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Deep Circulation in the Western Tropical Atlantic Inferred from CFCs and L-ADCP Measurements During ETAMBOT Cruises

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Direct velocity measurements have pointed out the complexity of the deep circulation in the western tropical Atlantic (Johns et al., 1993; Schott et al., 1993; Colin et al., 1994; Hall et al., 1994; Rhein et al., 1995; Fischer and Schott, 1997). The estimation of the net southward transport of the Deep Western Boundary Current (DWBC), which flows along the continental margin of the American continent, is complicated by the recirculations and their associated variability. The fate of the DWBC at the equator is of fundamental importance for the south Atlantic budget. SOFAR floats have shown that zonal flow, with strong variability, exists at depth along the equator (Richardson and Schmitz, 1993; Richardson, 1994). To address those questions, transient tracers, such as CFCs, are particularly useful in identifying the water masses. They have been measured during recent equatorial cruises: along repeated sections at 44°W and 35°W during Meteor cruises from 1990 to 1994 (Rhein et al., 1995; Rhein et al., 1996), and during the WOCE CITHER 1 cruise (along 7°30'N and 4°30'S, and at 35°W and 4°W in between) (Andrié et al., 1996).

In this context, one of the main objectives of the ETAMBOT programme was to study the western equatorial circulation between the American continent and the Mid Atlantic Ridge (MAR). The two cruises which have been carried out during the ETAMBOT programme took place during opposite seasons: ETAMBOT 1 in September–October 1995 and ETAMBOT 2 in April–May 1996. Both cruises followed the same tracks. The cruise tracklines (Fig. 1) consist of three sections, along 7°30'N between the coast and 35°W, along 35°W from 7°30'N to 5°S, and a slanted section crossing the Ceara rise, off Brazil. During those cruises, direct measurements of current were made from the surface to the bottom with a L-ADCP, Acoustic Doppler Current Profiler, attached to the rosette. During the ETAMBOT 1 cruise, profiles of current could only be made for the first 33 stations, between the coast and 37°W, at 7°30'N. During the ETAMBOT 2 cruise, profiles of current were made at every station. The data have been processed following the method described in details by Fischer and Visbeck (1993).

Here, we focus principally on the circulation features inferred from CFC-11 and L-ADCP measurements performed during the ETAMBOT 1 and 2 cruises.

ETAMBOT 1 - 7°30'N section

Figs. 2a and 2b display the CFC-11 and L-ADCP measurements obtained during the ETAMBOT 1 cruise (in September 1995) along 7°30'N, from the coast to 35°W. At the coast, the two maxima of CFC-11, which characterise the North Atlantic Deep Water (NADW), are clearly visible around 1700 m and 3900 m. The upper core (1500 m–1800 m) originates from the Labrador Sea. The vertical extension of that core is limited, presumably because of the weakness of the convection processes in the Labrador Sea before the late 80s. The lower core (3800 m–3900 m) originates from the Nordic Seas through the Denmark Strait. Those layers of maximum of freons are respectively called Shallow Upper NADW (SUNADW) and Overflow Lower NADW (OLNADW) after Rhein et al. (1995). Both freon cores are clearly conveyed southward by the DWBC between 1000 m and the bottom (Fig. 2b). The upper core of the DWBC, between 1000 m and 3000 m, has its maximum of velocity around 1500 m (>40 cm/s). The lower core is found farther offshore, centred around 3500 m, with velocities lower than 20 cm/s. At the level of the upper core (1500 m–1800 m), CFC-11 enriched waters extend to the MAR (Fig. 2a) and secondary maxima are observed around 150 km, 300 km, 500 km, and 800 km from the coast. The three former cores can be related to a southward drift (Fig. 2b), but the last core, centred on 800 km, is at the eastern border of a strong northward recirculation which extends from the surface to the bottom, between 600 km and 800 km.

