



Sea-surface temperature reconstruction of the Quaternary western South Atlantic: New planktonic foraminiferal correlation function

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ABSTRACT

We provide a new multivariate calibration-function based on South Atlantic modern assemblages of planktonic foraminifera and atlas water column parameters from the Antarctic Circumpolar Current to the Subtropical Gyre and tropical warm waters (i.e., 60°S to 0°S). Therefore, we used a dataset with the abundance pattern of 35 taxonomic groups of planktonic foraminifera in 141 surface sediment samples. Five factors were taken into consideration for the analysis, which account for 93% of the total variance of the original data representing the regional main oceanographic fronts. The new calibration-function F141-35-5 enables the reconstruction of Late Quaternary summer and winter sea-surface temperatures with a statistical error of ~0.5°C. Our function was verified by its application to a sediment core extracted from the western South Atlantic. The downcore reconstruction shows negative anomalies in sea-surface temperatures during the early–mid Holocene and temperatures within the range of modern values during the late Holocene. This pattern is consistent with available reconstructions.

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1. Introduction

The study of environmental changes throughout the geologic time requires consideration of biotic (e.g. species, populations, communities, biotic interactions), as well as of abiotic components (e.g. climate, water chemistry, water temperature and depth). When the abiotic components of past ecosystems can be reconstructed based on the analysis of fossil biotic components, the latter can be regarded as variables of a set of predictive functions within the past ecological system under investigation (Birks et al., 2010). In this sense, the development of quantitative techniques for inferring past environmental variables from multi-proxy studies enables the direct analysis of the biotic response in the face of environmental changes over a range of time scales in the past (Birks and Birks, 2006). In paleoceanography, the first studies that reconstructed abiotic components based on the analysis of the biotic components of the fossil record were the ones that related planktonic foraminifera with sea surface temperature (SST; e.g. Ericson, 1959; Boltovskoy, 1966; Bé, 1977) through the Indicator-Species Approach

(Birks et al., 2010). This method emphasized on the dominance, relative abundance and changes in the morphology of certain species (Murray, 1897; Ericson, 1959; Boltovskoy et al., 1996; Kohfeld et al., 1996). Such is the case of *Neogloboquadrina pachyderma*, whose sinistral morphotype has been associated to waters with temperatures lower than 9°C (e.g., Ericson, 1959; Bé, 1977; Boltovskoy et al., 1996; Niebler and Gersonde, 1998). However, the real breakthrough in the field came with the development of the transfer function of Imbrie and Kipp (1971), currently known as the Multivariate Calibration-Function (Birks et al., 2010).

The base of quantitative reconstructions that involves multivariate calibration-functions relies on the assumption that there are one or more environmental variables to be reconstructed from the fossil biotic assemblage, and that this reconstruction needs a numerical modeling of modern taxa responses in relation to modern environmental variables. As a consequence, the reconstruction requires a ‘calibration dataset’ of taxa from modern sediment samples with associated modern environmental variables. Once this relationship is modeled, a calibration function, resultant from a regression analysis, is used to transform the fossil data into quantitative estimates of the past climate variable (Birks et al., 2010). In particular, the Imbrie and Kipp Method (IKM; Imbrie and Kipp, 1971) uses the factor analysis (Q mode) to explain the existing variance within the modern taxa of a particular group from a smaller number of variables, which are linear combinations from the original ones. After that, as a result of a multiple regression

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between these variables and the known environmental parameters, the calibration function is obtained. This method has been applied to planktonic foraminifera in multiple studies throughout all ocean basins (e.g., Kipp, 1976; Bé and Hutson, 1977; Howard and Prell, 1984; McIntyre et al., 1989; Dowsett and Poore, 1991; Niebler and Gersonde, 1998; Kucera et al., 2005b). The first global quantitative reconstruction of SST was developed by the CLIMAP project (Climate: Long-Range Investigation, Mapping and Prediction, 1981, 1984) for the Last Glacial Maximum and Last Interglacial Climatic Optimum. Since then, several authors applied it, not only on planktonic foraminifera (e.g., Pflaumann, 1985; Prell, 1985; Mix et al., 1986; Labracherie et al., 1989; Bard et al., 1990; Howard and Prell, 1992; Labeyrie et al., 1996; Pflaumann et al., 1996; Niebler and Gersonde, 1998; Kucera et al., 2005b; Toledo et al., 2007), but also on calcareous nannoplankton, radiolarians and diatoms (e.g., Molfino et al., 1982; Pichon et al., 1987, 1992; Zielinski and Gersonde, 1997) in order to reconstruct hydrographic conditions of different ocean basins within the Quaternary.

