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Salinity-induced mixed and barrier layers in the southwestern tropical Atlantic Ocean off the northeast of Brazil

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Abstract

High resolution hydrographic observations of temperature and salinity were used to analyze the formation and distribution of isothermal (Z_T), mixed (Z_M) and barrier layers (BL) in a section of the southwestern Atlantic (0°30′ N–14°00′ S; 31°24′–41°48′ W), adjacent to the northeastern Brazilian coast. Analyzed data consisted of 279 CTD casts acquired during two cruises under the Brazilian REVIZEE Program, one in late austral winter (August–October 1995) and another in austral summer (January–April 1997). Results indicated that the intrusion of subtropical Salinity Maximum Waters (SMW) brought by the South Equatorial Current (SEC) from the subtropical region into the western tropical Atlantic boundary is the major process contributing to the seasonal BL formation. During late austral winter, BL 5–90 m thickness (*BLT*) (median=15 m) was observed, but *BLT* >30 m was restricted to latitudes higher than 8° S as a result of a combination of deep isothermal layers ($Z_T \geq 90$ m) and shallow mixed layers, where the latter was created by the intrusion of salty waters between 8–12.3° S. During austral summer, shallow isothermal and mixed layers prevailed and the BL formation was clearly driven by establishing a salt-induced pycnocline inside an isothermal layer. Observed *BLT* was less variable (5–70 m) and thicker (median=35 m). *BLT*≥30 m was observed not only in the southernmost part of the study area, as verified during late winter, but in the latitude range 2° S–14° S, where near surface salty waters were transported westward by the SEC flow.

1 Introduction

The southwestern tropical Atlantic Ocean is an area of prime importance to global climate change where oceanic signals from intra-seasonal to decadal scales must pass through (Dengler et al., 2004; Schott et al., 2005). Moreover, this region is subjected to cyclonic and anticyclonic gyres strongly controlled by surface winds (Stramma and Schott, 1999; Lumpkin and Garzoli, 2005). These gyres drive the divergence of the southern pathway of the South Equatorial Current (sSEC) (Rodrigues et al., 2007) that is partially at the birth site of several current systems that flows along the Brazilian coastline. The northern branch of the sSEC termination flows northward forming the North Brazilian Current-North Brazilian Under Current (NBC/NBUC) system. This powerful western boundary current contributes by feeding of the northward Guyana Current (Bourlès et al., 1999; Stramma et al., 2005) and the eastward North Equatorial Counter Current (NECC), as well as its associated complex retroflection system (Goes et al., 2005) and the eastward Equatorial Under Current (EUC). It is believed that NBC accounts for approximately one-third of the net warm-water flow transported across the equatorial tropical gyre boundary into the North Atlantic, compensating for the southward export of North Atlantic Deep Water (NADW) (Dengler et al., 2004; Schott et al., 2005). The southern branch of sSEC forms the Brazil Current (BC) that flows poleward along the Brazilian coast.

Offshore, the upper ocean density stratification is primarily controlled by temperature variations in the thermocline region. However, there is some evidence that salinity variations can regulate the mixed layer depth (e.g., Sprintall and Tomczak, 1992). This is the case for the western equatorial Pacific where salinity controls the surface stratification, which defines the base of the mixed layer (e.g., Delcroix and McPhaden, 2002).

The occurrence of isohaline layer shallower than the isothermal layer in the tropical ocean has been studied since the Meteor research cruises in 1936 (Defant, 1961). The barrier layer (BL), which is a layer between the halocline and the thermocline (Lukas and Lindström, 1991), may isolate the upper isohaline layer from the cold thermocline waters, affecting the ocean heat budget and its exchanges with the atmosphere (Swenson and Hansen, 1999; Pailler et al., 1999). When BL occurs, the energy transferred from the atmosphere to the ocean by the wind and the buoyancy forcing may be trapped into the upper mixed layer limited by the salinity stratification, which is thinner and theoretically more reactive than the one defined by the temperature mixed layer (Vialard and Delecluse, 1998; Montégut et al., 2007).

A number of studies on BL and related physical mechanisms have focused in the western equatorial Pacific. According to the theory, heavy precipitation in the western portion of an ocean basin was initially taken as the main mechanism accounting for BL formation (e.g., Sprintall and Tomczak, 1992; Ando and McPhaden, 1997). Recent works show that the thick climatologically important BL in the western Pacific is due to the eastward fresh jets flowing over subducted salty waters (Vialard and Delecluse, 1998). Cronin and McPhaden (2002) analyzed BL responses to westerly wind gusts over the Tropical Atmosphere Ocean (TAO) array in the equatorial Pacific and discussed the main mechanisms by which BL may form and spread. General charts of the seasonal variability of BL thickness (*BLT*) in tropical oceans were obtained using Levitus climatological data (Levitus, 1982) to determine the extent of the influence of salinity in the depth of the mixed layer (Sprintall and Tomczak, 1992).

