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Circulation of the thermocline salinity maximum waters off the Northern Brazil as inferred from in situ measurements and numerical results

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Abstract. High resolution hydrographic observations of temperature and salinity are used to analyse the subsurface circulation along the coast of North Brazil, off the Amazon mouth, between 2° S and 6° N. Observations are presented from four cruises carried out in different periods of the year (March–May 1995, May–June 1999, July–August 2001 and October–November 1997). Numerical model outputs complement the results of the shipboard measurements, and are used to complete the descriptions of mesoscale circulation. The Salinity Maximum Waters are here analyzed, principally in order to describe the penetration of waters originating in the Southern Hemisphere toward the Northern Hemisphere through the North Brazil Current (NBC)/North Brazil Undercurrent (NBUC). Our results show that, if the Equatorial Undercurrent (EUC) is fed by Northern Atlantic Waters, this contribution may only occur in the ocean interior, east of the western boundary around 100 m depth. Modeling results indicate a southward penetration of the Western Boundary Undercurrent (WBUC) below the thermocline, along the North Brazilian coast into the EUC or the North Equatorial Undercurrent (NEUC) (around 48° W–3° N). The WBUC in the region does not flow more south than 3° N. The northern waters are diverted eastward either by the NBC retroflection or by the northern edge of the associated clockwise rings. The existence of subsurface mesoscale rings associated to the NBC retroflection is evidenced, without any signature in the surface layer, so confirming earlier numerical model outputs. These subsurface anticyclones, linked to the NBC/NBUC retroflection into the North Equatorial Undercurrent and the EUC, contribute to the transport of South Atlantic high salinity water into the Northern Hemisphere.

Keywords. Oceanography: general (Equatorial oceanography, Descriptive and regional oceanography) – Oceanography: physical (Western boundary currents)

1 Introduction

The Western Tropical Atlantic Ocean plays an important role in the inter-hemispheric transports of mass, heat, and salinity (Schmitz and Mc Cartney, 1993). Along the western boundary, where the Deep Western Boundary Current transports cold North Atlantic Deep Water toward the Southern Hemisphere, the North Brazil Current (hereafter NBC) transports warm surface waters northward from the Southern Hemisphere. Both currents are major components of the global thermohaline circulation cell (Gordon, 1986).

The NBC and its subsurface component, the North Brazil Undercurrent (NBUC), feed, through complex retroflection patterns, eastward flowing equatorial currents at different depths and latitudes (e.g., Schott et al., 1995; Bourlès et al., 1999a, b): (i) the South Equatorial Undercurrent (SEUC) below the thermocline around 3° S, (ii) the Equatorial Undercurrent (EUC) centered at the thermocline and the equator; (iii) the North Equatorial Undercurrent (NEUC) found below the thermocline around 3° N; and (iv) the North Equatorial Counter Current (NECC) located above the thermocline north of 5° N.

These eastward currents may also be fed by North Atlantic waters through the recirculation of the North Equatorial

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Current (NEC) and the Western Boundary Undercurrent (WBUC), but a direct connection between the WBUC and the EUC is still unclear (Schott and Böning, 1991; Wilson et al., 1994; Bourlès et al., 1999a, b). Stramma et al. (2005), by using the 1/12° – Flame General Circulation Model, demonstrated that part of the salinity maximum water from the Northern Hemisphere contributes to the water feeding the NEUC and also showed that salinity maximum water from the South Atlantic is transported towards the north Brazilian Shelf. The same authors also demonstrated that the NBC suffers a recirculation feeding the EUC close to the equator, generating two eddy features, located near 50° W and 44° W.

North of the equator, the NBC/NBUC retroflection may be linked to the formation of rings (e.g., Johns et al., 1990, 2003; Didden and Schott, 1993; Richardson et al., 1994). Results based on satellite images and in situ observations demonstrate that these rings break away from the retroflection and move northwestward along the coast of Guyana, representing an important mechanism for transporting waters from both equatorial and South Atlantic to the Northern Hemisphere (Garzoli et al., 2003). During the last decade, many works have focused on the evaluation of the genesis and the water transport capacity of the NBC rings (Johns et al., 1990, 2003; Didden and Schott, 1993; Richardson et al., 1994; Fratantoni et al., 1995). More recently Wilson et al. (2002) described three different types of rings as follows: the first one is characterized by shallow, surface-trapped structures that are confined to the upper ocean layers; the second type is characterized by deep-reaching structures with significant swirl velocities ($\sim$0.2 m s^{-1}) extending down to 2000 m; whereas the third type presents thermocline intensified structures with almost no detectable surface signature.

All these above-mentioned features make the Western Tropical Atlantic a very important ocean crossroads, with strong confluence of water masses coming from the north, the south and the equatorial Atlantic, and thus with intense blending processes. Therefore, a particular attention should be given to the ocean area situated between the shelf break and the 2000 m isobath, which seems to be a key for a better understanding of the retroflection and the formation of the NBC/NBUC rings. Previous studies in this region have been either limited to the shelf region (e.g. AMASSEDS Program, Lentz and Limeburner, 1995) or focused on large scale ocean circulation (e.g. Schott et al., 1998; Bourlès et al., 1999a, b).

In this paper we use high resolution in situ data from four different cruises of the Brazilian REVIZEE Program (Programa de Avaliação do Potencial Sustentável de Recursos Vivos da Zona Econômica Exclusiva) carried out along the northern coast of Brazil limited by 2.5° S–8° N in latitude, and 40° W–52° W in longitude, i.e. in a key area where the NBC/NBUC system penetrates into the Northern Hemisphere. The main objective is to describe a seasonal and spatial variability of the thermocline salinity maximum waters circulation off the Northern Brazil. From field data, Silva et al. (2005a, b; 2007a, b) have studied the influence of the

Amazon plume in inducting shallow pycnoclines within the isothermal layers of the Northern Brazilian shelf. Observations indicate that, along the North Brazilian shelf break, the formation of barrier layers seems also to be associated with the advection of the subsurface maximum salinity waters formed in the region of the subtropical gyres and transported to the study area by the NBC/NBUC system (Stramma et al., 1995; Pailler et al., 1999; Silva et al., 2005a; Stramma et al., 2005).

These data sets, along with the results obtained from a realistic numerical simulation, are used in order to attempt a better description and comprehension of the complex circulation within the subsurface layers, where the eastward undercurrents are fed through the NBC/NBUC retroflection and where thermocline salinity maximum waters may be clearly identified.

