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Water masses and zonal current in the Western Tropical Atlantic in October 2007 and January 2008 (AMANDES project)

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Abstract

The properties and circulation of water masses are examined using data collected from a hydrographic and Acoustic Doppler Current profiler in the Western Tropical Atlantic during two cruises of the GEOTRACES process study “AMANDES” (AMazon-ANDEans): AMANDES I (October–November 2007) and AMANDES II (January 2008). In the upper layer (from the sea surface to 150 m) means of vertical sections of velocity are showing the structure of the Current (NBC) and North Equatorial Countercurrent. In the lower layer (below 150 m) the subsurface velocity core of the North Brazil UnderCurrent, Western Boundary Undercurrent (WBUC) and northern branch of the South Equatorial Current (nSEC) could be observed. In October the WBUC flows southeastward with a velocity of about 0.3 m s^{-1}. In the studied area during October 2007, the NBUC and nSEC are transporting South Atlantic Central Water (SACW) from the Southern Hemisphere whereas the WBUC transports North Atlantic Central Water (NACW) southeastward. In the deep layers, the North Atlantic Deep Water (NADW) is composed of three components: the Upper North Atlantic Deep Water – UNADW (between 1310 and 1650 m), the Middle North Atlantic Deep Water (between 1930 and 2400 m), the Lower North Atlantic Deep Water (centered around 3430 m).

Off Guyana, the Antartic Intermediate Water (AAIW) changes of composition between October 2007 (45.2% ACW, 32.2% $AAIW_{source}$ and 22.6% UNADW) and January 2008 (62.4% ACW, 23.5% $AAIW_{source}$ and 14.1% UNADW).

These intermediate waters are significantly warmer, less oxygenated and saltier than their southern source, reflecting both oxygen consumption and mixing with the Atlantic Central Water (ACW) and the Upper North Atlantic Deep Water during their northward transit.

1 Introduction

The ocean dynamic of the coastal system of the NE shelf of South America is extremely complex. This system comprises the Amazon's shelf and estuary as well as the French Guyana shelf. Wind stress is essentially due to the Trade Winds; other forcings are due to the enormous fresh water discharge (averages 180 000 $\mathrm{m}^3\,\mathrm{s}^{-1}$) and sediment load ($1.1$–$1.3\times10^9$ tons y^{-1}) as well as strong tidal currents (Oltman, 1968; Meade et al., 1985; Geyer et al., 1996). The coastal system is connected to the tropical Atlantic Ocean through complex Western Boundary circulation.

The southwest tropical Atlantic Ocean plays an important role in the inter-hemispheric changes of mass, heat and salt (Schmitz and Mc Cartney, 1993; Dengler et al., 2004). Along the western boundary, whereas the Deep Western Boundary Current transports cold North Atlantic Deep Water towards the Southern Hemisphere, the North Brazil Current/North Brazil UnderCurrent system (hereafter NBC/NBUC) transports warm surface waters northward from the Southern Hemisphere. Those are the most active currents at the western frontier area, mainly composed of waters from the Equatorial and South Atlantic, originating from the forking of the South Equatorial Current (SEC), with a northeast flow along the north Brazilian coast. These current systems are a major component of the global meridional overturning circulation – MOC (Gordon, 1986; Schott et al., 2005).

These eastward currents may also be fed by North Atlantic waters through the recirculation of the North Equatorial Current (NEC) and the Western Boundary Undercurrent, but a direct connection between the WBUC and the NEUC/EUC is still unclear (Schott and Böning, 1991; Wilson et al., 1994; Bourlès et al., 1999a, b). Actually, the complete seasonal and spatial comprehension of the WBUC circulation in the region is not clearly defined yet.

Crossing the equator, part of the NBC/NBUC is retroflected eastward into the Equatorial UnderCurrent (EUC), while another portion of the NBC continues northwestward and is retroflected again near 7° N–50° W into the North Equatorial Counter Current

(NECC; Johns et al., 1998; Bourlès et al., 1999a, b).

These retroflections cause the formation of rings (Didden and Schott, 1993; Johns et al., 1990; Richardson et al., 1994). Satellite images and in situ observations demonstrate that these rings break away from the retroflection and move northwestward along the coast of Guyana, representing one of the main process transporting surface waters from the equatorial and southern Atlantic toward the Northern Hemisphere as part of the Meridional Overtuning Circulation (Johns, et al., 2003; Garzoli et al., 2003).

Despite recent advances on the knowledge about all the mechanisms mentioned above, the meridional distribution and blending of the water masses converging to this dynamical ocean area have been poorly investigated so far. Metcalf and Stalcup (1967), Cochrane et al. (1979), Wilson et al. (1994), Bourlès et al. (1999a,b) and Goes et al. (2005) identified three different origins for the water masses encountered in the upper layers of the western equatorial Atlantic. The first was named the North Atlantic Water (NAW), originating from the subtropical region of the Northern Hemisphere, being advected towards the equator by the NEC, and characterized by high salinities above the thermocline and low O_2 concentrations below the thermocline. The second was named the South Atlantic Water (SAW), exhibiting high salinity values above the thermocline and low salinity values and high O_2 concentrations below the thermocline, when compared with the NAW. The SAW is carried to the studied coastal system by the NBC/NBUC system. The third water mass is identified as the Eastern Tropical Atlantic Water (EAW), advected via the southern edge of the NEC and the northern branch of the South Equatorial Current (SEC) and characterized by the lowest O_2 concentrations around the thermocline when compared to the SAW and NAW.

