The Deep Currents

in the Eastern Equatorial Atlantic Ocean

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Abstract

The deep equatorial circulation has been shown to be characterized by the vertical superimposition of alternating eastward and westward currents with short vertical scales. In the Atlantic Ocean, equatorial deep jets have been observed in the central and western equatorial basin. Here, we present three meridional velocity sections carried out in boreal summer 2000 in the eastern equatorial Atlantic. They reveal that the deep equatorial jets weaken or vanish when going eastward, toward the African coast in the Gulf of Guinea. At 10°W, the comparison with currents measured one year before, in boreal summer 1999, confirms the existence of an eastward route along the equator of part of the Deep Western Boundary Current at the level of the North Atlantic Deep Water.

Introduction

Since the observations by *Rual* [1969] of strong deep currents in the western equatorial Pacific Ocean, Equatorial Deep Jets (EDJs) have been evidenced in the three oceans [*Luyten and Swallow*, 1976; *Leetma and Spain*, 1981; *Ponte and Luyten*, 1990] and are characterized by a vertical superimposition of alternating eastward and westward currents. The mechanisms responsible for the existence of these jets and of their time fluctuations are still rather unknown [*Kawase et al*., 1992; *Muench et al*., 1994; *Send et al*., 2002]. In the same way, while *Send et al*. [2002] suggest that the EDJs may mix water mass properties across the equator, the role of the EDJs on the large scale circulation is still very poorly documented. In the Atlantic, EDJs have been described in the western and central part of the basin [*Böning and Schott*, 1993; *Gouriou et al*., 1999, 2001; *Send et al*., 2002] but no deep velocity profiles have been yet reported for the eastern equatorial Atlantic Ocean. Here, we present three top-to-bottom meridional velocity sections at 10°W, 0°E and 6°E (Plate 1). In addition to Lower Acoustic Doppler Current Profiler (L-ADCP) data, CFC measurements are used to distinguish CFC-free "old" waters from the ventilated waters, originating from the Labrador Sea or the Denmark Strait Overflow, which penetrate in the tropical Atlantic within the Deep Western Boundary Current. This paper follows up the paper of *Gouriou et al*. [2001; hereinafter referred to as *G*01], which discuss three velocity sections carried out in the western and central Equatorial Atlantic during the EQUALANT 1999 (hereafter EQ1) cruise (July-August 1999).

Data

The data presented in this paper were acquired during the EQUALANT 2000 (hereafter EQ2) cruise (July 25th to August 20th, 2000), carried out on board the R/V Thalassa, along three meridional sections at 10°W, 0°E and 6°E (Fig. 1). The zonal section at 6°S, between 6°E and the African coast is not discussed here. The 10°W section exactly repeated a section carried out in boreal summer 1999, during the EQ1 cruise [*G*01]. Note that the two 10°W sections were interrupted at 1°30N because of the lack of authorization to work within the Liberian exclusive economic zone, and they were completed to the north toward the coast of Ivory Coast along 7°W (Fig. 1). In this paper we mainly discuss top-to-bottom velocity measurements obtained with a L-ADCP attached to a rosette sampler together with a CTD probe. 86 velocity profiles were acquired with a high meridional resolution (0°20' between 1°S and 1°N, 0°30' elsewhere). Velocity measurements were processed following the method described by *Fischer and Visbeck* [1993]. CTD measurements were used to attribute a depth at each L-ADCP measurement cell as the instrument (RDI, broadband 150-kHz) has no pressure sensor. Comparisons with velocity profiles obtained with the Vessel-Mounted Acoustic Doppler Current Profiler (VM-ADCP) in the upper layers (20-750 m depth) indicate a mean difference between both types of measurements at each station rarely exceeding 4 cm s^{-1}, with standard deviation of the order of 2 cm s^{-1}. Below 750 m depth, careful inspection of the differences between the L-ADCP descent and ascent profiles let us very confident in the L-ADCP velocity measurements. Barotropic tides were removed from L-ADCP velocity data by using the OSU TOPEX/POSEIDON model version TPX O.5 [*Egbert and Erofeeva*, 2001]. Such a correction has been shown to be necessary to avoid any misinterpretation in the description of currents vertical structure and distribution. During EQ2, at 10°W, barotropic tide amplitude could reach up to 4 cm s^{-1}, while the tide phase line was almost parallel to the meridian, and successive stations occurred at opposite phases of the tidal signal (roughly every 6-7 hours). The tide correction was not applied to the EQ1 L-ADCP profiles presented by *G*01. The EQ1 L-ADCP section at 10°W reproduced here has been retreated to include the tide correction. Although the velocity amplitude of the barotropic tides was weaker in July 1999 than in July 2000, that correction suppressed some apparent vertical column structures (compare Plate 1 with the one of *G*01). Seawater samplings were taken with a 24-8l bottles rosette sampler, in order to get tracer measurements, as CFCs (CFC-11 & CFC-12; the present distributions only concern CFC-11, CFC in the following), partly presented in this study [refer to *Andrié et al*., 1999, for details about these tracers and data processing].

