Northern and southern water masses in the equatorial Atlantic: distribution of nutrients on the WOCE A6 and A7 lines

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Abstract

In the framework of the WOCE Hydrographic Program, two trans-Atlantic CTDO/tracer sections with closely-spaced stations, along 7°30'N and 4°30'S (WOCE Lines A6 and A7), and two meridional sections, along 3°50'W and 35°W joining the two zonal sections, were occupied in January–March 1993 (CITHER 1 cruise on board the N/O L'ATALANTE). CTD profiles and nutrient (silicate, phosphate and nitrate) data at 32 depths between surface and bottom were obtained at each station. The distributions on vertical sections, and on isopycnal surfaces, of these three chemical tracers are presented and discussed in the context of large-scale circulation in the equatorial Atlantic Ocean.

The nutrient fields are used to show the main components of the circulation on four main levels: near-surface, intermediate, deep and bottom layers. Near the surface the nutrient distribution pattern is dominated by westward advective flows on either side of the equator from the eastern regions enriched by coastal upwellings. Beneath the lower thermocline water, high silicate concentrations (at about 1000 m depth), at a larger depth than that of the salinity minimum of the Antarctic Intermediate Water, enable a differentiation of the Upper Circumpolar Water (UCPW) from the former. In the deeper layers, the nutrient distribution confirms the bifurcation of the Deep Western Boundary Current (DWBC), carrying the North Atlantic Deep Water, at the equator into an eastward flow and another one continuing southward along the western boundary. The eastward flow of the UNADW along the equator can be traced as far as 3°50'W. The analysis of nutrient distribution on isopycnal surfaces also shows the existence of

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recirculation components of the DWBC in the western equatorial region. The northward succession of bottom concentrations of silicate and phosphate indicates that the flow of the Antarctic Bottom Water (AABW) exiting the Brazil Basin is topographically constrained along the equator. The higher silicate and phosphate concentrations in the near-bottom waters west of the Mid-Atlantic Ridge (MAR) and north of the equator indicate that the main flow of bottom waters is northwestward rather than through the equatorial fracture zones into the eastern Atlantic. Finally, the distributions of silicate and phosphate on near-bottom and isopycnal surfaces suggests a recirculation of AABW in the northern part of the Brazil Basin.

1. Introduction

The equatorial Atlantic Ocean is fed by four major meridionally flowing water masses: the Antarctic Intermediate Water (AAIW), the Circumpolar Water (CPW), the North Atlantic Deep Water (NADW) with its lower and upper branches, and the Antarctic Bottom Water (AABW) [see Wüst (1935) for a description of their characteristics]. On entering the equatorial Atlantic, these water masses of polar origin partly interleave in the order of their densities and partly penetrate each other laterally, resulting in modifications of their conservative properties. Analyses of such changes could prove useful in deducing transequatorial spreading and equatorial zonal flows, if any, of these water masses, especially when they are carried out on a basin-wide coverage with closely spaced stations on meridional and zonal sections. The two trans-Atlantic CTDO/tracer sections, along 7°30'N and 4°30'S (WHP Lines A6 and A7), and the two meridional sections, along 3°50'W and 35°W joining the two zonal sections, occupied within the framework of WOCE Hydrographic Programme, were chosen with this objective. The comprehensive coverage of the equatorial Atlantic basin using a large inventory of conservative and transient tracers measured on samples from 32 depths over 223 stations in these sections was thus intended to provide better horizontal and vertical resolutions than were known before from other sections.

The hydrographic (T, S and O2) properties (Arhan et al., this issue) and the transient (freons F-11 and F-12, hereafter referred to as CFM) tracers (Andrie et al., this issue) are described elsewhere in this issue, and the present paper complements them with a report on the vertical and horizontal distribution of nutrients along these sections. Our analyses had two objectives: the first was to provide supporting evidence for features of circulation deduced from earlier studies and from analyses of hydrographic and transient tracer properties in these sections, and the second was to describe...
features that become apparent from the distribution of the geochemical tracers but not always with others.

2. Methods and data set

The nutrient data were obtained during the CITHER 1 cruise (2 January to 19 March 1993) on board the French oceanographic vessel N.O. L'ATALANTE. Fig. 1 shows the cruise track and the position of the stations (223 stations), and volume 1 of the CITHER 1 data report (Groupe CITHER 1, 1994) describes the general outline of the cruise. The distance between the stations was generally 56 km except over steep continental slopes, where it was reduced to 19–37 km. Water samples for nutrient measurements were obtained with 8 l General Oceanics samplers (type Niskin) mounted on a CTDO system. At all deeper stations, 32 depths between the surface and the bottom were sampled in a single cast. At shallower stations, the number of depths sampled was reduced proportionally. In addition to the planned 223 stations, 4 test stations were occupied, where the 32 samplers were closed simultaneously at a predetermined depth, and the results were then used to evaluate the precision of the analytical methods employed for the tracers.

The nutrient (silicate, phosphate and nitrate) concentrations were measured according to standard methods (Benschneider and Robinson, 1952; Mullin and Riley, 1955; Murphy and Riley, 1962; Wood et al., 1967) in a BRAN + LUEBZE Auto-analyzer equipped with an automated data acquisition system. The analytical precisions (±1 SD), obtained from the measurements at the test-stations and on more than 300 duplicate samples during the cruise, were 0.2% for silicate and nitrate and 0.4% for phosphate (Oudot and Baurand, 1994). The accuracy of the nutrient concentrations was also checked by comparison with the historical data for a given location. During the course of the cruise, some problems with the efficiency of the cadmium column to reduce the nitrate were encountered. The accuracy of the nitrate data are, therefore, slightly suspect, especially from the 7°30'N section. The vertical distribution of nitrate in this section, hence, is incomplete.