The aim of the present work is to investigate the spatial and seasonal variability of the water masses along the northern coast of Brazil, using hydrographic data ($CTDO_2$) and acoustic Doppler current profiler (ADCP) observations collected during two short oceanographic cruises, AMANDES I and II. A particular attention is given to the sea area comprised between the northern continental shelf and the 4000 m isobath, a region marked by the strong ocean dynamics associated to Amazon River discharges and by the confluence of water masses coming from the North Atlantic and the South Atlantic.

2 Data and methodology

2.1 Study area and data collection

The hydrographic data sets (Fig. 1 – CTDO$_2$ stations) were collected using the R/V *Antea* cruises, as part of the AMANDES project. The general objective of this GEOTRACES' process study is to better understand and quantify the land to ocean physical and chemical fluxes, including geochemical tracers. AMANDES focuses in particular on the physico-chemical exchange between the passive margin of the Amazon River estuary, characterized by an important continental influx, and its significant impact on neighboring Atlantic ocean water masses.

Data used in this work were sampled during the late boreal Fall (17–31 October 2007) – AMANDES 1 and boreal Winter (11–26 January 2008) – AMANDES 2 in the region bounded by the 4° N and 8° N, between 47.5° W and 51.5° W (Fig. 1). Sea data correspond to continuous vertical profiles of temperature, salinity and oxygen (CTDO$_2$) obtained using a *Sea Bird Electronics SBE911plus*CTD, with high resolution sensors for Conductivity measurement (resolution=0.0003 s m^{-1}), Temperature (resolution=0.0002 °C), Oxygen (0.02 ml l^{-1}) and Pressure (resolution=0.068 dbar). Measurements of the oxygen sensor are calibrated by comparing the results of the chemical analyses of waters (determined using a Winkler method) collected with 12-bottle Rosette and the measurements of the probe obtained at the same pressure. Comparison with the rosette-CTD system and occasional salinity determinations of pumped water on an Autosal salinometer indicated that the data are reliable to at least .01 °C in temperature and .01 in salinity.

Shipboard ADCP observations were collected continuously along the track lines during both cruises. The R/V *Antea* is equipped with a 75 kHz Ocean Surveyor, lowered into the ship's well. Data were collected with a vertical depth cell (bin) length of 16 m. The profiling range was 500–750 m depending on the sea state.

3 Results and discussion

3.1 The zonal current system in the region

Means of vertical velocity sections are showing the structures of the NBC, NBUC, WBUC, NECC and nSEC currents. During October 2007, along the transect #1, a current flowing eastwards at 5.7–5.8° N and advecting waters from the Southern Hemisphere (the nSEC) is observed up to the subsurface (∼200 m depth). The core of the NECC is centered around 50 m depth , displaying a maximum velocity of about 1.3 $\mathrm{m\,s^{-1}}$, located at 6.6° N (Fig. 2a). This observation is consistent with those of Bourlès et al. (1999a) who observed in summer the core of the NECC centered around 60–80 m depth, with maximum velocities of about 1.0–1.2 $\mathrm{m\,s^{-1}}$.

In the same period, along the transect #2 at 5° N–51° W a portion of the NBC flowing continuously northwestward along the coast is observed (Fig. 2b), suggesting that another portion of the NBC separates sharply from the coast to feed the NECC. Below the NBC the subsurface velocity core of the NBUC is located around 250 m, with maximum velocities above 1 $\mathrm{m\,s^{-1}}$. The WBUC is flowing southeastward along the boundary between 5.6–5.9° N, around 150–350 m depth (Fig. 2b). This current also displays a weak velocity (0.3 $\mathrm{m\,s^{-1}}$), but in the opposed direction to that of the NBUC. Colin and Bourlès (1994) have localized the WBUC slightly deeper (250–800 m), but with similar velocities of about 0.3 $\mathrm{m\,s^{-1}}$ in February and June. The same authors observed that during late winter, spring and beginning of summer, the WBUC was trapped along the upper part of the slope and flowing southeastward.

The current flowing westward along the same transect is the continuity of the nSEC. North of 6.6° N, currents flowing eastward are probably corresponding to the NECC with maximum velocity core of about 0.5 $\mathrm{m\,s^{-1}}$ at 150 m depth, weaker than the current observed in the region of transect 1 during the same period (Fig. 2b). These observations are also confirmed by water mass transports described in the Sect. 3.2.

In January 2008 (data not shown) ADCP data allow identifying the NBC near the surface, with a maximum velocity larger than in October (~0.7 $\mathrm{m\,s^{-1}}$) between 5.7° N–6.12° N, but these data do not allow distinguishing clearly NBUC, NECC or WBUC. This could result either from mesoscale eddies or from tidal forcing (internal waves). These points will be discussed in a further study.

