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Marine sediments from southeastern Brazilian continental shelf: A 1200 year record of upwelling productivity

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ABSTRACT

A sediment core from the Cabo Frio coastal shelf (−23.19 S, −41.8 W; 117 m depth), was analyzed for TOC, C/N ratio, organic petrography and planktonic foraminiferal content to evaluate variations in local productivity caused by changes in upwelling intensity and its relation to regional and global climatic variations during the last millennium. The Cabo Frio core recorded the last 1200 years of sedimentation, with rates varying from 0.11 to 0.32 mm yr^{-1}. Foraminiferal and organic geochemical analyses indicate the occurrence of three distinct periods of productivity. From 850 AD until 1070 AD, foraminifera fluxes consisting primarily of *Turborotalita quinqueloba* indicate stronger South Atlantic Central Water (SACW) transport onto the shelf, which induced high biological productivity that was also recorded by high TOC and marine palynomorphs content and a low C/N atomic ratio. This period coincided with a northward displacement of the atmospheric Intertropical Convergence Zone (ITCZ) and South Atlantic High (SAH) systems driven by positive temperature anomalies in the North Atlantic Ocean during the Medieval Climate Anomaly (MCA). From 1070 until 1500 AD, low TOC flux and planktonic foraminifera fluxes and high C/N atomic ratios suggest a reduction in marine productivity, probably driven by reduced transport of SACW associated with the southward displacement of the SAH and weakening of northeasterly winds. The period between 1500 and 1830 AD, which corresponds to the Little Ice Age, is marked by increased fluxes of planktonic foraminifera, principally of *Globigerina bulloides* and *Globigerinita glutinata*. These species mark an increase in productivity linked to SACW upwelling, supported by the enhancement of northeasterly winds and southward displacement of the ITCZ and SAH.

1. Introduction

The Earth has experienced periods of climate variability over the last millennium, two of which have been heavily investigated. The Medieval Climate Anomaly (MCA), documented primarily in the Northern hemisphere, marks a period of positive temperature anomalies recorded between 900 and 1150 AD. It was characterized by temperatures reaching values between 1° and 2 °C above 20th century averages (Bradley et al., 2003; Mann and Jones, 2003). Additional evidence of changes in climate, such as less rigorous winters in Europe and droughts in North America, was also recorded during this period (Bradley et al., 2003). Later, the Little Ice Age (LIA), which occurred between 1400 and 1800 AD in association with a negative temperature anomaly, was also marked by reduced insolation and high volcanic activity (Grove, 2004; Wanner et al., 2008). The LIA has been well documented in Europe and in North America, where reconstruction of paleotemperatures indicate a colder and drier climate (Bradley and Jones, 1993; von Storch et al., 2004), leading to reduction in solar activity (Maunder Minimum ~1645 – 1715 AD) (Bard et al., 2000; Shindell et al., 2001), expansion of glaciers in Europe (Wanner et al., 2000; Grove, 2004) and increased volcanic activity (Bradley and Jones, 1992). A strong latitudinal gradient was established during the LIA, with a cooled Northern hemisphere and heated tropics (Mann et al., 2009), which led to a strengthening of the trade winds and a southward shift of the Intertropical Convergence Zone (ITCZ) (van de Plassche, 2000; Goni et al., 2009; Gutiérrez et al., 2009).

Climatic variability during the MCA and LIA was small in amplitude, consisting of regional phenomena connected to the middle to high latitudes of the Northern hemisphere (Mann et al., 1998, 1999, 2009). However, the lack of data from this period has hindered global

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extensions of these climatic phenomena (Mann and Jones, 2003; Mann et al., 2003; Jones and Mann, 2004). Records of the MCA and LIA periods are still rare in South America, particularly on the Atlantic coast, in spite of the importance of this region as a connection between the North and South Atlantic, and between the Atlantic and Pacific oceans. Some paleoclimate studies that have investigated the Southern hemisphere have shown glacier advance in Patagonia (Araneda et al., 2007), variations in the precipitation regime of the high Bolivian plain (Rabatel et al., 2005) and changes in sedimentary patterns in the coastal regions of Peru (Sifeddine et al., 2008; Gutiérrez et al., 2009) and Venezuela (Haug et al., 2001; Peterson and Haug, 2006), all of which may be related to the LIA and/or MCA climatic variability.