3. Near-surface waters

The westward advective flows on either side of the equator from the eastern regions enriched by coastal upwellings (Kawase and Sarmiento, 1985; Levitus et al., 1993) can be recognized from the distribution of nutrients on the surface in the zonal sections (Figs. 2a, d, 3a, d, 4a, and d). Distribution of nutrients at 50 m depth (Fig. 5) more clearly shows the high nutrients (silicate and phosphate) on the eastern side, where they are supplied to the near-surface waters by intertropical upwelling along the African coast, and their westward extension coinciding with the flows of the North and South Equatorial Currents. Of particular interest is the wider spread of the nutrient-rich area south of the equator (>2200 km) than to the north of it (<1600 km), even though the eastern boundary concentrations in the southern
Fig. 2. Vertical distribution of silicate along (a) 7°30’N, (b) 35°W, (c) 3°50’W and (d) 4°30’S.
Fig. 3. Vertical distribution of phosphate along (a) 7°30'N, (b) 35°W, (c) 3°50'W and (d) 4°30'S.
Fig. 4. Vertical distribution of nitrate along (a) 7°30'S, (b) 3°30'S, (c) 3°50'W and (d) 4°30'S.
Near-surface nutrients

Fig. 5. Distribution of silicate and phosphate at 50 m depth along (a) 7°30'N, (b) 35°W, (c) 3°50'W and (d) 4°30'S. Positive and negative values on abscissa indicate East and West longitudes, and North and South latitudes.
section (silicate \( \sim 6 \) \( \mu \text{mol kg}^{-1} \), phosphate \( \sim 1.2 \) \( \mu \text{mol kg}^{-1} \), nitrate \( \sim 18 \) \( \mu \text{mol kg}^{-1} \)) are lower than in the northern section (silicate \( \sim 7.5 \) \( \mu \text{mol kg}^{-1} \), phosphate \( \sim 1.4 \) \( \mu \text{mol kg}^{-1} \), nitrate \( \sim 21 \) \( \mu \text{mol kg}^{-1} \)). This suggests that the vertical advection of nutrients associated with the eastward upsloping of the thermocline along the equator (Merle, 1980) is also an important process in supplying nutrients to the near-surface waters; this effect becomes more apparent to the west in the southern section, because of its proximity to the equator, than the northern one.

Other recognizable features of interest are the cyclonic circulation in the thermocline domes, emergence of the Equatorial Undercurrent (EUC) to the surface and the meanders of the North Brazil Current (NBC). The interruptions of the westward decrease of nutrients at 17°W, 20°W and 24–25°W along 7°30'N and at 5–6°E and 6–8°W along 4°30'S (Fig. 5a and d) are nutrient-rich waters probably meandering close to the surface in the domes or advected from the coastal upwelling. However, the maxima at 24–25°W along 7°30'N and 5–6°E along 4°30'S are more certainly the external boundaries respectively of the Guinea Dome in the tropical northeast Atlantic centered around 12°N, 22°W (Oudot, 1989) and of the Angola Dome in the tropical southeast Atlantic centred around 10°S, 9°E (Voituriez, 1981), as is also evident from the dynamic height maps (Merle, 1978; Gordon and Bosley, 1991). ADCP measurements (Gouriou et al., 1994) have shown the emergence of EUC, impoverished in nutrients, to the surface near the eastern boundary, and this can also be seen clearly from the decrease of nutrients at the equator in the 3°50'W section (Fig. 5c). Finally, the ridges on the shallower isopleths at 40°W and 46°W along 7°30'N (Figs. 2a, 3a and 4a) confirm the meanders of the NBC that retroflect and feed into the eastward flowing North Equatorial Countercurrent, as deduced from surface drift-buoy trajectories (Richardson and Reverdin, 1987; Richardson et al., 1994), CZCS images (Muller-Karger et al., 1988) and ADCP measurements (Gouriou et al., 1994).

4. Intermediate waters

The main characteristic of the intermediate waters is the nutrient-rich layer (500–1200 m) that spreads over the whole of the equatorial belt (Figs. 2–4). While all the three nutrients have a maximum in this layer, sharp contrasts in their horizontal and vertical distributions, however, become evident. Highest silicate concentrations (> 34 \( \mu \text{mol kg}^{-1} \)) occur in the western basin along the 4°30'S section (Fig. 2d), whereas highest phosphate and nitrate concentrations (> 2.4 and 36 \( \mu \text{mol kg}^{-1} \) respectively) occur, both to the north and south of the equator, in the eastern region (Figs. 3a, d, 4a, and d). A second nitrate maximum (Fig. 4d) appears at the extreme eastern end of the 4°30'S section over the continental slope. Its location at a lower density (27.00 \( \sigma_{0} \)) and nearer to the oxygen minimum of the eastern region suggests that its origin is related to an oxygen consumption by biogenic fallout from the euphotic zone. Along both the meridional sections, silicate concentrations decrease progressively from south to north (Fig. 2b and c), though the decrease is less pronounced along 3°50'W and is interrupted by an isolated core of high silicate at the equator (Fig. 2c). In contrast, the phosphate and nitrate maxima at 35°W (Figs. 3b and

4b) are more accentuated north of the equator than south of it, and along 3°50'W, the high concentrations are interrupted by lower concentrations (<2.3 and 36 μmol kg⁻¹ respectively) between 2°N and 2°S (Figs. 3c and 4c) (also see below). These differences reflect the differences in the origin of the maxima—a southern one for silicate and an eastern one for nitrate and phosphate—since silicate-utilizing organisms are far more abundant in polar waters than in the tropics, whereas regeneration of nitrate and phosphate is intense in the latter, especially near the eastern boundary.

