



# Surface-to-subsurface temperature variations during the last century in a western boundary upwelling system (Southeastern, Brazil)



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## ABSTRACT

The upper thermal gradient of a western boundary upwelling system was reconstructed for the last 100 years. The reconstruction was based on oxygen isotopic composition ( $\delta^{18}\text{O}$ ) of four planktonic foraminifera species derived from two boxcores (BCCF10-01 and BCCF10-04) located in the southeastern Brazilian shelf. Calcification depths of the four planktonic foraminifera species were estimated in order to understand which layer of the water column was assessed. Changes in the upper thermal gradient were evaluated by using the  $\delta^{18}\text{O}$  difference from the surface-dwelling species *Globigerinoides ruber* (pink) and the deep-dwelling *Neogloboquadrina dutertrei*. The relative abundance of cold-water species and the  $\delta^{13}\text{C}$  of *G. ruber* (pink) were also used to evaluate changes on the surface layer. Our results demonstrate a trend to reduction on the temperature difference ( $\Delta T$ ) between the surface and the thermocline layer towards the present for both cores, together with an increase on the relative abundance of cold-water species for the mid-shelf core (BCCF10-04) and a decrease in  $\delta^{13}\text{C}$  values of *G. ruber* (pink) for both cores. Despite the observable trend on the proxies, only the relative abundance of *Turborotalita quinqueloba* and the  $\delta^{13}\text{C}$  of *G. ruber* (pink) for the mid-shelf core presented statistically significant trends. These results were related to an increase in South Atlantic Central Water (SACW) intrusions in the sub-surface layer, especially on the middle shelf region. The SACW intrusions would lower the sea surface temperature and would bring a depleted  $\delta^{13}\text{C}$  of the dissolved inorganic carbon signature to the surface, which would be in agreement with our findings. Moreover, these mid-shelf SACW intrusions in the region were attributed to the Ekman pumping (wind stress curl-driven), which was previously reported to be an important mechanism in this upwelling system. The major outcomes to this western boundary current ecosystem from an intensification of the mid-shelf upwelling were discussed.

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## 1. Introduction

Coastal upwelling areas are characterized by low sea surface temperature (SST) values and enhanced primary production. Intrusions of cold and nutrient-rich waters from subsurface to surface influence the coastal ecosystem and affect the regional fisheries productivity (Bakun and Weeks, 2008). Further, upwelling areas play an important role in the air-sea  $\text{CO}_2$  exchange and can affect local climate (Narayan et al., 2010). Global climate may also influence upwelling systems from eastern and western boundaries (Bakun, 1990; Su et al., 2013). Therefore, intensification (or attenuation) of upwelling systems would influence ecologically and

economically the ocean margins. This highlights the global importance such coastal upwelling systems over the oceans (Pauly and Christensen, 1995).

Most of upwelling studies focus on the eastern boundary current systems (Bakun, 1990; Thomas et al., 2001; McGregor et al., 2007; Gruber et al., 2011). However, recently attention has been given to the western boundary upwelling systems (Belem et al., 2013; Su et al., 2013; Aguiar et al., 2014) due to the recognition of its global importance (Su et al., 2013). An example of such system is the coastal upwelling area located off Cabo Frio at 23°S on the southeastern Brazilian continental shelf. The area exhibits intrusions of the cold and nutrient-rich South Atlantic Central Water (SACW) near the coast (surface) and in the mid-shelf (subsurface) resulting in a regional increase in primary productivity (Castelao and Barth, 2006; Cerda and Castro, 2014). Considering the warm and oligotrophic realm that mark the Southwestern Atlantic, any change in temperature and nutrient availability produced by

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upwelling may cause a drastic geochemical and biological effect making Cabo Frio upwelling system a very sensitive site.

The majority of the studies in this area deal with analysis of hydrographic data in order to understand the atmosphere-surface ocean interaction, as well the main related oceanographic processes (Castelao and Barth, 2006; Belem et al., 2013; Cerda and Castro, 2014). However, these datasets are limited to the period of data collection of cruises and the beginning of satellite data records. Information on longer time scales must be provided by marine sediment archives retrieved on the continental shelves (Souito et al., 2011; Lessa et al., 2014). Such knowledge would be crucial in order to assess the variability and main trends of this western boundary upwelling system.

Since upwelling regions are characterized by the rising of cold waters in surface (or subsurface), one way of addressing the variability on longer time scales would be by reconstructing temperature in the upper layer of the water column. One of the most common proxies for this purpose is the oxygen isotopic composition ( $\delta^{18}\text{O}$ ) of the shells of planktonic foraminifera (Mullitza et al., 1997). The advantage of this proxy relies in fact that the geochemical composition of their carbonate shells is in equilibrium with the seawater and changes in the water column conditions are recorded and preserved in marine archives (Spero et al., 2003). Moreover, planktonic foraminifera species can inhabit different depths, which enables the record of temperature in a depth gradient by using multiple species (Mullitza et al., 1997; Steph et al., 2009). Such information would be crucial for the understanding of the dynamics of the water masses that occupy the shelf and to observe stratification variability on longer time scales.

Thus, the objectives of this study are: (1) reconstruct the upper layer thermal variability of the Cabo Frio upwelling system; (2) identify possible trends or phases of intensification (or attenuation) of this upwelling system and briefly discuss the consequences for the shelf environment; (3) propose a proxy for the surface-to-subsurface thermal gradient based on the  $\delta^{18}\text{O}$  of different planktonic foraminifera species. To achieve these objectives, we analyzed stable isotopic composition of four planktonic foraminifera species (*Globigerinoides ruber* (pink), *Neogloboquadrina dutertrei*, *Trilobatus sacculifer* (without sac-like chamber) and *Globorotalia menardii*) and the relative abundances of cold-water species (*Turborotalita quinqueloba* and *Globigerina bulloides*) on two boxcores covering the last 100 years from shelf environment.

## 2. Oceanographic settings

The continental shelf of southeastern Brazil, especially between parallels 21°S and 25°S, is widely studied due to the presence of a western boundary upwelling system (Ikeda et al., 1974; Matsuura, 1996; Castro and Miranda, 1998; Rodrigues and Lorenzetti, 2001; Castelao and Barth, 2006; Castelao, 2012; Cerda and Castro, 2014; Castro, 2014). The Brazil Current flows southward along the shelf break and slope of Brazilian margin, as a component of the South Atlantic Subtropical Gyre, acquiring intensity and speed southward of the Abrolhos Bank (Silveira et al., 2000). Moreover, this western boundary current carries the Tropical Water (TW) at the upper layer of water column, as well as the South Atlantic Central Water (SACW) at an intermediate depth southwards (Stramma and England, 1999). TW is straightforwardly associated with temperatures higher than 20 °C and salinity values above 36.4, while SACW is characterized by temperatures and salinity values respectively below 20 °C and lower than those of TW (Castro and Miranda, 1998; Silveira et al., 2000). Besides the TW and SACW, Coastal Water (CW), characterized by lower salinity, resulting from mixing of water masses on the continental shelf and continental runoff is the third water mass of the region and is located at the

upper part of the water column of the southeastern Brazilian margin (Castro and Miranda, 1998).