Results

The zonal component of velocity along 10°W (Plate 1) confirms the presence of EDJs between 1°30S and 1°30N. EDJs are observed at about the same depth ranges during EQ1 and EQ2; the strongest westward jets, with a zonal component exceeding 20 cm s^{1}, are observed around 500 m, 1000 m and 2000 m. Maximum westward velocity is measured around 1000 m for the two cruises (29.4 cm.s^{-1} at 968 m during EQ2, 26.7 cm.s^{-1} at 904 m during EQ1). Note that at this depth the 25 cm.s^{-1} isotach is wider during EQ2 than during EQ1. The most intense eastward velocities are measured around 1500 m (up to 18 cm s^{-1}) during EQ1 and around 1600 m (up to 24 cm s^{-1}) during EQ2. The EDJ vertical scale (depth difference between consecutive maxima of eastward, or westward, velocity) is about 500 m and is relatively constant with depth, at least above 2500 m.

*G*01 observed a noticeable relationship between the intensity and the latitudinal extent of the EDJs. The meridional extension of the core velocity of almost every jet is wider during EQ2 than during EQ1, and so is the meridional extension of the jets. During EQ1 the jets are confined between 1°N and 1°S while they extend to 1°30 during EQ2. As the jets maximum velocity decreases with depth from 1000 m down to about 2500 m depth, the envelope of the deep equatorial currents exhibits a V-shape centred at the equator during EQ2, with a latitudinal extent up to 3° in the upper layers. Below 2500 m depth, westward flows are more intense during EQ1 than during EQ2.

For both sections, the EDJs appear surrounded by deep eastward flowing currents, called the Extra Equatorial Jets (EEJs) by *G*01 (and earlier by *Firing et al*. [1998] in the Pacific), and referred as southern and northern jets by *Richardson and Fratantoni* [1999]. The EEJs velocity maxima are located at the same depths than the westward EDJ ones. EEJs in the northern hemisphere are less visible than in the southern one; this may be caused by the trackline, which could generate an apparent front at 1°30N on the vertical sections (Fig. 1).

*GO*1 explained why the maximum CFC concentration of the Upper North Atlantic Deep Water (UNADW), that extends eastward from the American coast to the Gulf of Guinea at 1700 m depth [*Rhein et al*., 1995; *Andrié et al*., 1998, 1999], is centered at 2°S rather than on the equator. *GO*1 showed that the relative equatorial CFC minimum concentration is probably the consequence of a higher temporal variability of the EDJs at the equator than of the EEJs at 2°S. Thus along the equator CFC concentration reflects the mixing of high CFC water advected from the West with depleted CFC water coming from the East. The striking vertical coherency between CFC and EDJ profiles described at 35°W and 23°W by *GO*1 is observed at 10°W during both cruises (Fig. 2). The maximum CFC concentration is measured at the depth of the fastest eastward jet around 1500 m. Note that CFC concentration is stronger in 2000 than in 1999 possibly indicating the eastward progression of the CFC tongue [*Andrié et al*., 1998]. The two cruises evidence that the CFC vertical distribution at the equator is strongly constrained by the EDJ variability : during EQ1 there is an eastward jet between 1900 and 2400 m associated with a CFC maximum, and during EQ2 velocity is westward from 1700 to 2250 m and the CFC maximum concentration is not visible anymore.