Among all the used proxies in paleoceanography, planktonic foraminifera represent one of the best tools for the reconstruction of past surface water properties due to their (i) biogeographic distribution following global surface water temperature, (ii) widespread distribution, and (iii) high fossilization potential (Bé and Tolderlund, 1971; Bé, 1977). Here, our purpose is to develop a new foraminiferal multivariate calibration-function for the reconstruction of South Atlantic SST during the Late Quaternary, with particular focus in the western South Atlantic. In order to test the performance of our function, we applied it to the planktonic foraminiferal assemblages of a Holocene marine sediment core from the western South Atlantic, namely core GeoB2806-4. Its temporal resolution and strategic location under the influence of two of the most important oceanographic fronts of the South Atlantic, the Subtropical and Subantarctic fronts, make it an exceptionally sensitive site for SST changes due to the latitudinal shifts of the fronts.

2. Modern oceanographic setting

The South Atlantic Ocean plays an essential role in the thermohaline circulation and the distribution of water masses to other basins, making it an important region for interhemispheric heat and nutrient exchange (Berger and Wefer, 1996). It is strongly influenced by the Antarctic Circumpolar Current, which represents the most important connection in global oceanic circulation (Garrison, 2008). The South Atlantic is dominated by a system of oceanographic fronts that results in three zones of relatively uniform water properties: the Subtropical Front Zone, the Subantarctic Front Zone and the Antarctic Polar Front Zone (Fig. 1). The Subtropical Front represents the southern boundary of the anticyclonic Subtropical Gyre and separates the gyre circulation from the Subtropical Zone (Peterson and Stramma, 1991). The eastern boundary current of the Subtropical Gyre is the Benguela Current which is characterized by strong upwelling (e.g., Lutjeharms and Meeuwis, 1987; Lutjeharms and Valentine, 1987; Shannon et al., 1990). The western boundary of the gyre is formed by the Brazil Current, which transports tropical warm and salty waters towards the south (Piola and Matano, 2001). The Subtropical Zone is characterized by warm, salty and nutrient poor waters. Its southern boundary is determined by the Subantarctic Front, characterized by an abrupt decline in salinity and temperature of surface waters, defining the Subantarctic Zone. Finally, the Antarctic Polar Zone is delimited by the Antarctic Polar Front to the north and the Antarctic continent to the south (Fig. 1). This zone is characterized by the dominance of waters with very high nutrient content and SST lower than 10°C, as well as by the seasonal formation of sea-ice. Here, the Antarctic Intermediate Water is formed by sinking along the Antarctic Polar Front, being the most extensive intermediate depth water mass in the world ocean (Gordon, 1981).

The western sector of the South Atlantic presents a highly dynamic frontal zone: the Brazil–Malvinas Confluence, bounded by two highly energetic surface western boundary currents, the warm Brazil Current

and the cold Malvinas–Falkland Current (Gordon, 1981; Peterson and Stramma, 1991; Stramma and England, 1999) (Fig. 1). The Brazil Current originates in the bifurcation of the South Equatorial Current at ~15°S. It carries warm and salty waters along the continental slope of South America towards the south. The Brazil Current encounters the Malvinas Current between ~35°S and 39°S. The Malvinas Current carries cold and well oxygenated waters of subantarctic origin towards the Equator (Piola and Gordon, 1989). It represents the septentrional branch of the Antarctic Circumpolar Current, flowing northwards along the Argentinean continental margin. The encounter of these currents generates sharp horizontal and vertical gradients in temperature, salinity, density and nutrient content (Gordon, 1989; Peterson and Stramma, 1991; Bianchi et al., 1993; Wilson and Rees, 2000; Piola and Matano, 2001). The interaction of these currents dominates the oceanographic circulation system between ~29°S and 49°S (Peterson and Stramma, 1991; Stramma and England, 1999), making the western South Atlantic a natural target of several oceanographic and paleoceanographic studies (e.g. Gordon, 1981; Peterson and Stramma, 1991; Boltovskoy et al., 1996; Stramma and England, 1999; Piola and Matano, 2001; Henrich et al., 2003; Chiessi et al., 2007; Toledo et al., 2007, 2008; Laprida et al., 2011; Chiessi et al., 2014).