At the latitude of approximately 23°S, where is located the Cabo Frio continental shelf, occurs a conspicuous change in the shoreline orientation from NE-SW to E-W resulting in a complex regional oceanographic circulation. Synergies among geomorphological features (Rodrigues and Lorenzetti, 2001), BC instabilities, NE prevailing winds and wind curl stress (Castelao et al., 2004; Castelao and Barth, 2006; Belem et al., 2013) cause the pumping of the South Atlantic Central Water (SACW) over the continental shelf, hence forming the upwelling system. Such interplay is believed as a main modulator of upwelling dynamics in Cabo Frio, controlling also the regional primary production. Typically, western boundary oceanic systems exhibit oligotrophic features (Belem et al., 2013) – nevertheless, as discussed by some authors (e.g., Jennerjahn et al., 2010; Albuquerque et al., 2014), the Cabo Frio Upwelling System (CFUS) has been associated to higher productivity levels, which could be explained by the SACW intrusions at the photic zone.

Recent studies in the CFUS region (e.g., Albuquerque et al., 2014; Cordeiro et al., 2014; Venancio et al., 2014) defined the presence of three compartments in a cross-shelf section. The inner shelf is the shallower compartment mainly characterized by a coastal upwelling area, where northeasterly prevailing winds favor the Ekman transport and upward movement of the SACW (Valentin, 1984). The mid-shelf compartment is a wide area influenced by the effects of the thermal fronts, wind stress curl and eddies (Castelao and Barth, 2006; Calado et al., 2010; Castro, 2014). In the mid-shelf, the SACW could reach the sub-surface layer, enhancing primary production (Albuquerque et al., 2014). Finally, the outer shelf area is the compartment dominated by mesoscale regional dynamics modulated by the internal front of BC, as well as the breaking of internal waves and tidally induced vertical displacements (Pereira and Castro, 2007; Lessa et al., 2016).

## 3. Materials and methods

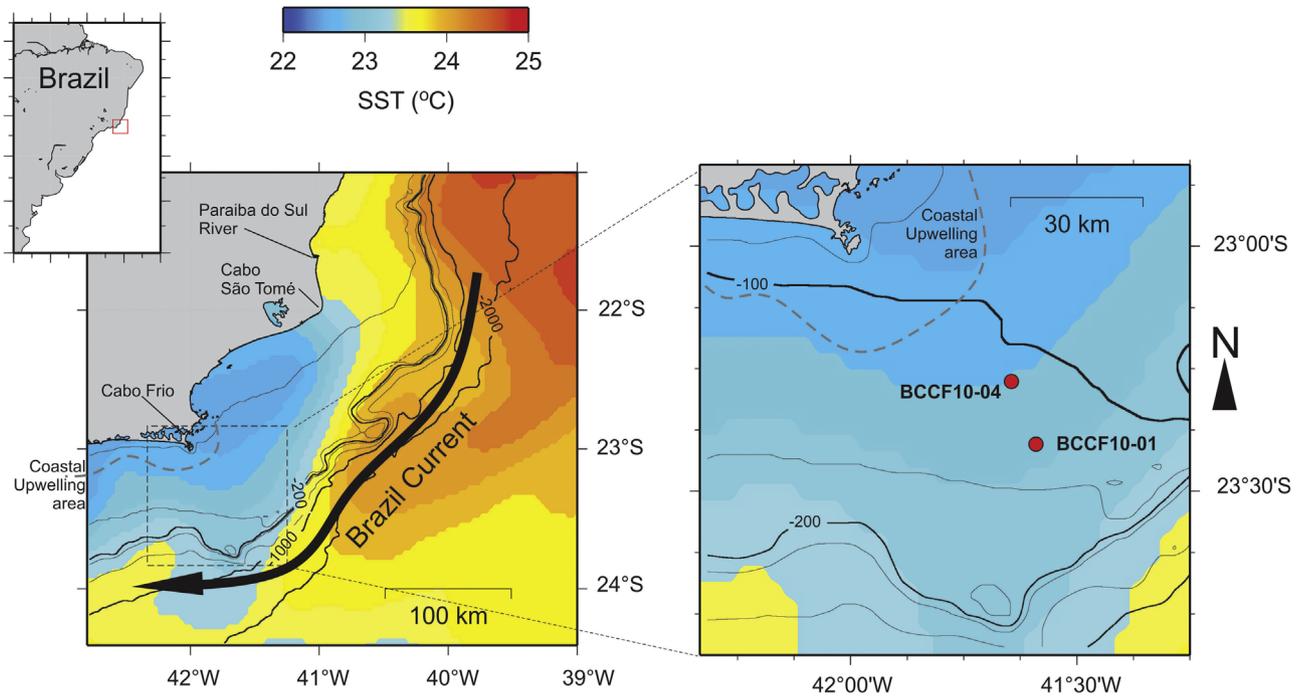
### 3.1. Boxcores sampling and age model

The boxcores BCCF10-01 (23°40'38"S, 41°59'01"W) and BCCF10-04 (23°27'64"S, 41°64'98"W) were collected in 2010 aboard the Brazilian Navy Ship "Diadorim" (Fig. 1). The core BCCF10-01 was located 142 m deep, has 15.5 cm long and sedimentation rate of 0.1 cm/y (Sanders et al., 2014). The core BCCF10-04 was located 120 m deep, has 21.5 cm long and sedimentation rate of 0.14 cm/y (Sanders et al., 2014). The age model was based on the  $^{210}\text{Pb}$  excess along the boxcore profile, which was performed by gamma spectrometry and estimated according to the sedimentation rates obtained by the "Constant Initial Concentration" method as described by Sanders et al. (2014) (Table 1).

