Continental Shelf Research 125 (2016) 97–106

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

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

Igor M. Venancio [a,b,*], Vitor P. Gomes [b], Andre L. Belem [c], Ana Luiza S. Albuquerque [b]

[a] MARUM—Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, d-28359 Bremen, Germany
[b] Departamento de Geoquímica, Universidade Federal Fluminense, Outeiro de São João Batista, s/no., Niterói, Rio de Janeiro CEP: 24020-141, Brazil
[c] Departamento de Engenharia Agrícola e Meio Ambiente, Escola de Engenharia - Universidade Federal Fluminense, R. Passo da Pátria, 156 - Sala 209 - São Domingos, Niterói RJ, 24210-253, Brazil

ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form
30 May 2016
Accepted 10 July 2016
Available online 12 July 2016

Keywords:
Ekman pumping
Planktonic foraminifera
Wind stress curl
Southeastern Brazil

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 ($\delta^{18}O$) 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 $\delta^{18}O$ difference from the surface-dwelling species *Globigerinoides ruber* (pink) and the deep-dwelling *Neogloboquadrina dutertrei*. The relative abundance of cold-water species and the $\delta^{13}C$ 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 (ΔT) 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 $\delta^{13}C$ values of *G. ruber* (pink) for both cores. Despite the observable trend on the proxies, only the relative abundance of *Turborotalita quinqueloba* and the $\delta^{13}C$ 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 $\delta^{13}C$ 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.

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 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

* Corresponding author at: MARUM—Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, d-28359 Bremen, Germany.
E-mail address: ivenancio@marum.de (I.M. Venancio).

http://dx.doi.org/10.1016/j.csr.2016.07.003
0278-4343/

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 (Souto 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 ($\delta^{18}O$) of the shells of planktonic foraminifera (Mulitza 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 (Mulitza 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 $\delta^{18}O$ 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 Lorenzzetti, 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, Costal 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 Lorenzzetti, 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}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 $\delta^{18}O$ and $\delta^{13}C$ 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 μm sieve fraction in order to avoid large deviations in the isotopic values. For the others species shells were picked from sizes greater than 250 μm due to difficulties in obtaining shells in a small size range. Only the $\delta^{13}C$ 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