current extends from 200 m down to 800 m. The Etambot 2 profile clearly shows that, at the time of the measurements, this current consists of two maxima, at 250 and 500 m. Below these two known features of the equatorial circulation, we observe alternating maxima and minima of velocity, the "stacked jets." The strongest jet is observed at 1300 m with a westward velocity of 20 cm s^{-1}. The vertical scale of the jets increases with depth. Between 500 and 2500 m, consecutive maxima of westward velocities are 400 to 600 m apart. In the Atlantic Ocean the vertical scale is larger than in the Pacific Ocean, where consecutive maxima are 250 to 400 m apart [*Firing*, 1987]. Note that between 200 and 2000 m the current is mainly westward; the jets are superimposed on a large-scale linear, vertical shear. Below 2500 m, currents with velocities between 5 and 10 cm s^{-1} are observed. As their meridional and zonal coherence is small, they will not be considered in this paper.

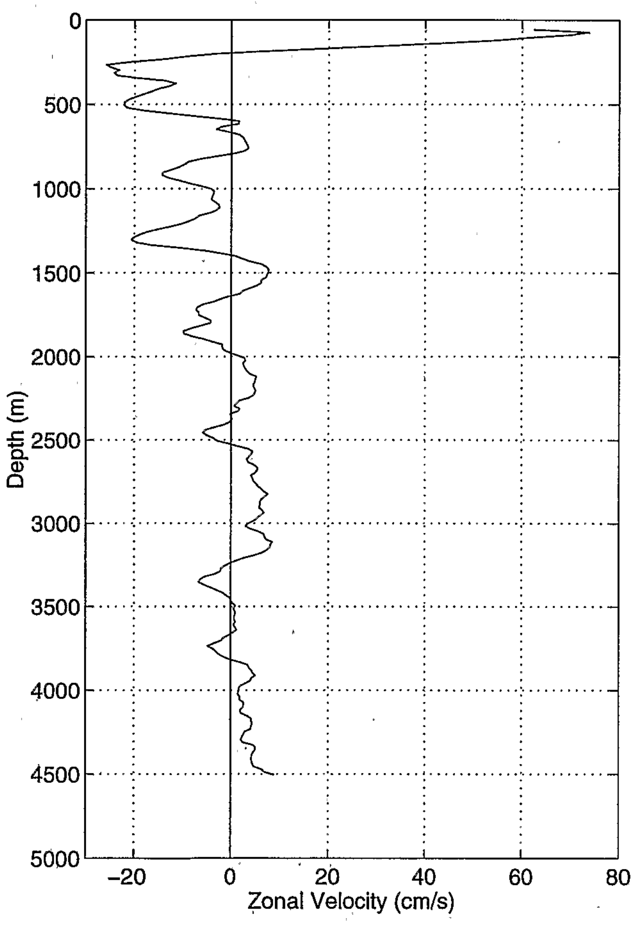

Figure 4. Depth profile of the zonal component of velocity, in cm s^{-1}, at 0°-35°W, on April 29, 1996, during the Etambot 2 cruise.

The similarity between the Etambot 2 velocity profile, at 0°-35°W in May 1996, and the velocity profile of *Böning and Schott* [1993], at 0°-30°W in June 1991, is striking (Figures 1 and 4). The two profiles present the same short vertical scale with the maxima and minima observed at the same depths. Only the jet observed at 500 m on the Etambot 2 velocity profile does not appear on the June 1991 one. Therefore, in June 1991, the vertical extent of the Equatorial Intermediate Current is greatly reduced. As the behavior of the 500-m jet differs from the 250-m one, we here restrict the "Equatorial Intermediate Current" denomination to the permanent westward flowing jet observed at 250 m.

3.2. Zonal Scale

In the Pacific Ocean the deep current profiles presented by *Leetmaa and Spain* [1981] show that the deep jets are identifiable over 10° to 15° longitude, but each individual jet is not clearly traceable over the entire section, i.e., 34° of longitude. In the Indian Ocean, too, the deep jets can be traced over 10° to 15° of longitude, the maximum extent of the measurements [*Ponte and Luyten*, 1990]. In the Atlantic Ocean, no synoptic measurements have been made at different longitudes yet. We present in Figure 5 a velocity profile made in the center of the Atlantic Basin at 0°22'N-12°35'W on November 7, 1994, during the Romanche 3 cruise (dashed line) and compare it with the profile made at 0°20'N-35°W on April 29, 1996 (solid line). These two profiles, which are separated by 22° of longitude and were realized at a 16-month interval, have the same short-vertical-scale structures between the surface and 2500 m. Below 2500 m the vertical shears of velocity are hardly comparable between the two profiles. Although the two profiles are not synoptic, the deep jets present extrema of zonal velocity located at almost the same depths. The vertical shift of the position of the jets between the two profiles is estimated to 85 m with a standard deviation of 28 m. We draw attention to the fact that the large-vertical-scale current, in which the jets are embedded above 2500 m, has opposite sign, westward at 35°W and eastward at 12°35'W. So while the jets observed around 700 and 1000 m have an eastward component on the Romanche 3 profile, they have a near-zero velocity on the Etambot 2 profile (Figure 5). These measurements might suggest that the zonal scale of the jets in the Atlantic Ocean is comparable to the one observed in the Indian and Pacific Oceans.