Montégut et al. (2007) and Mignot et al. (2007) used instantaneous T/S profiles, including ARGO data, to construct global ocean climatology of monthly mean properties of the BL phenomenon. These charts suggest that subduction of subtropical salty surface waters toward the equator during winter and their advection by the equatorial current system might be the mechanism that forms the BL in the western tropical Atlantic. This hypothesis is partially supported by the presence of subsurface Salinity Maximum Waters (SMW) along the western Atlantic boundary (Pailler et al., 1999; Stramma et al., 2005; Silva et al., 2005). These authors argued that this salty water, which is formed in the South Atlantic subtropical gyre, is entrained into the region within the NBUC that flows northwestward along the Brazilian continental slope.

The presence and the formation of salinity-induced barrier layers at the southwestern boundary of the tropical Atlantic is investigated here based on the analysis of 279 high resolution CTD vertical profiles obtained under the Brazilian REVIZEE Program. Although differences between the isohaline and isothermal depths have been reported in the literature for other western equatorial ocean basins (e.g., Sprintall and Tomczak, 1992; Delcroix and McPhaden, 2002), little has been done to identify the existence of barrier layers in the western tropical Atlantic where this discrepancy may also exist. Therefore, the aim of this paper is to map the large-scale distribution of these differences in the southwestern tropical Atlantic off the northeast of Brazil. In this way, this paper is outlined as follows. Data and methods are delineated in Sect. 2 where the area of study is presented and the criteria used for determining the isothermal, mixed and barrier layers are described. Results are presented in Sect. 3 followed by summary and conclusions in Sect. 4.

2 Data and methodology

2.1 Study area and data collection

The area of study comprised a section of the western tropical Atlantic (0°30′ N–14°00′ S; 31°24′–41°48′ W), adjacent to the Brazilian NE coast (Fig. 1a). Hydrographic data were collected onboard the R/V Antares under the REVIZEE Program (Brazilian Program for Assessing the Sustainable Potential of the Live Resources of the Exclusive Economic Zone). The dataset for this work comprised 279 continuous CTD casts, 146 obtained during the late austral winter, (2 August 1995–26 October 1995) and the 133 during the austral summer (20 January 1997–17 April 1997).

2.2 Criteria for determining isothermal, mixed and barrier layers

The criteria used for determining isothermal and mixed layers in the ocean requires the deviation of temperature T (or density, σ_t) from its surface value to be smaller then a certain fixed value T value (or density) (Brainerd and Gregg, 1995). Normally considered surface values for evaluating Z_T varies from 0.5°C (Monterrey and Levitus, 1997) to 0.8°C (Kara et al., 2000) depending on the used criteria. Z_M is estimated as the depth where density is equal to its sea surface value plus an increment $\Delta\sigma_t$ equivalent to a desired net decrease in temperature. Spall (1991), e.g., uses $\Delta\sigma_t$=0.125 σ_t(0) for determining the mixed layer depth, while Sprintall and Tomczak (1992) and Ohlmann et al. (1996) adopt $\Delta\sigma_t$=0.5°C $(\partial\sigma_t/\partial T)$, where $\partial\sigma_t/\partial T$ is the coefficient of thermal expansion.

The criteria used here is the same defined by Sprintall and Tomczak (1992), where the isothermal and mixed layer depths (Z_T and Z_M) are evaluated in terms of temperature and density steps $-\Delta T$=0.5°C and $\Delta\sigma_t$=0.5°C ($\partial\sigma_t/\partial T$) – from the sea surface temperature and density ($T(0)$ and $\sigma_t(0)$) obtained from CTD vertical profiles:

$$Z_T = z\,(T = T\,(0) - \Delta T) \quad Z_M = z\left(\sigma_t = \sigma_t\,(0) + \frac{\partial\sigma_t}{\partial T}\Delta T\right) \tag{1}$$

where $\partial\sigma_t/\partial T$ was calculated as a function of the surface temperature and salinity (Blanck, 1999). Since the SBE911plus CTD has two thermometers with an accuracy of about 0.001°C, the error in computing Z_T for a ΔT=0.5°C is around 0.2% for a local Z_T. Barrier layer thickness (BLT) is calculated as $BLT=Z_M-Z_T$.

When density stratification is exclusively controlled by temperature, the isothermal layer depth becomes equivalent to the mixed layer depth and BLT=0. A particular situation happens when near surface distribution of salinity is anywhere sufficiently strong for inducing a pycnocline inside of the isothermal layer, or $Z_M<Z_T$. In such case, $BLT>0$ and surface warm waters may be maintained isolated from cool thermocline waters.

As in Montégut et al. (2007) and Mignot et al. (2007) works, an analysis of individual T/S profile combined to a kriging interpolation (within a radius of 400-km with at least 5 grid points) is used to construct isothermal, mixed and BL layers charts.