3. Modern distribution of planktonic foraminifera in the South Atlantic

The distribution of planktonic foraminifera mainly responds to SST, as a consequence five biogeographic provinces have been characterized: Tropical, Subtropical, Transitional, Subpolar and Polar (Boltovskoy, 1966; Bé, 1969; Bé and Tolderlund, 1971; Bé, 1977; Kucera, 2007). Even though most species are cosmopolitan, in the South Atlantic they present certain preference to specific SST. *Globigerinoides sacculifer*, *Globorotalia menardii*, *Globorotalia tumida*, *Globigerinoides ruber* pink, *Globigerinoides trilobus*, *Pulleniatina obliquiloculata*, *Sphaeroidinella dehiscens*, *Globoquadrina conglobata*, *Globigerinella adamsi* and *Globigerina hexagona* are defined as tropical species. *G. ruber* white, *Globigerinella siphonifera*, *Globorotalia truncatulinoides*, *Globigerina falconensis*, *Globorotalia hirsuta*, *Globoturborotalita rubescens*, *Globigerinoides conglobatus*, *Hastigerina pelagica*, *Globoturborotalita tenella*, *Globigerinella calida*, *Beella digitata* and *Candeina nitida* are defined as subtropical species from oligotrophic waters; whereas *Neogloboquadrina dutertrei* and *Orbulina universa* are considered subtropical species found associated to upwelling areas in the vicinity of continental margins (Bé and Tolderlund, 1971). However, some species occur in more than one province (cf. Kucera, 2007). Such is the case of *G. menardii* (s.l.), which was also found near the Brazil–Malvinas Confluence (Boltovskoy, 1970, 1976); or *G. truncatulinoides* and *Globorotalia scitula*, species initially associated to cold waters (Boltovskoy, 1966; Bé, 1969), but which are actually deep dwelling species that calcify at depths higher than 250–500 m (Bé, 1969; Niebler et al., 1999).

In transitional waters, where warm and cold waters overlap, there is a strong contrast of fauna where very different planktonic foraminiferal assemblages can be found (Bé and Tolderlund, 1971). The dominance of *Globorotalia inflata* results an excellent indicator of transitional waters such as the Brazil–Malvinas Confluence (Boltovskoy, 1966), populating waters with SSTs between 13°C and 19°C. Transitional waters in this part of the South Atlantic are dominated by *Globorotalia inflata*, *Globigerina bulloides* and *N. pachyderma*, and *Globigerina sacculifer* to the north of the Confluence (Boltovskoy, 1966; Bé and Tolderlund, 1971). In polar waters sinistral *N. pachyderma* represents >90% of the total assemblage (Niebler and Gersonde, 1998), whereas dextral *N. pachyderma*, *Turborotalita quinqueloba*, *G. bulloides*, *G. scitula*, *G. truncatulinoides*, *Neogloboquadrina incompta*, *Globigerinita glutinata* and *Globigerinita uvula* are rather related to subpolar waters (Boltovskoy, 1966, 1976; Bé, 1969; Bé and Tolderlund, 1971; Kucera, 2007).