3.3. Seasonal Variability?

Two deep velocity profiles obtained in the Atlantic Ocean at 0°-30°W, at opposite seasons and different years (in

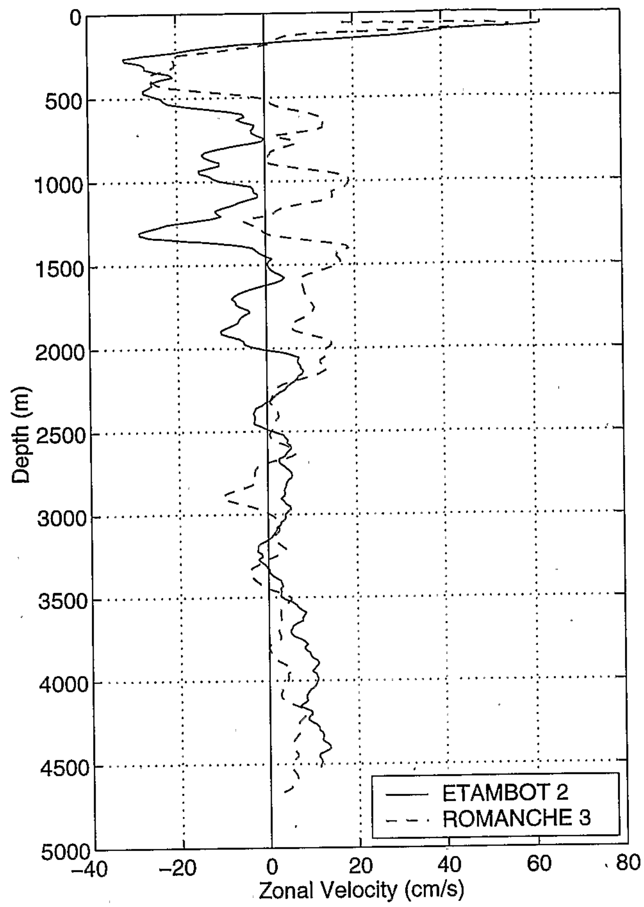

Figure 5. Depth profiles of the zonal component of velocity in cm s^{-1} from the Etambot 2 cruise, 0°20'N-35°W, on April 29, 1996 (solid line), and the Romanche 3 cruise, 0°20'N-13°W, on November 7, 1994 (dashed line).

January 1989 [*Ponte et al.*, 1990] and in June 1991 [*Böning and Schott*, 1993]), display the jets with opposite direction (Figure 1). A high-resolution model of the Atlantic Ocean forced with seasonally varying winds revealed that the simulated deep currents also reversed at an annual period [*Böning and Schott*, 1993]. Although the modeled jets have larger vertical scales (~1000 m) than those observed in the ocean, the question of the seasonal reversal of the jets is raised. The Cither 1 and Etambot 2 velocity profiles provide new evidence of the opposite direction of the deep jets, at two different seasons, in the equatorial Atlantic Ocean (Figure 6). The Cither 1 cruise occurred in February when the InterTropical Convergence Zone (ITCZ) is close to the equator and the equatorial winds are low, whereas the Etambot 2 cruise took place in May when the ITCZ had migrated northward, strengthening the winds at the equator. We then consider that these two cruises took place at two different seasons (but at a 3-year interval). Between 500 and 2000 m depth, the jets during the Cither 1 cruise have opposite directions to those observed during the Etambot 2 cruise. Only the jet at 2200 m depth has not reversed. As the comparison made by *Böning and Schott* [1993] only extends to 2000 m, we have no other information on the behavior of that 2200 m jet (Figure 1). The Etambot 2 and Cither 1 velocity profiles show that the jets have the same vertical scale. This is not clear in the comparison made by *Böning and Schott* [1993] since two westward jets are observed in June 1991, at 900 m and 1300 m depth, when one large, vertical-scale eastward current is measured in January 1989, between 800 and 1400 m (Figure 1). We think that the January 1989 velocity profile was made in a "transitory" period when some jets were not fully developed (i.e., the 1300-m jet).

Note that the Equatorial Undercurrent at 80 m depth and the Equatorial Intermediate Current at 250 m depth have not reversed. On the other hand, the jet observed at 500 m depth just below the Intermediate Equatorial Current has changed sign, confirming that at this depth there is no permanent westward flowing current (Figure 6).