3 Mixed and barrier layers in the southwestern tropical Atlantic

3.1 South Atlantic (SAW) and Salinity Maximum Waters (SMW)

Wilson et al. (1994) and Bourlès et al. (1999) identified three different origins for the water masses at the upper western equatorial Atlantic: the North Atlantic Water (NAW), the South Atlantic Water (SAW), and the Eastern tropical Atlantic Water (EAW). The NAW, which has its origin at the subtropical region of the Northern Hemisphere, is advected towards the equator by the NEC and is mostly characterized by high salinity values and low O_2 concentrations below the thermocline. The SAW, which exhibits high salinity values above the thermocline and low salinity values and high oxygen concentrations below it relative to the NAW, is advected to the study region through subduction processes from subtropical areas by the southern branch of the SEC. The EAW reaches the area of interest via the southern edge of the NEC and the central and northern branches of the SEC. This EAW is characterized by the lowest concentrations of oxygen and salinity around the thermocline when compared to the SAW.

The origin of the waters masses entering the area of study is identified using T/S diagrams of the easternmost boundary of the hydrographic stations (Fig. 1a). Particular attention is given to those areas where SMW cores are observed between the 24.5 and 26.25 isopycnals. Three distinct signatures are found in late winter and summer seasons: (i) EAW at 2°–4° S (Fig. 1b); (ii) EAW-SAW transitional zone at 4°–8° S (not shown here); and (iii) SAW for latitudes higher than 8° S (Fig. 1c).

Vertical sections of salinity along this boundary (Fig. 2a, b) indicate a salinity maximum around 120 m deep, a signature of subtropical underwaters that may be due to the presence of SAW. Salinity maximum cores vary seasonally around the 24.5 isopycnal. In late austral winter of 1995 a maximum salinity core ($\geq$36.5) is observed at the thermocline level (Fig. 2a) between the latitudes of 6° and 12.3° S, and around 10° S at the surface. In austral summer of 1997, a shallow core of maximum salinity ($\geq$36.5) is found at the 7°–14° S latitude range, which is combined with persistent high salinity values ($\geq$36.0) in upper ocean layer (down to 80 m depth) at 2°–10° S (Fig. 2b). Excepting for a single surface point around 4° S, low latitude ($\leq$6° S) salty surface waters is not observed in 1995 late winter.

Salinity cores observed to the south of 6° S (Fig. 2a, b) can only be due to the signature of the SEC penetrating into the region from the south and transporting westward SAW formed in the South Atlantic subtropical gyre (Bourlès et al., 1999; Rodrigues et al., 2007).

3.2 Spatial distribution

Spatial distribution of isothermal (Z_T) and mixed layer (Z_M) depths, and BL thickness (*BLT*) in the southwestern tropical Atlantic at late austral winter (August–October 95) and summer (January–April 97) are presented in Figs. 3 and 4, respectively.

During winter, a *BLT* of 5–90 m thick (median=15 m) is observed (for $BLT \geq 5$ m) at 83.5% of the CTD stations. The BL distribution during summer differed from that in late winter, showing a low thickness range of 5–70 m (median=35 m) and the highest frequency occurrence of 91.0% of the CTD stations. Shallow (5–50 m) Z_M depths are observed during summer, while Z_M depths reached 135 m during winter. Isothermal layers are deeper during winter (15–135 m) than summer (5–105 m).

At late winter high Z_T values, limited by the 90 m depth isoline, is detected in two offshore subregions in the study domain: (i) at N-NE from 2°–5° S, and (ii) at S-SE from 7°–12.3° S (Fig. 3a). Still during this period a thick mixed layer (70–80 m) is also seen offshore between 2° and 10° S (Fig. 3b), resulting in thin barrier layer widely observed over the study area north of 8° S (Fig. 3c). However, a thick BL prevails only south of 8° S, as a result of the combination between deep isothermal layer (Fig. 3a) and salt-induced (Fig. 2a) shallow mixed layer during late winter.

A qualitative similar distribution of isothermal depth can be found during the austral summer (January–April 1997), with high Z_T values, limited by the 60 m contour, in the N (1°–3° S; 37°–42° W) – NE (4°–9° S; 32°–35° W) subareas, and from 9° to 14° S (Fig. 4a). However, what is really different from the late winter period is the computed values of mixed layer depths during summer, with Z_M not exceeding 50 m. These shallow mixed layers are due to the near surface intrusion of salty SAW (Fig. 2b), which is transported westward from subtropical region by the intensified SEC flow verified during this period (Rodrigues et al., 2007). Consequently, high BL values during austral summer are not only concentrated in the southernmost part of the study area, as observed during late winter (Fig. 3c), but also present from 1° to 10° S (Fig. 4c).

4 Summary and conclusion

Climate is strongly linked to the upper tropical Atlantic dynamics and its exchange with the atmosphere. Thus, its prediction tends to improve with the increase on understanding the processes that governs the relative distribution of thermodynamic properties of the ocean. This paper focused on the isolation of warm surface waters from cool deep waters by a salinity-induced mixed and barrier layers in the southwestern tropical Atlantic (0°30′ N–14°00′ S; 31°24′ W–41°48′ W). During late austral winter, a thick barrier layer (BL) of ~90 m deep was a common feature in the southernmost offshore portion of the area of study. During the austral summer shallow depths of isothermal, mixed and barrier layers were observed, although a *BLT* ≥30 m were observed all over the region. In both case, the formation of BL seems to be also associated with the advection of salinity maximum waters formed in the region of the subtropical gyre and transported to the study area by the SEC and NBC/NBUC system (Stramma et al., 2005).