The paper is organized as follows. The main aspects of the hydrographic observations and numerical simulations are introduced in Sect. 2. In Sects. 3 and 4, we describe the vertical and horizontal sections obtained with high resolution hydrographic data observations of temperature and salinity, principally in order to describe the penetration of maximum salinity waters. The hydrographic data were complemented by modelling results to obtain additional information about the maximum salinity waters and mesoscale transport variability in this area. In these two sections, we also discuss the circulation of the seasonal and interannual variability, by using modelling results, to obtain additional information about the maximum salinity waters and mesoscale transport variability in this area. We conclude with a discussion relating the principals results obtained from our combined hydrographic data observations and numerical results.

2 Data and methods

2.1 Shipboard surveys

The hydrographic data sets were collected during four cruises performed at different times of the year, in March–May 1995, October–November 1997, May–June 1999 and July–August 2001, carried out on board the R/V Antares, as part of the activities of the Brazilian REVIZEE Program. The REVIZEE Program, coordinated by the Comissão Interministerial de Recursos do Mar/Inter-ministerial Commission of Sea Resources (CIRM), is the result of the commitment made by Brazil before the United Nations (UN), to ratify in 1988 the International Convention of the Law of the Sea, in effect since 1994. The main objective of the REVIZEE Program is to perform a survey of the living resources (and of the correlated abiotic factors) present in the Brazilian Exclusive Economic Zone (CIRM, 1994).

Field data correspond to a total amount of 307 vertical and continuous profiles of temperature and salinity obtained using a CTD probe Sea Bird Electronics SBE911plus, with a

Table 1. REVIZEE cruises periods and the number of CTD profiles.

Cruise period	Number of CTD
March–May 1995	114
October–November 1997	62
May–June 1999	88
July–August 2001	43

centrifuge pump and high resolution sensors for Conductivity (resolution $= 0.00004\,\mathrm{S\,m}^{-1}$), Temperature (resolution $= 0.0003°\mathrm{C}$) and Pressure (resolution $= 0.068\,\mathrm{dbar}$) measurements. Calibration of the CTD sensor has been performed before each cruise directly by the manufacturer of the apparetus, and indicated that the error value on temperature was negligeable. In order to validate the salinity sensor, values collected by the CTD were compared with values obtained with bottle salinity. The obtained values of the water-sample salinities are comparable to the precision (0.001) and accuracy (0.003).

During all the cruises, the CTD was operated until around 1000 m depth, with a descent speed of $1\,\mathrm{m\,s}^{-1}$, and a sample frequency of 24 Hz. During the profiling, the equipment remained connected to a boarding platform *SBE 11plus*, which permitted real time monitoring of data acquisition and quality control. Spacing between hydrographic stations ranged from 14 to 55 km depending on the distance from shore (Fig. 1). Table 1 shows a synthesis of the REVIZEE data.

These data sets have already been used to analyze Amazonian water lenses and barrier layer formation in this particular region (Silva et al., 2005a, b).

2.2 Model description

The CLIPPER modelling Project represents a French contribution to the World Ocean Circulation Experiment (WOCE). We use here the so-called ATL6-26 experiment of the CLIPPER model, based on the OPA 8.1 code primitive equation parallel model (Madec et al., 1998). The horizontal grid is a Mercator isotropic grid with a 1/6° horizontal resolution at the equator, covering the Atlantic Ocean from 98° W to 30° E in longitude and 75° S to 70° N in latitude. The model is initialised using the seasonal climatology from Reynaud et al. (1998). The model is forced by daily mass and heat surface fluxes, and average output has been stored every 5 numerical days. The ATL6 model has been spun up for 8 years with the ECMWF reanalysis monthly climatology, then integrated for the 15 years of the reanalysis (1979 to 1993), and then with the ECMWF analysis (1994–2001). The heat flux is formulated as suggested in Barnier et al. (1995), using their feedback coeficient for relaxation to the Reynolds SST field, but using the interannual ECMWF heat fluxes rather than the climatology of years 1986–1988. It results from a
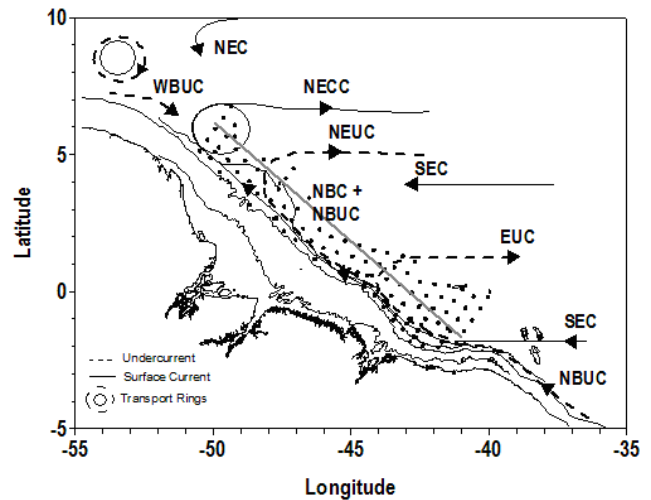

Fig. 1. Map of the north Brazilian zone. Dots are the locations of the CTD stations. Surface and subsurface currents area represented by solid and dashed lines, respectively. NBC – North Brazil Current, NECC – North Equatorial Countercurrent, SEC – South Equatorial Current, EUC – Equatorial Undercurrent, NEUC – North Equatorial Undercurrent, NEC – North Equatorial Current. Isobaths 20 m, 100 m and 2000 m depth are also represented. The alongshore solid straight gray line indicated the position vertical distributions in Fig. 2.

linearisation of bulk formulae and is therefore very close to the bulk formulation of Miami Isopycnic Model – MICOM (Garraffo et al., 2003). The evaporation minus precipitation (E-P) fuxes are formulated as a pseudo salt flux, including river run-off (Treguier et al., 2001); a relaxation of surface salinity to climatology with the same coeficient as the SST is added to the flux.

The vertical z-level grid has 42 levels for temperature, salinity and velocity points, with a grid spacing varying from 12 m at the surface to 200 m below 1500 m. The model run used herein has been particularly focused on Equatorial Atlantic studies, and the mixing parameterization chosen after a series of simulation tests in order to reproduce the EUC in the best way (Michel and Tréguier, 2002). Arhan et al. (2006) used the same simulation to diagnose the annual cycle of the EUC. Gulev et al. (2007) have analyzed the water mass transformation in coarse (1°) and high (1/6°) resolution ocean simulations with the identical configuration of the CLIPPER model and interannual ERA15 forcing function.

In this work the numerical velocity and salinity fields data obtained during the same periods of the four REVIZEE cruises are used to associate the large-scale circulation with the mesoscale observations that span a relatively limited area.