It is also interesting to note that while the jets are superimposed on a large-vertical-scale westward current in the Etambot 2 profile (Figure 4) and on an eastward current in the Romanche 3 profile (Figure 5), the magnitude of this large-vertical-scale current is close to zero during the Cither 1 cruise (Figure 6). Below 2500 m the current extrema do not match among the profiles; there is no clear reversal of the currents.

3.4. Meridional Scale

The profiles of the zonal velocity component collected along 35°W during the Etambot 2 cruise, at the end of April

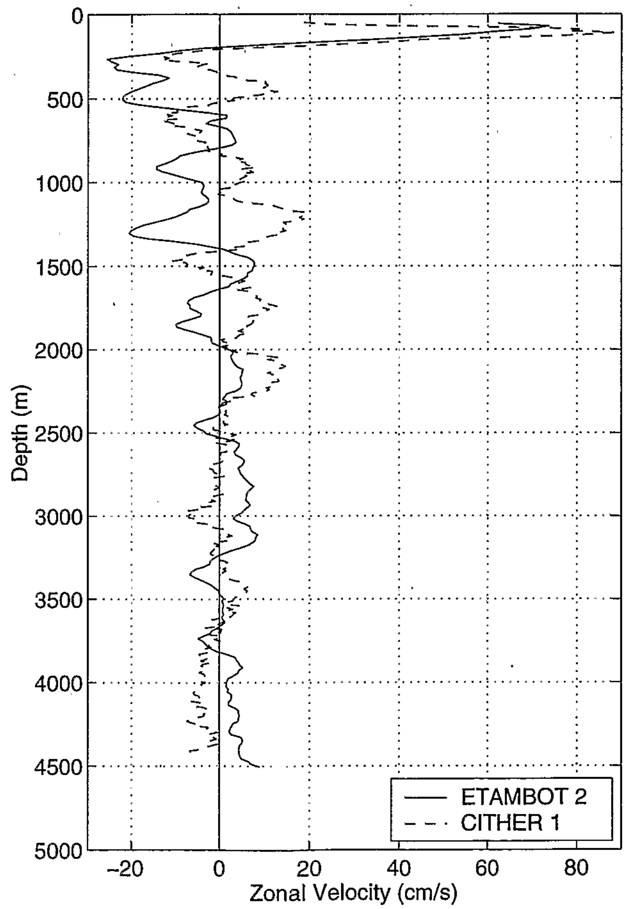

Figure 6. Depth profiles of the zonal component of velocity in cm s^{-1} from the Etambot 2 cruise, 0°N-35°W, on April 29, 1996 (solid line), and the Cither 1 cruise, 0°02'S-35°W, on February 3, 1993(dashed line).

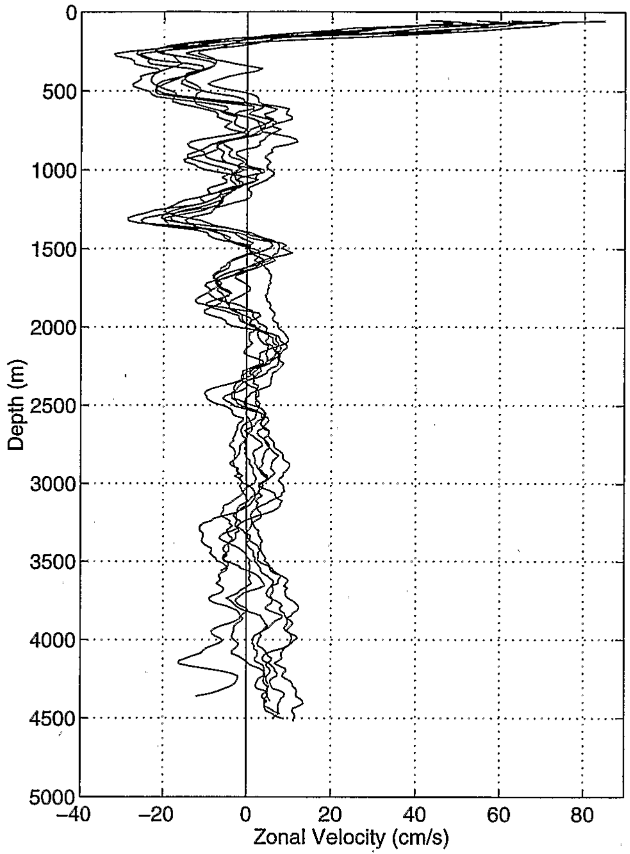

Figure 7. Depth profiles of the zonal component of velocity, in cm s^{-1}, at 35°W, at 1°N, 0.6°N, 0.3°N, 0°, 0.3°S, 0.6°S, and 1°S (April 27-30, 1996).