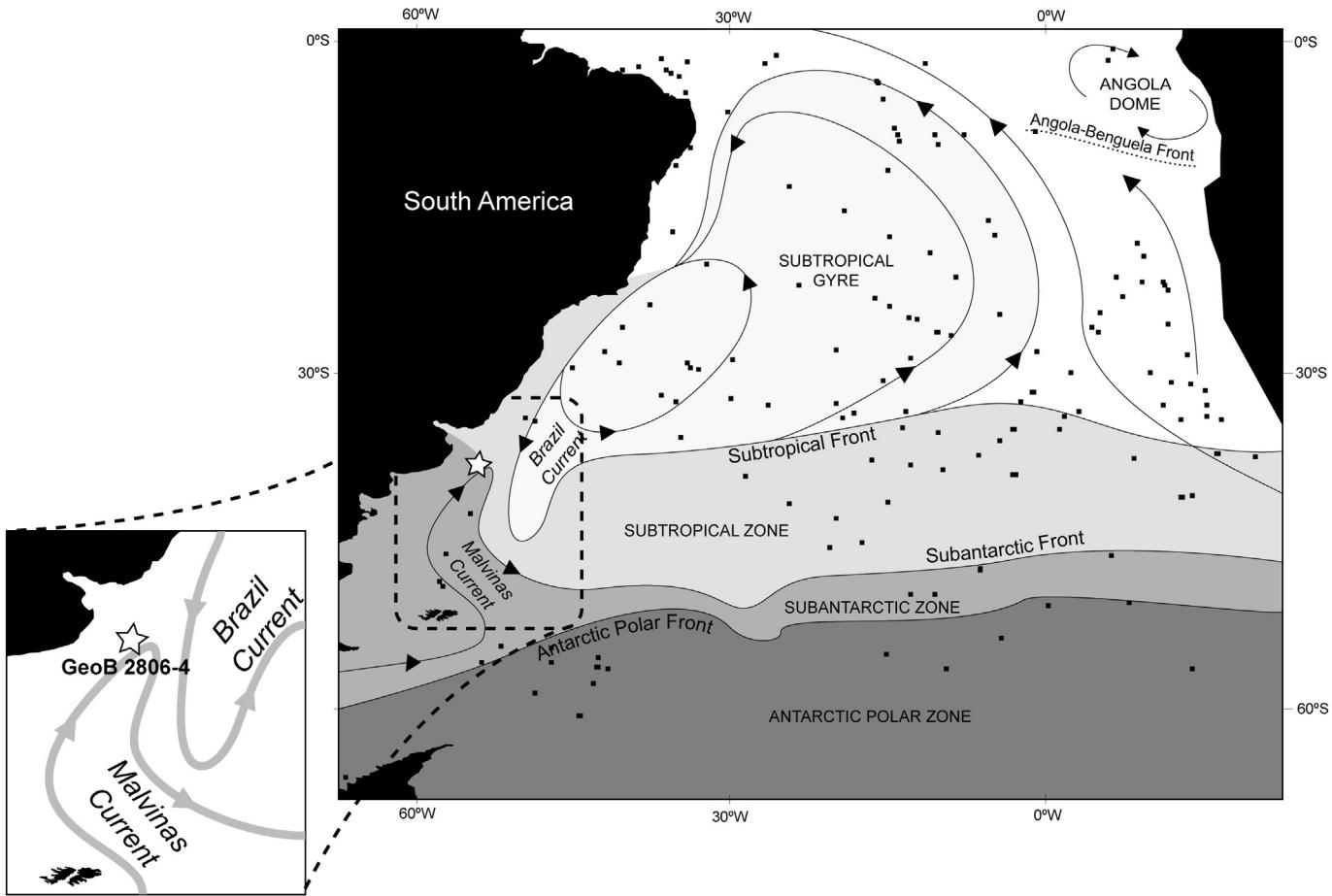


Fig. 1. Main oceanographic fronts and surface currents of the South Atlantic Ocean after Peterson and Stramma (1991); Stramma and England (1999). Black dots represent the top cores used in the calibration dataset. Location map of core GeoB2806-4 within the western South Atlantic.