3　Results

3.1　Vertical distribution – transect analysis (T, S)

For a better visualization and interpretation of the thermo-haline characteristics in the study region, in particular the formation of depression at the isopycnal structure, vertical temperature transects are presented (Fig. 2).

High temperature values are observed everywhere in the surface layer. Below this layer, one can observe be-yond 150 m the presence of a depression structure on the isotherms, associated with two cores of salinity maximum, resulting in the heating of the waters below 150 m (Fig. 2a, c, e and g). The model results and hydrographic measurements also show waters with maximum temperature ($\geq 28°$C) in the 50 first meters of the water column. These maximum of tem-perature are influenced by freshwater plumes associated with the Amazon river discharge (Fig. 2c, f, g and h).

In order to describe the penetration of Salinity Maximum Waters (SMW) originating in the Southern Hemisphere to-ward the Northern Hemisphere through the NBC/NBUC sys-tem in the studied area, we present, for each cruise, ver-tical salinity sections along transects almost parallel to the coast line. These data are compared to CLIPPER model re-sults for the same periods and positions, i.e. along the mean northwestward route of the NBC/NBUC system (Fig. 3). These transects are located between the longitudes 50° W and 40° W (Fig. 1). The results show that even if observed SMW values are higher than the simulated values, the model follows a tendency similar to the hydrographical observa-tions.

These sections first allow us to observe the maximum of salinity located around 100 m depth, signature of the sub-tropical underwaters formed in the subtropics (Worthington, 1976), that may be due to the presence of either North At-lantic Water (NAW) or South Atlantic Water (SAW). For each cruise, different salinity maximum cores may be identi-fied around 24.5 kg m^{-3}.

During March–May 1995, two cores of maximum salinity (≥ 36.6) are present at the thermocline level (Fig. 3a). The first core is located at the longitudes of 49° W–46° W, be-tween the depths of 90 m and 170 m. Its western edge is associated with a strong deepening of the deep isopycnals over a very short distance. The second core is found east of 44.7° W, centred around 100 m depth, with a maximum of salinity higher than 37 east of 42° W. Model simulations also indicated a core of maximum salinity (≥ 36.2) at longitude 45° W–41° W for this same period, always centred around 100 m depth (Fig. 3b).

During May–June 1999 (Fig. 3c), a core of maximum salinity (≥ 36.6) is found between 49.5° W and 48° W, at depths of 100–170 m. East of 44° W, another maximum salinity is found centred at about 100 m depth, with a well identified salinity core (>36.8) around 42° W. Below these salinity cores, isopycnals in the range of 26.25–26.75 kg m^{-3}

are anomalously deep, although on a lesser scale than that ob-served during March–May 1995 described above (Fig. 3a). Model outputs confirm the presence of salty waters (≥ 36.6) at longitudes 44° W–45° W, as well as east of 42° W, both in the range of 100–170 m depth (Fig. 3d). East of 48° W the model results show a salinity core (≥ 36.0) at depths of 100–170 m.

During July–August 2001 (Fig. 3e), we may note the pres-ence of four maximum salinity cores around 24.5 kg m^{-3}, located between 49.5°–48.5° W, 48°–46.5° W, 46°–45.5° W, and 45°–42° W, and a low salinity lens closer to the sea sur-face between 50° W and 48° W (Fig. 3f), which is also ob-served in the hydrographic data (Fig. 3c).

All these salinity cores, although less marked for the last one, are associated with deepening of underlying isopycnals. Model results did not underline high salinity cores around 24.5 kg m^{-3} but a deepening of isopycnals around 44° W. One particular result of the modelling is the presence of low salinity waters between 50°–49° W, above 50 m depth (Fig. 3f).

During October–November 1997 (Fig. 3g), we can also observe a salinity maximum vein located around the 100 m–150 m depth range all along the transect, with a maximum core (>36.6) east of 44° W. Below $\sigma_\theta = 26.25$ kg m^{-3}, deep-ening of the isohalines is observed around 48.5° W, 45.5° W and 42° W. At 48° W, this deepening is very pronounced, as illustrated with the 26.75 and 27.0 isopycnals behaviour. These features exhibit similarities with those found during March–May 1995 and May–June 1999 (Fig. 3a and c). The model simulation in this period also registered low salinity water above 50 m depth west of 48° W (Fig. 3h), as observed from the cruise data (Fig. 3g). Previous studies have shown that these low salinity surface waters between 6° N and 10° N may be incorporated in rings and retroflected eastward dur-ing summer and fall (Johns et al., 1990, 1998, 2003).

The salinity cores observed in the southeast of the tran-sects (east of 44° W in Fig. 3) may only be due to the signa-ture of the NBC/NBUC system, penetrating into the region from the south and transporting northward SAW formed in the South Atlantic subtropical gyre (Metcalf and Stalcup, 1967; Cochrane et al., 1979; Schott et al., 1995; Bourlès et al., 1999b). Concerning the maximum salinity cores ob-served west of 52° W, it is not possible at this stage to de-termine if they are due to: (i) the NBUC continuation after being partly diverted eastward and separated from the coast, (ii) rings separated from the NBC retroflection, transporting SAW northward, or (iii) signature of NAW within a south-eastward penetration of the WBUC in the region.