1996, exhibit a vertical baroclinic structure coherent between 1°N and 1°S, above 2500 m (Figures 7, 8, and 9). Only one profile, at 1°N-35°W, does not display a westward current between 1700 and 1900 m (Figures 7 and 8). The jet at 1300 m extends from 1°30'S to at least 1°N, but its northern limit is ill-defined since there are no velocity measurements between 1°N and 2°N (Figure 9). This jet is also the swiftest, with velocities greater than 25 cm s^{-1} north of the equator. The meridional extension of the jet observed at 500 m is more difficult to define, as its "signal" is blurred by the Equatorial Intermediate Current at 250 m. South of the equator, it extends clearly to 1°30'S. The velocity section confirms that the westward current below the Equatorial Undercurrent (between 1°30'S and 1°N) is made up of two distinct cores at 250 and 500 m depth (Figure 9). Note that the velocity maxima of these two cores are found north of the equator, as was also the case for the 1300-m jet. The meridional scale of the currents observed below 2500 m is narrower than the scale of jets above. For example, the two westward maxima of velocity at 3300 and 3750 m are only visible at 0°20'S and 0° (Figures 8 and 9). A striking feature of the velocity section is the position, relative to the equator, of the maxima of westward velocity; it is found north of the equator above 1700 m and south of it below 1700 m (Figure 9). However, that observation should be taken with some caution since the precision of the velocity measurements is not known accurately. The comparison between LADCP and SADCP measurements, between the surface and 300 m, shows a 5 cm s^{-1} difference (LADCP underestimates SADCP measurements) at stations 54 and 53 (the source of that bias is not known). Nevertheless, velocities larger than 10 cm s^{-1}, i.e., greater than the observed bias, are measured at 1700 and 3400 m south of the equator, at station 53. The maximum velocity of the strongest and largest jet at 1300 m is clearly situated north of the equator, as its core is captured by several stations. *Firing* [1987] remarks that the eastward jets in the equatorial Pacific Ocean are centered south of the equator and the westward jets north of it. Firing's observation is more robust because it is based on an average section. In the Indian Ocean there is no mention of a northward or southward shift of the jets, but the spatial resolution of the unique existing meridional section of deep velocity profiles was insufficient to reveal that characteristic [*Ponte and Luyten*, 1990].

It is striking to see how the profiles of velocity present the same large-scale vertical shear above 2000 m (Figure 7). That figure is astonishingly similar to the average of the velocity profiles sampled in the equatorial Pacific Ocean [see *Hua et al.*, 1997, Figure 2a].

On the section of Figure 9, known features of the equatorial Atlantic circulation are clearly visible. The Southern Intermediate Countercurrent (at 2°S-800 m) and the Northern Intermediate Countercurrent (at 1°30'N-800 m), which transport eastward the Antarctic Intermediate Water, have been described by *Schott et al.* [1995], from a section made at 35°W in March 1994. The column of eastward velocity

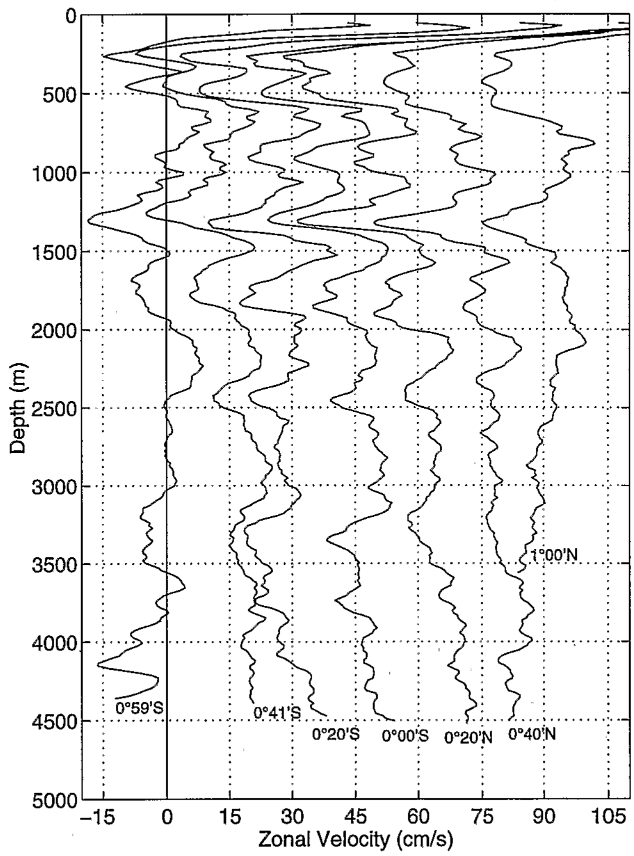

Figure 8. Depth profiles of the zonal component of velocity, in cm s^{-1}, during the Etambot 2 cruise, at 35°W (April 27-30, 1996). Each profile has been shifted by 15 cm s^{-1} from the preceding one.