Farther east, at 0°E and 6°E, the deep circulation does not exhibit so clear-cut sheared vertical structures (Plate 1). At the equator, we can still observe opposite stacked zonal currents, but flows are weaker than at 10°W. Both sections indicate the existence of a westward current around 1000 m depth, slightly deeper and weaker at 6°E than at 0°E and 10°W (but at the same isopycnals, not shown), and of an eastward flow around 1600-1800 m depth with velocity values larger than 10 cm s^{-1}. The CFC cores observed at these two longitudes (not shown) clearly indicate that the eastward flow around 1600 m depth is directly linked to the intense flow observed at 10°W in the same depth and isopycnal range. Below 2000 m velocities are generally weaker than 5 cm s^{-1}, so it is hazardous to consider the changes of the current directions as significant. Thus, EDJs are present at 0°E only above 2000 m depth. EEJs, around 2°S and 2°N, are only visible at 0°E and above 1000 m depth.

Discussion

These new deep observations carried out in the Gulf of Guinea confirm that EDJs are permanent features of the equatorial circulation, and that they weaken in the eastern part of the basin in August 2000. *Muench et al.* [1994] showed that potential vorticity and zonal velocity of EDJs resembled that of a first meridional-mode long Rossby wave. Furthermore *Thierry* [2000] showed that the circulation variability reproduced by an OGCM of the tropical Atlantic Ocean is due to the vertical propagation of a first meridonal-mode long Rossby wave originating below the thermocline in the East of the basin. East of the ray path of this wave, *i.e.* in the Gulf of Guinea, the circulation is sluggish. So the weakening of the EDJ velocity and their disappearance below 2000 m in the Gulf of Guinea is in favour of the linear theory. The only previous deep current measurements carried out in the area, but limited to the upper 1800 m around 4°W [*Weisberg and Horigan*, 1981], already suggested the deep current oscillations as due to first meridional mode linear waves, but without any possibility to distinguish between Kelvin or Rossby waves.

We showed that the EDJs were observed at 10°W at about the same depths at one year interval, and the most energetic ones are found around 1000 m for westward flows and around 1500 m for eastward flows. The observation of these two energetic flows at 1000 m and 1500 m depth as far as 6°E suggests that the wave theory cannot entirely explain the presence of EDJs. An other hypothesis to explain the existence of EDJs is the inertial instability theory, through a nonlinear equilibration of the equatorial flows, in the presence of asymmetry of the zonal flow around the equator [*Hua et al*., 1997; *Send et al*., 2002]. Such a theory suggests that inertial instability may occur when the angular momentum is relatively homogeneous, *i.e.* implies a direct relationship between direction and extension of the jets and the Ertel potential vorticity. Figure 3 presents the dominant term of the angular momentum integrated according to the latitude. It shows that this term is quasi-constant within westward EDJs, meaning that the zonal flow (u) is equilibrated by the planetary vorticity ($f_{*}y$), in agreement with the theory [*Hua et al*., 1997]. An other argument in favor of this theory lies on the fact that the intensity of the westward EDJs is related to their latitudinal extension, yielding to the V-shape of the EDJs envelope. This kind of interpretation however cannot explain the absence of stacked jets in the far eastern part of the basin (*i.e.* at 6°E). We cannot exclude an intermittent relaxation of the jets during EQ2 (as documented at relatively low frequency in *Hua et al*., 1997 and *Send et al*., 2002) but it is tempting to interpret the EDJ dynamics as the result of both inertial effects and waves propagation. It is worth noting that the existence and dynamics of the EDJs and EEJs seem closely related : the maximum westward (eastward) EDJs are associated with maximum (minimum) EEJs (see also *G*01), and both the EDJs and the EEJs disappear in the far east of the basin.