Meridional flows of the AAIW and UCPW are the major sources of intermediate waters in the equatorial Atlantic, but the traditional hydrographic tracers do not permit identifying them separately in the low latitudes (Arhan et al., this volume). Our study shows that the silicate maximum is generally deeper (~900–1000 m) than those of phosphate and nitrate (~700–800 m) and lies near 27.40 σ₀, as was observed in earlier studies (Mann et al., 1973; Kawase and Sarmiento, 1985; Tsuchiya et al., 1992), whereas the latter lie on a shallower isopycnal surface (27.25 σ₀), near the salinity minimum and oxygen maximum of the AAIW, which lie at around 27.30 σ₀ in the vicinity of the equator (Reid, 1989; Suga and Talley, 1995; Arhan et al., this issue). The association of the silicate maximum with a layer denser than that of the AAIW shows that it is derived from the UCPW and not from AAIW, as suggested by Tsuchiya et al. (1994), where the silicate maximum north of 21°S was regarded as belonging to AAIW and not as a northward extension of the silicate maximum of the UCPW. Our conclusion is also supported by the low CFM concentrations measured at the depth of the silicate maximum (Andrié et al., this issue). Besides, the concentration of silicate at the denser layer is around 35 μmol kg⁻¹ whereas that of the AAIW at its origin in the 25°W section of Tsuchiya et al. (1994) is about 30 μmol kg⁻¹ (salinity 34.2).

Northward flow of AAIW along the South American continental slope has been shown earlier from direct current measurements at 8°N (Johns et al., 1990), from a hydrographic section along 11°N (Friedrichs and Hall, 1993) and from the observations of Schott et al. (1995) near the South American coast at 5°S, 35°W. The vertical distributions of salinity and oxygen along the western boundary at 4°30'S also demonstrate the entrance of AAIW in the equatorial belt (Arhan et al., this issue) and our nutrient data provide supporting evidence for this: the high oxygen anomaly is accompanied by a sharp decrease of nutrients (Figs. 2d, 3d and 4d), which is also evident on the isopycnal σ₀ = 27.25 (Fig. 6e). The low nutrient anomaly carried by the northward flow of AAIW is again found at the southern edge of the 35°W section (Fig. 6c). The hydrographic data along 7°30'N do not show any clear trace of boundary flow of AAIW along the Guiana continental slope (Arhan et al., this issue), but the nutrient data do show this: the sharp decrease of phosphate and nitrate on the isopycnal σ₀ = 27.25 (Fig. 6a) at the two westernmost stations and the minima at 50°W could be the signatures of an escape of AAIW into the tropical North Atlantic.

The northward spreading of AAIW into the North Atlantic across the equator is not totally meridional, and a part of this might enter as zonal flows just south and north of the equator (Reid, 1994; Tsuchiya et al., 1994; Suga and Talley, 1995). The minima of phosphate and nitrate at 2–3°S and 1–2°N along 35°W (Fig. 6c), which coincide with salinity and oxygen anomalies (Arhan et al., this issue), in a manner similar to the observations of Suga and Talley (1995), confirm the eastward branching
Phosphate and nitrate on $\sigma_0 = 27.25$ (AAIW stratum)

Fig. 6. Distribution of phosphate and nitrate on 27.25$\sigma_0$ along (a) 7°30'N (western boundary), (b) 7°30'N (eastern boundary), (c) 35°W, (d) 3°50'W, (e) 4°30'S (western boundary) and (f) 4°30'S (eastern boundary) in the core of AAIW. Positive and negative values on abscissa indicate East and West longitudes, and North and South latitudes.
The zonal flow is carried eastward through the South and North Intermediate Counter Currents (SICC and NICC) described by Schott et al. (1995); ADCP measurements (0–700 m depth) made during this cruise (Gouriou et al., 1994) show a distribution of different branches of eastward and westward currents along 35°W, similar to those observed by Schott et al. (1995) during the same season (February–March 1994). The zonal flows north and south of the equator may explain the decrease in the concentrations of phosphate and nitrate on either side of the equator—more pronounced to the south than to the north—between 3°50′W and 35°W, while they do not change much at the equator (Fig. 6c and d). A reversal of the direction of the eastward equatorial flow, as suggested by the trajectories of floats at 800 m depth (Richardson and Schmitz, 1993), can account for the homogenization of tracers along the equator.

The entry of AAIW in the eastern basin can be seen from the large minima of phosphate and nitrate—coinciding with a high oxygen anomaly (Arhan et al., this issue)—centred slightly south of the equator (around 1°S) along 3°50′W and embedded within high-nutrient equatorial waters (Fig. 6d). According to the circulation pattern proposed by Warner and Weiss (1992) for the AAIW, the south equatorial branch turns southward in the eastern Atlantic. The sharp decrease of phosphate and nitrate at the eastern end of the 4°30′S section (Fig. 6f) provides clear evidence for this southward recirculation of the zonal flow even though the hydrographic data of CITHER 1 provide only scant evidence, in the form of a pair of temperature minima lower than 4.25°C at the eastern end of the 4°30′S section (Arhan et al., this volume), for this. The nutrient distribution in the 7°30′N section (Fig. 6b), on the other hand, does not show a poleward flow of AAIW in the north equatorial Atlantic.