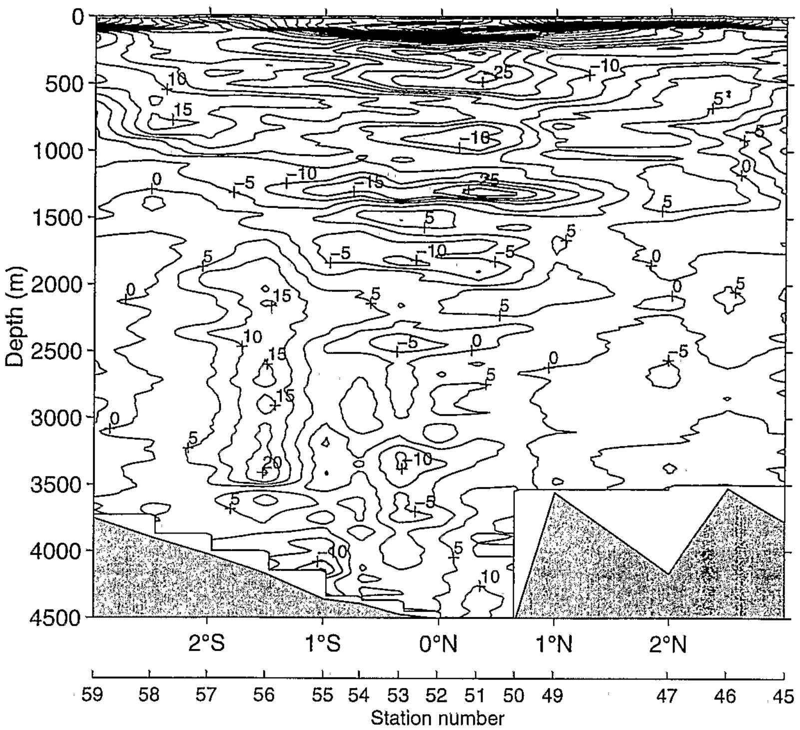

Figure 9. Latitude-depth section of the zonal component of velocity, in cm s^{-1}, along 35°W at the end of April 1996 (westward current is shaded).

centered on 1°30'S, between 1500 and 3500 m, has been identified by *Rhein et al.* [1995], always at the same longitude and on three sections, as a bifurcation of the Deep Western Boundary Current.

During Romanche 3, deep velocity profiles were made over 3° of longitude, from 14°47'W to 12°24'W, between 1°20'N and 1°S (Figure 2). The meridional coherence of the jets is not as good during that cruise compared with that along 35°W (Figure 10): for example, the 800 to 900-m jet is hardly discernable at 0°07'S, whereas it is present on the other profiles; the 1650-m and 1900-m jets are clearly visible only at 0°07'S and 0°22'N. The profile at 0°22'N presents the same short, vertical scale in the velocity structure as the one observed at 35°W, at the same latitude (Figure 5). The comparison of the other Romanche 3 profiles with those made at 35°W at the same latitude is less satisfactory. When meridionally coherent, the jets at 13°W are confined between 1°N and 1°S, as along 35°W (Figure 10). At 35°W the largest and swiftest jet located at 1300 m depth extends at least to 1°30'S (Figure 9), while at 13°W that jet does not appear on the profile at 1°20'S. Because some of the jets seen on the 0°22'N-13°W profile are not meridionally coherent, the Romanche 3 profiles do not define the meridional positions of the velocity maxima.

During the Cither 1 cruise, only four velocity profiles were made in the equatorial zone, along 35°W. The jets observed on the equatorial profile are again not visible on all profiles (Figure 11). For example, the jets at 1700 and 2200 m are not visible on the profile at 0°46'S. As was the case during the Romanche 3 cruise, the meridional coherence of the jets is not as good as observed during the Etambot 2 cruise (Figures 7 and 8).

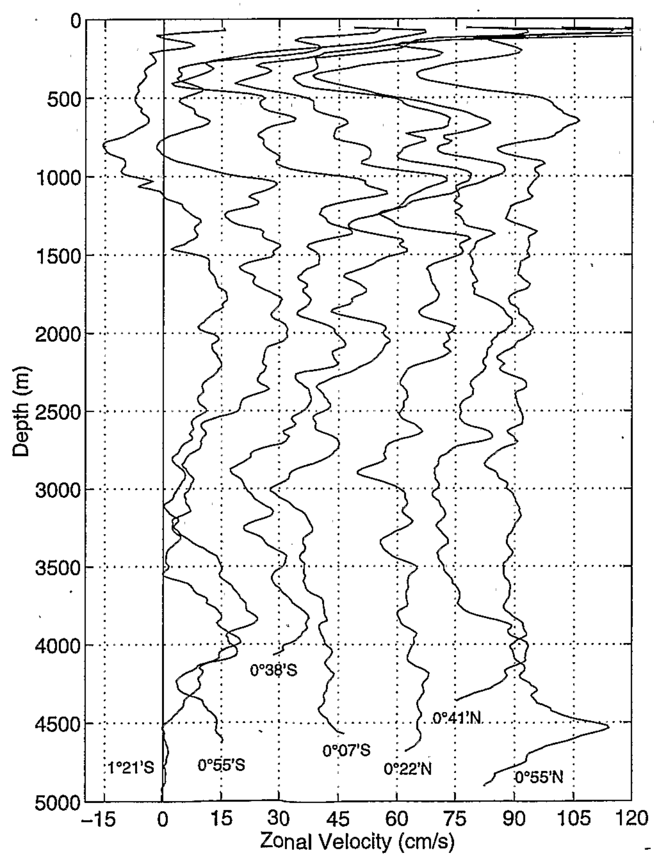

Figure 10. Depth profiles of the zonal component of velocity, in cm s^{-1}, during the Romanche 3 cruise, at 13°W (November 2–8, 1994). Each profile has been shifted by 15 cm s^{-1} from the preceding one.