4. Material and methods

4.1. The calibration data set

A total of 141 surface sediment samples from the Brown University Foraminiferal Data Base (Prell et al., 1999) were used as calibration dataset to calculate the present calibration function. The ages of the samples range from 0 to 4 cal kyr BP in accordance with the criteria defined in the MARGO Project (Kucera et al., 2005a). The corresponding SST for each surface sample site was obtained from Reynolds and Smith (1995), defined as the temperature at 10 m water depth (Kucera et al., 2005a) and was calculated as the mean temperature of the three colder and warmer months for Southern Hemisphere winter and summer, respectively. The selected samples range between 0°S and 56°S, covering the whole South Atlantic and the Atlantic sector of the Southern Ocean. This ensures the representation of the entire SST ecological ranges where the species of planktonic foraminifera occur (Kucera et al., 2005b). Samples from the North Atlantic Ocean were excluded because they are associated to different oceanographic features not necessarily present in the South Atlantic.

To facilitate the statistical analysis, *G. menardii* s.l., *G. tumida*, *G. menardii* var. *ungulata* and *G. menardii* var. *flexuosa* were combined into the *G. menardii* (complex) group as these species have similar biogeographic distribution (CLIMAP, 1981, 1984; Dowsett and Poore, 1991; Pflaumann et al., 1996; Kucera et al., 2005b). The identification of the intergrades between *N. dutertrei* and *N. pachyderma* was as precise as possible, and species that occurred at abundances below 2% were removed from the analysis (Imbrie and Kipp, 1971).

4.2. Calibration function

The calibration function was performed using CABFAC software (Klovan and Imbrie, 1971) according to the statistical method developed by Imbrie and Kipp (1971). It consists in two steps: first, a Q-mode factor analysis which combines a large number of planktonic foraminiferal species (original variables) into a smaller number of variables (factors) reducing the data dimensionality. The species scores explain their importance in each factor; meanwhile the factor loadings explain the importance of the individual factors in each sample. Species scores >0.6 were considered significant and the communality coefficient of the factor loadings was used as a measure of how much of the variance of the original variables is reproduced by the factors of the model. The second step consists in a multiple regression that relates the factor loadings to modern SSTs, resulting in a regression equation that can be applied to the geological record to reconstruct past SSTs. The regression error was obtained by cross-validation.

4.3. Core faunal analyses and paleo-SST estimation

Sediment core GeoB2806-4 (37°50'S-53°08.6'W/870 cm long/3500 m water depth) was collected at a water depth of 3500 m during RV Meteor cruise M29/2 (University of Bremen, Germany) from the Argentine continental margin (Bleil et al., 1994). The core site is located at the transition from the Necochea terrace to the so call "transitional zone with turbiditic deposits" close to the base of the slope (Preu et al., 2013), 500–700 m above the modern western South Atlantic lysocline

(Johnson et al., 1982; Shor et al., 1982; Bickert and Wefer, 1996) and within the Brazil–Malvinas Confluence zone (Fig. 1; Arhan et al., 2002, 2003). It consists mainly of mud, with moderate evidences of bioturbation between 70 cm and 150 cm (Bleil et al., 1994).

The core was subsampled every 10 cm except for the first 50 cm, where it was subsampled every 5 cm. Samples were prepared according to classic micropaleontological methods: wet sieved with warm tap water over a 63 µm sieve and dried in oven at 50°C; foraminiferal specimens were hand-picked, sorted, identified and glued to 60-square micropaleontological slides. Only planktonic foraminifera from the >150 µm fraction were considered in SST reconstruction analyses in order to be consistent with the calibration dataset (Pflaumann et al., 1996; Kucera et al., 2005b; Kucera, 2007). Faunal identification followed the criteria of Loeblich and Tappan (1988), Kennett and Srinivasan (1983), Saito et al. (1981), and Kemle-Von Mücke and Hemleben (1999). Because the two different morphotypes of *N. pachyderma* (sinistral and dextral) and *G. ruber* (pink and white) have different geographic distributions and paleoenvironmental implications (Bé and Tolderlund, 1971; Boltovskoy et al., 1996), these species were split into the two forms for identification. The species belonging to the *G. menardii* (complex) group were analyzed as one taxonomic group as in the calibration dataset. For each core sample, SST estimates for winter and summer were calculated using the calibration function developed in this study.