All these considerations do not take into account possible topographic induced processes : the African coast proximity, and the presence of the São Tomé Island, located around 6°30'E on the equator, may dramatically perturb the circulation at the equator. Actually, EDJ analysis through CTD observations carried out in the eastern Pacific Ocean suggests that the EDJs are more easily seen in this part of the basin that in the west, where their observation may be perturbed by the presence of shorter period Rossby waves [*Johnson et al*., 2002]. Thus the influence of São Tomé Island, very close to our 6°E section, on the equatorial circulation has obviously to be investigated. It is interesting to note here that significant westward flows are present from about 2500 m depth down to the bottom between 1°S and 3°S, both at 6°E (Plate 1) and at 86°W in the Pacific [*Firing et al*., 1998; their Fig.7]. Both flows are present just south of a bottom relief, the São Tomé Island in the Atlantic and the Carnegie Ridge in the Pacific.

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References

Andrié, C., J. F. Ternon, M. J. Messias, L. Memery and B. Bourlès, Y. Gouriou, and C. Oudot, Chlorofluoromethane distributions in the deep equatorial Atlantic during January-March 1993, *Deep-Sea Res., I 45, C9,* 903-930, 1998.

Andrié, C., J. F. Ternon, B. Bourlès, Y. Gouriou, and C. Oudot, Tracer distributions and deep circulation in the western tropical Atlantic during CITHER1 and ETAMBOT cruises (1993-1996), *J. Geophys. Res., 104, C9,* 21,195-21,215, 1999.

Böning, C.W., and F.J. Schott, Deep currents and the eastward salinity tongue in the equatorial Atlantic: results from an eddy-resolving, primitive equation model, *J. Geophys. Res., 98,* 6991-6999, 1993.

Egbert, G. D., and S. Y. Erofeeva, Efficient inverse modeling of barotropic ocean tides, *submitted to J. Atmos. Oc. Technol.*, 2001.

Firing, E., S. E. Wijffels, and P Hacker, Equatorial subthermocline currents across the Pacific, *J. Geophys. Res., 103*, 21413-21423, 1998.

Fischer, J., and M. Visbeck, Deep velocity profiling with self-contained ADCPs, *J. Atmos. Oc. Technol., 10(5),* 764-773, 1993.

Gouriou, Y., B. Bourlès, H. Mercier, and R. Chuchla, Deep jets in the equatorial Atlantic Ocean, *J. Geophys. Res., 104*, 21,217-21,226, 1999.

Gouriou, Y., C. Andrié, B. Bourlès, S. Freudenthal, S. Arnault, A. Aman, G. Eldin, Y. DuPenhoat, F. Baurand, F. Gallois, and R. Chuchla, Deep circulation in the Equatorial Atlantic Ocean, *Geophys. Res. Letters, Vol. 28 , No. 5* , 819-822, 2001.

Hua, B. L., D. W. Moore, and S. Le Gentil, Inertial non-linear equilibration of equatorial flows, *J. Fluid Mech., 331*, 345-371, 1997.

Johnson, G. C., E. Kunze, K. E. McTaggard, and D. W. Moore, Temporal and Spatial Structure of the Equatorial Deep Jets in the Pacific Ocean, *submitted in J. Phys. Oceanogr.*, 2002.

Kawase, M.L., M. Rothstein, and S.R. Springer, Encounter of a deep western current with the equator: a numerical spin-up experiment. *J. Geophys. Res., 97*, 5,447-5,463, 1992.

Kessler, W. S., and J. P. McCreary, The annual wind-driven Rossby wave in the subthermocline equatorial Pacific, *J. Phys. Oceanogr., 23,* 1,193-1,207, 1993.

