GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 5, PAGES 819-822, MARCH 1, 2001

Deep Circulation in the Equatorial Atlantic Ocean

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Abstract. In the Atlantic Ocean, the northward export of warm surface water is compensated by a southward flow of cold North Atlantic Deep Water (NADW). The NADW is transported southward along the American continental margin within the Deep Western Boundary Current (DWBC). Some tracer and float observations have shown that part of the DWBC water flows eastward along the equator. Here we present three meridional velocity sections which give an instantaneous image of the top-to-bottom zonal circulation along the equatorial Atlantic. They reveal the presence of Equatorial Deep Jets (EDJs) between 1°30'N and 1°30'S, alternating eastward-westward currents with short vertical scale, surrounded by columns of eastward currents (the Extra Equatorial Jets or EEJs) at 2°N and 2°S. In addition to direct velocity measurements, tracer distributions give indications of water-mass feeding of the EDJs and EEJs by the DWBC.

Introduction

In the Atlantic Ocean, the southward flowing DWBC transports the cold NADW (lower than 4°C below 1000 m), formed by convection in the northern polar and subpolar regions, along the continental margin of the American continent. This equatorward flow of deep water is compensated by a northward flow of warm surface water (0-1000 m). This thermohaline circulation cell generates a net positive heat flux toward the northern hemisphere, and is a major component of the world climate system [*Broecker*, 1991]. The newly convected NADW is characterised by maximum concentration of chlorofluoromethanes (CFCs) [*Weiss et al.*, 1985] at the density levels of the Upper NADW (UNADW) (around 1700 m-depth), originating in the Labrador Sea, and of the Lower NADW (LNADW) (around 3800 m-depth), flowing from the Denmark Strait Overflow. High CFC concentrations indicate the NADW path, within the DWBC, from its origin to the equatorial region: part of the NADW flows southward in the southern hemisphere while the other portion splits off and extends eastward along the equator [*Weiss et al.*, 1985; *Rhein et al.*, 1995; *Andrié et al.*, 1998]. The complexity of the equatorial circulation was revealed by deep velocity profiles made in the three oceans [*Firing*, 1987; *Ponte et al.*, 1990; *Ponte et Luyten*, 1990]. They showed the presence of vertically alternating eastward and westward currents with short vertical scale, the Equatorial Deep Jets (EDJ). The sparse direct top-to-bottom velocity profiles recorded in the western and central basins of the equatorial Atlantic have identified EDJs [*Ponte et al.* 1990; *Böning and Schott*, 1993; *Gouriou et al.*, 1999], but their three-dimensional description is far from complete. SOFAR floats tracked at 1800 m-depth evidence a 2-regime system within the tropical band [*Richardson and Fratantoni*, 1999]: EDJs between 2°N and 2°S, highly variable in time, and continuous eastward flowing Extra-Equatorial Jets (EEJ) on the northern and southern flank of the EDJs. Three top-to-bottom velocity sections are presented here; they describe the zonal circulation over the equatorial Atlantic with a high meridional resolution.

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Paper number 2000GL012326.
0094-8276/01/2000GL012326$05.00

Data

Data discussed in this paper were acquired during the EQUALANT 99 (EQ99) cruise (July 13 to August 21, 1999) along the meridians 35°W, 23°W, and 10°W (Fig. 1). The velocity profiles were made using a technique that became widely used during the World Ocean Circulation Experiment: the Lowered Acoustic Doppler Current Profiler (LADCP) [*Fischer and Visbeck*, 1993]. This current profiler, mounted on a rosette frame together with a conductivity-temperature-pressure profiler (CTD), is lowered from the surface down to the bottom of the ocean. As the LADCP has no pressure sensor, the depth of each cell is determined by using the pressure time series given by the CTD measurements. CFCs samples (CFC-11 and CFC-12) were taken with a 24-8l bottle sampling rosette. The vertical sampling resolution of bottles was high (100 m-depth interval) around 1800 m and 3800 m, i.e at the levels of the upper and lower NADW.