The association of the silicate maximum with the UCPW, as shown earlier, and the potential temperature minimum characteristic of it (Reid, 1989) provides an ideal combination of tracers for the UCPW in the equatorial Atlantic. The distribution of these tracers on the isopycnal \( \sigma_0 = 27.40 \) in the 4°30′S section (Fig. 7d) shows that the UCPW enters the equatorial Atlantic as a narrow northward flow along the South America continental slope, with another branch about 300 km offshore at 32°W, which also flows northward as shown by the slope of the isopycnal (Arhan et al., this issue). The high silicate and low temperature anomalies at 4°30′N along 35°W (Fig. 7b), corresponding to a northward deepening of the isopycnal \( \sigma_0 = 27.40 \), suggest a westward extension of the meridional flow, which can be traced to the large signal of a northward flow visible at 47°W, about 500 km from the continental slope, on the 7°30′N section (Fig. 7a). Other meridional flows of UCPW visible in this section are at 31°W on the eastern flank of the Middle Atlantic Ridge and at 18°W, about 400 km from the continental slope (Fig. 7a). However, in contrast to the AAIW, there are no clear signatures of UCPW flowing along the Guiana coast.

Zonal flows of UCPW can be recognized from the lateral extremas of silicate and potential temperature at 3°30′S, 1°S, and 1°30′N along 35°W (Fig. 7b) that agree with the reversals of the slope of isopycnals. Along 3°50′W section, these can be seen as interruptions by anomalies of the northward decrease in silicate and increase in potential temperature, supported by the slope of the isopycnal \( \sigma_0 = 27.40 \), at 2°30′S, 0° and 3°N. (As is the case with AAIW, zonal variations of silicate at the equator
Fig. 7. Distribution of silicate on \sigma_0 = 27.40 along (a) 7°30'N, (b) 35°W, (c) 3°50'W and (d) 4°30'S in the core of UCPW. Positive and negative values on abscissa indicate East and West longitudes, and North and South latitudes.
between 35°W and 3°50'W are absent). However, in contrast to AAIW, the UCPW does not appear to escape poleward from the eastern equatorial basin along the African continental slope (Fig. 7d) but does rather away from the coast, as seen by the silicate and temperature anomalies at 7°W, 0–1°E, 5°E and 9°E, associated with the westward deepening of the isopycnal $\sigma_0 = 27.40$.

5. Deep waters

5.1. Upper North Atlantic Deep Water

The North Atlantic deep water is a thick layer of warm, highly-saline, oxygen-rich and nutrient-poor water that extends southwards across the equator between 1000 and $>3500$ m (Wüst, 1935), and its upper part, the UNADW, is characterized by a salinity maximum derived from the Mediterranean outflow and a silicate minimum (Kawase and Sarmiento, 1986).

In earlier studies, the low-latitude circulation of NADW has often been described as a Deep Western Boundary Current (DWBC) crossing the equator from north to south on the western edge of the equatorial belt, but the recent studies (Molinari et al., 1992; McCartney, 1993; Richardson and Schmitz, 1993), where geochemical tracers were used, suggest a more complex pattern, with the DWBC bifurcating at the equator into an eastward flow along the equator and another one continuing southward along the western boundary. Most of the recent investigations (Molinari et al., 1992; Friedrichs and Hall, 1993; McCartney, 1993; Richardson and Schmitz, 1993; Schmitz and McCartney, 1993) on the exchange of water at middepths between the North and South Atlantic also recognize recirculation in the interior of the basin between the DWBC and the Mid-Atlantic Ridge (MAR).

Because of vertical mixing with the overlying UCPW, the silicate, phosphate and nitrate minima of UNADW shift slightly from 36.86 $\sigma_2$ to deeper isopycnals between the two zonal sections, and this is best illustrated by the change in the silicate minimum from 36.86 to 36.88 $\sigma_2$ (Fig. 8a). As noted earlier by Reid (1989), the phosphate and nitrate minima (Figs. 3 and 4) are slightly deeper (by about 200–300 m) than that of silicate and are found on isopycnals ranging from 36.90 to 36.98 $\sigma_2$. Even though the denser isopycnals lie towards the eastern boundary along 7°30'N, the fact that the lowest minima of silicate and phosphate were on the western side led us to analyse the nutrient anomalies on an intermediate isopycnal $\sigma_2 = 36.90$ (Fig. 9).

On the 7°30'N section, silicate and phosphate minima appear at 50°W, 45–47°W, 41–42°W and 38–39°W (Fig. 9a), and coincide with the anomalies of hydrographic (Arhan et al., this issue) and CFM (Andrić et al., this issue) tracers. The 50°W anomaly is obviously the transport of UNADW by the DWBC. Among the rest, the 45–47°W anomaly is present at a location where a reversal of the isopycnal slope indicates a northward flow (Arhan et al., this issue) and reflects the eastern branch of the Guiana gyre (McCartney, 1993), and the 41–42°W anomaly, between the western and eastern boundaries of the Para Abyssal Plain, is probably the eastern edge of the recirculation branch of the UNADW in the interior of the Guiana Basin, according to
the circulation pattern hypothesized by Friedrichs and Hall (1993). The minimum at 38–39°W, taken together with the CFM data (Andrié et al., this issue), indicates a southeastward branch of UNADW along the western flank of the MAR.