### 3.2. Stable isotopes analysis

The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  were analyzed for the planktonic foraminifera species *Globigerinoides ruber* (pink), *Neogloboquadrina dutertrei*, *Trilobatus sacculifer* (without sac) and *Globorotalia menardii* in both cores. The shells of *G. ruber* (pink) were picked from the 250–350  $\mu\text{m}$  sieve fraction in order to avoid large deviations in the isotopic values. For the others species shells were picked from sizes greater than 250  $\mu\text{m}$  due to difficulties in obtaining shells in a small size range. Only the  $\delta^{13}\text{C}$  values of *G. ruber* (pink) were used in our interpretations, since there was no control of the shell size for the other species.

The samples were analyzed at the University of California, Santa Cruz Stable Isotope Laboratory. Stable isotopic composition was

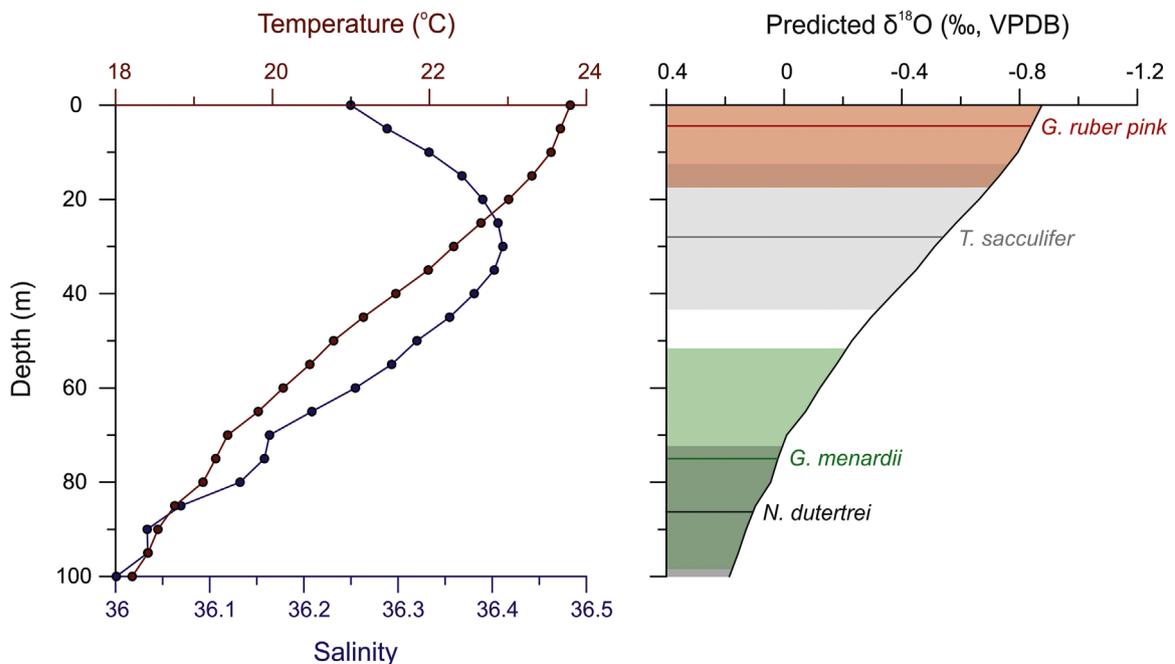


**Fig. 1.** Cabo Frio continental shelf with the study area indicated with a polygon, the sediment cores are highlighted (red dots) and showing the 10-year mean sea surface temperature (SST) distribution from AVHRR/PFEL-NOAA. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**  
Sampling locations, core length (cm), sedimentation rate (cm/y)<sup>a</sup> and water depth (m).

Box core	Latitude (S)	Longitude (W)	Length (cm)	Sedimentation rate (cm/y) <sup>a</sup>	Water Depth (m)
BCCF10-01	23°40'39,00"	41°59'00,00"	15,5	0,1	142
BCCF10-04	23°28'03,99"	42°04'47,00"	21,5	0,14	120

<sup>a</sup> Sanders et al. (2014).



**Fig. 2.** T-S profile extracted from World Ocean Atlas (WOA) 2013 in the left panel. The profile was extracted from the nearest station in relation to the sediment cores. In the right panel, the predicted δ<sup>18</sup>O (see methods) of the calcite with the mean calcification depth (thick line) and the range (colored polygons) based on the δ<sup>18</sup>O of each species.

determined using a Thermo Scientific MAT-253 Isotope Ratio Mass Spectrometer (IRMS), with precision of  $\pm 0.05\%$  for the  $\delta^{13}\text{C}$  and  $\pm 0.08\%$  for  $\delta^{18}\text{O}$ . The samples were processed at  $75\text{ }^\circ\text{C}$  with phosphoric acid (density =  $1.92\text{ g/cm}^3$ ) to generate carbon dioxide and water. Water was removed cryogenically and the non-condensable gases were pumped out before the introduction of the  $\text{CO}_2$  purified in IRMS. A calibrated in-house standard (Carrera Marble) is used to correct data, which includes a drift correction. The corrected delta values are expressed relative to the standard Vienna Pee Dee Belemnite (VPDB).

### 3.3. Calcification depths

In order to estimate the calcification depths for each species, we calculated the  $\delta^{18}\text{O}$  values of equilibrium calcite according to Kim and O'Neil (1997) following the equation provided by Sagawa et al. (2013):

$$\delta_{\text{C}} = \frac{4.64 - \sqrt{21.53 - 0.36 \times (16.1 - T)}}{0.18} + \delta_{\text{W}}$$

where T is temperature in Celsius and  $\delta_{\text{C}}$  is the  $\delta^{18}\text{O}$  value of carbonate and  $\delta_{\text{W}}$  is the  $\delta^{18}\text{O}$  value for the seawater, both values in ppm relative to VPDB. The values of temperature and salinity were extracted from World Ocean Atlas 2013 version 2 (Fig. 2), using nearest profile of annual data interpolated in  $0.25^\circ$  grids (Locarnini et al., 2013; Zweng et al., 2013). The  $\delta_{\text{W}}$  values were estimated using a regional  $\delta_{\text{W}}$ -salinity linear equation derived from the study of Pierre et al. (1991):

$$\delta_{\text{W}} = 0.382 \times S - 12.845$$

where S is the salinity and the  $\delta_{\text{W}}$  was converted from Vienna Standard Mean Ocean Water (VSMOW) to VPDB by subtracting  $0.27\%$  (Hut, 1987). The resulted curve of the  $\delta^{18}\text{O}$  of equilibrium calcite is similar to the temperature profile (Fig. 2), which suggests that the influence of varying temperature in the estimated  $\delta^{18}\text{O}$  values are higher if compared to salinity.