Result

One of the most striking features of the equatorial circulation is the vertical stacking of westward and eastward

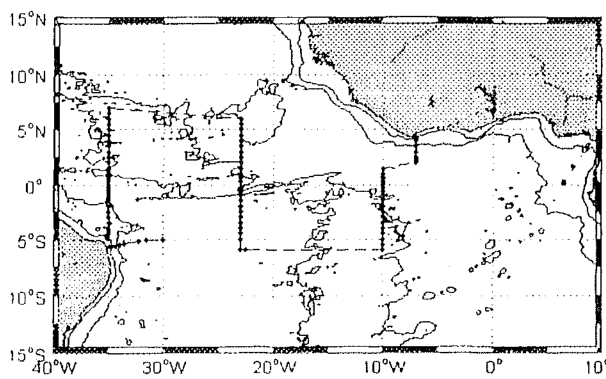

Figure 1. Track of the EQUALANT 99 cruise, July 13 to August 21, 1999.

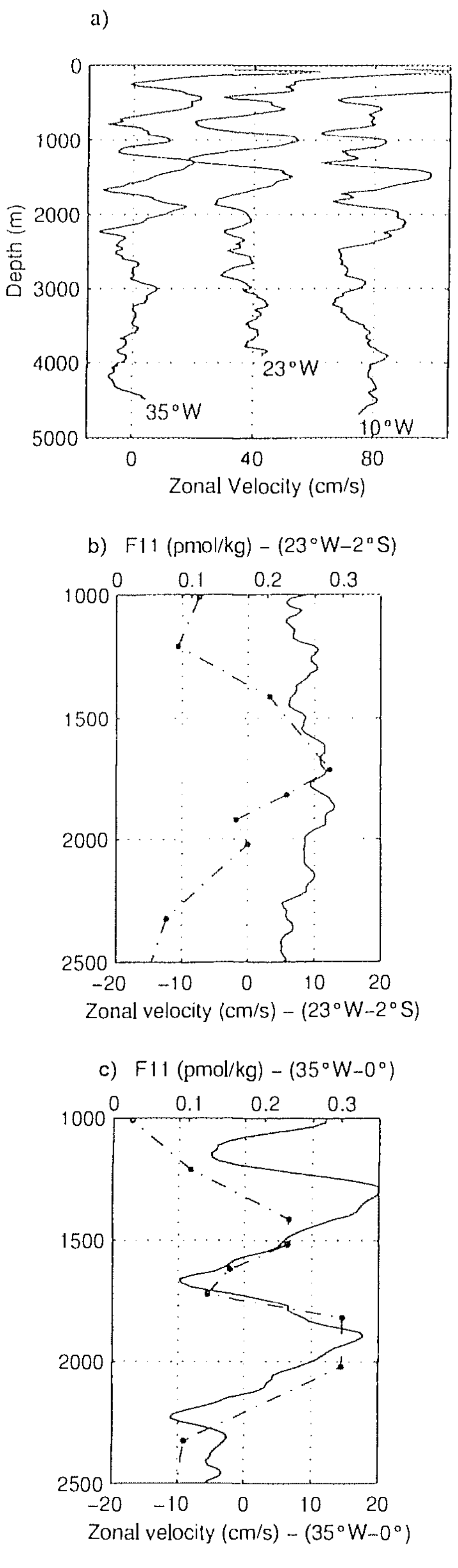

Figure 2. Vertical profiles of CFC-11 and LADCP measurements. (a) Depth profiles of the zonal component of velocity in cm s^{-1}, at 35°W-0°, 23°W-0°, 10°W-0°. Each profile has been shifted by 40 cm s^{-1} from the preceding one. Eastward (westward) currents are positive (negative). (b) CFC-11 profile (dashed-dotted line) and zonal velocity profile (solid line) at 23°W-2°S. (c) CFC-11 profile (dashed-dotted line) and zonal velocity profile (solid line) at 35°W-0°. The detection limit for the CFC-11 measurements was about 0.009 pmol.kg^{-1}.