4.4. Age model

Dating of sediment core GeoB 2806-4 was performed by five AMS-¹⁴C measurements on monospecific samples of planktonic foraminifera *G. inflata* (>150 µm fraction) (Table 1, University of Arizona and Beta Analytic Inc. Laboratory, United States). The radiocarbon dates were calibrated with the Calib 7.0.2 (Stuiver and Reimer, 1993) by applying the Marine13 calibration curve (Reimer et al., 2013) and no ΔR. We considered linear interpolation between dated depths. All ages are given in calibrated thousands of years before present (kyr BP). A detailed interpretation of this data is in preparation and will be published elsewhere.

5. Results and discussion

5.1. Factor analyses

A Q-mode factor analysis of the selected dataset was performed. The first five factors explain 93% of the total variance and, in consequence, most of the planktonic foraminiferal distribution in the South Atlantic. We obtained communality coefficients >0.7 for most of the 141 analyzed samples, with the exception of four sites for which coefficients were >0.58. The geographic distribution of the factor loadings reflects the present spatial pattern of surface oceanographic fronts of the South Atlantic (Fig. 2). Factor 1 was defined as the Tropical Factor, Factor 2 as the Subtropical Factor, Factor 3 as the Polar Factor, Factor 4 as the Subpolar Factor and Factor 5 as a Marginal Gyre Factor. The factor scores for all species used in the calibration dataset are listed in Table 2.

Table 1
Radiocarbon datings and respective calendar ages for core GeoB2806-4.

| Sample depth (cm) | Analyzed species | ¹⁴ C age | Error (¹⁴ C age) | Calendar age | Error (2σ) (Calendar age) | Laboratory |
|-------------------|-----------------------------|---------------------|------------------------------|--------------|---------------------------|-----------------------|
| 13 | <i>Globorotalia inflata</i> | 1640 | 30 | 1202.5 | 71.5 | University of Arizona |
| 88 | <i>Globorotalia inflata</i> | 4000 | 30 | 4006.5 | 108.5 | Beta Analytics |
| 138 | <i>Globorotalia inflata</i> | 5520 | 30 | 5908 | 82 | Beta Analytics |
| 228 | <i>Globorotalia inflata</i> | 8739 | 56 | 9395.5 | 115.5 | University of Arizona |
| 308 | <i>Globorotalia inflata</i> | 10,960 | 40 | 12,506 | 126 | Beta Analytics |

5.1.1. F1: Tropical Factor

Factor 1 explains 38% of the total variance being defined by *G. ruber*, *G. sacculifer*, *G. glutinata* and *G. menardii* (Table 2). This factor is related to annual SSTs between 16° and 29 °C corresponding to the region north of the Subtropical Front (Fig. 2), where the Subtropical Gyre controls surface circulation.

5.1.2. F2: Subtropical Factor

Explaining 32% of the total variance, the Subtropical Factor is mainly characterized by *G. inflata*, followed by *G. falconensis*, *N. pachyderma* (dextral), *G. bulloides* and *G. truncatulinoides* (Table 2). It is characterized by annual surface water temperatures between 15° and 20°C, being the factor with the largest geographic extension. It covers the transitional waters between the Subantarctic and the Subtropical Front, partially including the Benguela upwelling (Fig. 2).

5.1.3. F3: Polar Factor

Defined mostly by *N. pachyderma* (sinistral) and a low contribution of *G. bulloides*, this factor explains 13% of the total variance. It dominates the region where summer SST does not reach 10°C, including the Subantarctic and the Antarctic Polar Fronts (Fig. 2).

5.1.4. F4: Subpolar Factor

This factor explains 6% of the total variance being characterized by surface temperatures around 20°C. It is defined by *N. pachyderma* (dextral) and *G. bulloides*, species that usually present high percentages between the Subpolar and the Subtropical Fronts (Fig. 2).

5.1.5. F5: Marginal Gyre Factor

Explaining only 4% of the total variance, Factor 5 represents almost exclusively the region of the Angola–Benguela Front (Fig. 1 and 2). It is defined by high scores of *G. sacculifer*, *G. inflata*, *Pulleniatina obliquiloculata* and *N. dutertrei*, and practically no contribution of *G. falconensis* and *G. bulloides*. Even though this factor is related to rather local oceanographic conditions, such as localized upwelling, we decided to include it in the calibration function given that the accuracy of a model with the chosen number of species and a low number of factors loses too much of the original information.