In this study, we examined foraminifera and organic markers in sediment cores to determine changes in ocean productivity over the last 1200 years. A box-core sediment sample collected from the continental shelf was analyzed (Fig. 1) for multiple proxy data, including: grain size, total organic carbon (TOC), carbon to nitrogen atomic ratio (C/N), organic palynomorphs and planktonic foraminifera. Data were then compared to paleoclimate and paleoceanographic records that have documented global climate extremes during the MCA and LIA, which were collected from the Peru upwelling region (Gutiérrez et al., 2009), the Cariaco basin (Haug et al., 2001), the Andes glaciers area (Rabatel et al., 2008) and sea surface temperatures (SST) in the Sargasso Sea (van de Plassche et al., 1998) (Fig. 1).

2. Oceanographic settings

The Cabo Frio upwelling zone, off the southeastern coast of Brazil, is situated between two different physiographic features: a narrow continental shelf and a steep slope and predominant carbonate sedimentation to the north; and a large and deep continental shelf with a gentle slope and terrigenous sedimentation to the south (Alves and Ponzi, 1984; Mahiques et al., 2005). In this region, the southward offshore circulation is dominated by the meandering flow of the Brazil Current (BC) at 200 m (Campos et al., 2000), transporting the Tropical Water (TW, T>22 °C, S<35) in the surface layers, and South Atlantic Central Water (SACW, T<20 °C, S>36) at the level of the pycnocline (Miranda, 1985; Castro et al., 1987; Silveira et al., 2000). Near Cabo Frio the BC develops cyclonic meanders as a consequence of the change in coastline orientation (Campos et al., 2000). This meandering is located mainly on the continental slope, between 100 and 200 km from coast and 200 m depth (Silveira et al., 2000). South Atlantic Central Water is formed in the Brazil–Malvinas confluence (BMC) zone and flows within the southern subtropical gyre toward the Brazilian shelf. A portion of the SACW flows within the subsuperficial gyre between the confluence zone and the eastern Brazilian margin, reaching the Cabo Frio shelf (Stramma and England, 1999).

The predominance of northeastern trade winds, mainly during austral summer–spring, favors the Ekman transport and the upwelling of SACW onto the Cabo Frio shelf (Valentin, 1984; Rodrigues and Lorenzzetti, 2001). Seasonal changes in the wind pattern, with an enhancement in the frequency of SW winds caused by the passage of cold-fronts during winter, reduce upwelling of SACW and induce oligotrophic conditions on the shelf (Valentin et al., 1987; Campos et al., 2000). Campos et al. (2000) showed the occurrence of upwelling associated with the BC meandering in the Brazilian Southeastern coast between Cabo Frio (23°) and Cabo de Santa Marta (28°S). During the summer, with favorable NE wind, the upwelling seems to be a combination of wind-driven and shelf break induced by the BC meandering capable of bringing the SACW from the slope area to near the coast (Campos et al., 2000). During the winter, the SACW can still be found in the outer shelf due to the meander induced shelf break upwelling, however much less of it reaches the surface layers (Campos et al., 2000).

According to Sumida et al. (2005) and Yoshinaga et al. (2010) the major influence of Cabo Frio coastal upwelling over the planktonic and benthic communities was observed near the 100 m isobath (~60–80 km from the coast) during summer–winter coastal upwelling events. Yoshinaga et al. (2010) recorded high clorophyll-a concentration in the water collumn around 60 km from the coast at 70 m isobath during February and related this with a SACW upwelling event.

Seasonal migrations of the South Atlantic High (SAH) associated with the ITCZ displacement may also affect the Cabo Frio upwelling. During the austral winter, the subtropical high pressure area is more strongly developed and situated farther to the northwest. This situation intensifies SE-trades and shifts heat towards the equator. Simultaneously, NE trade winds become weaker, given the inverse relationship with the SE-trades (Johns et al., 1998). Therefore, the Atlantic annual SST anomalies may alter the mean positioning of both the ITCZ and SAH systems (Peterson and Haug, 2006), and also influence the Cabo Frio upwelling.