These results suggest that the mechanisms contributing to the seasonal variation of the mixed layer and the BL formation along the northeast Brazilian shelf are influenced by the spatial and the seasonal variability of the upper ocean heat budget. It is speculated that this variability is mostly driven by ocean-atmosphere exchange and horizontal advection/vertical diffusion terms, and the westward transport of these salty subducted waters by the sSEC. Nonetheless, the above results highlight the importance of including the effects of salinity stratification when defining the mixed layer depth. Historically, it was thought that the halocline significance in the surface layer was solely meaningful when dealing with higher latitude regions. However, our results suggest that the inclusion of salinity dynamics and its variability are also necessary for studying the mixed layer behavior in the southwestern tropical Atlantic. Depth variations in the mixed layer controlled by temperature distribution alone do not truly represent the depth of the convective overturn due to turbulence which physically defines the extent of a mixed layer.

Therefore, the BL genesis in the southwestern tropical Atlantic needs to be further assessed and the contribution of each mechanism that controls the thickness of the BL should be scrutinized. These scientific tasks can only be achieved through the acquisition of long-term time series of in situ data (e.g., temperature, salinity and current velocity) derived from mooring arrays and ARGO drifters deployed at some key sites along the western tropical Atlantic combined with numerical modeling efforts.

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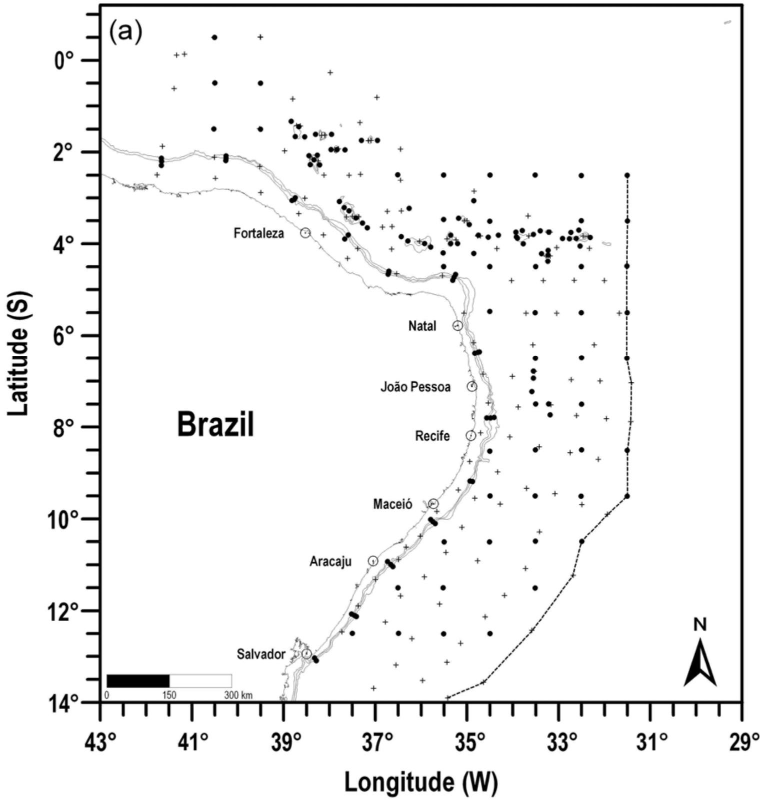

Fig. 1a. Area of study with indication of the 20, 100 and 2000 m isobaths. Dots and crosses indicate, respectively, CTD stations during late austral winter (August–October 1995) and austral summer (January–April 1997). Dashed lines indicate limit area along which salinity and water masses origin were investigated (T/S diagrams).