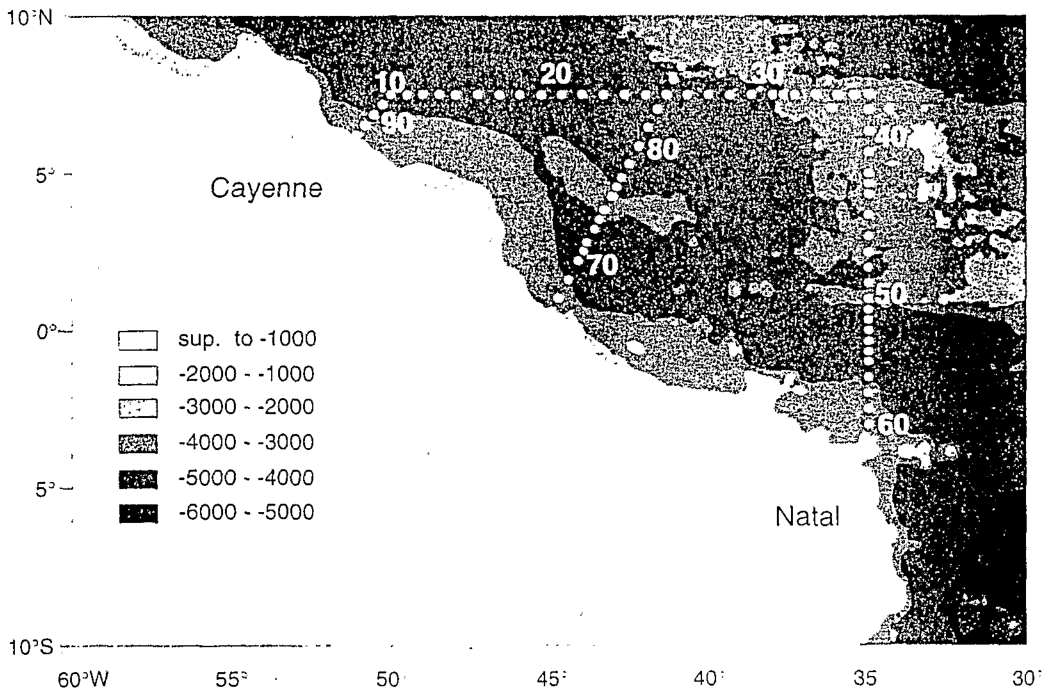

Figure 1. ETAMBOT stations (white dots) superimposed on the principal features of the bathymetry: the Mid Atlantic Ridge in the east, the Ceara Rise centred around 4°N–43°W and the equatorial channel, east of 35°W, centred around 1°S with depth greater than 4500 m.

The deeper CFC-11 core has a smaller eastward extension than the upper core (Fig. 2a): the topography plays an important role in blocking the eastward and southward progression of the lower DWBC. During the ETAMBOT 1 cruise, there is no real evidence of a northward deep recirculation west of the MAR as suggested by Plähn and Rhein (1997). The slanted section, which crosses the Ceara rise, leads to the same conclusion (figure not shown). Similar observations are inferred from CFC-11 and L-ADCP measurements during the ETAMBOT 2 cruise, in April–May 1996. Results on that cruise are displayed on two isopycnal levels corresponding to the UNADW $\sigma_2 = 36.88$: Fig. 3a, page 21) and the LNADW ($\sigma_3 = 41.50$: Fig. 3b, page 21).

UNADW circulation

During the ETAMBOT 2 cruise, CFC-11 and L-ADCP velocity maxima are trapped against the Continental Rise at 7°30'N, on the slanted section, and at 35°W (Fig. 3a). The maximum of CFC-11 concentration has increased, at 7°30'N and on the slanted section, compared to the ETAMBOT 1 cruise. Centred on 46°W at 7°30'N, the northward recirculating flow with high CFC-11 concentration, already observed during the ETAMBOT 1 cruise, is clearly visible.

On the slanted section there is a sharp front in the CFC-11 concentration south of the Ceara Rise, at 4°N. North of the Ceara Rise, one isolated CFC-11 core is observed near 5°N, associated with a southeastward flow. For both ETAMBOT cruises there is no evidence for a recirculated flow between the Ceara Rise and the MAR. This observation differs from the mean circulation scheme proposed at that depth by Friedrichs et al. (1994). On the other hand, there is a strong northwestward flow, centred on 2°N, during ETAMBOT 2 between the coastal DWBC and the Ceara Rise (Fig. 3a).