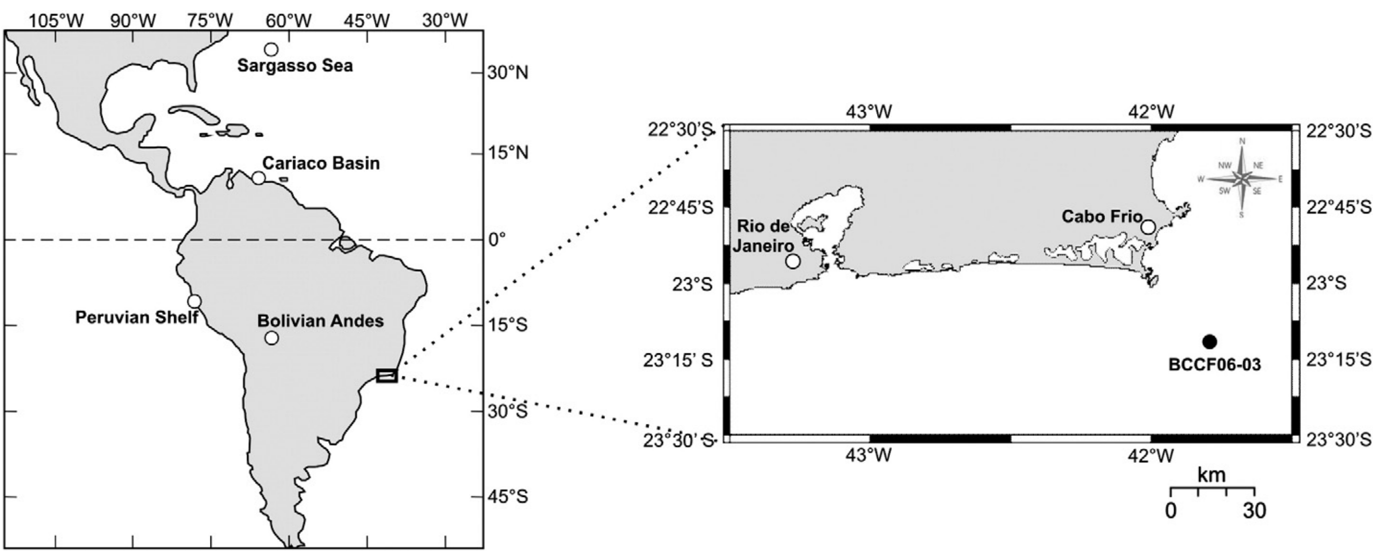

Fig. 1. Map of South America displaying the Cabo Frio upwelling paleorecord (black circle) and the other paleorecord studies discussed in the text (white circles).

Table 1
AMS radiocarbon ages of the organic matter of selected samples. Calibrated ages were calculated using a SW Atlantic reservoir effect (ΔR = 8 ± 17) according Angulo et al. (2005).

Core	Sample (cm)	Material	Code	Age 14C (AD)	Calibrated age in calendar years (2σ)		
					Minimum	cal year AD	Maximum
BCCF06-03	6–7	Organic matter	SacA9478	1311 ± 30	1720	1701	1630
	9–10	Organic matter	SacA9479	1136 ± 30	1543	1516	1494
	14–15	Organic matter	SacA9480	601 ± 30	1104	1071	1028
	21–22	Organic matter	SacA9481	421 ± 30	929	851	825

3. Materials and methods

A 22 cm box-core (BCCF06-03) was collected in 2006 from the Cabo Frio shelf (23°11′24″S, 41°47′59.9″W) at 117 m and about 28 km offshore (Fig. 1). The core was sampled at centimeter intervals by extrusion. The age model of the core was based on four organic matter AMS radiocarbon ages. Calibrated ages were calculated using the Calib 5.0.2 software (Stuiver et al., 1998), with the standard marine correction of 400 years and a regional reservoir effect of ΔR = 8 ± 17 years (Angulo et al., 2005). Calibrated ages between 2σ intervals were interpolated using linear regression and sedimentation rates were calculated for each cm along the core.

Total organic carbon and nitrogen were measured with a LECO CHN elemental analyzer, after removal of inorganic carbon with 1 N HCl. The organic petrography study was performed on kerogen fractions isolated from the carbonate and silicate phases of the sediment via the classical HCl and HF acid treatments (Durand and Nicaise, 1980). Identification and relative quantification of organic matter fractions were performed using 400x magnification transmitted light microscopy, following the Amsterdam Palynological Organic Matter Classification (Traverse, 1994). The ratio between percent abundance of marine and terrestrial palynomorphs was then calculated and expressed as Mar/Ter ratio.

Planktonic foraminifera analyses were performed on 10 cm^3 sediment samples, which were washed through a set of sieves of 500 µm, 125 µm and 63 µm mesh. Sediment samples were dried at temperatures below 50 °C. The >125 µm size fraction was separated using a gravity quarter until a minimum of 300 foraminifera individuals were picked. Tests were identified using stereomicroscopy according to previous studies (Parker, 1962; Bé, 1977; Kennett and Srinavasam, 1983).