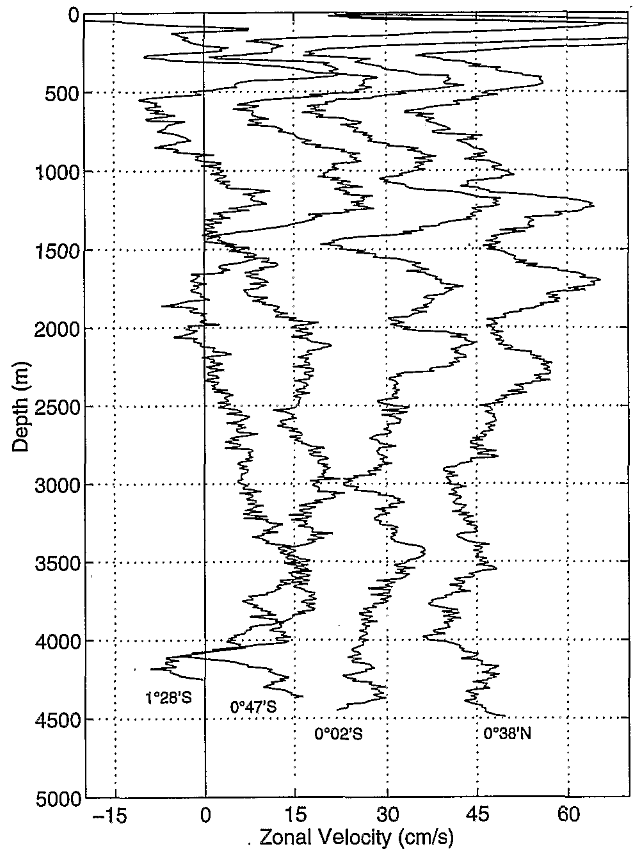

Figure 11. Depth profiles of the zonal component of velocity, in $cm s^{-1}$, during the Cither 1 cruise, at 35°W (February 3–4, 1993). Each profile has been shifted by 15 $cm s^{-1}$ from the preceding one.

The jets are present at the equator in the geostrophic calculation. We have determined the vertical profile of eastward velocity at the equator from the second derivative of the geostrophic relationship [*Hayes*, 1982]. To compute that second derivative, the dynamic height between 1°N and 1°S, corresponding to the meridional scale of the jets, has been fitted to a quadratic by using a least squares fit. The computation confirms that the small-vertical-scale jets have a geostrophic signature (Figure 12); but the comparison is far from perfect since neither the amplitude of the jets nor the amplitude and sign of the large-vertical-scale current is correct. This result is not surprising, as it is generally recommended to make the equatorial geostrophic computation with averaged profiles in order to filter out high-frequency motions such as internal waves. See *Eriksen* [1982] for a discussion on the limitation of the geostrophic computation at the equator. Nevertheless, these estimations show clearly that jets with opposite direction can be detected from the geostrophic estimation. Furthermore, *Eriksen* [1982], *Wijffels* [1993], and *Muench et al.* [1994], using averaged profiles of dynamic height, have shown the geostrophic nature of the deep jets.

4. Concluding Discussion

The new measurements presented here show that the equatorial deep jets are a common feature of the three oceans and that they share similar characteristics: they are clearly seen above 3000 m, trapped between 1°N and 1°S, and embedded in a larger vertical shear of velocity. While they are zonally coherent over at least 15° longitude in the Pacific Ocean [*Leetmaa and Spain*, 1981] and 10° longitude in the Indian Ocean [*Ponte and Luyten*, 1990], in the Atlantic Ocean our profiles might suggest that the zonal coherence could be as large as 20° of longitude (but the measurements were not synoptic). The Etambot 2 equatorial profile has a vertical scale, given by the distance between maxima of westward velocity, larger (400-600 m) than those observed in the Pacific Ocean (250-400 m) [*Firing*, 1987].