3.2 Water masses analysis

3.2.1 Surface water layer (<400 m)

October–November 2007 (Amandes I)

Surface waters with low salinity values (Table 1, Fig. 3a), observed at the coastal stations in October 2007 (station 1–4), are reflecting the influence of South America river discharges (e.g., the Amazon) and of tropical rains. The NBC retroflexion induces that Amazon fresh waters influence is predominating in large areas off the Amazon shelf as observed at stations 1–5 and 1–7. The salinity maximum corresponding to densities higher than 25.0 $\mathrm{kg\,m^{-3}}$ represent the Salinity Maximum Water (SMW), part of the Tropical Surface Waters (TSW) (Stramma et al., 2005; Fig. 3a).

The Atlantic Central Waters are flowing between the thermocline and the isopycnal σ_θ = 27.1 kg m–3 (around 450 m depth), their core being at σ_θ = 26.7 kg m–3. These waters are characterized by a nearly linear θ-S diagram (Fig. 3a). Silva et al. (2009) describe the penetration of cores of maximum salinity (≥36.6) located around 100–150 m depth originating in the Southern Hemisphere and flowing towards the Northern Hemisphere through the NBC/NBUC system in the studied area.

At stations 1–5 and 1–7 (Fig. 3a and b), the North Atlantic Central Water (NACW) is characterized by high salinity values above and below the thermocline associated with relatively high O_2 concentrations (Bourlès et al., 1999a; Stramma et al., 2005).

The NACW is also occurring at station 1–4, but slightly mixed with waters of lower salinity. Contrastingly, lower salinities and high O_2 concentrations at station 1–6 reveal the occurrence of the South Atlantic Central Water (SACW), flowing at the same depths as the NACW (Fig. 3a and b). At this station, the southern waters observed are likely carried by westward flows of the nSEC.

At the northern stations (1–5 and 1–7), the occurrence of the NACW is likely due to a stronger NECC in October–November. The NECC at this location receives a contribution of waters from the north carried by the NEC. Indeed, Garzoli et al. (2004) and Bourlès et al. (1999a) describe that a retroflected portion of the Atlantic NEC could be entrained into the NECC, fact confirmed here by our data.

Mixture of waters of northern and southern origins, enhanced by the two currents flowing in opposite direction (NBUC and WBUC, Fig. 2) are likely explaining the lower salinities characterizing station 1–4 (Fig. 3a).

Januray 2008 (Amandes II)

During AMANDES II at station 2–31 and at station 2–9 (both $\sigma_\theta > 26\,\mathrm{kg\,m^{-3}}$), the salinity maximum is associated to low O_2 concentrations that are characterizing the NACW in subsurface (Fig. 3c and d).

At station 2–9, rapid O_2 concentration decreases and salinity increases between 19.5 °C and 21 °C could reveal the intrusion of NACW, precluding a southern origin for these salty waters. From $\sigma_\theta = 26.0\,\mathrm{kg\,m^{-3}}$ to $\sigma_\theta = 27.0\,\mathrm{kg\,m^{-3}}$, the linear θ-S (Fig. 3c) corresponds to the NACW. The NACW are observed at station 2–9 below 150 m depth (Fig. 3c and d).

Potential Temperature-Salinity diagram (θ-S) and Potential Temperature-Oxygen (θ-O_2) diagrams also reveal the NACW occurrence at stations 2–7, 2–8 and 2–13 along the isotherm 20 °C. In this region the presence of waters transported southeastward from the Northern Hemisphere was observed (Fig. 2).

3.2.2 Intermediate water layer (400–1200 m)

Intermediate layers being less disturbed by currents and various contributions, the water masses are characterized by curved profiles of potential temperature – salinity (θ-S; Fig. 4a) and potential temperature – dissolved oxygen (θ-O_2; Fig. 4b).

October–November 2007 (AMANDES I)

During boreal fall, a mixture of water masses is observed below 400 m (about 8–7 °C) at station 1–6, characterized by an increase of oxygen concentration associated to a decrease of salinity values at this depth (Fig. 4a and b). In the same region, Goest et al. (2005) identified the EAW, with an increase of oxygen concentration at the same depth (about 8 °C). The EAW is carried to the studied area by northern edge of the SEC (Fig. 2).

The salinity minimum corresponds to $T = 5.09$°C (Fig. 4a and Table 1), typical for the Antartic Intermediate Water (AAIW). Formed at the sub-surface in the Subantartic Front region, AAIW spreads along the western boundary and crosses the equatorial zone with the North Brazil UnderCurrent (NBUC). This water mass is a priori characterized by low salinity and high oxygen concentration (Oudot et al., 1998; Tsuchiya et al., 1994). However, the θ-O_2 profile shows low oxygen concentrations (about 140 μmol kg^{-1}) for this water, reflecting that oxygen depletion occurred during its transport from the austral ocean, which could be biological, or due to mixture of waters, or both (Fig. 4b). This water mass will be designed as "AAIW-Guyane" in the following.

January 2008 (AMANDES II)

As in October, AAIW-Guyanne (low S, low O_2, $T \sim 5$°C, Fig. 4d) was observed during winter.