4. Results

4.1. Age model and sedimentation rates

The BCCF06-03 core has continuously recorded the period between 850 AD up to the present (Table 1 and Fig. 2). Samples ages were linearly interpolated assuming variable sedimentation over the last 1200 yrs.

There were three major regions of varying sedimentation rates observed along the core: 0.32 mm yr^{-1} from the 22 to 15 cm (850–1070 AD), followed by decreased values of 0.11 mm yr^{-1} between 15 and 10 cm (1070–1500 AD) and 0.23 mm yr^{-1} from 10 cm to the top (1500 AD until present).

4.2. Bulk density and organic and inorganic parameters

Bulk sediment density varied between 0.80 and 1.05 g cm^{-3} throughout the core. From 850 to 1240 AD, bulk density was higher, with average values of 1 g cm^{-3}, and decreased from 1330 AD to the present. The sediment profile was muddy with a predominance of silt (59–75%).

Fluxes of TOC were higher (~0.6 mg cm^{-2} yr^{-1}) at the bottom core layer, from 850 to 1070 AD, and were reduced (~0.1 mg cm^{-2} yr^{-1}) between 1070 and 1500 AD. After 1500 AD, TOC fluxes increased, reaching 0.4 mg cm^{-2} yr^{-1} (Fig. 3). There was a narrow range of atomic C/N values along the core, varying between 6.8 and 8.6. From the core bottom, C/N decreased until the minimum value of the profile in 1070 AD. From 1070 to 1500 AD, C/N increased until 8.5 and then showed a decreasing trend until the core top, reaching values of 8.0. Amorphous organic matter, which is formed by agglomerations without defined form, predominated along the core, with an average value of 78%. Mar/Ter values ranged from 24 to 575, with peaks values in 880 AD (132), 1000 AD (186), 1580 AD (98) and at the top (575). Lower Mar/Ter values were observed between 1250 AD and 1430 AD; a gradual increase in the ratio occurred from 1500 AD to 1920 AD (Fig. 3).

4.3. Planktonic foraminifera data

Twenty-six species of planktonic foraminifera were identified, nine of which could be used as indicators of upwelling intensity. In agreement with Bé (1977), *Globigerina bulloides*, *Globigerinita glutinata* and *Turborotalita quinqueloba* are associated with low temperature and high productivity environments and represent the SACW assemblage, while *Globigerinoides ruber*, *Globoturborotalita rubescens*, *Globigerinoides sacculifer* and *Globigerinoides conglobatus* are linked to high temperature and low productivity water masses, representing the TW typical assemblage. *Neogloboquadrina dutertrei* and *Globigerina falconensis* are also present in the TW assemblage but their abundances are more controlled by productivity changes.

The total planktonic foraminiferal flux (Fig. 3) was high (13 to 23 ind cm^{-2} yr^{-1}) between 950 AD and 1040 AD, while low values, of less than 2 ind cm^{-2} yr^{-1}, were observed between 1070 AD and 1500 AD. From 1500 AD to the present, the total flux of foraminifera remained between 2 and 3 ind cm^{-2} yr^{-1} (Fig. 3). From 850 to 1070 AD, *G. bulloides*, *T. quinqueloba*, *G. ruber* and *G. sacculifer* were dominant and an increase in the abundances of *N. dutertrei* and *G. falconensis* was recorded from ca. 1040–1070 AD (Fig. 4). Species

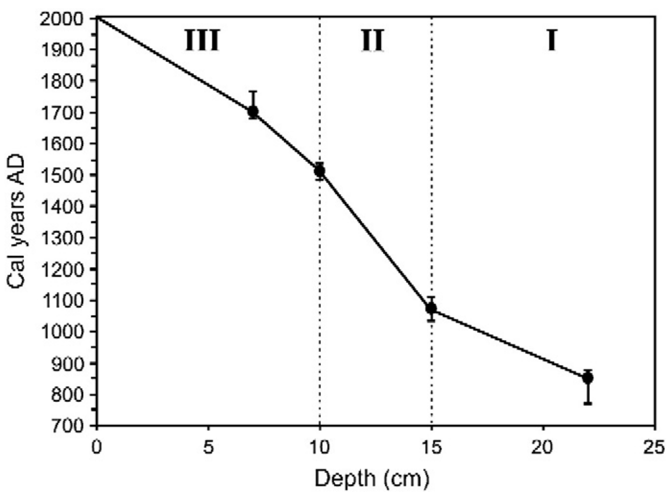

Fig. 2. Age-depth model for the Cabo Frio core based on C-14 AMS radiocarbon dating.