The equatorial profiles of zonal velocity are the result of the vertical combination of two different scales: a large-scale, linear, vertical shear upon which the small, vertical scale of the jets is superimposed. It is thus more accurate to describe the jets as alternating minima and maxima of velocities than alternating eastward and westward velocities. Thus if the

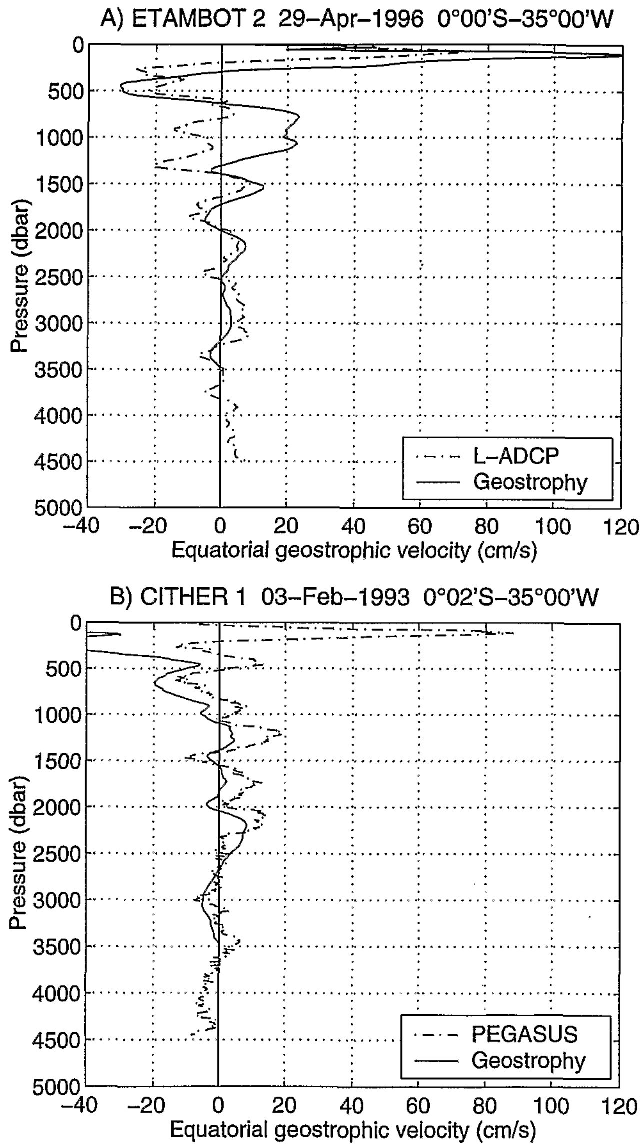

Figure 12. Comparison, at the equator, of the zonal component of velocity, in $cm s^{-1}$, measured by the LADCP (dashed line) and geostrophycally computed (solid line), for (a) Etambot 2 cruise, 0°-35°W, on April 29, 1996, and (b) Cither 1 cruise, 0°-35°W, on February 3, 1993.

vertical baroclinic structure of the zonal velocity component of the Etambot 2 and Romanche 3 equatorial profiles is similar between 500 and 2000 m depth, the observed short-scale jets are embedded in a westward current during Etambot 2 and in an eastward current during Romanche 3. That superimposition of scales has already been noted in the Pacific Ocean by *Firing* [1987] and in the Indian Ocean by *Ponte and Luyten* [1990]. *Firing*'s [1987] profiles, in the Pacific Ocean, are clearly embedded in a westward flow at the beginning of the measurements, in April-July 1982, and in an eastward flow at the end of the measurements, in April-July 1983 [see *Muench et al.*, 1994, Figure 3]. *Luyten and Swallow* [1976] also reported that in the Indian Ocean the amplitude of the first baroclinic mode nearly doubled over 1 month of measurements. At present, no time series of measurements is sufficiently complete to determine the period of variation of this large-scale vertical shear in any of the three oceans.

The profiles, showing jets with opposite direction (Figure 6), have been made 3 years apart, but at opposite seasons. Four velocity profiles made on different years are not sufficient to discriminate between intra-annual or interannual variability in the equatorial Atlantic Ocean. SOFAR float trajectories launched at 1800 m depth in the equatorial Atlantic Ocean clearly show that, between 1°N and 1°S, the westward or eastward drift lasts at least several months [*Richardson and Schmitz*, 1993]. This is an indication that the persistance of the large-vertical-scale current plus that of the deep jets is at least several months. Unfortunately, these floats are of no help to determine the seasonal cycle of the 1800-m depth current, as they sank owing to a deformation of their pressure housing and as their exact depth was unknown [*Richardson and Schmitz*, 1993]. Subtracting the large-scale vertical shear from the Etambot 2 and Cither 1 profiles reveals that the amplitude of the opposite jets, at a given depth, is very similar. The close amplitudes of the jet plus the position of the node (minimum of velocity) could indicate that the reversal of the jets occurs in place. (one of the reviewers does not share that view and does not see how those observations in any way distinguishes in place reversal (standing wave), from a vertical propagation.) This is visually evident for the 1300-m jet, which has the same absolute magnitude (20 cm s^{-1}) but an opposite direction, in February 1993 and in May 1996 (Figure 6). In the Pacific Ocean, *Firing* [1987] compares a mean equatorial velocity profile at 159°W-0°, averaged from March 1982 through June 1983, to a velocity profile made in March-April 1980 at the same location [*Leetmaa and Spain*, 1981]. He shows that the jets of both velocity profiles coincide if one of the profiles is vertically shifted downward by 130 m or upward by 220 m; but the data at hand did not allow these authors to deduce a steady vertical phase propagation, and we cannot dismiss that hypothesis for the observations in the equatorial Atlantic Ocean.