The most important difference between the ETAMBOT 1 and ETAMBOT 2 cruises appeared along the 35°W section. During the ETAMBOT 1 cruise, the CFC-11 pattern presents a north-south asymmetry with CFC-11 enriched cells preferentially concentrated south of the equator (not shown). This situation was already observed during the CITHER 1 cruise, in January–February 1993, when a CFC-11 core was observed around 3°S (Andrié, 1996). A very different situation is noticeable during the ETAMBOT 2 cruise as the most important CFC-11 core is observed in the 5°N–7°N latitude range. This maximum of concentration of CFC-11 corresponds to a moderate southward flow. It is difficult to link that core to the measurements along 7°30'N and along the slanted section.

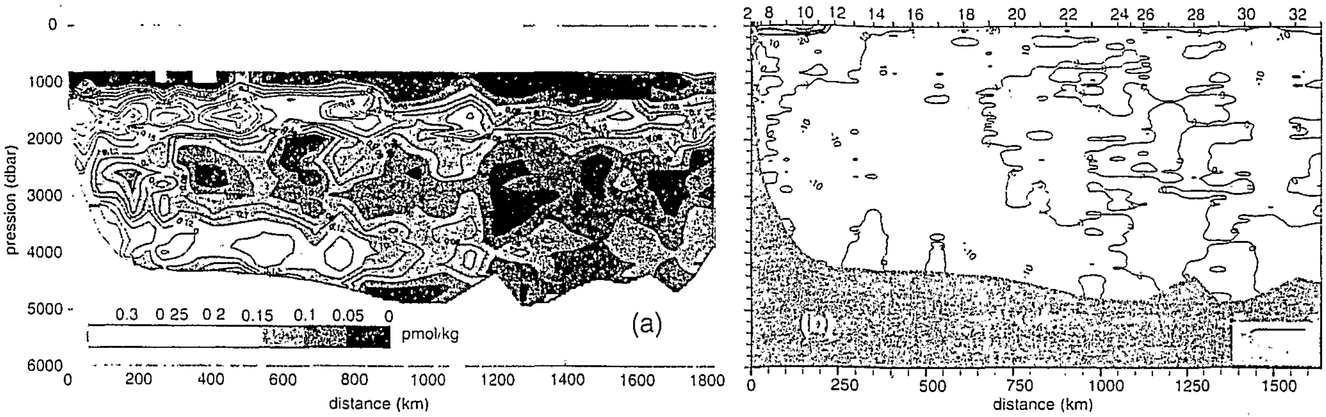

Figure 2. Vertical sections along 7°30'N during ETAMBOT 1 of (a) CFC-11 concentrations in pmol/kg, (b) the north-south component of L-ADCP measurements (negative values for southward flows, in grey).

LNADW circulation

Rhein et al. (1995) and Andrié et al. (1997) have shown that the LNADW circulation within the DWBC is strongly constrained by the topography, mainly the Ceara rise, between 3°N and 6°N, and the flanks of the equatorial channel centred around 1°S (Fig. 1). Offshore, along the 7°30'N section, the ETAMBOT cruises exhibit high CFC-11 concentrations linked to re-circulated northward flows (between 44°W and 48°W during ETAMBOT 2, Fig. 3b).

Along the slanted section, the LNADW is revealed, on both side of the Ceara rise, by strong concentrations of CFC-11 and southeastward flows, at 2°N and 4°N (Fig. 3b). As it was also observed at the upper level core, L-ADCP measurements do not show evidence of northward recirculation west of the MAR. This is in contradiction with the assumption of Plähn and Rhein (1997). In the equatorial channel, at 35°W, a strong eastward flow is associated with high concentration of CFC-11. This flow seems to be a permanent feature of the deep circulation as it was observed in the repeated sections of the METEOR (Rhein et al., 1995, 1996) and during CITHER 1 (Andrié, 1996).

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