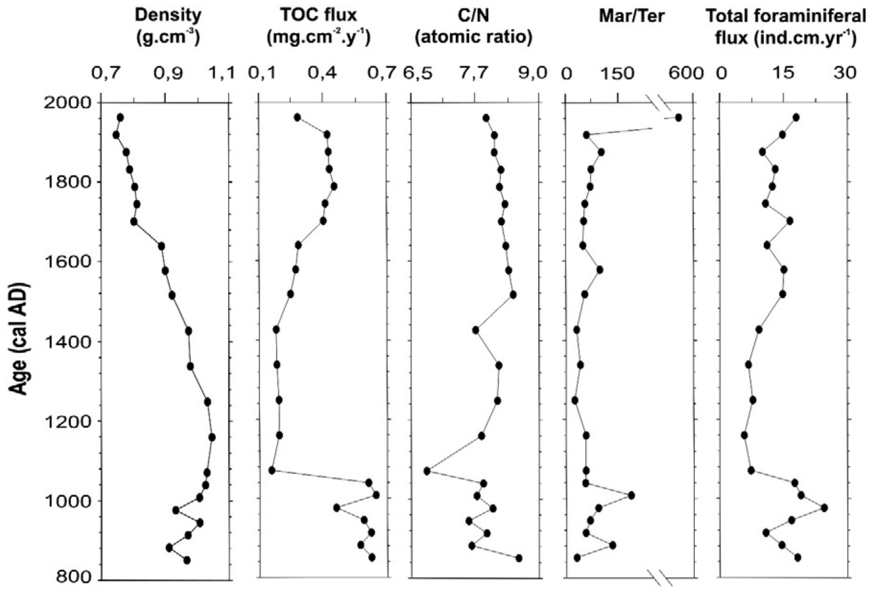

Fig. 3. Along-core variation in density, TOC flux, C/N atomic ratio, palynomorphs ratio (Mar/Ter) and total foraminiferal flux.

associated with warm and oligotrophic conditions increased in abundance between 1070 AD and 1500 AD, except for *G. ruber*, which remained constant (Fig. 4). Gradual increases in *G. bulloides* and *G. glutinata* abundances were observed after 1500 AD, as well as reductions of *T. quinqueloba* and species associated with warm and oligotrophic waters (Fig. 4).

5. Discussion

5.1. Multiproxy evidence of productivity and water masses on the Cabo Frio continental shelf

TOC, atomic C/N ratio, petrography and the assemblage of planktonic foraminifera were used as indicators of changes in water mass distribution and marine productivity.

The low total foraminiferal flux before 950 AD, associated with high abundances of *G. ruber* and *G. sacculifer*, suggest a short record of TW predominance on the Cabo Frio shelf. From 950 AD until 1070 AD, the increase in foraminiferal flux coupled with high *G. bulloides* and *T. quinqueloba* abundances indicate the presence of the SACW on the shelf (Bé, 1977). This situation may have fertilized the euphotic zone with nutrients, leading to high marine productivity and the high observed fluxes of TOC and Mar/Ter values.

The reduced TOC and planktonic foraminiferal fluxes between 1070 AD and 1500 AD reflect a low productivity period. The increase in the relative abundance of species from warm and oligotrophic waters, such as *G. conglobatus*, *G. sacculifer* and *G. rubescens*, suggest predominance of TW on the Cabo Frio shelf and weakened SACW upwelling, which would have reduced nutrient availability in the region and is consistent with reduced productivity and decreased sedimentation rates. The enhanced C/N ratio and the low Mar/Ter values throughout this period are also consistent with a decrease of phytoplanktonic production. After 1500 AD, the increased TOC flux, planktonic foraminiferal flux and Mar/Ter values indicate an intensification of marine productivity. The simultaneous increase in abundances of *G. bulloides* and *G. glutinata* mark the predominance