3.2　Horizontal distributions along $\sigma_\theta = 24.5$ kg m^{-3}

These in situ data are compared with numerical 5-day av-eraged snapshots of horizontal velocity and salinity charts obtained with the CLIPPER model on $\sigma_\theta = 24.5$ kg m^{-3} dur-ing the months of April 1995, May 1999, August 2001 and
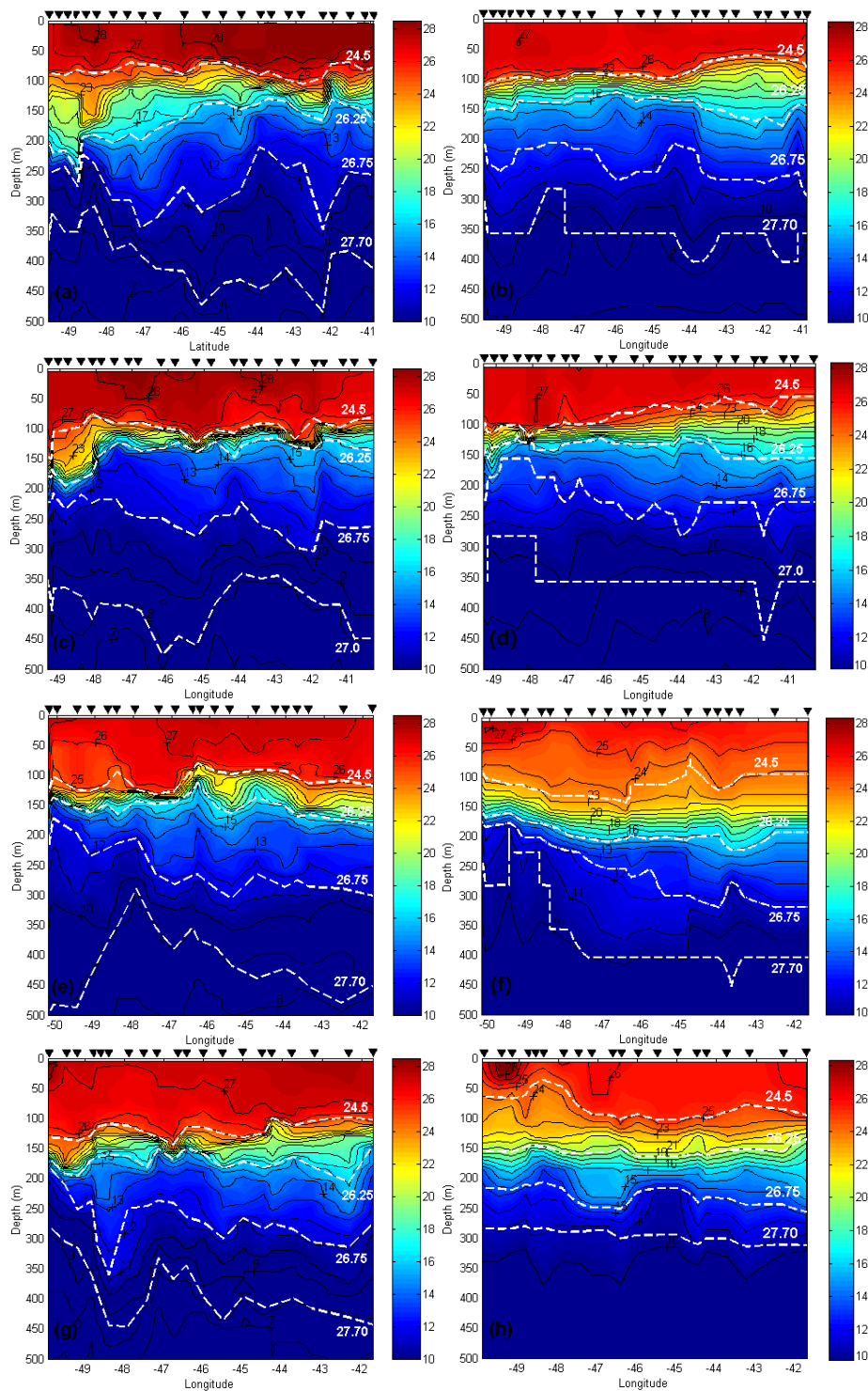
Fig. 2. Vertical distribution of temperature from the surface down to 500 m depth along transects almost parallel to the coast is indicated by a solid straight gray line (see Fig. 1) during REVIZEE cruises from field data and CLIPPER model results: **(a)** hydrographic data for March–May 1995, **(b)** model results for March–May 1995, **(c)** hydrographic data for May–June 1999, **(d)** model results for May–June 1999, **(e)** hydrographic data for July–August 2001, **(f)** model results for July–August 2001, **(g)** hydrographic data for October–November 1997 and **(h)** model results for October–November 1997. The superimposed dashed lines (white) indicate the depth of the σ_θ=24.5, 26.25, 26.75 and 27.70 kg m^{-3}. In the left panels, inverted (black) triangles represent the location of hydrological stations during the cruises. In the right panels, the same triangles represent the selected numerical model grid nodes coincident with the cruise hydrological stations.
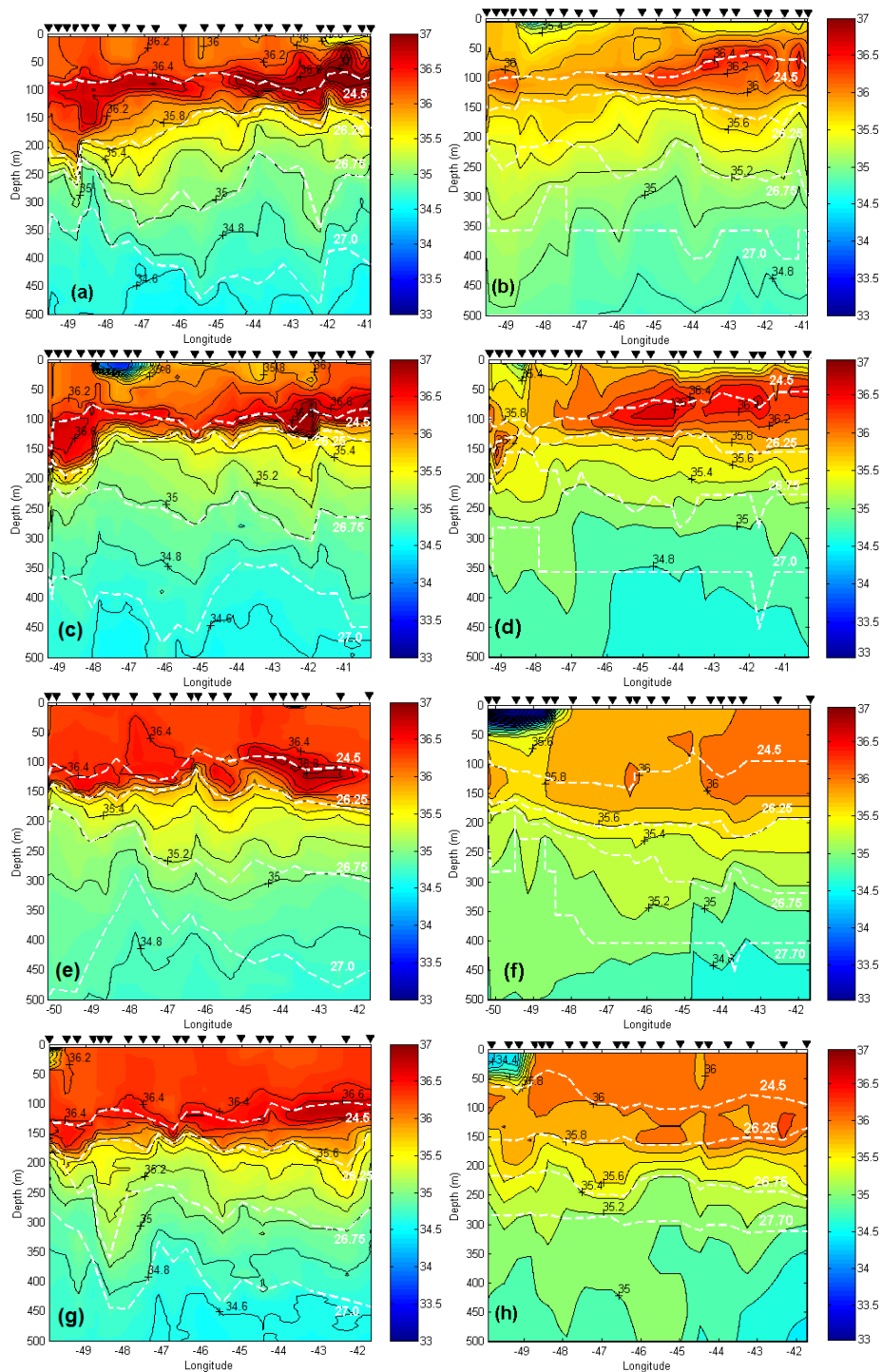
Fig. 3. Vertical distribution of salinity from the surface down to 500 m depth along transects almost parallel to the coast is indicated by a solid straight gray line (see Fig. 1) during REVIZEE cruises from field data and CLIPPER model results: **(a)** hydrographic data for March–May 1995, **(b)** model results for March–May 1995, **(c)** hydrographic data for May–June 1999, **(d)** model results for May–June 1999, **(e)** hydrographic data for July–August 2001, **(f)** model results for July–August 2001, **(g)** hydrographic data for October–November 1997 and **(h)** model results for October–November 1997. The superimposed dashed lines (white) indicate the depth of the σ_θ=24.5, 26.25, 26.75 and 27.70 kg m^{-3}. In the left panels, inverted (black) triangles represent the location of hydrological stations during the cruises. In the right panels, the same triangles represent the selected numerical model grid nodes coincident with the cruise hydrological stations.