### 3.4. Surface-to-subsurface temperature reconstruction

In order to estimate the temperature for the boxcores we used the equation of Shackleton (1974) for all species. For the calculation, we used the  $\delta^{18}\text{O}_{\text{C}}$  of planktonic foraminifers in both cores and the  $\delta^{18}\text{O}_{\text{W}}$  end-members for the region proposed by Venancio et al. (2014). For the shallow-dwellers (*G. ruber* pink and *T. sacculifer*) we used the  $\delta^{18}\text{O}_{\text{W}}$  end-member of the TW and for the deep-dwellers (*N. dutertrei* and *G. menardii*) the values for SACW were used. This method implies that those species inhabit those water masses, which is in good agreement with previous studies for the region (Lessa et al., 2014). The  $\delta^{18}\text{O}_{\text{W}}$  were also scaled from VSMOW to VPDB by subtracting  $0.20\%$  (Bemis et al., 1998).

### 3.5. Cold-water species abundances

The relative abundances of the cold-water species *Turborotalita quinqueloba* and *Globigerina bulloides* were estimated for both cores. For that,  $10\text{ cm}^3$  of the sediment was washed through a  $125\text{ }\mu\text{m}$  mesh sieve. The residue was dried at  $50\text{ }^\circ\text{C}$  and subjected to planktonic foraminifera faunal analysis, in which 300 specimens per sample were identified at the species level. The relative abundances (%) of *T. quinqueloba* and *G. bulloides* were then estimated in relation to the total foraminiferal assemblage.

### 3.6. Statistical analysis

Linear trends on the  $\Delta T$  (*N. dutertrei*-*G. ruber* pink), % of *T. quinqueloba*, % of *G. bulloides* and  $\delta^{13}\text{C}$  of *G. ruber* (pink) for the last 100 years on both cores were evaluated using statistical analysis.

We performed a *t* test on the slopes of each linear regression equation, in order to evaluate if the slopes of the regression lines are significantly different from zero, which would imply that there is a significant trend on the data through time. For this analysis, the significance level of 95% was set.

## 4. Results

### 4.1. Stable isotopic composition of planktonic foraminifera species

Isotopic data measured on the four species of planktonic foraminifera are illustrated in Fig. 3. Both cores exhibited different mean  $\delta^{18}\text{O}$  values between species. Generally, *G. ruber* (pink) showed the lowest values of  $\delta^{18}\text{O}$  over the time series, followed in ascending order by *T. sacculifer*, *G. menardii* and *N. dutertrei*.

In the boxcore BCCF10-01 (outer shelf) *G. ruber* (pink)  $\delta^{18}\text{O}$  signal presented values ranging from  $-1.02$  to  $-0.57\%$  and  $\delta^{13}\text{C}$  values ranged from  $1.36$  to  $1.73\%$ . *T. sacculifer*  $\delta^{18}\text{O}$  had values ranging between  $-0.87$  and  $-0.22\%$ . *G. menardii* showed wide variation in  $\delta^{18}\text{O}$  values of  $-0.43$  to  $0.29\%$ . *N. dutertrei* in its turn presented  $\delta^{18}\text{O}$  oscillating values between  $-0.26$  and  $0.47\%$ .

In the boxcore BCCF10-04 (mid-shelf) *G. ruber* (pink)  $\delta^{18}\text{O}$  signal presented values between  $-1.10$  and  $-0.63\%$  and  $\delta^{13}\text{C}$  values ranged from  $1.15$  to  $1.91\%$ . *T. sacculifer* showed  $\delta^{18}\text{O}$  values ranging from  $-0.92$  to  $0.06\%$ . *G. menardii* presented the highest oscillation between all species and between the two parts of Cabo Frio continental shelf studied to the  $\delta^{18}\text{O}$  values, with the isotopic signal ranging from  $-1.29$  to  $0.72\%$ . *N. dutertrei* had  $\delta^{18}\text{O}$  values ranging between  $-0.18$  and  $0.43\%$ .

### 4.2. Calcification depths

As expected, the surface dwellers species *G. ruber* (pink) and *T. sacculifer* showed the lowest depth values based on the  $\delta^{18}\text{O}$ . The results indicate that even being grouped as surface-dwelling species, *G. ruber* (pink) inhabits shallower depths in comparison to *T. sacculifer*. Deep-dwelling species as *G. menardii* and *N. dutertrei* showed closer values of range calcification depths. These results suggest that both species live in the same depth, which could be related to the thermocline depth. The ranges of calcification depths estimated for these four species are showed in Table 2.