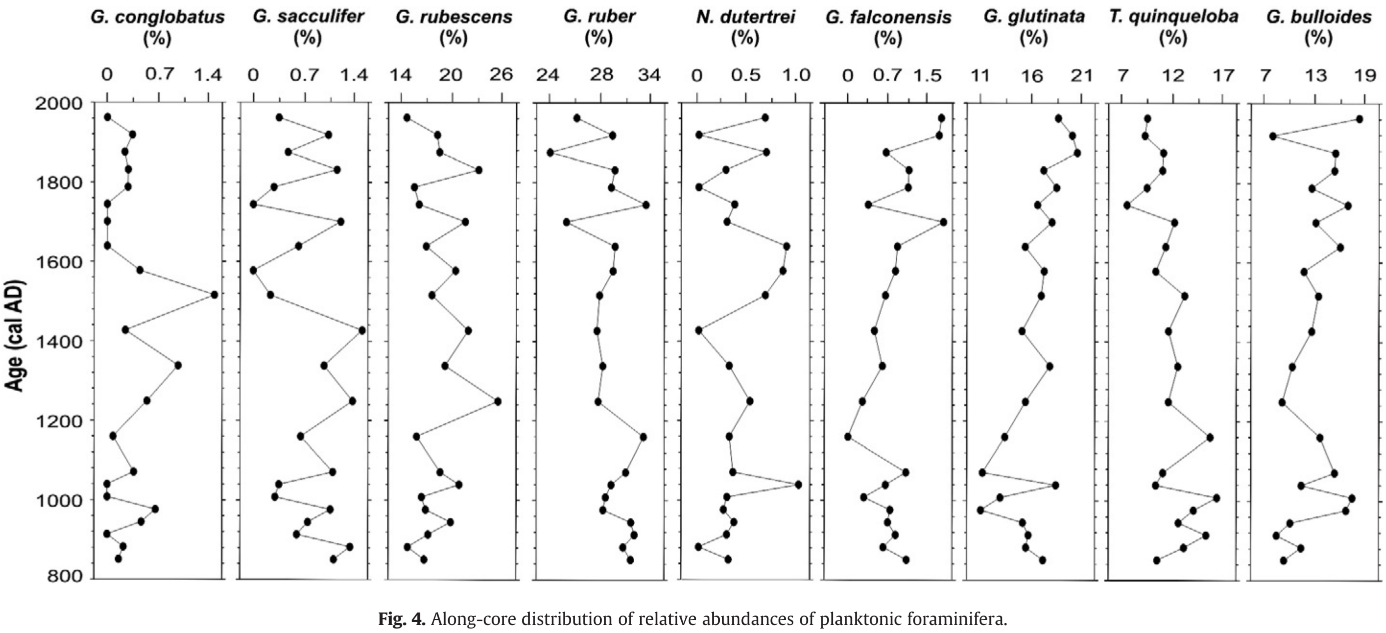

Fig. 4. Along-core distribution of relative abundances of planktonic foraminifera.

of low SSTs and high productivity conditions on the Cabo Frio shelf, consistent with enhanced upwelling intensity. The lower abundances of *G. conglobatus*, *G. sacculifer* and *G. rubescens* also indicate the prolonged presence of SACW on the shelf during this period, while increases in *N. dutertrei* and *G. falconensis* abundances are related to high productivity.

The occurrence of *T. quinqueloba*, *G. bulloides* and *G. glutinata* reflect the presence of cold waters from the SACW (Peeters et al., 2002; Kucera, 2007; Naidu, 2007), otherwise the abundance of *G. glutinata* would have varied differently from that of *T. quinqueloba* similar to that observed lower in the core (Fig. 4). Therefore, these two species seem to indicate different mechanisms that control Cabo Frio upwelling. According to Bé (1977), Hilbrecht (1996), Boltovkoy et al. (1996) and Niebler et al. (1999), *T. quinqueloba* is a very common Malvinas Current species related to low temperature conditions and water stratification. Ding et al. (2006) and Schmuker and Schiebel (2002) correlated *G. glutinata* with high productivity conditions, such as upwelling areas and on the edges of meanders and eddies. Thus, the occurrence of *T. quinqueloba* in Cabo Frio may be associated to lower temperatures due to coastal upwelling, while *G. glutinata* indicates both SACW upwelling and meandering influence on the local productivity.

Similarly to *T. quinqueloba*, *G. ruber* peaked in abundance between 850 and 940 AD and did not follow the variations of the typical TW assemblage. According to Hilbrecht (1996), *G. ruber* inhabits warm and oligotrophic waters but it is able to survive in temperatures down to 13 °C, which is equivalent to the SST on the Cabo Frio shelf when the SACW occupies the entire water column (Valentin, 1984; Gaeta et al., 1994; Franchito et al., 1998). The reduction of the mean SST in Cabo Frio may have favored *G. ruber* over other warm water species, which exhibited high abundances even when typical cold water species became more abundant.

5.2. Cabo Frio upwelling and climatic variability during the last 1200 years

The ratio between relative abundances of *G. bulloides* and *G. ruber* (Gb/Gr) has been used as an indicator of water temperature in upwelling areas, with low values representing warm temperature (weak upwelling) and high values representing cold temperature (intense upwelling) (Bé and Tolderlund, 1971; Kucera, 2007).