November 1997, i.e. during the same periods of the cruises (Fig. 4).

Hydrographic observations obtained during March–May 1995 show the presence of Salinity Maximum Water – SMW ($\geq$36.6) east of 45° W (Fig. 4a). Model results for April 1995 confirm the presence of SMW, within a loop pattern that suggests the presence of the retroflection of the NBC feeding the EUC around 43° W–1° N (Fig. 4b). The observed salinity maximum distribution appears within a curving structure that is in good agreement with an eastward deviation of the SAW through the NBC retroflection. Farther in the northwest, the CLIPPER model results suggest that the relative salinity maximum observed around 48° W–4° N is due to the presence of SAW, entrained from the NBC retroflection area by a partial northwestward NBC continuation.

Observations conducted during May–June 1999 reveal the presence of SMW east of 44° W (Fig. 4c). The model simulation for May also indicates a high contribution of SMW at the same location within a loop structure (Fig. 4d). Such a distribution along with the simulated currents clearly shows the retroflection of the NBC around 44° W–2° N, in very good agreement with the field measurements. The simulation also clearly indicates the presence of a ring around 50° W–6° N, with the presence of a relative salinity maximum along its northern edge.

In July–August 2001 the horizontal distribution of salinity confirms the presence of SMW between 45° W and 42° W, as well as the presence of lower salinity structures along the shelf break (Fig. 4e). Model results for August 2001 indicate that the intense NBC continues northwestward, associated with relatively high values of salinity ($>$36.0) trapped along the shelf break (Fig. 4f). Model outputs show NBC retroflection around 48° W–4° N, that feeds the eastward NECC, well simulated with a meandering structure around 42° W, in agreement with earlier observations (e.g. Schott et al., 1998; Bourlès et al., 1999b). The model also indicates the presence of an anticyclonic ring with relatively salty waters centred at 50° W–7° N, in good agreement with the higher salinity measured around 5° N during the REVIZEE cruise. These results and circulation features well agree with previous descriptions and analysis for the months of August–November in this area, that show the northwestward entrainment of the NBC retroflection during a NBC retroflection formation and shedding, when the NBC is intensified (Johns et al., 1990; Bourlès et al., 1999b; Garzoli et al., 2004).

Cruise observations conducted in October–November 1997 reveal once again the presence of SMW from the Southern Hemisphere, with the highest concentration values measured between 43° W and 41° W (Fig. 4g). Salinity measurements also indicate the presence of small lens structures along the shelf break area. These lens structures are associated with vertical disturbance of the halocline positions (between 24.5 and 26.25 kg m^{-3}, see Fig. 3h). Modeling results also indicate the presence of SMW in the eastern part of the study area, i.e. east of 43° W, associated with an anticyclonic

circulation attributable to a retroflection of the NBC (Fig. 4g and h). The relatively high salinity concentrations observed farther in the northwest are associated with a large ring-like structure located about 48° W–5° N, transporting SMW on its boundaries. It is not clear if this structure should be attributed to a NBC retroflection ring (as suggested by the absence of a continuous northwestward flow off the continental shelf around 44° W) or to the NBC retroflection itself.

3.3 Seasonal and interannual variability

The model output results for January–March 1997 and January–March 1999 (Fig. 5a–b and Fig. 6a–b), demonstrate that a large part of the SMW is transported by the NBUC northwestwards along the shelf break (towards the North Brazilian Shelf) reaching the longitude of 50° W, where it suffers an eastward deviation (near 7° N, 50° W). Another important feature registered by the model is the presence of SMW, originated from the Northern Hemisphere, which is diverted eastward near 7–8° N by the retroflection of the NBC/NBUC, feeding the NEUC. These results are also confirmed through the REVIZEE oceanographic campaigns carried out in March–May 1995 (Fig. 4a).

CLIPPER model results during April–June 1997 and April–June 1999 (Fig. 5c–d and Fig. 6c–d), demonstrate the existence of NBUC retroflection, located 44° W–46° W, which transports a high contribution of SMW coming from the South Atlantic along the North Brazilian coast into the EUC or NEUC. These retroflections were also observed by Schott et al. (1998); Molinari and Johns (1994); recorded for 1/12 deg modelling (MICOM) Garraffo et al. (2003) and 1/12 deg (FLAME) Stramma et al., 2005, and similar to those found by Barnier et al. (2001).

During July–September 1997 and July–September 1999 (Fig. 5d–e and Fig. 6d–e), an increase in the NBUC flow was recorded, causing in response an intensification in the formation of subsurface rings at the 50°–52° W. These rings are formed by the retroflection of the NBUC into the NEUC. At the edges of these rings, a great part of SMW coming from the South Atlantic is transported westward. In the centre of these rings the SMW originates from the South Atlantic. According to Johns et al. (1990) and Bourlès et al. (1999a) the southeastward undercurrent WBUC has been observed to flow along the boundary from the eastern Caribbean to also join the NEUC.