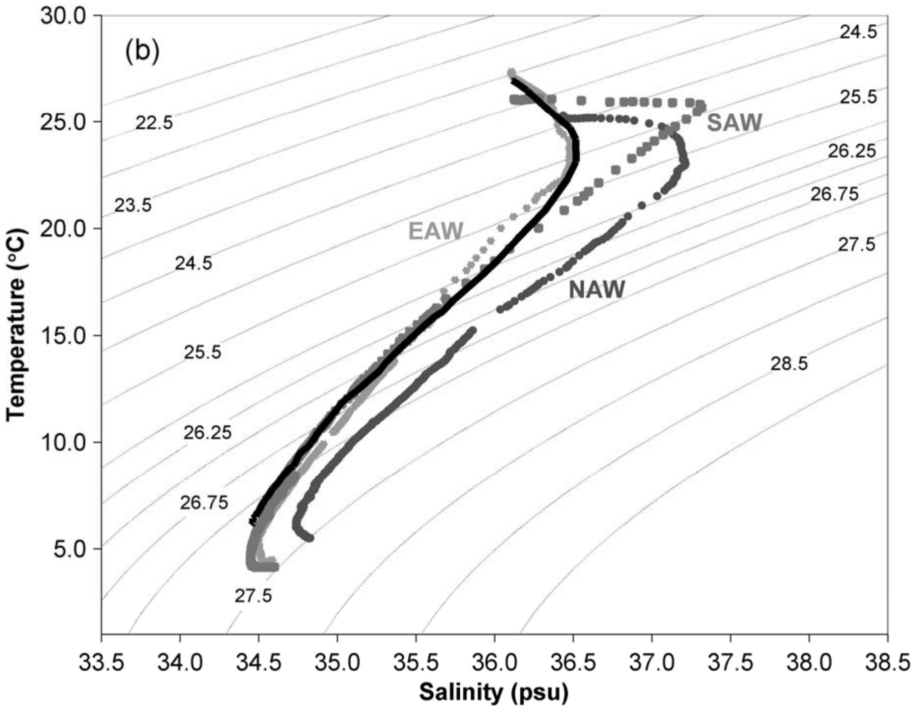

Fig. 1b. Typical T/S diagram for the easternmost REVIZEE stations located between 2° S and 4° S.

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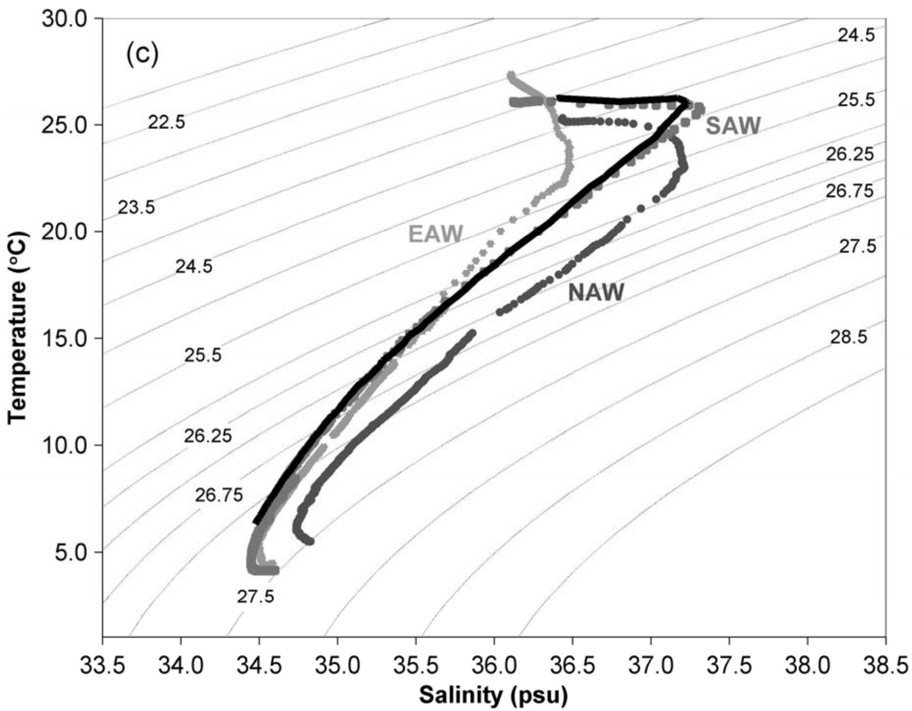

Fig. 1c. Typical T/S diagram at the easternmost REVIZEE stations located between 8° and 14° S.

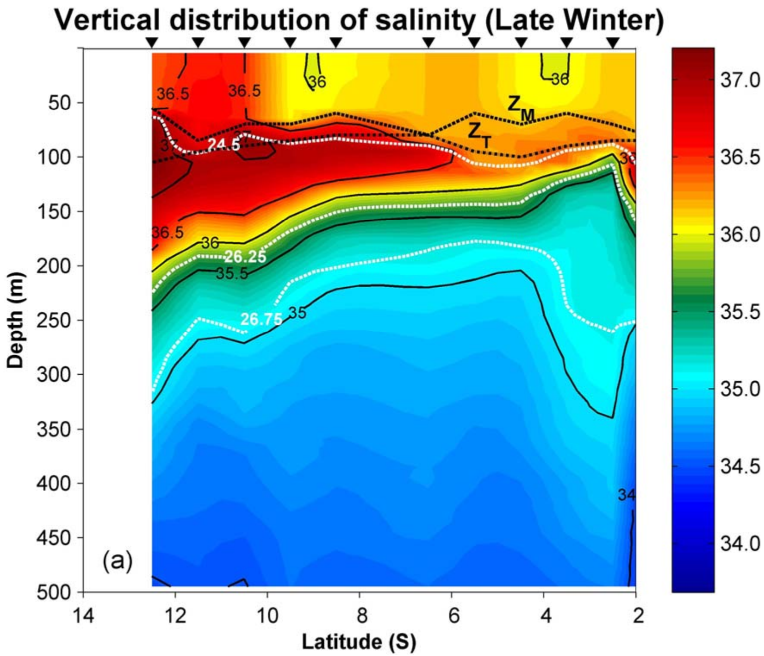

Fig. 2a. Vertical distribution of salinity (surface to 500 m depth) along the transect indicated by a dashed line (see Fig. 1a) during REVIZEE cruises for: late austral winter (August–October 1995). The black dashed lines indicate isothermal (Z_T) and Mixed layer (Z_M) depths. Dashed white lines indicate the depth of the σ_θ=24.5, 26.25, 26.75 and 27.70. The location of the CTD casts are shown by the black inverted triangles.