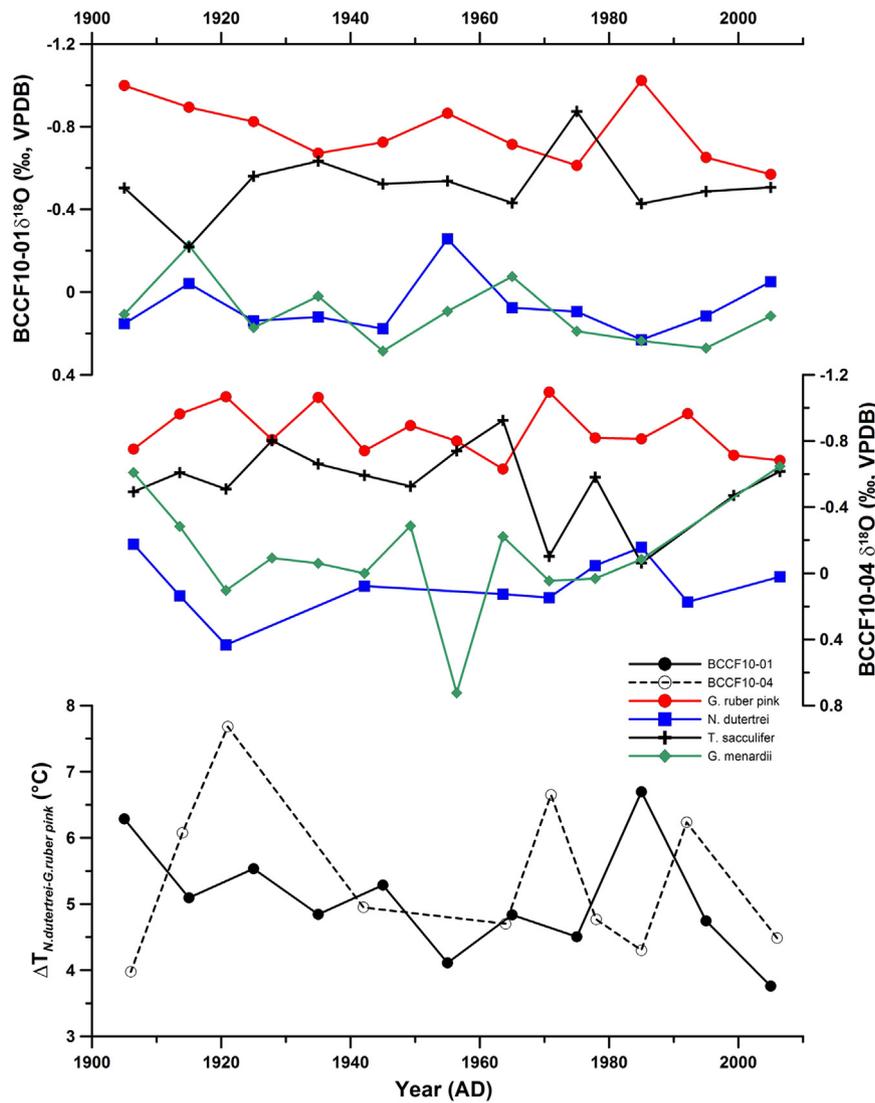
### 4.3. Temperature reconstructions

The  $\delta^{18}\text{O}$  results for all chosen species from both cores were used to generate past temperature (last 100 years) estimations for the region. The temperatures values for *G. ruber* (pink) ranged from  $21.9$  to  $23.7\text{ }^\circ\text{C}$  in the outer shelf and from  $22.1$  to  $24\text{ }^\circ\text{C}$  in the mid shelf. In the case of *T. sacculifer*, the values ranged from  $20.5$  to  $23.1\text{ }^\circ\text{C}$  in the outer shelf and from  $19.9$  to  $23.3\text{ }^\circ\text{C}$  in the mid shelf.

For the deep-dwelling species, the temperatures values were lower compared to the surface-dwelling as expected. Values for *N. dutertrei* ranged from  $16$  to  $18.9\text{ }^\circ\text{C}$  in the outer shelf and from  $16.2$  to  $18.6\text{ }^\circ\text{C}$  in the mid shelf. For *G. menardii* the temperatures ranged from  $16.8$  to  $19.7\text{ }^\circ\text{C}$  in the outer shelf and from  $15$  to  $20.5\text{ }^\circ\text{C}$  in the mid shelf. For *G. menardii* we excluded one outlier value prior to the estimations.

### 4.4. Cold-water species abundances

The relative abundances of the cold-water species *T. quinqueloba* were generally higher on the mid-shelf (BCC10-04) in relation to the outer shelf (BCCF10-01), while *G. bulloides* presented similar values for both cores. The boxcore BCC10-04 presented percentages values of *T. quinqueloba* ranging from  $9.5\%$  to  $17.3\%$ , and for *G.*



**Fig. 3.** Oxygen isotopic composition of each species and reconstructed thermal gradient for the last 100 years in both cores. In the upper panel, the outer shelf core (BCCF10-01) and below the mid-shelf core (BCCF10-04). The lower panel exhibits the difference in reconstructed temperatures ( $\Delta T$ ) using the equation of Shackleton (1974) for *N. dutertrei* and *G. ruber* (pink).

**Table 2**  
Estimated calcification depth ranges for the planktonic foraminifera species.

Species	Calcification depth range (m)
<i>Globigerinoides ruber</i> (pink)	0–18
<i>Trilobatus sacculifer</i>	12–44
<i>Globorotalia menardii</i>	52–98
<i>Neogloboquadrina dutertrei</i>	72–100

\*negative values were excluded

*bulloides* the values ranged from 3.9 to 10.5%. For the core BCCF10-01, the relative abundances of *T. quinqueloba* ranged from 1.2% to 9%, while *G. bulloides* presented values ranging from 5.1% to 10.9%.

#### 4.5. Statistical analysis

The results of the *t* test demonstrated that the majority of the proxies tested present no statistical significant trends through the time series (Table 3). However, the relative abundances of *T. quinqueloba* and the  $\delta^{13}\text{C}$  of *G. ruber* pink from the mid-shelf core (BCCF10-04) exhibited slopes statistically different from zero. The

results demonstrate the presence of significant trends (*p*-value < 0.05) for increasing relative abundances of *T. quinqueloba* and decreasing  $\delta^{13}\text{C}$  of *G. ruber* pink towards the present on the mid-shelf region.

### 5. Discussion

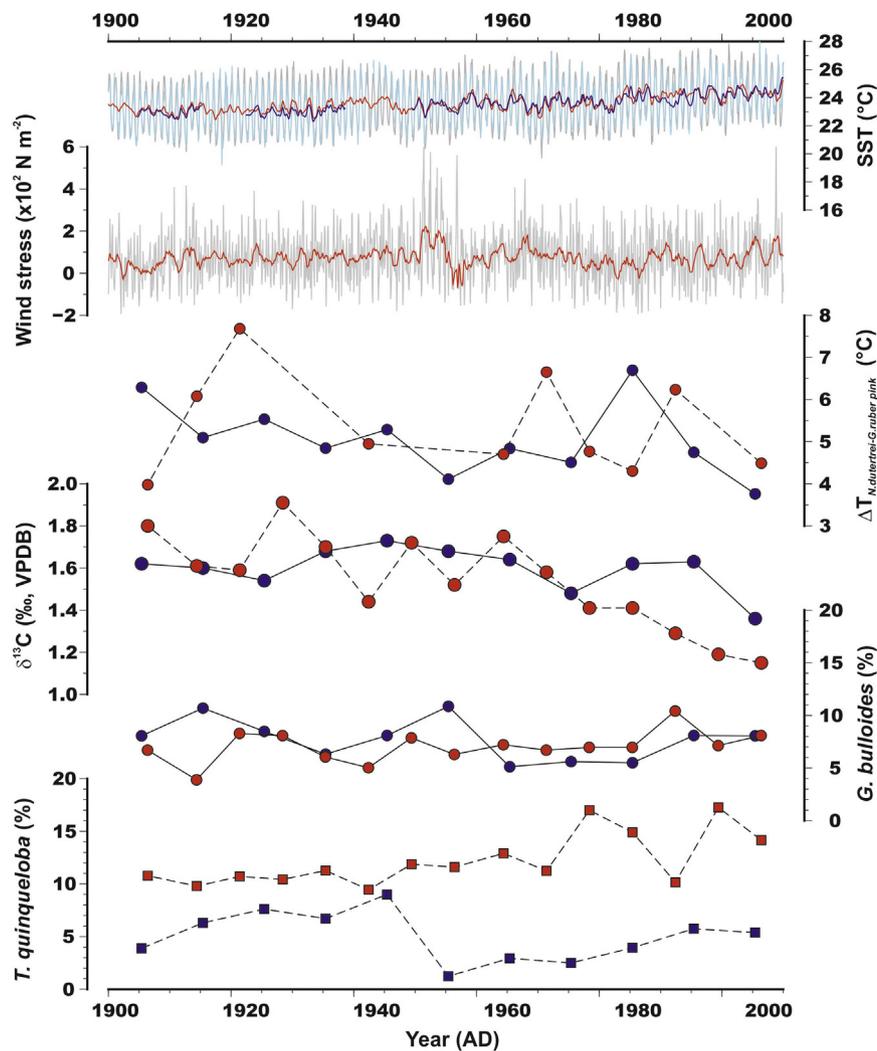
Based on estimations of calcification depths and temperature for different planktonic foraminifera species we proposed a proxy for surface-to-subsurface thermal gradient for the southeastern Brazilian continental shelf (Figs. 2 and 3). Calcification depths estimations confirmed that *G. ruber* (pink) calcifies in the more superficial layer, while *N. dutertrei* appears to acquire most of the isotopic signal from the subsurface or thermocline (Fig. 2). Although calcification depth for *G. menardii* can also be related to the thermocline layer, there is a larger range of depths where it can calcify, thus we decided to use *N. dutertrei* instead of *G. menardii* for the proxy application in the cores. However, variations in the  $\delta^{18}\text{O}$  values for all the chosen species are also included in this discussion.