Richardson and Schmitz [1993] hypothesized that the variations in the Deep Western Boundary Current transport are linked to the low-frequency variations in the direction of the equatorial currents. The Deep Western Boundary Current in the Atlantic Ocean has a vertical scale that is comparable to the large-scale vertical shear superimposed on the deep jets [*Rhein et al.*, 1995; *Fischer and Schott*, 1997]. We therefore suggest that the Deep Western Boundary Current will be more closely related to the variation of that large-scale vertical shear than to the deep jets.

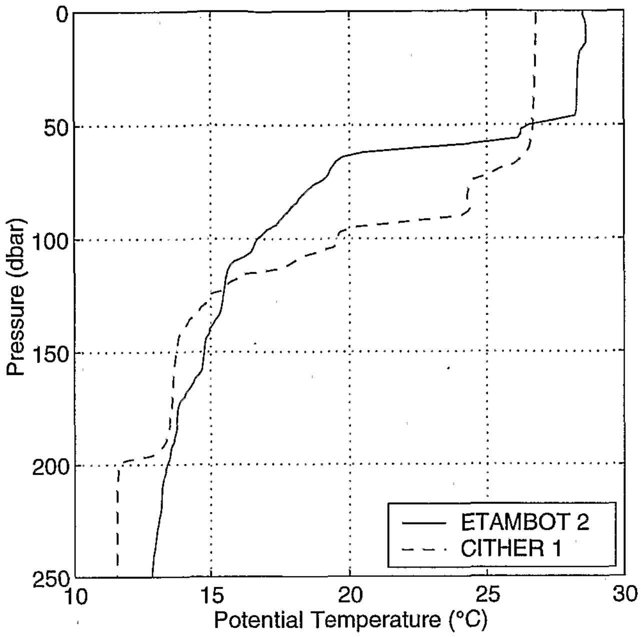

Figure 13. Depth profile of temperature at 0°N-35°W for Etambot 2 cruise on April 29, 1996 (solid line) and Cither 1 cruise on February 3, 1993 (dashed line).

At present, three types of interpretation have been put forward to explain the presence of the deep jets in the equatorial oceans: in terms of linear equatorial waves [*Luyten and Swallow*, 1976; *Eriksen*, 1981; *McCreary*, 1984; *O'Neill and Luyten*, 1984; *Ponte*, 1988; *Ponte and Luyten*, 1989; *Muench et al.*, 1994], in terms of forcing by the Deep Western Boundary Current [*Kawase*, 1987; *Kawase et al.*, 1992], and in terms of bifurcation from a state without jets to a state with small vertical jets [*Hua et al.*, 1997]. The first two types of explanations, reviewed by *Muench et al.* [1994] and *Hua et al.* [1997], are not conclusive, as they fail to explain how the jets can equilibrate. The interpretation of *Hua et al.* [1997] explains the existence of the deep jets through the mechanism of inertial instability and shows that the large-scale vertical shear superimposed on the jets is necessary to balance the horizontal Coriolis parameter in the Ertel vorticity expression, taking into account the horizontal Coriolis parameter in the vertical momentum equation. *Hua et al.*'s [1997] theory is also able to explain why the westward jets are displaced north of the equator onto the "dynamical equator" (the center of symmetry of the mean flow). *Hua et al.*'s [1997] theory was mainly motivated by the long time series measurements made in the Pacific Ocean presented by *Firing* [1987]. The measurements made in the three oceans require an extension of that theory to explain how the jets can change direction at different times and how they can accommodate the variability of large-scale vertical shear. There is some presumption that the reversal of the jets in the Atlantic Ocean is seasonal [*Böning and Schott*, 1993]. In the western equatorial Atlantic Ocean the northeast and southeast trade winds are separated by the ITCZ, which undergoes a north-south seasonal migration [*Servain et al.*, 1996]. The equatorial winds are the weakest in February-March, when the ITCZ is at its southernmost position, and around the equator, and are the strongest in August when the ITCZ is at its northernmost position, around 10°N. The Etambot 2 cruise took place at the end of the period of minimum wind at the equator: the thermocline is at its shallowest position (Figure 13, solid line). The Cither 1 cruise took place at the end of the period of strong equatorial southeast trade wind, and the thermocline is 40 m deeper than during the Etambot 2 cruise (Figure 13, dashed line). Whether the reversal of the jets could be triggered by the seasonal vertical displacement of the thermocline, as suggested by *Philander* [1990, chapter 4.4, p.173], is an open question.

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