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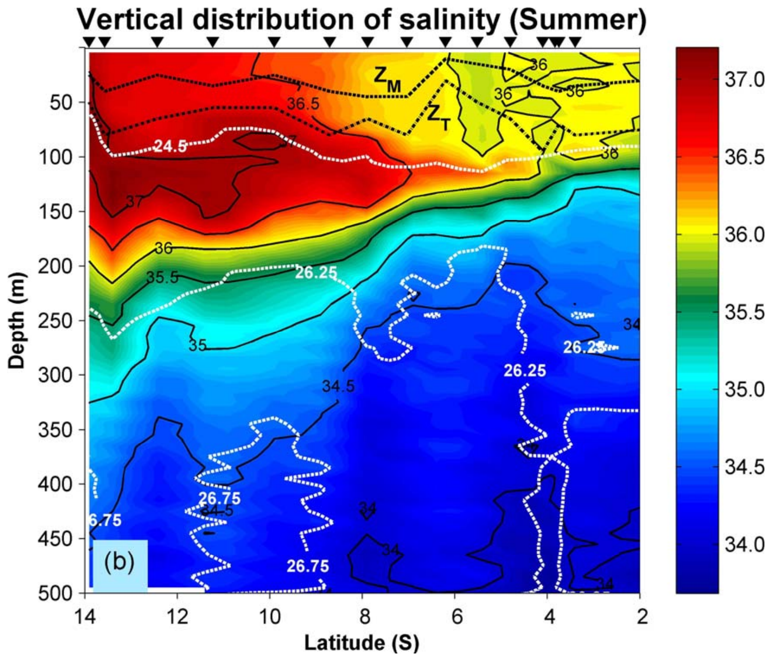

Fig. 2b. Vertical distribution of salinity (surface to 500 m depth) along the transect indicated by a dashed line (see Fig. 1a) during REVIZEE cruises for: austral summer (January–April 1997). The black dashed lines indicate isothermal (Z_T) and Mixed layer (Z_M) depths. Dashed white lines indicate the depth of the σ_θ=24.5, 26.25, 26.75 and 27.70. The location of the CTD casts are shown by the black inverted triangles.

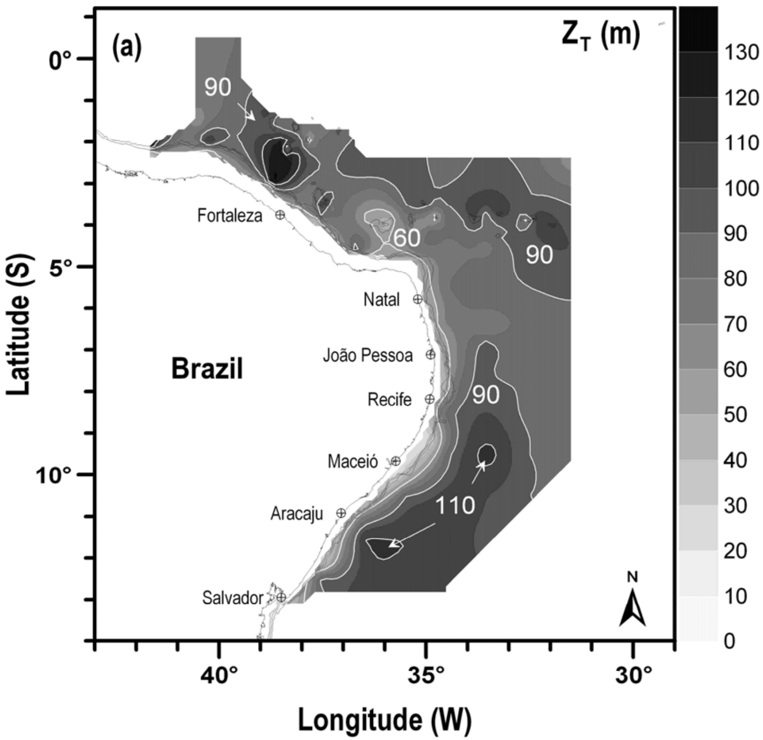

Fig. 3a. Spatial distribution of isothermal layer depth (Z_T) during late austral winter (August–October 1995).