Leetmaa, A., and P.F. Spain, Results from a velocity transect along the equator from 125 to 159°W, *J. Phys. Oceanogr., 11*, 1,030-1,033, 1981.

Luyten, J.R., and J.C. Swallow, Equatorial undercurrents, *Deep-Sea Res., 23*, 999-1001, 1976.

Muench, J., E. Kunze, and E. Firing, The potential vorticity structure of Equatorial Deep Jets, *J. Phys. Oceanogr., 24*, 418-428, 1994.

Ponte, R.M. and J. Luyten, Deep velocity measurements in the western equatorial Indian ocean, *J. Phys. Oceanogr., 20*, 44-52, 1990.

Ponte, R.M., J. Luyten, and P.L. Richardson, Equatorial deep jets in the Atlantic Ocean, *Deep-Sea Res., 37*, 711-713, 1990.

Rhein, M., L. Stramma, and U. Send, The Atlantic deep western boundary current: Water masses and transports near the equator. *J. Geophys. Res., 100*, 2,441-2,457, 1995.

Richardson, P.L., and D.M. Fratantoni, Float trajectories in the deep western boundary current and deep equatorial jets of the tropical Atlantic, *Deep-Sea Res. II, 46*, 304-333, 1999.

Rual, P., Courant équatoriaux profonds, *Deep-Sea Res., 16*, 387-391, 1969.

Send, U., C. Eden, and F. Schott, Atlantic Equatorial Deep Jets : space/time structure and cross-equatorial fluxes, *J. Phys. Oceanogr., in press*, 2002.

Thierry, V., Observation et modélisation de la variabilité saisonnière dans l'océan Atlantique Equatorial profond, *Thèse de doctorat, Université de Brest, UBO 701*, 211pp, 2000.

Weisberg, R. H., and A. M. Horigan, Low-frequency variability in the Equatorial Atlantic, *J. Phys. Oceanogr., 11*, 913-920, 1981.

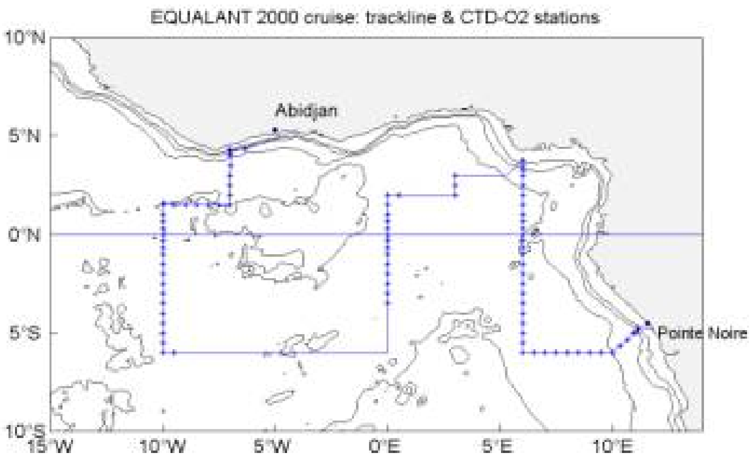
Figure captions

Figure 1. Track of the EQUALANT 2000 cruise July, 25th to August 20th, 2000. The dots indicate the position of the CTD-O_2 and L-ADCP stations.

Figure 2: Vertical profiles of the zonal component of the current velocity (green line) and CFC-11 concentration (red line), as measured at 10°W-0°N in boreal summer 1999 (left) and 2000 (right).

Figure 3. Fonction ($^2y^2/2 - u$), representative of the angular momentum, according to the latitude (between 2°S and 1°30’N) along the section 10°W, at the depths of the three most intense EDJs observed around 500 and 1000 m depth (westward jets; dark and light blue, purple and pink lines) and around 1500m depth (eastward jet; yellow and brown lines) during Equalant 99 and Equalant 2000.