*G. ruber* (pink) is a dominant species in tropical and subtropical waters and is restricted to the Atlantic Ocean. This species is especially abundant in warm and oligotrophic waters (Tolderlund and Bé, 1971). In addition, it is considered to inhabit the first 20–30 m of the mixed layer and the  $\delta^{18}\text{O}$  signal obtained from its shell is widely used as a proxy for sea surface temperatures (Tolderlund and Bé, 1971; Ravelo et al., 1990; Ravelo and Fairbanks, 1992; Thunell et al., 1999; Farmer et al., 2007). Meanwhile, *N. dutertrei* is a thermocline layer species and is commonly associated with productive waters and upwelling regions (Tolderlund and Bé, 1971). This species inhabits depths between 30 and 80 m (Ravelo et al., 1990; Ravelo and Fairbanks, 1992; Farmer et al., 2007). *N. dutertrei* is also associated with the deep chlorophyll maximum (Fairbanks et al., 1980; Ravelo and Fairbanks, 1992).

The use of the  $\Delta\delta^{18}\text{O}$  (*N.dutertrei*–*G.ruber* pink) was previously reported as a suitable proxy for stratification of the upper layer (Tedesco and Thunell, 2003; Wejnert et al., 2013). For example, in a recent study by Wejnert et al. (2013) this same proxy was used to document past stratification on the Cariaco Basin. There is a close

match between the calcification depth of *N. dutertrei* and *G. me-nardii* estimated by our data. Both species calcify at similar depths and this can be related to the depth of the 18 °C isotherm, since oceanographic studies (Valentin, 2001; Albuquerque et al., 2014) indicated the presence of this isotherm between 50–80 m. This highlights the importance of reconstructions using these species on the study area. Based on these evidences, we used the  $\delta^{18}\text{O}$  values of multi-species as a proposed proxy for assess the upper thermal gradient in this western boundary upwelling system.

The  $\delta^{18}\text{O}$  values of multi-species of planktonic foraminifera in the boxcores revealed a relevant variability of the upwelling system for the last 100 years (Fig. 3). The mid-shelf exhibited a higher variability of the  $\delta^{18}\text{O}$  values, which suggest that the upper layer thermal gradient on this region is more dynamic. There is a general trend towards the present showing a decrease in temperature differences between *G. ruber* (pink) and *N. dutertrei*. This can be interpreted as a cooling taking place at the surface layer (above 30 m) and a warming of the thermocline layer due to its shallower position in the water column, which is tracked by *N. dutertrei*  $\delta^{18}\text{O}$  values.



**Fig. 4.** Temporal changes on sea surface temperature (SST), cross-shelf wind stress and on our main proxies for the mid-shelf (red symbols) and outer shelf (blue symbols). (A) SST values extracted from the ICOADS database with  $2^\circ \times 2^\circ$  resolution ([https://coastwatch.pfeg.noaa.gov/erddap/griddap/esrlcoads2ge\\_LonPM180.html](https://coastwatch.pfeg.noaa.gov/erddap/griddap/esrlcoads2ge_LonPM180.html)) and from the HadISST database with a  $1^\circ \times 1^\circ$  resolution (<https://coastwatch.pfeg.noaa.gov/erddap/info/erdHadISST/index.html>). The red thick line is a 13-term Henderson filter (detrend) of HadSST data and the blue thick line is a polynomial deconvolution of ICOADS data, showing deseasonalized data. (B) Cross-shelf wind stress values calculated using monthly data extracted from the NCEP 20th Century Reanalysis V2 and the red thick line is a 13-term Henderson seasonal filter ([http://www.esrl.noaa.gov/psd/data/gridded/data.20thC\\_ReanV2.html](http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html)). Spatial coverage for the wind stress data is  $2^\circ \times 2^\circ$ . (C) Reconstructed temperature difference ( $\Delta T$ ) using the  $\delta^{18}\text{O}$  values of *N. dutertrei* and *G. ruber* (pink). (D)  $\delta^{13}\text{C}$  values of *G. ruber* (pink). (E) Relative abundances of *G. bulloides*. (F) Relative abundances of *T. quinqueloba*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