Southward spreading of UNADW is visible as minima of silicate and phosphate, along with CFM maxima (Andrié et al., this issue), at 3–4°N, 1°N, 1°S and 3°S in the 35°W section (Fig. 9b), but signatures of it crossing the 4°30'S section are less evident, marked only by a weak minimum of both silicate and phosphate at 34°W and another one at 30–31°W, about 500 km from the continental slope (Fig. 9d). The shape of the isopycnals at this level (Arhan et al., this issue) suggests a southward flow of DWBC carrying UNADW along the continental slope and a northward counterflow offshore, described further south at 11°S by McCartney (1993).

What we consider as the most important feature in the 35°W section is the location of the main phosphate minimum core at 3°S and the silicate minimum core at 1°N (Fig. 9b) and not against the American continental slope. Taken together with the dissolved oxygen anomaly (Arhan et al., this issue), this shows that the UNADW may flow eastward as an equatorial current rather than southward as a western boundary current (see above). Weiss et al. (1983), using the freon F-11 as the tracer, showed the extension of the eastward branch up to 44°W along 3°N, and Tsuchiya et al. (1994) later showed the presence of this branch at 25°W along the equator. Our results demonstrate that this flow extends further, as far as the 3°50'W section, as shown by the lower concentrations immediately on either side of the equator (1°N and 1°30'S) than at its northern (4°N) and southern (4°S) boundaries (Fig. 9c). The eastward
Fig. 9. Distribution of silicate and phosphate on $\sigma_2 = 36.90$ along (a) 7°30'N, (b) 35°W, (c) 3°50'W and (d) 4°30'S in the core of UNADW. Positive and negative values on abscissa indicate East and West longitudes, and North and South latitudes.
flowing core of the UNADW, centred at around 2°S along 3°50'W, is also seen in the CFM data (Andrié et al., this issue).

During its entire eastward flow along the equator, the UNADW remains substantially unaltered. This is shown by the closeness of the lowest concentrations of nutrients at 3°50'W with those observed at 35°W: the concentrations between 35°W and 3°50'W along the equator (Fig. 9b and c), over a distance of about 3500 km, increase by only 1 μmol kg⁻¹ for silicate and 0.05 μmol kg⁻¹ for phosphate, compared with the larger increase (3 and 0.1 μmol kg⁻¹ respectively) along the western boundary between 7°30'N and 4°30'S over a much shorter distance (2200 km). A comparison of the silicate-σ两类 diagrams of stations 217 (1°30'S, 3°50'W) and 104 (1°S, 35°W) with those of stations 206 (4°N) and 223 (4°30'S), located on extreme equatorial latitudes of the 3°50'W section (Fig. 8b), also illustrates the weak erosion of UNADW along the equator. Reversals of the equatorial flows, as shown by the float trajectories at 1800 m along the equator (Richardson and Schmitz, 1993), at a level slightly below the 36.90 σ2 isopycnal, may also homogenize the UNADW properties. The southward turn of the zonally flowing UNADW can be recognized from the decrease in silicate and phosphate east of the Greenwich meridian on the 4°30'S section (Fig. 9d) and is evident also in the slope of the isopycnals (Arhan et al., this issue).

The northward passage of the UNADW, in accordance with the circulation pattern proposed by Friederichs and Hall (1993), can be seen from the nutrient minima at about 17°W and near 27°W in the 7°30'N section (Fig. 9a). The first corresponds to a flow into the Sierra Leone Basin, and the second into the southern part of the Gambia Basin.

5.2. Lower North Atlantic Deep Water

The nutrient minima, also characteristic of the lower NADW that derives from the Denmark Strait Overflow Water and is transported southward from the North Atlantic by the western boundary current (Speer and McCartney, 1991; Tsuchiya et al., 1992), can be seen below 3000 m on the nutrient profiles west of the MAR (Fig. 10). These minima are greatly reduced in sharpness from the one above and, because of vertical mixing with the underlying AABW, shoal from 45.87 σ4 (3750 m) along 7°30'N to 45.85 σ4 (3550 m) along 4°30'S. This nutrient minimum coincides well with the second maximum in CFM (Andrié et al., this issue).

The two nutrient minima observed at the UNADW level (at 41–42°W and 38–39°W) in the 7°30'N section also become apparent at approximately the same locations (42–43°W and 38–39°W) at the LNADW level (45.87 σ4) (Fig. 11a), suggesting a circulation pattern of LNADW similar to that of UNADW, with southward boundary flow against the continental slope, a northward recirculation branch at 42–43°W and a southeastward flow against the western slope of the MAR. The silicate and phosphate concentrations of the LNADW nutrient minima between 7°30'N and 4°30'S sections change only through 2 and 0.06 μmol kg⁻¹ respectively, supporting the conclusion of Speer and McCartney (1991) that the LNADW crosses the equator on the western side without substantial modifications. However, the small minima of silicate and phosphate at 34°W (about 100 km off the continental slope) in the 4°30'S
Fig. 10. Vertical distribution of silicate, phosphate and nitrate at stations to the north (a, b) and south (c, d) of the equator in the western equatorial Atlantic.
Fig. 11. Distribution of silicate and phosphate on $\sigma_z = 45.87$ along (a) $7^\circ30'N$, (b) $35^\circW$, (c) $3^\circ50'W$ and (d) $4^\circ30'S$ in the core of the LNADW. Positive and negative values on abscissa indicate East and West longitudes, and North and South latitudes.
section (Fig. 11d) suggests that LNADW crosses this section only as a narrow flow. The other anomalies at 30°W, 27°W and 23°W, in the same locations as those of the UNADW, indicate the northward recirculation branches of LNADW. The other northward flow of LNADW, visible with the hydrographic properties (Arhan et al., this issue) at 20°W, is seen in the anomaly of phosphate but not that of silicate.