Causes of the O_2 depletion affecting this water layer are discussed in Sect. 3.3.

3.2.3 Deep water layer (1200–4000 m)

The North Atlantic Deep Water (NADW) was observed during October 2007 (Fig. 4c and d) and January 2008 (Fig. 5a and b). The NADW is warm, salty, highly oxygenated and poor in nutrients (Tsuchiya et al., 1994; Oudot et al., 1998) and flows southward primarily by the Deep Western Boundary Current (DWBC). The NADW is composed of three components (Oudot et al., 1998; Ahran et al., 1998) (Fig. 4c and d and Table 1). In October, stations were deep enough to allow the observation of the three layers whereas only two could be sampled in Januray (Figs. 4 and 5).

- the Upper North Atlantic Deep Water (UNADW), characterized by a salinity maximum due to the intrusion of the Mediterranean Sea observed between 1550 and 1650 m in October and slightly higher in January (1310–1450 m);
- the Middle North Atlantic Deep Water (MNADW) originating in the Labrador Sea and characterized by a O_2 maximum (here, 254–261 μmol kg^{-1}) and flowing just below the minimum concentration of nutrients between 1930 and 2400 m in October and 2050 and 2300 m in January;
- the Lower North Atlantic Deep Water (LNADW), that primarily results from the convection in the Arctic Seas. The LNADW displays an O_2 maximum, is less salty but colder therefore more dense than the two other components. At 7° N 49.8° W (station 1–5), the LNADW core is located at 3430 m.

According to Tsuchiya et al. (1994), the minimum of oxygen concentrations observed between the MNADW and the LNADW could be attributed to the influence of the Upper Circumpolar Deep Water (UCDW).

3.3 AAIW-Guyana

AAIW off the French Guyana coast (AAIW-Guyana) is oxygen poor whereas this water mass is oxygen saturated in its formation zone. Two processes are susceptible to consume oxygen during the transit between the Sub Antarctic Front and the AMANDES zone: bacterial respiration during the remineralization of organic material and/or mixing with water masses already oxygen depleted. In order to quantify the bacterial consumption impact within the core of AAIW, we used the Apparent Oxygen Utilization parameter (AOU). AOU is defined as the difference between the supposed initial oxygen content of the water mass (deduced from its potential temperature) and the oxygen value measured at the sampling site and time (Fig. 7, AOU = $\text{O}_{2\ \text{sat}}$-$\text{O}_{2\text{m}}$).

Parameters of the AAIW-Guyana are:

θ_m = 5.09 °C, S_m = 34.56, $\text{O}_{2\text{m}}$ = 140 µmol kg^{-1}

Based on its potential temperature, the dissolved oxygen content at saturation for this water mass should be $\text{O}_{2,\text{sat}}$ = 307 µmol kg^{-1}. Subtracting the above $\text{O}_{2\text{m}}$ value yields and AOU of 167 µmol kg^{-1}.

AAIW$_\text{s}$ is subducting in the Sub Antarctic front (~32.5° W 46.9° S), where its is characterized by the following “source” parameters (subscript s): θ_s = 3.61 °C, S_s = 34.168 and $\text{O}_{2,\text{s}}$ = 322 µmol kg^{-1} (e-WOCE atlas http://odv.awi.de/).

Assuming that the oxygen content of AAIW$_s$ had only been consumed by biology, AOU of the AAIW-Guyana should be equal to 322–140 = 182 µmol kg^{-1}. However, AOU values along a section of the south-west Atlantic (~150 µmol/l, e-WOCE atlas http://odv.awi.de/) for the same water mass and latitude are generally smaller than that estimated here. In other words, AAIW-Guyane is warmer, less oxygenated and saltier than AAIW$_s$ arriving from its source and having experienced only oxygen consumption during its transit (Fig. 8). These results suggest that AAIWs experienced mixing with other water masses before reaching the studied area.

The warmer temperature and lower oxygen suggest a mixture with the Atlantic Central Waters (ACW) whereas salinity content likely reflects an influence of the Upper North Atlantic Deep Water (UNADW).

Mixing proportions were estimated using the hydrological properties for ACW and UNADW end-members reported in Table 1 and Fig. 4c and d and the following equations:

$$M_m = \alpha M_1 + \beta M_2 + \gamma M_3$$

$$S_m = \alpha S_1 + \beta S_2 + \gamma S_3$$

$$\theta_m = \alpha \theta_1 + \beta \theta_2 + \gamma \theta_3$$

$$\alpha + \beta + \gamma = 1$$

Where:
M is the water mass, S and θ are its physical parameters
α , β and γ are the mixing coefficients
m is the water mass to be characterized
1 refers to the ACW, 2 to the AAIW – source and 3 to the UNADW.

Based on these data, we obtained a mixture composed of 45.2% ACW, 32.2% AAIWs and 22.6% UNADW for AAIW-Guyana measured October 2007, and a mixture composed of 62.4% ACW, 23.5% AAIWs and 14.1% UNADW for AAIW-Guyana measured in January 2008. Such differences underline that seasonal forcing are significantly impacting the composition of waters, down to intermediate levels. Maamaatuaiahutapu et al. (1994) also observed seasonal variations of the AAIW composition in the region of Brazil-Malvinas confluence, though less pronounced (84.5% AAIW in spring, and 88.6% AAIW in winter). Mechanisms yielding to these differences will be discussed in a further study.