However, this smaller difference between both species  $\delta^{18}\text{O}$  values could also be caused by vertical migration of these species or changes in depth habitat, or both processes (Field, 2004). We assume that changes in  $\delta^{18}\text{O}$  values of these species are more related to temperature variations at certain depths, and not changes in habitat, since other oceanographic studies reinforce that the mixed layer (*G. ruber* pink) and thermocline layer (*N. dutertrei*) are the habitats of these species (Ravelo et al., 1990; Ravelo and Fairbanks, 1992). Such surface cooling on the mid-shelf region is also supported by the decreasing trend of the thermal gradient for the same period (Fig. 3) and by the increasing trend of relative abundances of the cold-water species *T. quinqueloba* and *G. bulloides* (Fig. 4). However, as shown in Table 2, the linear trend is only statistically significant for the increasing pattern of the relative abundances of *T. quinqueloba*. This could be linked to an intensification of the upwelling induced by the wind stress curl (Castelao and Barth, 2006) on the mid-shelf region. This can also be reinforced by the  $\delta^{13}\text{C}$  data of *G. ruber* (pink) for both cores. The values exhibit a clear decreasing trend towards the present, which can be related to an increase in SACW volume in the surface layers, since this water mass carries a lower  $\delta^{13}\text{C}_{\text{DIC}}$  signature (Venancio et al., 2014). However, the  $\delta^{13}\text{C}$  trend is statistically significant only for the mid-shelf core (BCCF10-04). The  $\delta^{13}\text{C}$  trend was only assessed for *G. ruber* (pink), because for that species we have a defined size range (250–350  $\mu\text{m}$ ), which reduces the influence of ontogenetic effects. Wind stress curl-driven upwelling was also reported to be a crucial process in the California Current system (Pickett and Paduan, 2003). In this process, the negative wind stress curl generates divergence in the ocean surface, causing upwards movements of SACW in the water column (Castelao and Barth, 2006). Recently, Belem et al. (2013) highlighted the influence of this wind stress curl process on subsurface temperatures recorded by a mooring deployed on the same study area. High stratification variability was also reported for the mid-shelf area in another study (Castro, 2014). Based on hydrographic data on the southeastern Brazilian continental shelf, Castro (2014) concluded that buoyancy advection is a relevant physical process on the mid-shelf. Buoyancy advection appears to be linked to stratification in the mid-shelf region and is associated to cross-shelf intrusions of SACW towards the coast (Castro, 2014).

The results from the outer shelf reveal a clearer separation of the  $\delta^{18}\text{O}$  values of planktonic foraminifera species (Fig. 3). The  $\delta^{18}\text{O}$  values of the deep-dwellers (*N. dutertrei* and *G. menardii*) appear to be much more stable through time. These observations points to a well stratified water column in the outer shelf. This seems coherent since this region is more influenced by the presence of the internal front of BC (Belem et al., 2013; Cerda and Castro, 2014). The proximity of that current would cause a deepening of the thermocline, caused by the increased volume of TW on the upper layer. However, oscillations on the BC front and short upward movements of the SACW close to the thermocline, are possible mechanisms that could cause variations on the upper thermal gradient. As shown by Belem et al. (2013), there are very dynamic and intermittent movements of the SACW between 40 and 100 m in the shelf region, which highlights the high frequency variability of this process. This is evidenced by our surface-to-subsurface temperature reconstruction for the outer shelf, which also exhibits variability through time, as well as a decreasing trend on the upper thermal gradient ( $\Delta T$  *N. dutertrei*-*G. ruber* pink) (Fig. 3). However, the trends on the outer shelf are not statistically significant regarding all tested proxies. This demonstrates that variations related to subsurface upwelling events are not very strong on the outer shelf. This reinforces the idea of an intensification of the upwelling towards the present day only on the mid-shelf region, and probably extending from the mid-shelf to the inner shelf.

Our data was also cross-checked with SST and wind fields for

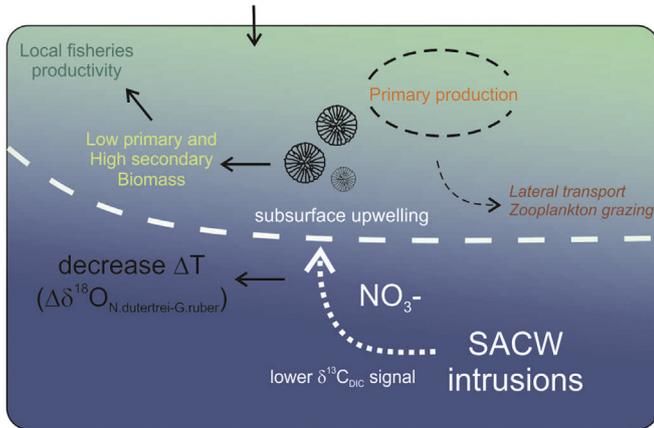
the region during the same time period (Fig. 4). We extracted SST data from International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and from the Hadley Center Sea Ice and Sea Surface Temperature dataset (HadISST), the resolution was  $2^\circ \times 2^\circ$  for the ICOADS dataset and  $1^\circ \times 1^\circ$  for the HadISST dataset. The cross-shelf wind stress was derived from the NCEP 20th Century Reanalysis V2, assuming angle of the coast of  $40^\circ$  and the resolution was  $2^\circ \times 2^\circ$ . We observed no clear trends on SST and wind datasets for the last 100 years. There is a slight increase in SST from 1980 towards the present and a considerable change in the cross-shelf wind stress around 1950–1955. This change in the wind stress is simultaneous with lower  $\Delta T$  values from the cores. However, in general there is no direct coupling between our data and the SST and wind datasets. This coupling may be hampered by: (1) different time resolutions, our data exhibit very sparse values compared to the SST and wind datasets; (2) spatial coverage, the datasets present a spatial coverage that may be not sufficient to resolve these coastal processes, such as sub-surface intrusions of the SACW. Remarkably, the CFUS present distinct oceanographic processes in a cross-shelf section of the southeastern Brazilian coast and cores collected in less than 20 km of distance from each other can record different changes in the water column. Cordeiro et al. (2014) presented reconstructed SST values derived from alkenones ( $U_{37}^K$ ) for three boxcores on the same study area and observed a spatial heterogeneity in SST values. The  $U_{37}^K$ -SSTs showed a clear distinction between the outer shelf region and the coastal region, containing the middle and inner sections of the shelf. Furthermore, the  $U_{37}^K$ -SSTs from a mid-shelf core (BCCF10-09) analyzed by Cordeiro et al. (2014) exhibited a clear decreasing trend of the SST values from 1890 towards the present. By contrast, the outer shelf core (BCC10-01) which is the same used in this study, exhibited no clear SST trend and only slight SST oscillations from 1840 until the present. These results are in good agreement with our observations. Our data derived from the mid-shelf core (BCCF10-04), which is less than 10 km far from the core BCCF10-09 analyzed by Cordeiro et al. (2014), shows statistically significant trends on the dataset that suggest an increase of sub-surface intrusions of the SACW (Table 3; Fig. 4), being coherent with the cooling trend observed by the reconstructed  $U_{37}^K$ -SSTs. The results for the outer shelf core (BCC10-01) from both studies also point to the same conclusion, that this region exhibit no clear stratification trends and only slight temperatures oscillations through time, and reflects variations on thermal front of the BC. These observations demonstrated the complex spatial patterns on the CFUS region related to oceanographic features, such as thermal boundaries and upwelling mechanisms, which need to be considered for further interpretations.