Plate 1: Latitude-depth sections of the zonal component of velocity, in cm s^{-1}, along the meridian 10°W, as observed in August 1999 (top left) and July 2000 (top right), and along the meridian 0°E (bottom left), and 6°E (bottom right), as observed in August 2000. Eastward (westward) currents are positive (negative). Contour interval is 5 cm s^{-1}.



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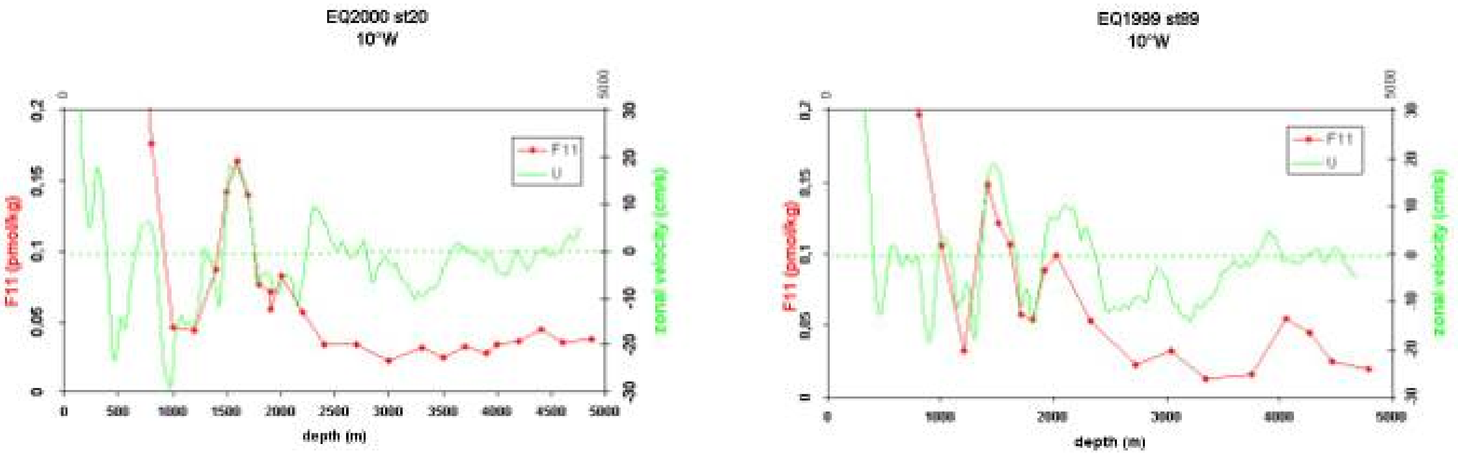

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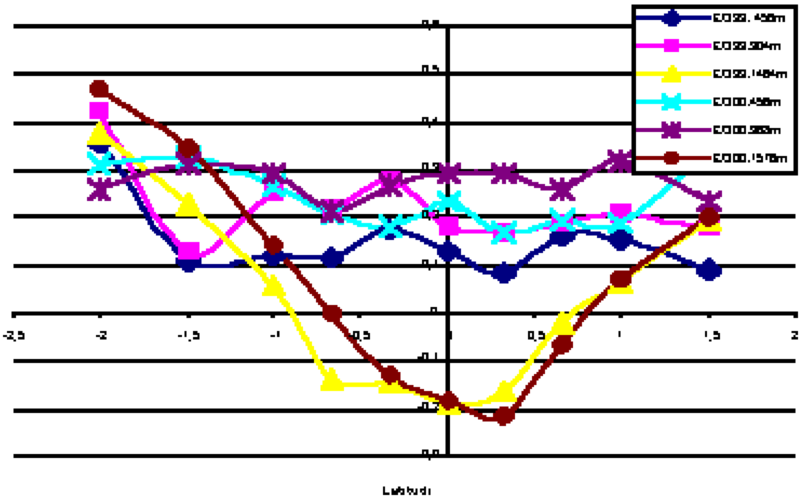