The trough of low nutrients characterizing LNADW that appears in the equatorial channel between the southern flank of the MAR (0°40′N) and the Ceara Seamounts (2°S) with the minima centered at 1°S (Fig. 11b) shows that the flow of LNADW at the equator, unlike that of UNADW, is strongly constrained by the topography. The eastward spreading of the LNADW in the Brazil Basin does not extend as far as the western flank of the MAR but is arrested at around 18°W by the Circumpolar Water (see below), as shown by the eastward increase of concentrations of phosphate and silicate from 18°W in the 4°30′S section (Fig. 11d). However, the silicate and phosphate minima on 45.87 σ4 (depth ~4000 m) in the 3°50′W section (Fig. 11c), just north and south of the equator (~1°N and 1°S), shows that the LNADW enters the Guinea Basin as deep zonal flows, obviously through the Romanche and Chain Fracture Zones. But, unlike with UNADW, where zonal changes in nutrient concentrations along the equator (Fig. 9b and c) are negligible, the silicate and phosphate concentrations on 45.87 σ4 within LNADW increase considerably (through 15 μmol kg⁻¹ and 0.20 μmol kg⁻¹ respectively) from 35°W to 3°50′W (Fig. 11b and c) indicating a substantial mixing with the bottom waters that occurs in these fracture zones (Mercier and Morin, 1997). The silicate and phosphate minima on 45.87 σ4 at 1°W and 2°E, on either side of the Guinea Rise (0°), in the 4°30′S section (Fig. 11d) indicate the poleward escape of the LNADW from the Guinea Basin.

5.3. Circumpolar Water

The Circumpolar Water (CPW) can be seen as a large body of nutrient-rich water in the 4°30′S section (Figs. 2d and 3d). Its westward and then northward progression in the bulk of NADW can be recognized from the shape of the 35 μmol Si kg⁻¹ and the 1.4 μmol P kg⁻¹ isolines (Figs. 2d and 3d) and the nutrient maxima at ~45.79 σ4 (depth ~2900 m) along 4°30′S and ~45.84 σ4 (depth ~3200 m) along 7°30′N in the western basins (Fig. 10). The meridional flow of CPW is best illustrated by the nutrient distribution on the 45.79σ4 isopycnal in the two zonal sections and the 35°W section (Fig. 12): the continuous westward decrease in the concentrations, due to a mixing with NADW, is interrupted by an increase at 31–33°W in the 4°30′S and at 47–48°W in the 7°30′N sections. A similar increase can also be seen at 2–3°S in the 35°W section. The location of this maximum at a distance of about 200–400 km off the continental slope in all these sections suggests an offshore recirculation of the DWBC at ~3000 m that carries the CPW into the north Atlantic (Mc Cartney, 1993).

The meridional flow of CPW into the north Atlantic also occurs as a deep boundary current above the eastern flank of the MAR (Warren and Speer, 1991). This flow can be seen from the dome-shaped distribution of silicate and phosphate on the 45.79σ4 isopycnal at 10°W in the 4°30′S section and their eastward monotonous increase, in spite of the Sierra Leone Rise (21°W) barrier, along the 7°30′N section.
Fig. 12. Distribution of silicate and phosphate on $\sigma_z = 45.79$ along (a) $7^\circ30'N$, (b) $35^\circW$, (c) $3^\circ50'W$ and (d) $4^\circ30'S$ in the core of the CPW. Positive and negative values on abscissa indicate East and West longitudes, and North and South latitudes.
(Fig. 12a and d). However, the trough of low nutrients centred at 1°N on the 45.79\(\sigma_4\) isopycnal (2700 m depth) along 3°50'W (Fig. 12c) shows that there is no trans-equatorial flow of CPW east of the MAR and that, instead, the deep flow in the eastern part of the equatorial belt is a zonal flow, characterized by an equatorial tongue of low nutrients.

6. Bottom waters

The prominent feature in the distribution of nutrients below the 4000 m isobath is the very high concentrations of silicate (>100 \(\mu\)mol kg\(^{-1}\)), phosphate (>2.0 \(\mu\)mol kg\(^{-1}\)) and nitrate (>30 \(\mu\)mol kg\(^{-1}\)) along 4°30'S and in the equatorial channel at 35°W in the western basin but not in the northern and the eastern sections (Figs. 2–4). This demonstrates, in conformity with the earlier studies, the predominant flow of the AABW into the Brazil basin and its northward escape into the North Atlantic through the equatorial channel. However, the bottom water in the Brazil Basin across the 4°30’S section is not zonally homogeneous: the high silicate layer splits into two cores hugging the western and eastern slopes of the basin (Fig. 2d). The distribution of silicate and phosphate on the 46.03\(\sigma_4\) isopycnal (≈5000 m deep in the eastern side and 4750 m in the western side of the basin) shows more clearly the separation of the two cores (silicate >110 \(\mu\)mol kg\(^{-1}\) and phosphate >2.1 \(\mu\)mol kg\(^{-1}\)) on both sides of the basin (Fig. 13a). The distribution of silicate in the near-bottom waters (Fig. 13b) shows this separation more clearly; the highest silicate concentrations are on the western edge and not in the deepest stations where the lower concentrations suggest a northern influence. This is evidence of a recirculation of AABW in the Brazil Basin (see also Arhan et al., this volume) and supports the cyclonic gyre circulation proposed for AABW by Speer and Zenk (1993) and Durrieu De Madron and Weatherly (1994) in this basin. Distribution of nutrients on the 46.03\(\sigma_4\) isopycnal (Fig. 13a) as well as in the near-bottom waters (15 m depth above the seafloor) (Fig. 13b) show an increase in the eastern flank of the basin, suggesting another northward flowing component of AABW that becomes also apparent as a recently ventilated branch of the AABW in the CFM section (Andrié et al., this volume).