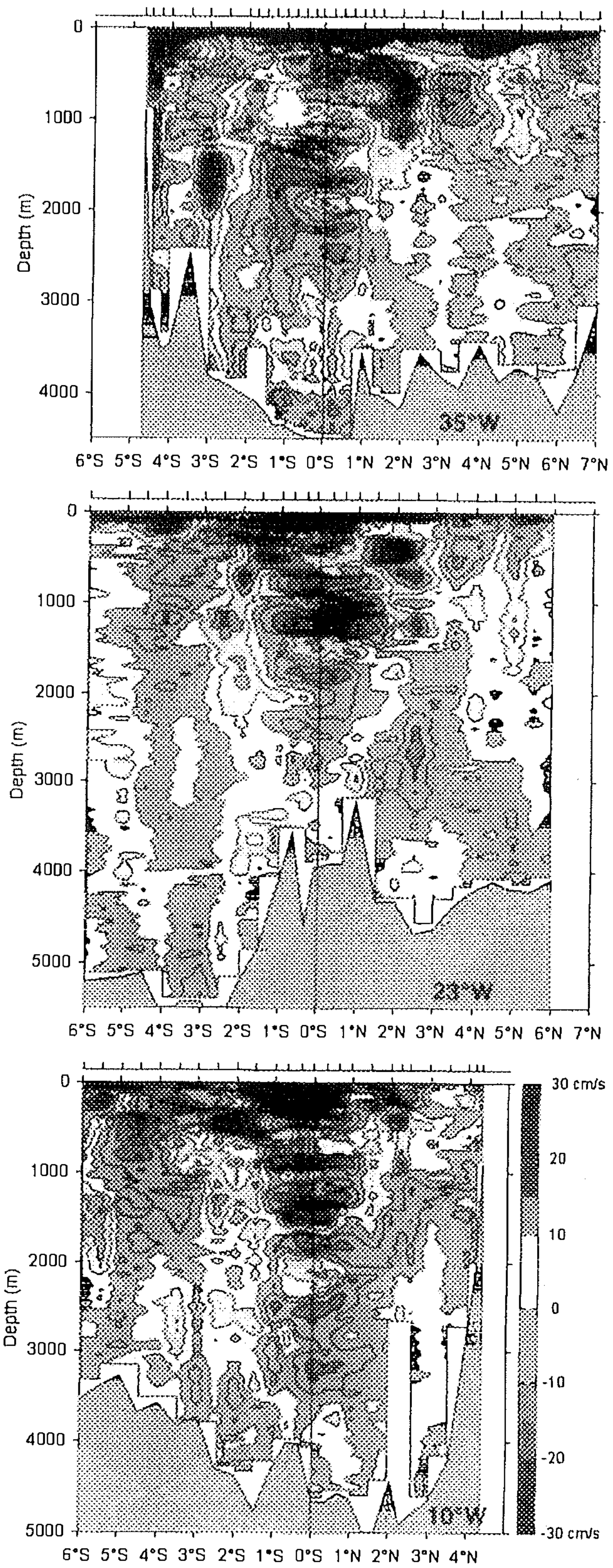

Plate 1. Latitude-depth section of the zonal component of velocity, in cm s^{-1}, along 35°W, 23°W, and 10°W. Eastward (westward) currents are positive (negative). Contour interval is 5 cm s^{-1}. Station positions are reported on the top of every section.

currents between 500 m and 2500 m: the EDJs (Fig. 2a and plate 1). They share common characteristics all across the basin: (i) they are confined between 1°30'N and 1°30'S, (ii) their vertical scale (measured between consecutive maxima of westward velocity) is about 500 m, and (iii) their maximum zonal component reaches 25 cm s^{-1} (around 1250 m at 23°W). The equatorial profiles display about 6 alternating eastward-westward jets between 500 m and 2500 m at 35°W, 23°W, and 10°W (Fig. 2a). These quasi-synoptic measurements provide new information on the zonal coherence of the jets over the basin. The eastward flowing jet at 1000 m depth is traceable over the 25° of longitude of the measurements. In the upper part of the equatorial profiles, the 750 m westward flowing jet is clearly visible at 35°W and 23°W. Below 1000 m the jets are found at the same depth at 23°W and 10°W, at 1250 m, 1500 m, and 1750 m; whereas it looks like there is an upward shift of those jets at 35°W (Fig. 2a). Despite the global zonal coherence of the jets, the individual profiles cannot be perfectly superimposed. It thus appears that the jets did not get established simultaneously (during the duration of the cruise) across the basin, over the whole column of water.

At 23°W, a striking relationship exists between the velocity of the jets and their latitudinal extension. The swiftest jet at 1200 m-depth (-21 cm s^{-1}) has the largest latitudinal extension (1°30'N-1°30'S). *Gouriou et al.* [1999] already noted that feature at 35°W, during a cruise made in May 1996. They described a westward jet at 1300 m depth, with maximum velocity (-25 cm s^{-1}) and maximum latitudinal extension. But it must be noted that at 10°W (Plate 1), the width of the swiftest jet (-28 cm s^{-1}) at 900 m-depth is similar to the width of the 1200 m westward jet.