During this period the retroflection of the NBUC was observed further north, approximately at 6° N, that could be linked to the current system, when the NBC transport is high (low), the retroflection occurs further northwest (southeast) as shown by Garzoli et al. (2004).

Model results for the months of September–November 1997 and 1999 (Fig. 5e–f and Fig. 6e–f), also record a greater influence of the SMW diverted eastward by the retroflection of the NBC/NBUC feeding the NEUC, characterized by an
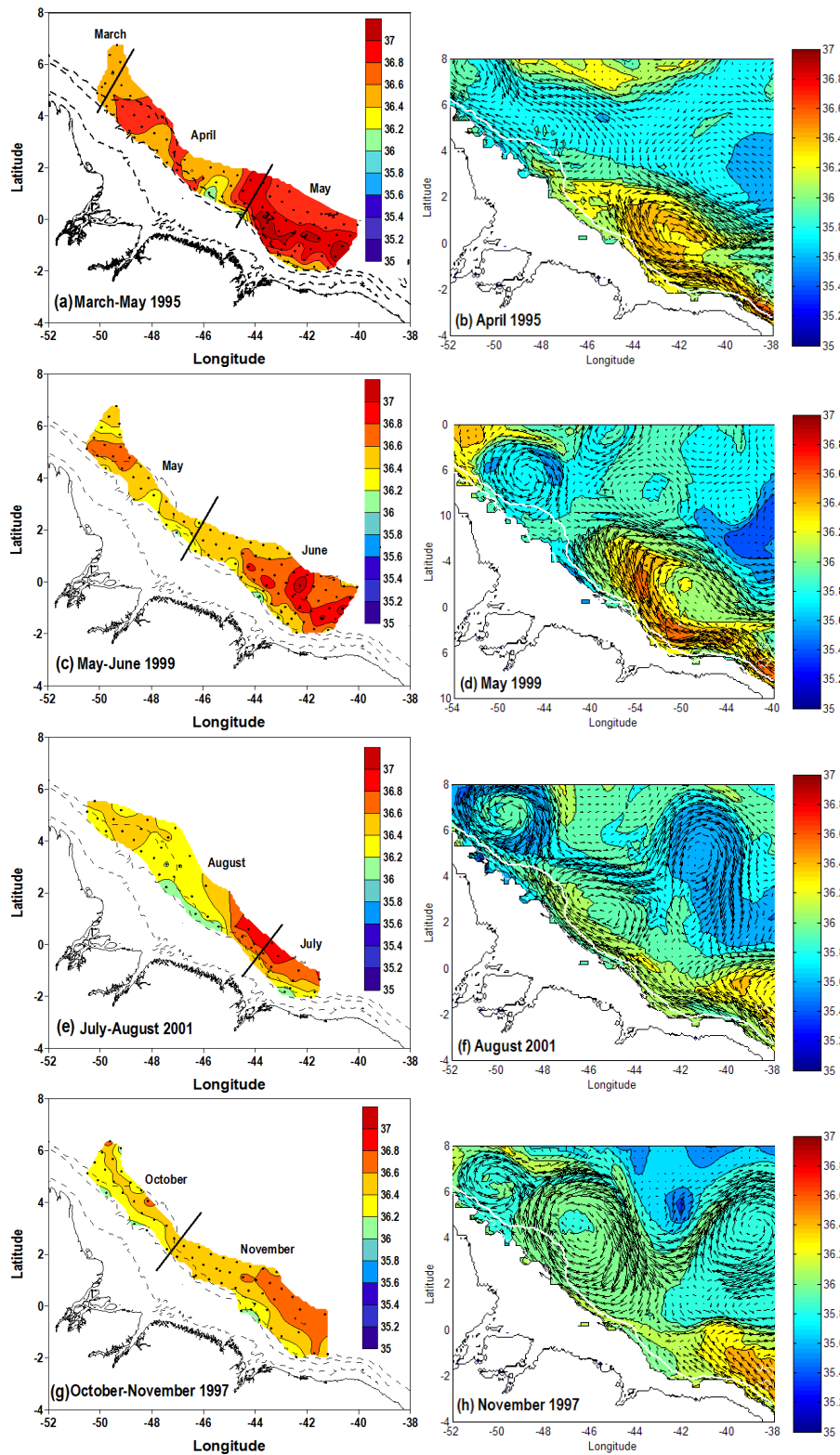
Fig. 4. Horizontal distribution of salinity and velocity during REVIZEE cruises and from CLIPPER model results along $\sigma_\theta = 24.5 \, \text{kg m}^{-3}$: **(a)** hydrographic data for March–May 1995, **(b)** model results for April 1995, **(c)** hydrographic data for May–June 1999, **(d)** model results for May 1999, **(e)** hydrographic data for July–August 2001, **(f)** model results for August 2001, **(g)** hydrographic data for October–November 1997, **(h)** model results for November 1997. Dashed lines represent the isobaths 20 m, 100 m and 2000 m. The black lines perpendicular to the coast define each month of the cruise.

intrusion of the WBUC or NEC recirculation which joins to the NBC/NBUC retroflection.

This analysis indicates the presence of SMW flow between 5°–8° N in the area of waters originated from the Northern Hemisphere, which could feed the EUC. This suggests that if the EUC is fed by Northern Atlantic Waters, this contribution may occur in the ocean interior, east of the western boundary.

4 Discussion

This study allowed us to examine subsurface hydrology and circulation off the Northern Brazil. High resolution hydrographic observations from four cruises carried out in different periods of the year (March–May 1995, October–November 1997, May–June 1999 and July–August 2001) were complemented by modelling results to obtain additional information about the salty water masses and mesoscale transport variability in this area. Previous studies have been either limited to the shelf region (e.g. AMASSEDS Program, Lentz and Limeburner, 1995) or focused on large scale ocean circulation (e.g. Schott et al., 1998; Bourlès et al., 1999a, b).

The hydrographic data obtained during all oceanographic cruises showed the presence of Salinity Maximum Water (SMW) at σ_θ=24.5 kg m^{-3} between 45° W and 40° W. Model results for these same periods confirm that a large part of this SMW is transported by the NBC northwestward along the shelf break (parallel to the North Brazilian shelf). Another part of the South Atlantic waters are diverted eastward by the retroflection the NBC/NBUC feeding the EUC and the NEUC (Schott et al., 1998; Bourlès et al., 1999a). Numerical output also confirmed that during April 1995 only a small fraction of the NBC flows along the Brazilian coast, as previously showed by Bourlès et al. (1999b).