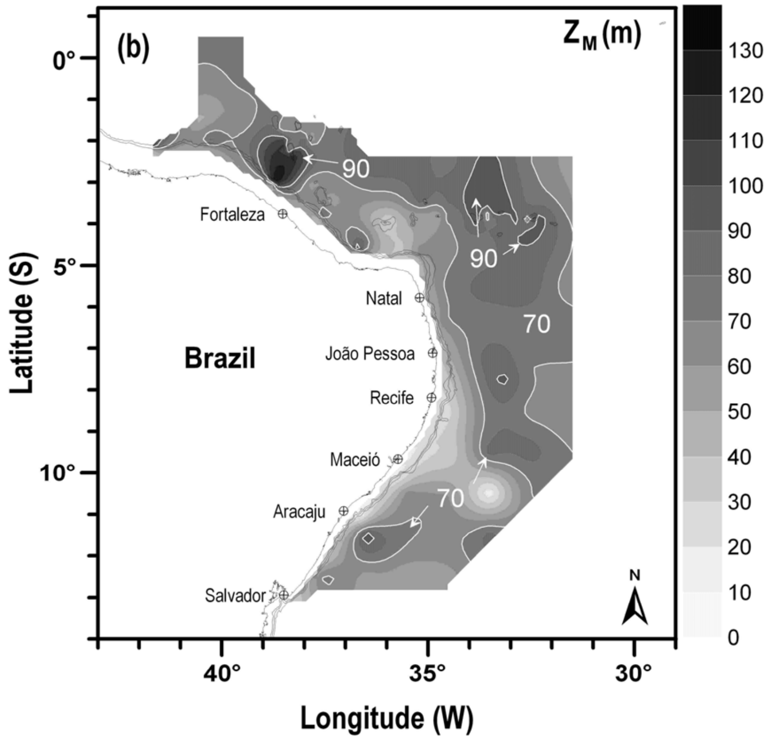

Fig. 3b. Spatial distribution of mixed layer depth (Z_M) during late austral winter (August–October 1995).

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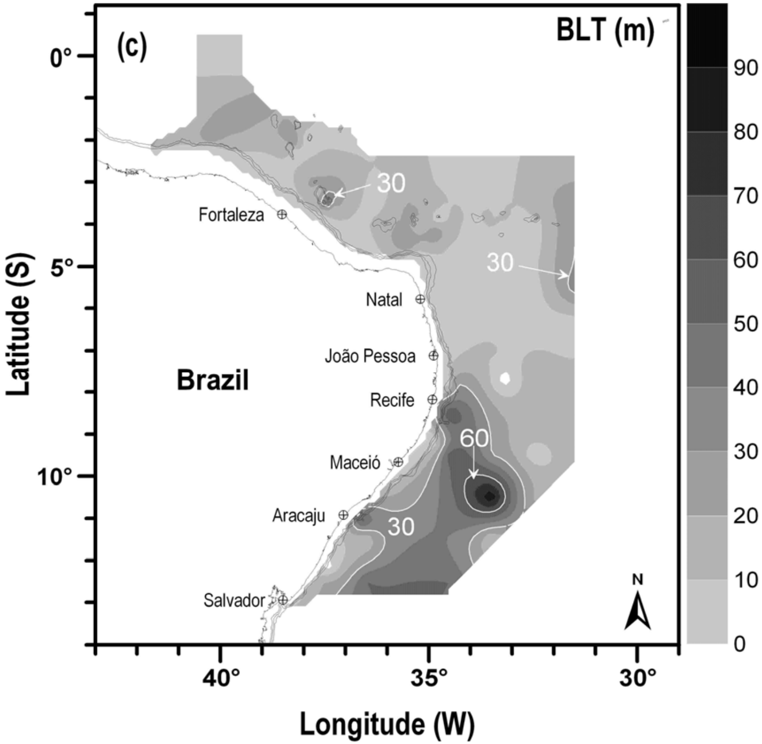

Fig. 3c. Spatial distribution of barrier layer thickness (*BLT*) during late austral winter (August–October 1995).

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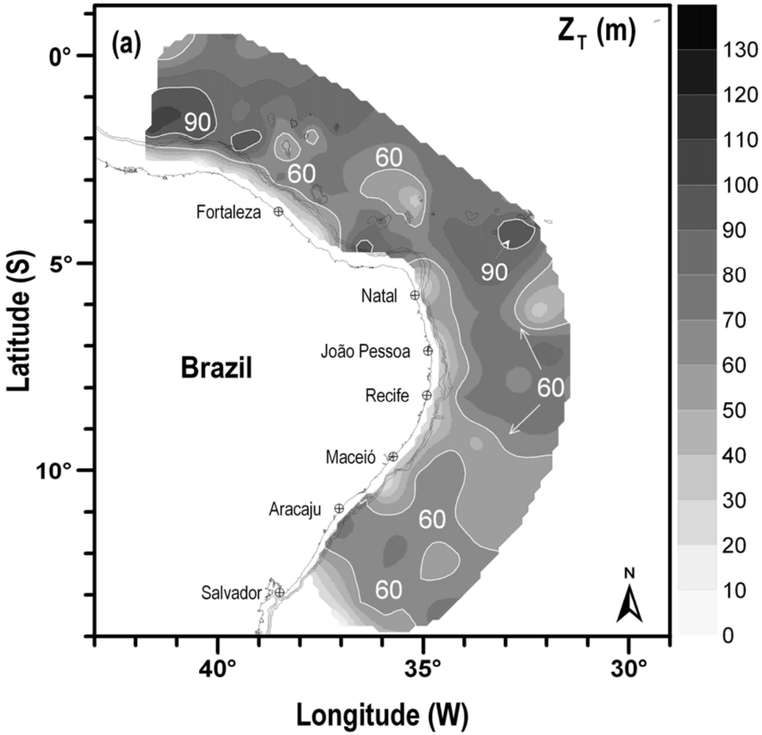