The AABW may exit the Brazil Basin via two paths: an eastern equatorial branch through the RFZ and a western branch that crosses the equator through a narrow zonal channel (sill depth <4500 m) into the Guiana Basin (Mantyla and Reid, 1983). It is not clear, however, whether the main flow of AABW is eastward along the southern flank of the MAR toward the RFZ or westward across the equator into the Guiana basin (Warren and Speer, 1991; Speer and Zenk, 1993; McCartney and Curry, 1993; Durrieu De Madron and Weatherly, 1994; Mercier et al., 1994).

The higher silicate and phosphate concentrations in the near-bottom waters west of the MAR (Para and Demerara Abyssal Plains) in the 7°30’N section (Fig. 14a) indicate that the AABW moves northwestward with less modification, and probably in a greater volume, than through the RFZ into the eastern North Atlantic; in fact, the bottom water that is present over a width of 160 km (0°40’N to 0°50’S) in the equatorial deep channel at 35°W still retains a large fraction of the AABW properties
Fig. 13. Distribution of silicate and phosphate in the northern Brazil Basin along 4°30’S on (a) 46.03σ4 and (b) near the bottom (15 m above the sea-floor). The depth of the bottom is also shown. Negative values on abscissa indicate West longitudes.

[density >46.00σ4, silicate >100 μmol kg−1 (Fig. 2b), phosphate >2.0 μmol kg−1 (Fig. 3b), nitrate >30 μmol kg−1 (Fig. 4b)]. The incidence of the highest silicate value (109 μmol kg−1) stuck against the southern flank of the MAR (0°40’N) (Fig. 14b) implies that AABW flow occurs mainly in the northern half of the channel, rather than in its southern half as proposed by Hall et al. (1994) and Rhein et al. (1995). The higher
concentrations of silicate and phosphate in the near-bottom waters on the western side (42–45°W) of the Guiana basin than on its eastern side (38–40°W) (Fig. 14a), similar to what was observed in the Brazil basin (Fig. 13b), suggests that a larger proportion of the AABW flows near the continental margin than offshore, although at 7°30′N the isopleths rise eastwards against the western flank of the MAR (Fig. 2a), as was also observed along 11°N by Friedrichs and Hall (1993): the westward downslope of the isopleths results from a strong vertical gradient of the properties due to the superposition of the LNADW flowing south and the AABW flowing north.

The silicate and phosphate contents of the bottom water between 38°W and 45°W in the Demerara Abyssal Plain north of Ceará Rise scarcely reach 80 and 1.75 μmol kg⁻¹ (Fig. 14a). The decrease in silicate content is through about 30 μmol kg⁻¹ over a distance of about 800 km north of the equator, whereas it is through only 9 μmol kg⁻¹ over ~500 km in the south (Fig. 15a). This shows that the passage of AABW in the equatorial channel, already constrained by the topography, is also accompanied by a strong mixing with the overlying, relatively nutrient-poor NADW.

The MAR excludes the densest and nutrient-rich waters of Weddell Sea origin from the eastern Atlantic (Sierra Leone, Guinea, Angola, and Cap Verde) Basins. Below 4000 m, the Angola Basin is cut off from the south and the bottom water, hence, enters only from the north (Warren and Speer, 1991). This occurs through the Romanche and Chain Fracture Zones of the MAR, but the strong mixing between with the LNADW in the fracture ones (Mercier and Morin, 1997) alters the properties of the AABW to such an extent that the bottom water exiting the fracture zones into the eastern Atlantic is vertically homogeneous (Fig. 15b) and has a silicate content no more than 60 μmol kg⁻¹ in the Guinea (Fig. 14c) and Angola (Fig. 14d) Basins, supporting the finding of Mantyla and Reid (1983) that the bottom silicate concentrations in the Angola Basin are about half of those in the Brazil.

Highest concentrations of silicate (56 μmol kg⁻¹) and phosphate (1.54 μmol kg⁻¹) in near-bottom waters are found in the northern part (16–19°W) of the Sierra Leone Basin east of the Sierra Leone Rise (21–22°W) (Fig. 14a). These are only slightly lower than those of the waters exiting the fracture zones and suggests that a part of the bottom water moves northward. The silicate and phosphate concentrations in the Sierra Leone Basin are, however, higher than in the Gambia Abyssal Plain (22–30°W) of the Cape Verde Basin at the same depth (4800 m) (Fig. 14a). This indicates that there is not much exchange of bottom water between the Sierra Leone Basin fed by the RFZ and the Gambia Abyssal Plain fed by the Vema Fracture Zone (VFZ) at 11°N (Mantyla and Reid, 1983; McCartney et al., 1991; Tsuchyia et al., 1992). The phosphate maximum at 7°30′N in the Sierra Leone basin lies nearer the continental rise, coincident with an oxygen minimum observed by Arhan et al. (this volume) and McCartney et al. (1991), suggesting that regeneration from organic matter sinking on the continental rise is the cause for this.