Another remarkable feature of these sections is the ring of eastward flowing currents surrounding the EDJs at 2°N and 2°S (Plate 1): the EEJs. At 23°W, where neither boundary currents nor continental masses alter the current structure, this pattern completely surrounds the EDJs. In this ring, maxima of eastward velocity coincide with EDJ maxima of westward velocity at 500, 700, 1200 and 1800 m. The maximum meridional extension of the ring is found at 1200 m-depth (the EEJs are centred on 2°30'S and 2°30'N), where the EDJ is the swiftest. At 10°W the EEJs are clearly visible at 500 m-depth, and maxima are distinguishable at 1000 and 1300 m. On that section, north of the equator, the eastward flowing currents are only present in the top 1500 m, but the section was interrupted at 1°30'N, to be continued north of 2°N along 7°W (Fig. 1). At 35°W, EEJs are clearly visible at 700 and 1000 m at the same levels as westward EDJs. The eastward currents at 2°N and 2°S around 800 m depth transport Intermediate Water to the interior, and are called the Southern and Northern Intermediate Current [*Schott et al.*, 1995; *Boebel et al.*, 1999]. Similar currents were also evidenced in the equatorial Pacific [*Firing*, 1987]. The EQ99 sections show that the columns of eastward current extend at depth, and are not limited to the depth range of the Equatorial Intermediate Water mass.

The three velocity sections (Plate 1) give an improved understanding of the equatorial circulation hinted at by the float trajectories. The existence of EEJs had been previously inferred from SOFAR floats [*Richardson and Fratantoni*, 1999] tracked at a mean depth of 1800 m, giving a crude estimate of their width as 2° latitude, and of their thickness as at least 500 m. The northern EEJ was also evidenced at 1000 m depth by PALACE float trajectories [*Molinari et al.*, 1999]. Our measurements bring new information concerning the spatial structure of the EEJs: the vertical extension of the eastward current is very large (the entire water column) and cores of velocity maxima appear symmetrically about the equator, at the depth of the westward EDJs. Non-synoptic sections in the equatorial Pacific Ocean suggest the presence of elongated recirculation gyres, symmetrical around the equator [*Firing et al.*, 1998]. The three quasi-synoptic sections made in the equatorial Atlantic strongly support this hypothesis. Furthermore they indicate that these recirculation patterns are reinforced at the depth of the westward flowing EDJs and associated eastward flowing EEJs, creating a vertical stacking of gyres. At first glance there does not appear to be any relationship between the intensity of the EDJs and the EEJs. The swiftest EEJs are found at 500 m, at 2°N-23°W (> 35 cm s^{-1}) and at 2°S-10°W (> 25 cm s^{-1}).

At 23°W, we observe columns of westward currents at 3°S-4°S and 3°N-4°N, and, poleward, columns of eastward currents south of 4°S and north of 4°N. This succession of columns of eastward and westward flow with short meridional scales is somewhat different from the large-scale circulation pattern deduced by *Talley and Johnson* [1994] from tracer distribution, giving a westward flows at 5-8°N and 15-20°S, and an eastward flow, centred on 1-2°S, in between.

The CFC measurements, together with the LADCP ones, shed new light on equatorial circulation dynamics. Since the first CFC measurements in 1983 showing the CFC tongue at 1700 m centred on the equator [*Weiss et al.*, 1985], *Andrié et al.* [1998] have shown the maximum CFC-11 concentration to be at 2°S. That southward position of the CFC-11 plume was confirmed during the EQ99 cruise and it coincides with the location of the EEJs (23°W-2°S at 1700 m) (Fig. 2b). This observation confirms that the CFC enriched waters of the DWBC directly feed the EEJs south of the equator, as suggested from float trajectories [*Richardson and Fratantoni*, 1999]. At 35°W, the south-eastward flowing DWBC separates from the coast and is clearly visible at 3°S from 1300 m down to the sea-floor (Plate 1). It must be noted that the position of the DWBC at this longitude is highly variable, as it fluctuates between 3°S and 1°30'S [*Rhein et al.*, 1995; *Gouriou et al.*, 1999]. The upper level of the NADW is thus advected eastward by the EEJs toward the interior of the basin. The absence of a CFC-11 enriched core in the northern EEJs may indicate that they are not directly fed by the DWBC at the western boundary. One reason can be that, in the northern hemisphere, the southward flowing DWBC is tightly confined along the western boundary, making difficult any link with the pure equatorial dynamics basin.