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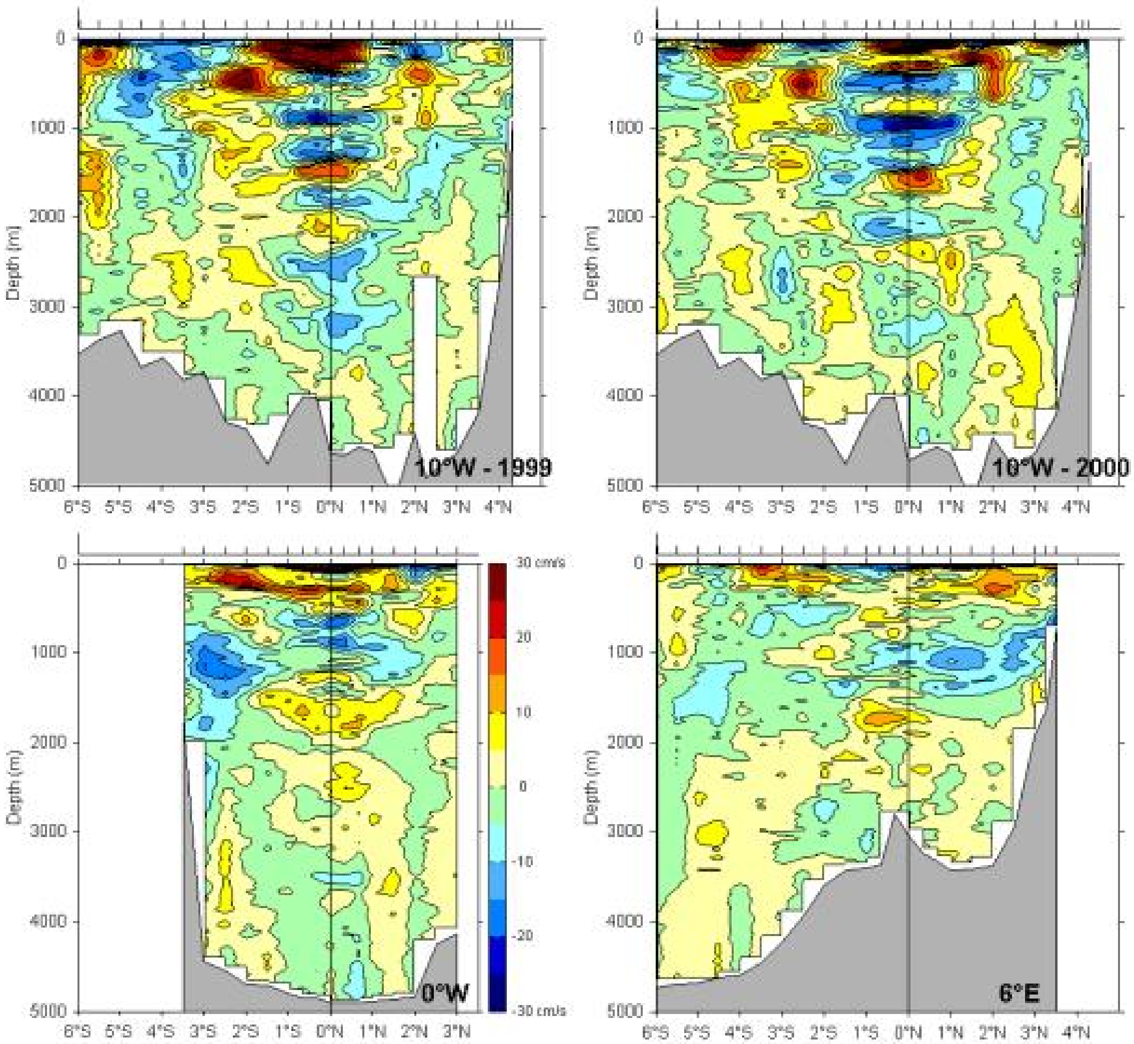

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