High productivity on the continental shelf of Cabo Frio between 940 AD and 1070 AD coincided with low temperature waters (Fig. 5A), and could be associated with regional factors, such as the formation of SACW in the Brazil–Malvinas Confluence (BMC) and its transport within the subtropical gyre to the Brazilian coast. This period is coincident with the MCA (900 – 1150 AD) (Bradley et al., 2003), when positive SST anomalies were recorded in the North Atlantic (van de Plassche, 2000) (Fig. 5C). The variation in the North Atlantic SST contributes to the displacement of the tropical and subtropical atmospheric systems of the Southern Hemisphere, such as the ITCZ and the SAH, which follow positive SST (Wainer and Venegas, 2002). In fact, the northern position of the ITCZ during the MCA led to an increase in precipitation, as recorded in sediments of the Cariaco Basin (Fig. 5D) (Peterson and Haug, 2006). This period also coincided with an interval of strong La Niña-like conditions recorded in sediments off the Peru margin (Makou et al., 2010), which may have been one of the mechanisms responsible for the intensification of the BMC because La Niña-like conditions are associated with stronger westerlies.

Because the southward position of the SAH leads to the intensification of NE trade winds (Johns et al., 1998), it is supposed that during the MCA, the displacement of the SAH to the north resulted in more intense SE-trades. Therefore, another factor must have been generated the intensification of the maintenance of lower SSTs in Cabo Frio during the MCA. According to Wainer et al. (2000) and Wainer and Venegas (2002), the position of the BMC position reflects the seasonal displacement of the SAH and Subpolar Anticyclone due to an antagonistic intensification and weakening of winds produced by these two systems. Silva et al. (1996) identified a Malvinas Current penetration plume over the S–SW Brazilian continental shelf reaching near the South Guanabara Bay (23°S, 43°W) in the austral winter of 1993, when MC was more intense. Thus, it is possible that the Malvinas Current reached Cabo Frio during 950–1070 AD and maintained low temperatures by the influence of the MC, displacement of the BMC to the north and consequent increase in SACW transport to the shelf.