An interesting result of this paper is the space and time variability of the presence of SMW from the Northern Hemisphere, which contributes to feed the NEUC or EUC in the study area as revealed by both in-situ data and model results. if the EUC is fed by Northern Atlantic Waters, this contribution may occur in the ocean interior, east of the western boundary.

In fact, the southeastward WBUC has been observed to flow along the boundary from the eastern Caribbean to also join the NEUC (Johns et al., 1990; Bourlès et al., 1999a). However Bourlès et al. (1999a), based on hydrographic observations, suggest that the EUC is not fed by the Northern Hemisphere waters west of 44° W, while Schott et al. (1998) and Goes et al. (2005) found indications about the presence of northern waters feeding the EUC between 35° W and 44° W. Seasonal and interannual model results along σ_θ=24.5 kg m^{-3} showed the presence of SMW eastward between 5°–8° N (more significantly during January–March 1999 and October–December 1997).

CLIPPER model results along σ_θ=24.5 during all seasons suggest that the SMW coming from the north Atlantic is transported through the boundaries of rings (near 8° N), while the SMW coming from the South Atlantic are transported within the core of the rings during their northwestward displacement (Figs. 4 and 5). Johns et al. (2003) described in the region the presence of intensified subsurface rings above the thermocline but without any signature at the surface. These structures were also reproduced in the numerical modelling works of Barnier et al. (2001), Garraffo et al. (2003), and Stramma et al. (2005). More recent observations of the North Brazil Current Rings (NBCR) Experiment (Johns et al., 2003) confirmed the existence of a hierarchy of surface and subsurface NBC rings between 60° W and 50° W, transporting SAW on the ring core and NAW on its boundaries. Our field and numerical results for May 1999 and November 1997 indicate that the WBUC is always diverted eastward either by the rings associated to NBC/NBUC retroflection, or by the retroflection itself. In both cases, these salty northern waters do not return to the western boundary.

We have seen from field data that the salty water masses are brought from subtropical regions to the study area associated with isopycnal anomalies in some specific ocean places between 50° W–40° W. Johns et al. (2003) used ADCP/LADCP/CTDO$_2$ data to show the presence of rings between 60° W–50° W, during four cruises of the NBCR Experiment. These authors noted that all observed surface rings were marked by a weak depression located at the centre of the thermocline around 50–75 m. Vertical displacements of isopycnals were also observed during all REVIZEE cruises. During March–May 1995, for example, a subsurface core of maximum salinity ($\geq$36.6) is present in field data between 43° W and 41° W. This maximum salinity core is connected to the presence of depressional structures on σ_θ=26.25, 26.75 and 27.0 kg m^{-3} (Fig. 3a), probably the signal of the retroflection. At the same time, model results for April 1995 indicate an important NBC retroflection in this ocean area during the same period (Fig. 4b). These interactions can be generated by NBC/NBUC retroflection, which may induce ring formation, as well as by the action of baroclinic Rossby waves along the Amazonian shelf break region (Jochum and Malanotte-Rizzoli, 2003). The available field observations are not yet sufficient to explain the rings' genesis and to distinguish the specific effects of each mechanism. Meantime temporal series of field hydrographic and current data obtained from mooring devices placed at some sites along the shelf break are still necessary to assess some of these open questions about this complex key area of the Atlantic Ocean.

5 Conclusion

Vertical sections obtained with high resolution hydrographic data of temperature and salinity are used to analyse the subsurface circulation along the coast of North Brazil,
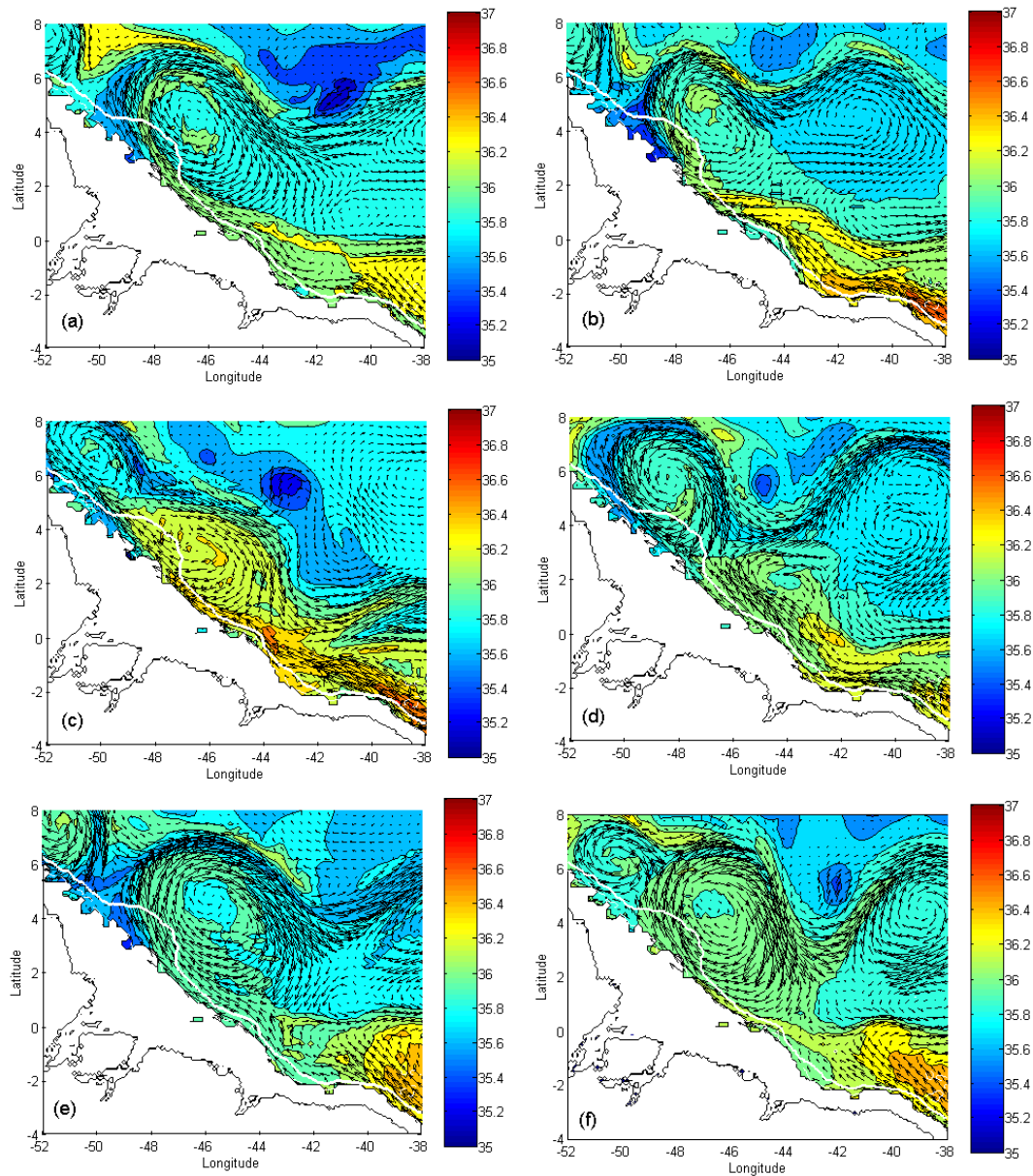
Fig. 5. Seasonal distribution of salinity and velocity from CLIPPER model results at 100 m depth for: **(a)** January 1997, **(b)** March 1997, **(c)** May 1997, **(d)** July 1997, **(e)** September 1997 and **(f)** November 1997. Dashed lines represent the isobath 2000 m.