CFCs and velocity distributions confirm preceding observations of an eastward flow of the LNADW layer [*Rhein et al.*, 1995; *Andrié et al.*, 1999]. This flow is constrained by the bottom topography at 35°W, the so-called equatorial channel between 1°N and 3°S (Plate 1). At 23°W, the eastward velocity core at 3800 m-1°30'S is linked to a CFC maximum (not shown) showing the eastward extension of the LNADW tongue. No CFC core is found at 10°W, south of the equator; probably because of a blocking by the mid-Atlantic ridge (Fig. 1).

A new feature concerning EDJs can be inferred from the comparison between the vertical distributions of CFC-11 concentrations and zonal velocities. At the equator, and for each section, we no longer observe the usual 1700 m CFC-11 maximum, characteristic of the UNADW within the DWBC in the west [*Rhein et al.*, 1995]. This maximum is clearly visible within the EEJs, south of the equator (Fig. 2b). Actually, what we observe is an absolute minimum between two relative maxima at 1500 m and 2000 m (Fig. 2c). The vertical CFC-11 profile then matches the zonal velocity profile: maxima of CFC-11 concentration are linked to the eastward flowing jets, while the 1700 m minimum is found at the depth of a westward flowing jet. Above 1400 m, the upper CFC-11 maximum does not coincide exactly with the maximum of eastward velocity, because this depth level is above the ventilated NADW and is CFC-11 depleted. The minimum of CFC-11 concentration observed at 1700 m indicates that the associated westward flowing jet is fed with CFC-11 depleted water, of eastern origin. Previous measurements made in different years and at different seasons showed jets with opposite directions [*Böning and Schott*, 1993; *Gouriou et al.*, 1999]. But it could not be concluded from those measurements whether this was due to in-place reversal or to vertical propagation. The CFC distribution gives a time-integrated view of the equatorial circulation. We are thus tempted to conclude that the minimum CFC-11 concentration at 1700 m, at the equator, indicates that the mean flow at this depth is predominantly westward; while the maximum CFC-11 concentration at 2°S suggests continuous eastward current at that latitude.

Conclusion

This study has shown how the improvement of current measurement techniques and the use of tracer distributions can give new insights regarding equatorial circulation. However, measurements are too few for any definitive conclusion on the mechanisms responsible for the EDJs: vertical propagation of linear waves [*Eriksen*, 1982; *Muench et al.*, 1994], forcing by the DWBC [*Kawase et al.*, 1992], or non-linear theory [*Hua et al.*, 1997]. Annual and semi-annual variability of the zonal component of the velocity was recently observed in mooring measurements below 1700 m in the central Atlantic [*Thierry*, 2000]. *Thierry* [2000] has shown that this variability could be forced by the fluctuations of the wind stress through the vertical propagation of Rossby waves, which originate in the eastern basin, below the thermocline. To our knowledge Global Circulation Model are far to reproduce the vertical stacking of the jets with the right vertical scale [*Böning and Schott*, 1993]; or when they do it, the results are subject to some controversy [*Suginohara et al.*, 1991; *Weaver and Sarachik*, 1991]. It has been proposed that the equatorial currents, the EDJs and the EEJs act as a reservoir for the DWBC waters [*Richardson and Schmitz*, 1993], but their residence time is not yet known. Thus further measurements will be essential to understanding the role of equatorial dynamics in the temporal regulation of the large-scale meridional overturning cell.

Acknowledgements. This work was supported by IRD (Institut de Recherche pour le Développement), IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer) and CNRS/INSU (Centre National de la Recherche Scientifique/Institut National des Sciences de l'Univers) as part of the Programme National d'Etude de la Dynamique du Climat and its CLIVAR/France subprogramme. We thank H.Mercier for comments on the manuscript and the officers and crew of the R/V Thalassa for their help and cooperation.

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(Received September 21, 2000; Accepted November 27, 2000)