4 Summary and conclusions

Observations collected during two cruises carried out at different periods of the year (October 2007 and January 2008) contributed to the comprehension of the water masses and zonal currents in the Western Tropical Atlantic.

In October 2007, shipboard ADCP data showed the structures of the NBC, NBUC, WBUC, NECC and nSEC. Upper level mean currents were flowing northwestward along the shelf break and the NBC was outcropping at the surface. Its low velocity ($0.2\,\mathrm{m\,s^{-1}}$) suggested that a significant fraction left the coast to feed the NECC, the remaining fraction keeping flowing northwestward along the shelf. Below the NBC, the subsurface velocity core of the NBUC flowed in the same direction with a maximum velocity ($>1\,\mathrm{m\,s^{-1}}$), whereas a southeastward undercurrent -corresponding to the WBUC- has been observed along the boundary, with maximum velocity core of about $0.3\,\mathrm{m\,s^{-1}}$. At 6.0°–7.5° N the eastward flow of the NECC is observed with maximum velocity core ($>1\,\mathrm{m\,s^{-1}}$) centered around 60–80 m whereas south of it only a small fraction of the nSEC has been observed. At the same season, surface waters with low salinity values reflecting the influence of the Amazon fresh waters were observed off the Amazon shelf, extending offshore within the retroflection of the NBC/NECC system. In January 2008 ADCP data collected over the continental slope, allow identifying NBC near the surface, but do not allow distinguishing clearly NBUC or WBUC. This could result either from mesoscale eddies or from tidal forcing (internal waves), and need further investigation.

The linear θ-S relationship observed in the thermocline characterizes the Atlantic Central Waters (ACW). Its North Atlantic component (NACW, salty and oxygen rich) is advected by WBUC/NECC. Contrastingly, South Atlantic Central Waters (SACW, low in oxygen) are transported from the Southern Hemisphere by NBUC and nSEC.

During its transports from Antarctic, AAIW is submitted to both oxygen consumption and water mass mixing, probably with the ACW and the Upper North Atlantic Deep Water (UNADW). AAIW off Guyana are warmer, saltier and less oxygenated in winter than in fall, because of the larger proportion of its ACW end-member (62.4% instead of 45.2%).

Below these depths, North Atlantic Deep Water (NADW) is found. At 1500 m flows the UNADW, characterized by its maximum salinity ($S = 35$) due to an intrusion of the Mediterranean Sea. Then, the Middle NADW is observed around 2000 m, with maximum oxygen concentration (255–260 µmol kg^{-1}). A second maximum of oxygen concentration around 3500 m illustrates the Lower NADW, less salty and colder than the two previous currents.

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Table 1. Characteristics and depth locations of the water masses observed during AMANDES cruises.

Water Masses	Depth (m)	Potential temp. (°C)	Salinity	Oxygen Dissolved (μmol kg^{-1})	Potential Density σ_θ	AOU (μmol kg^{-1})
Amazon fresh waters	Surface	29.4	25.9	205.6	15.1	0
SMW	93	23.0	36.9	156.0	25.3	53.0
NACW	163	13.9	35.65	109.2	26.7	142.8
SACW	225	11.9	35.1	164.8	26.7	98.9
ACW	680	6.55	34.62	123.94	27.18	174.2
Water Mass Mixture	795	5.09	34.56	140.0	27.3	170.0
AAIW-Guyane	700	5.56	34.58	134.60	27.28	171
UNADW	1630	4.28	35.0	234.69	27.76	79.4
MNADW	1980	3.43	34.97	254.5	27.8	66.3
LNADW	3430	2.09	34.91	252.3	27.9	79.6