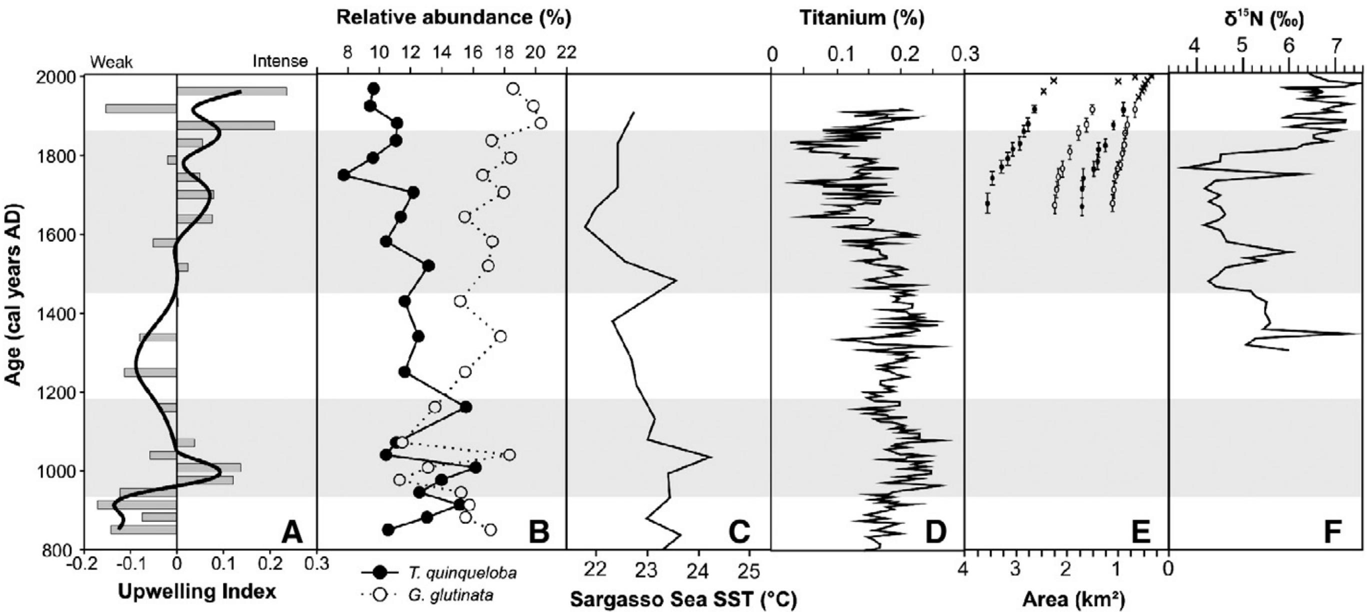

Fig. 5. Comparison between (A) Gb/Gr ratio and (B) *G. glutinata* and *T. quinqueloba* abundances over a time-series in Cabo Frio (this study) and other paleorecords: (C) Sargasso Sea SST variability reconstructed by ^{14}C (Van de Plassche, 2000); (D) Titanium concentration variability in Cariaco Basin sedimentary record as a signal of variations in regional runoff and precipitation (Haug et al., 2001); (E) variation in Bolivian Andes glacier surface area associated with changes in temperature and precipitation (Rabatel et al., 2008); (F) δ^{15}N sedimentary record in the Peruvian shelf associated to changes in oceanic circulation and sediment biogeochemistry (Gutiérrez et al., 2009). Gray bars indicate the MCA (900–1150 AD) and LIA (1400–1800 AD).

The following period of low productivity and TW predominance in Cabo Frio (1070–1500 AD) was probably driven by a weakening of the SACW transport (Fig. 5A and B). This period is coincident with a gradual decrease in North Atlantic SST (Fig. 5C), which was responsible for maintaining the northward position of the ITCZ and the reduced NE-trades. SAH and BMC thus migrated southward, weakening the SACW transport, reducing the Cabo Frio upwelling.

From 1500 to 1830 AD, a re-intensification of the Cabo Frio upwelling occurred (Fig. 5A). High foraminiferal flux, especially the higher abundances of *N. dutertrei* and *G. falconensis* during the beginning of this period, suggest a gradual increase of upwelling intensity as these subtropical species do not tolerate very low temperatures. Increased *G. bulloides* and *G. glutinata* abundances and the reduction of *T. quinqueloba* during this period (Fig. 5A and B) indicate that upwelling re-intensification was more linked to regional atmospheric factors. Indeed, a cooling of the North Atlantic occurred during the LIA (Fig. 5C), leading to a southward displacement of the ITCZ, as recorded by increased glacier area in the Bolivian Andes (Rabatel et al., 2008; Vuille et al., 2008) and weakened upwelling in Peru (Gutiérrez et al., 2009) (Fig. 5E and F). The southward shift of the ITCZ shift associated with the intensification and southern positioning of the SAH could have intensified the NE winds over Cabo Frio and consequently induced upwelling. A strengthening of the Cabo Frio upwelling in the last 700 years was also reported by Mahiques et al. (2005) using SSTs reconstructed by alkenones which, similarly, attributed to intensification of atmospheric systems; however they found discrepancy among the cores. Probably this discrepancy was caused by easy scattering of cocolitophore settling, since they belong to the nanoplankton. Yet, estimated SST range were in general above 22 °C, while present annual SSTs in Cabo Frio are 21 °C in average (Valentin, 1984; Yoshinaga et al., 2010), suggesting the BC could have brought the most of cocolitophore from north.

6. Summary

Over the last 1200 years, three periods of different ocean productivity characteristics associated with changes in upwelling were identified on the continental shelf of Cabo Frio. The first change occurred in 1070 AD, when high productivity, resulting from intense transport of SACW to the southwestern Brazilian margin, was replaced by low productivity conditions by virtue of the reduced influence of northeastern winds and the offshore Ekman transport. The period between 1070 and 1500 AD was characterized by the predominance of the TW foraminifera assemblage, related to low organic deposition. After 1500 AD, high productivity conditions prevailed on the Cabo Frio shelf due to an intensification of the upwelling associated with the migration of the SAH to the region in response to reduced Northern Atlantic SST and migration of the ITCZ to the south during the LIA.

This study also demonstrated that regional scale climatic variations occurred throughout the last millennium and were recorded by the Cabo Frio upwelling system. The influence of the variability of the BMC on the Cabo Frio upwelling system during the MCA was also considered; however, more paleoceanographic research in the western tropical Atlantic, especially from the BMC, is required to provide a better understanding of the controls of Cabo Frio upwelling. Paleotemperature and paleosalinity reconstructions for the Cabo Frio area are also required to further evaluate the effects of the South Atlantic Convergence Zone on the region.

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