Enhanced upwelling on the southeastern Brazilian shelf towards the present is not an exclusively pattern of this system. Enhanced alongshore wind stress and coastal upwelling was previous reported by Bakun (1990), and the intensification was linked to global

**Table 3**  
Results of a *t*-test for regression slopes (linear trends) on the dataset.

BCCF10-01	slope	std error	t	p-value
<i>N.dutertrei</i> - <i>G.ruber</i> pink ( $\Delta T$ )	-0.007	0.004	-1.771	0.098
% <i>T. quinqueloba</i>	-0.020	0.012	-1.693	0.112
% <i>G. bulloides</i>	-0.013	0.010	-1.337	0.202
$\delta^{13}\text{C}$ <i>G. ruber</i> pink	-0.001	0.001	-1.196	0.252
BCCF10-04				
<i>N.dutertrei</i> - <i>G.ruber</i> pink ( $\Delta T$ )	-0.007	0.005	-1.318	0.207
% <i>T. quinqueloba</i>	0.028	0.010	2.899	0.009
% <i>G. bulloides</i>	0.008	0.006	1.255	0.224
$\delta^{13}\text{C}$ <i>G. ruber</i> pink	-0.006	0.001	-4.710	0.000

## Wind stress Curl (negative)



**Fig. 5.** Conceptual model showing the oceanographic processes and the main consequences of an enhanced wind stress curl-driven upwelling for the ecosystem in our study area.

warming. Other studies report intensification of upwelling regions based on the analysis of SST and wind stress obtained from global datasets (Demarcq, 2009; Narayan et al., 2010; Gutiérrez et al., 2011). One of the consequences of this intensification would be the increase of primary production and phytoplankton biomass (Demarcq, 2009). In this study, Demarcq (2009) also find a significant relationship between equatorward wind and phytoplankton biomass. In the case of the Cabo Frio upwelling system, a model study confirmed the importance of physical factors on driving changes in biomass (Valentin and Coutinho, 1990). As reported by Valentin and Coutinho (1990), the upwelling in our study area is extremely sensitive to wind, which could initially favor the primary production but can also interrupt the process by rapid alternation of water masses and consequent dilution of the produced biomass. On the other hand, Fontana et al. (submitted) remarked the crucial role of SACW coastal upwelling and mid-shelf intrusions on nitrogen input and subsequent uptake in Cabo Frio area. In addition, Matsuura (1998) also pointed out that the presence of SACW on the bottom layer of the southeastern Brazilian shelf is an important factor for creation of sardine spawning habitat. These discussions demonstrate the importance of assessing variations on the Cabo Frio upwelling system intensity and its potential biogeochemical consequences to the southeastern Brazilian shelf.

Based on our observations and available literature of the region we built a conceptual model to summarize the main oceanographic consequences in a scenario of intensification of the Cabo Frio upwelling system (Fig. 5). The decreasing trend observed through our surface-to-subsurface temperature reconstruction can be related to more frequent SACW intrusions on the surface layer (0–30 m) in the mid-shelf and a slightly shallow thermocline on the outer shelf. In the mid-shelf this more frequent intrusions can be linked to an intensification of the wind stress curl (Castelao and Barth, 2006), while in the outer shelf such subsurface temperature variations are more complex and are as consequences of multiple forcing mechanisms (Belem et al., 2013). A recently study by Aguiar et al. (2014), also indicates that Ekman pumping due to wind stress would be the main mechanism of wind-driven upwelling in our site. The intrusion may reach the euphotic zone in the southeastern Brazilian shelf (Braga and Müller, 1998; Albuquerque et al., 2014), increasing the nutrient concentration in the upper layer (Fontana et al., submitted) and decreasing the  $\delta^{13}\text{C}_{\text{DIC}}$  (Venancio et al., 2014). Consequently, the enrichment of the euphotic zone with nutrients ( $\text{NO}_3^-$ ) can enhance primary

production and a short phytoplankton bloom can occur one day after the nutrient injection (Carbonel and Valentin, 1999). However, low primary biomass is observed in our study site, which can be the result of high grazing pressure by the zooplankton or lateral advection inducing the dispersion (Valentin and Coutinho, 1990; Gonzalez-rodriguez et al., 1992; Carbonel and Valentin, 1999). Therefore, SACW intrusions may also influence zooplankton dynamics (Guenther et al., 2008) and its biomass accumulation near Cabo Frio (Lopes et al., 2006). As pointed out by Lopes et al. (2006), the short-term increases in the zooplankton biomass, due to SACW intrusions in the euphotic zone, could promote high survival rates in pelagic fishes, such as sardines (Matsuura, 1996).

## 6. Conclusions

We evaluated changes on the water column conditions of a western boundary upwelling system for the last 100 years using multiple proxies from two boxcores. Besides, we propose a proxy for reconstructions of surface-to-subsurface temperature on the southeastern Brazilian continental shelf. Our proxy ( $\Delta\delta^{18}\text{O}_{\text{N.dutertrei-G.ruber}}$  pink) has a great potential for paleoceanographic studies on the region. The proxy relies on the fact that the chosen planktonic foraminifera species have different calcification depths, which were estimated by our data, and can thus record temperature in a depth gradient.

Our results demonstrated a difference between reconstructed water column conditions for the mid-shelf and the outer shelf. In the mid-shelf, we observed a trend on distinct proxies that point to an increase on SACW intrusions on sub-surface layers of the water column. This interpretation is mainly supported by the increase in the relative abundances of *T. quinqueloba* and the decrease in the  $\delta^{13}\text{C}$  values of *G. ruber* (pink), which were both statistically significant trends. However, in the outer shelf the trends on the dataset were not statistically significant and present slight oscillations through time.

Based on these results, we suggested that the changes in the mid-shelf are related to an intensification of the wind stress curl-driven upwelling, while the outer shelf appears to be dominated by oscillations on the position of the thermal front of the BC. However, we were not able to confirm our interpretations by cross-checking our data with SST and wind fields extracted from datasets. Meanwhile, we reinforced that differences in temporal resolution and spatial coverage may hamper this direct comparison. Beyond that, our observations were in good agreement with previous studies in the same area, which also reconstructed temperature variations for the last century. We also evaluated consequences of such intensification on the upwelling system near Cabo Frio. The main consequences would be related to changes on water mass distribution, primary production and would influence the regional ecosystem. Although we have discussed some of the consequences, was not our main objective to evaluate the impact of such intensification in the system. However, we have made clear the need for studies to clarify such biogeochemical responses related to intensification of this upwelling system.

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