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Fig. 14. Distribution of silicate and phosphate near the bottom (15 m above the sea floor) along (a) 7°30′N, (b) 35°W, (c) 3°50′W and (d) 4°30′S. The depth of the bottom is also shown. Positive and negative values on abscissa indicate East and West longitudes, and North and South latitudes.
Near-bottom nutrients

(a) 7°30'N
- ▣ Silicate
- ○ Phosphate

(b) 35°W
- ▣ Silicate
- ○ Phosphate

(c) 3°50'W
- ▣ Silicate
- ○ Phosphate

(d) 4°30'S
- ▣ Silicate
- ○ Phosphate
On the eastern continental rise of the 4°30'S section, high nutrient concentrations appear at 4000 m (Fig. 14d), with core values of 65.1 µmol kg⁻¹ silicate, 1.64 µmol kg⁻¹ phosphate and 23.5 µmol kg⁻¹ nitrate on 45.865°E at 8°10'E. These nutrient maxima spread offshore at the same depth over a distance of >400 km, as evident from the vertical profiles of nutrients at all stations up to Sta. 17 (4°20'E). Van Bennekom and Berger (1984) described such maxima between 5°S and 8°S latitudes, and Warren and Speer (1991), later, from a section at 11°S. It has been hypothesized (Van Bennekom and Berger, 1984; Reid, 1989; Warren and Speer, 1991) that these maxima are derived from decomposition of organic material carried down by the Congo River outflow through the deep submarine canyon at 6°S and accumulated within the sediments. The cores of high silicate and phosphate that appear blocked against the continental rise (Figs. 2b and 3b) coincide with an oxygen minimum (Arhan et al., this issue), lending support to this hypothesis. From their observation of this feature of nutrient minimum at the 11°S section, Warren and Speer (1991) concluded that the flow along the African continental slope is southward and that the deep circulation in the Angola Basin is cyclonic. The location of the nutrient maxima at 4°30'S, north of the river mouth (6°10'S), however, is compatible with a northward extension of the Congo plume, so that the bloom of marine phytoplankton can develop offshore and to the north (Van Bennekom and Berger, 1984).

7. Conclusions

The nutrient data presented in this paper complement several deductions on circulation patterns made with other tracers measured simultaneously during the
CITHER 1 cruise (Andrié et al., this issue; Arhan et al., this issue) and from earlier studies. The most important results are the following.

7.1. Near surface waters

The enhanced nutrient concentrations illustrate, on one hand, the meanders of the North Equatorial Countercurrent generated by the retroflection of the North Brazil Current in the western area and, on the other, the effects of the cyclonic circulation cells on both sides of the equator in the eastern boundary.

7.2. Intermediate waters

The nutrients, especially the silicate, enable the differentiation between the AAIW and the UCPW, both of which have a southern origin. The entrance of AAIW in the equatorial belt along the western boundary and its eastward spreading along the equator are shown, while its possible escape through the northwestern and southeastern boundaries are discussed. The silicate distribution illustrates the complicated nature of the equatorial flow and the possibility of reversal of the direction of UCPW, as shown by the float trajectories (Richardson and Schmitz, 1993).

7.3. Deep waters

The nutrient distribution confirms the earlier descriptions of recirculation branches at the levels of UNADW and LNADW in the Guiana Basin in the northwestern equatorial area. The observations along 35°W reveal that the flow of NADW (upper and lower branches) is more eastward as an equatorial current than southward as a western boundary current.

The eastward spreading of UNADW along the equator as far as 3°50'W, without substantial modifications of its nutrient contents, is a remarkable feature. The eastward progression of LNADW is impeded by the Mid-Atlantic Ridge, and its properties are considerably altered by mixing with the underlying waters on crossing the equatorial fracture zones (Romanche and Chain), as shown by Mercier and Morin (1997) from hydrographic observations. As was the case with the intermediate layers, silicate anomalies in the UNADW core at 3°50'W support the assumption of a reversal of the direction of the equatorial flow. Some possibilities of leakages of UNADW and LNADW on the northeastern and southeastern ends of the equatorial belt are suggested.

South of the equator in the western basin, the eastward progression of NADW, except for its upper part, is blocked from reaching the MAR by the westward spreading of CPW advected from the south on the eastern flank of the MAR.

7.4. Bottom waters

Our data confirm the southward recirculation of AABW flowing northward on the western rise of the Brazil Basin, as reported in previous hydrographic studies (Durrieu
de Madron and Weatherly, 1994). The higher nutrient concentration in near-bottom waters west of the MAR and north of the equator indicate that AABW flows with less modification, and probably in a greater volume, northwestwards into the Para and Demerara Abyssal Plains than through the equatorial fracture zones into the eastern Atlantic. They also demonstrate that the northwestern passage of AABW is concentrated in the northern half of the equatorial channel rather than in its southern half, as concluded by Rhein et al. (1995).

Highest nutrient concentrations east of the MAR are not encountered at the greatest depths in the centre of basins, but on the continental rise, where, consistent with earlier observations (Van Bennekom and Berger, 1984; Mc Cartney et al., 1991; Warren and Speer, 1991), the decomposition of suspended organic material enhances the nutrient content. The vertical distribution of silicate in the Guinea and Sierra Leone Basins, i.e. after the passage of bottom waters through the equatorial fracture zones, clearly shows their mixing with overlying waters and the homogenization of the properties in deep layers.

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