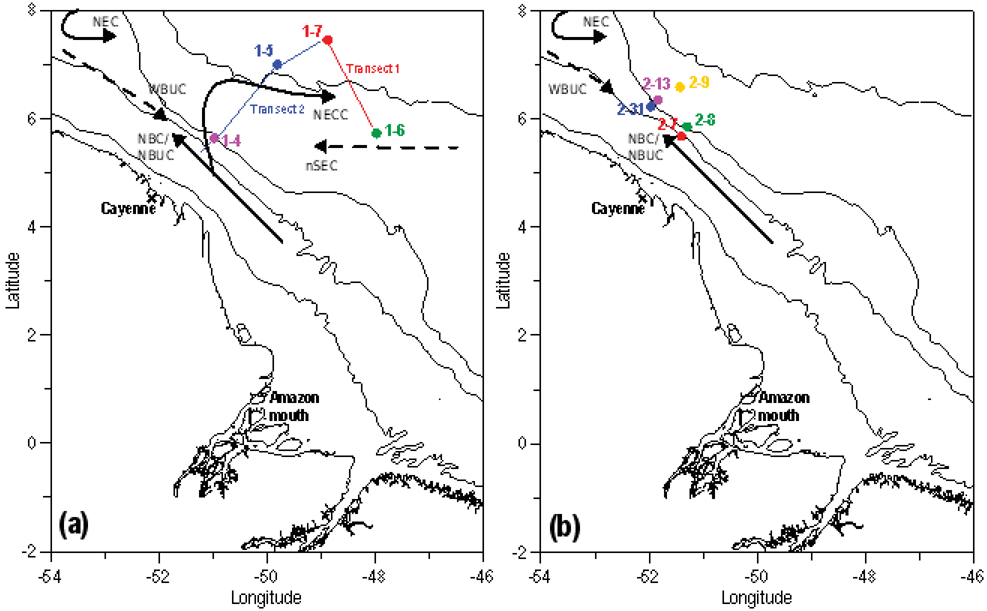

Fig. 1. Maps of the two cruises considered in this study: **(a)** October 2007 – AMANDES 1, **(b)** January 2008 – AMANDES 2. The track lines (Transects 1 and 2) indicate the location of the coverage for acoustic Doppler current profiler (ADCP) and circles represent conductivity-temperature-depth-O_2 ($CTDO_{2}$) profiles stations. Schematic diagram of the surface currents (NBC – North Brazil Current; NECC – North Equatorial Counter-current) and subsurface current (NBUC – North Brazil Undercurrent; WBUC – Western Boundary Undercurrent; nSEC – north South Equatorial Current). The 20-, 200-, 2000- and 4000-m isobaths are shown.

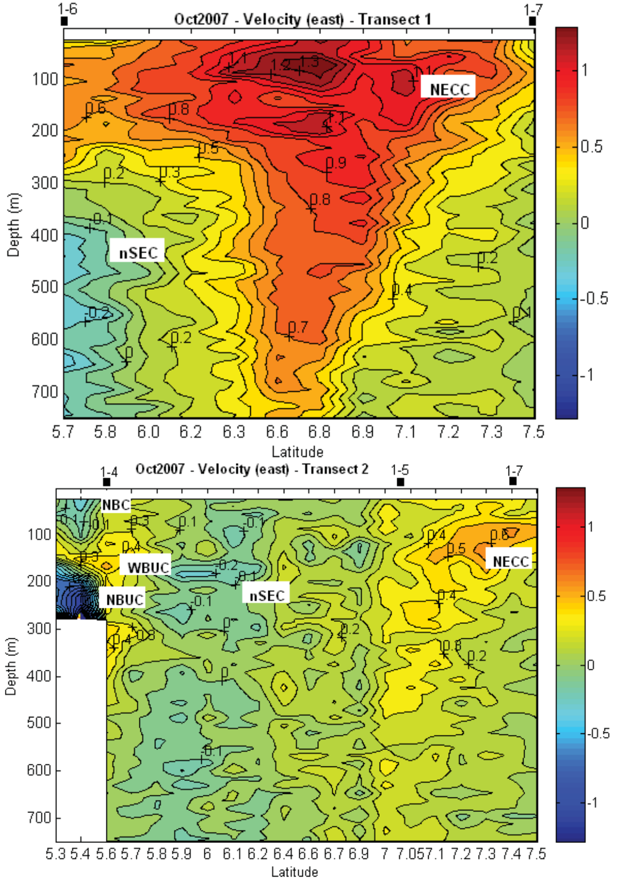

Fig. 2. Vertical sections of eastward velocity component (in meter per second) along two transects – Transect 1 (a) and Transect 2. The latitude reported on the X-axis corresponds to the locations of the ADCP velocity measurements in the studied area (see Fig. 1). CTDO$_2$ station positions are indicated at the top of each panel.