Fig. 4a. Spatial distribution of isothermal layer depth (Z_T) during austral summer (January–April 1997).

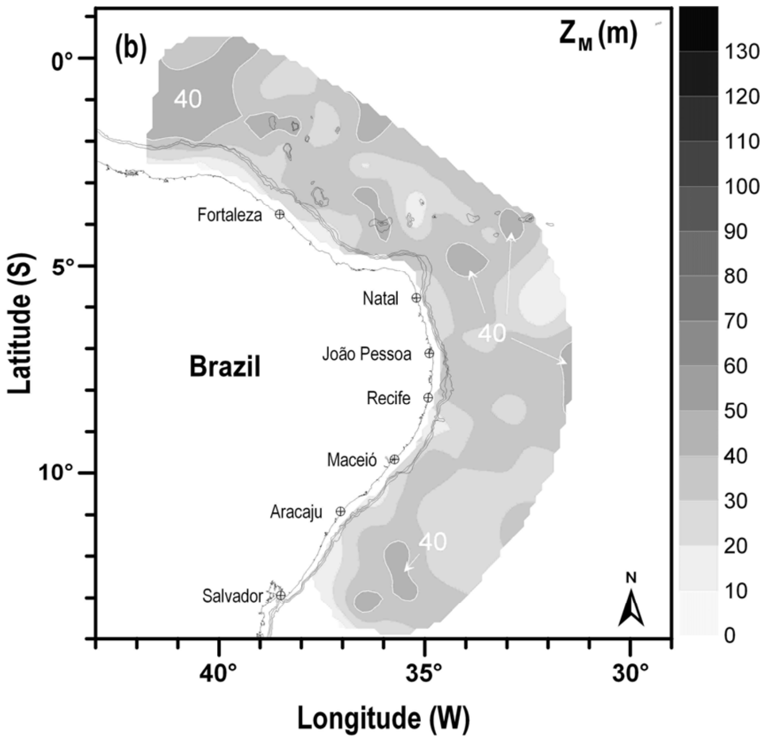

Fig. 4b. Spatial distribution of mixed layer depth (Z_M) during austral summer (January–April 1997).

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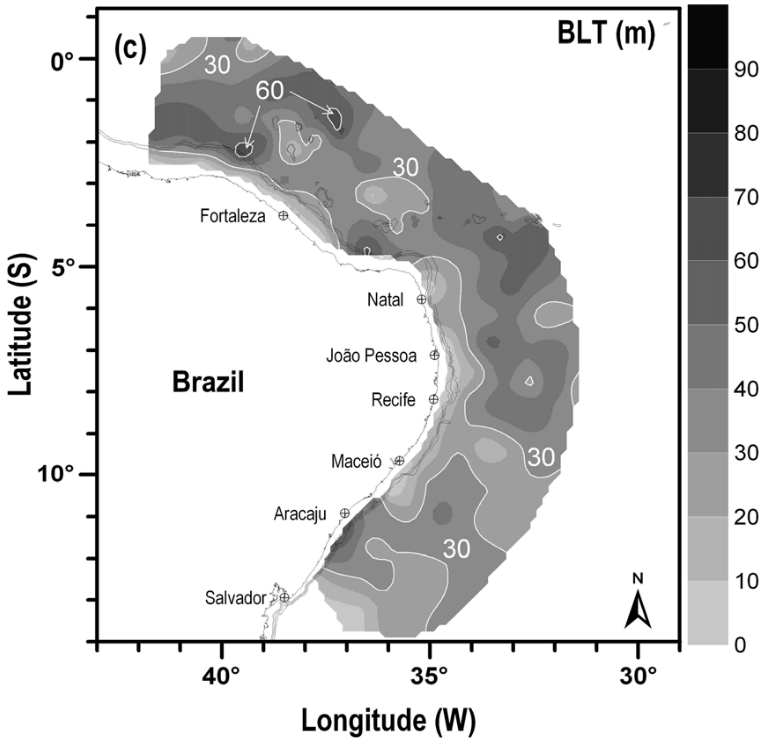

Fig. 4c. Spatial distribution of barrier layer thickness (*BLT*) during austral summer (January–April 1997).

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