principally in order to describe the penetration of waters originating in the Southern Hemisphere toward the Northern Hemisphere through the NBC/NBUC system.

Vertical salinity sections along transects almost parallel to the coast line, located between the longitudes 50° W and 40° W, show that core of maximum salinity ($\geq$36.6) are present at the thermocline level during each cruise. Different salinity maximum cores may be identified around the 24.5 kg m^{-3} isopycnal. For example, during March–May 1995 a subsurface core of maximum salinity ($\geq$36.6) is present in field data between 43° W and 41° W. In the same place one can observe the presence of a depression structure

on the isotherms, resulting in the heating of the waters below 150 m. Model simulations also indicate a core of maximum salinity ($\geq$36.2) at longitude 45° W–41° W for this same period, always centred around 100 m depth.

Seasonal and interannual hydrographic observations and model results along σ_θ=24.5 kg m^{-3} also show the presence of SMW toward the Northern Hemisphere through the NBC/ NBUC. Model results also highlight the presence of SMW eastward between 5°–8° N (more significantly during January–March 1999 and October–December 1997), below the thermocline, with a southeastward penetration along the North Brazilian coast into the EUC or NEUC
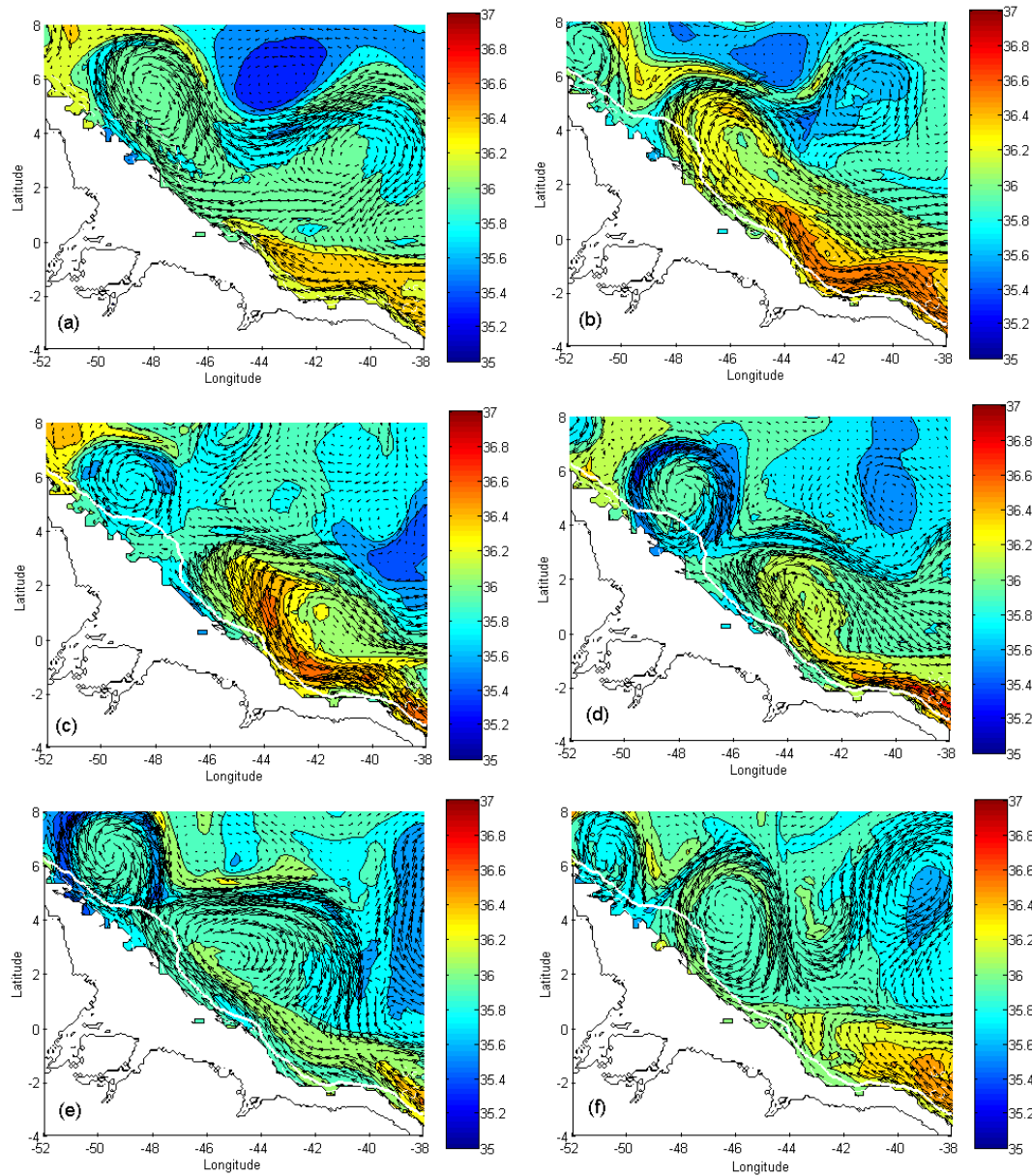
Fig. 6. Seasonal distribution of salinity and velocity from CLIPPER model results at 100 m depth for: **(a)** January 1999, **(b)** March 1999, **(c)** May 1999, **(d)** July 1999, **(e)** September 1999 and **(f)** November 1999. Dashed lines represent the isobath 2000 m.

(around 48° W–3° N). One other important point to be highlighted from the model results is that, during all the seasons, the SMW coming from the north Atlantic are transported through the boundaries of rings (near 8° N), while the SMW coming from the South Atlantic are transported within the core of the rings during their northwestward displacement.

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