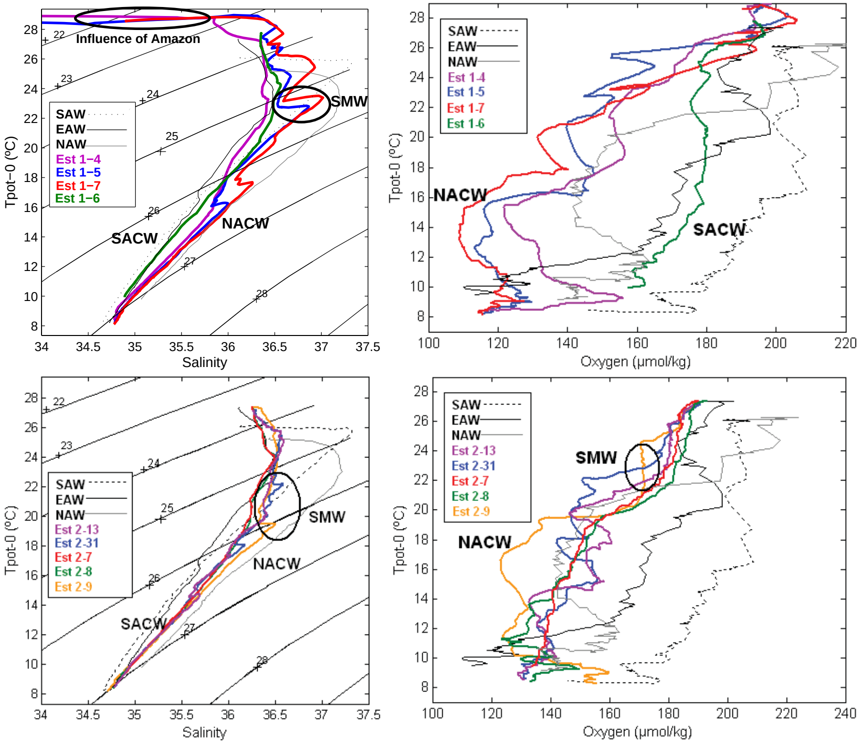

Fig. 3. (a) θ-S diagrams and **(b)** θ-O_2 plotted Surface water layer (<400 m) derived from the conductivity-temperature-depth-O_2 ($CTDO_2$) profiles stations during October 2007 and **(c)** θ-S diagrams and **(d)** θ-O_2 plotted Surface water layer derived from $CTDO_2$ profiles stations during January 2008. Yellow, blue, red, green and black lines represent the profiles of the stations identified with the same colours in Fig. 1. In all figures the bold lines are used to define typical θ-S and θ-O_2 features of the North Atlantic Water (NAW), South Atlantic Water (SAW) and Eastern Atlantic Water (EAW).

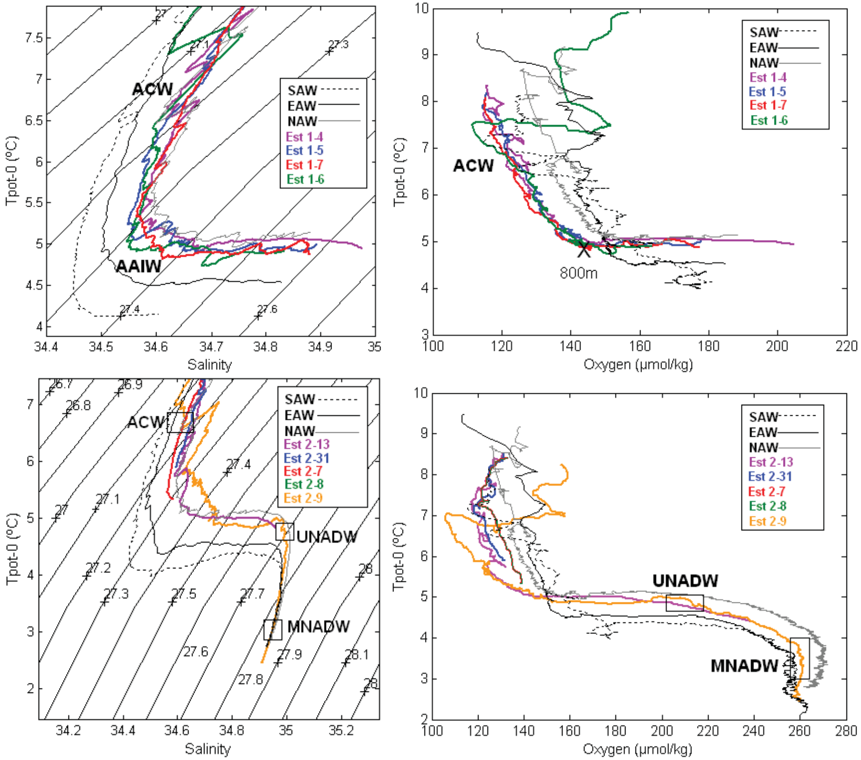

Fig. 4. **(a)** θ-S diagrams and **(b)** θ-O_2 plotted intermediate water layer (400–1200 m) derived from the conductivity-temperature-depth-O_2 ($CTDO_2$) profiles stations during October 2007; and **(c)** θ-S diagrams and **(d)** θ-O_2 plotted intermediate and deep water layer derived from the $CTDO_2$ profiles stations during January 2008 (see circles in Fig. 1).

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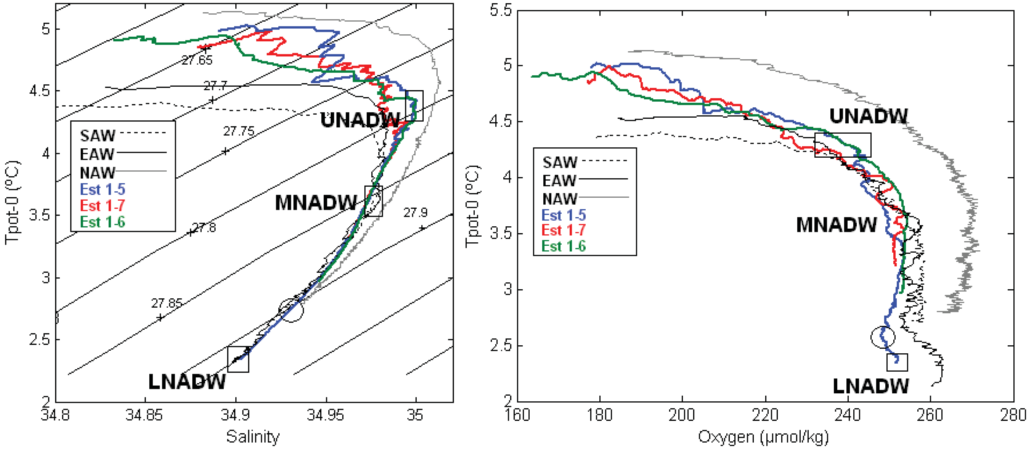

Fig. 5. **(a)** θ-S diagrams and **(b)** θ-O_2 plotted deep water layer (1200–4000 m) derived from the conductivity-temperature-depth-O_2 ($CTDO_2$) profiles stations during January 2008 (see circles in Fig. 1).

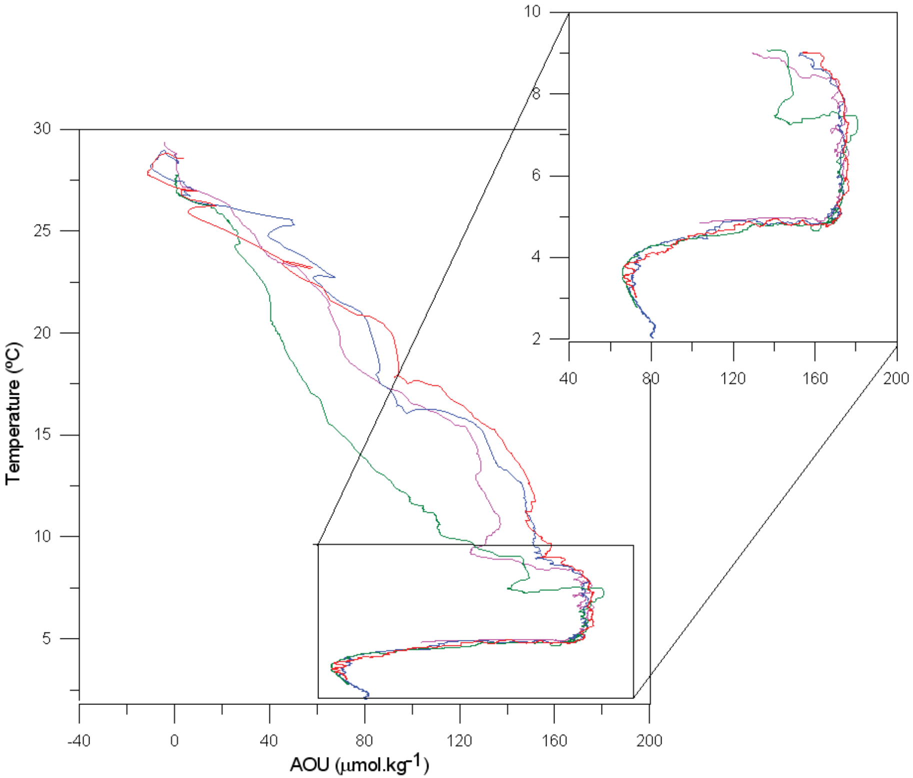

Fig. 6. Profil of the Apparent Oxygen Utilization parameter (AOU) versus temperature (˚C).

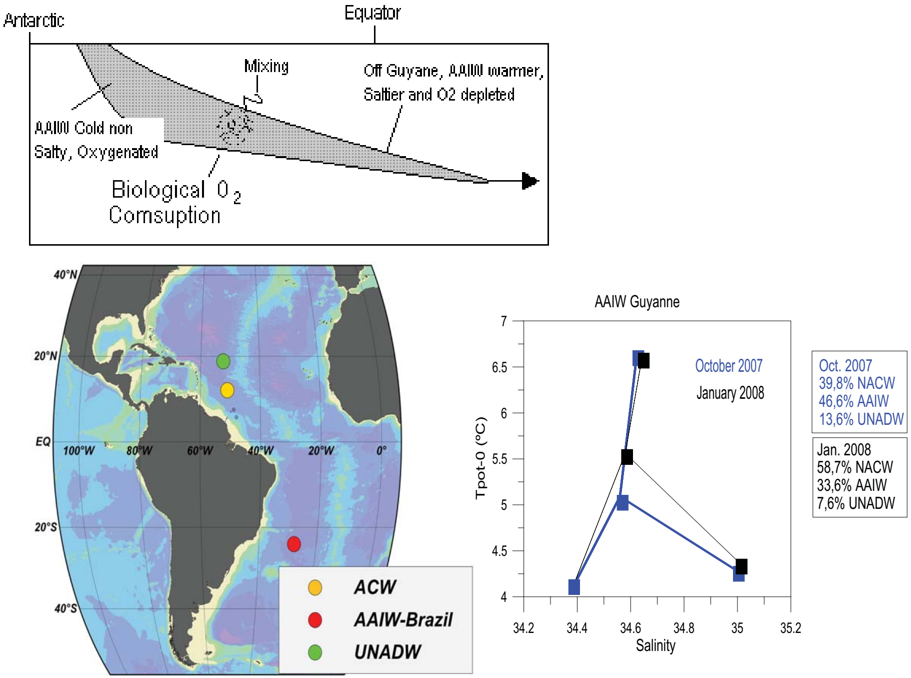

Fig. 7. Evolution of the water masses composition (mixture and oxygen consumption) during the AMANDES cruises.