5.2. Calibration function

A multiple regression between the foraminiferal assemblage distributions described by the factor analysis and the modern SST from Reynolds and Smith (1995) dataset was performed in order to establish a calibration function that could be used for the reconstruction of past SSTs. Estimated values for each of the individual surface sediment sample were obtained from the calibration function. Regression between measured and estimated SST values evidenced multiple correlation coefficients of $r = 0.98$ for summer and $r = 0.97$ for winter (Fig. 3). The standard deviation for the estimated summer SSTs was $\sigma = 0.52^\circ\text{C}$, whereas for the estimated winter SST was $\sigma = 0.58^\circ\text{C}$. Temperature residuals between measured and estimated SST did not reflect any particular pattern (Fig. 4) showing a standard deviation of $\sigma = 0.95$ for summer SST and of $\sigma = 1.1$ for winter SST (Table 3). Positive residuals indicate an underestimation of summer SST and negative residuals indicate an overestimation.

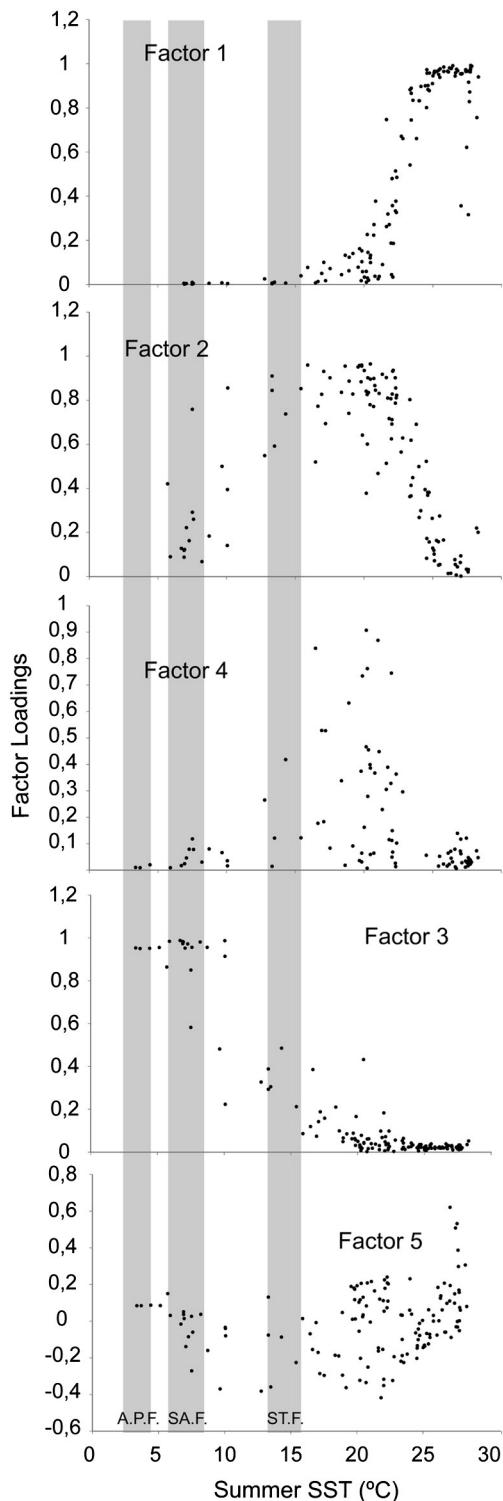


Fig. 2. Relationship between principal component loadings and summer SST (data from Reynolds and Smith, 1995). The oceanographic fronts are represented by gray areas, being the abbreviations: ST.F.: Subtropical Front, S.A.F.: Subantarctic Front, A.P.F.: Antarctic Polar Front. Factor 1: Tropical Factor, Factor 2: Subtropical Factor, Factor 3: Polar Factor, Factor 4: Subpolar Factor, Factor 5: Marginal Gyre Factor.

The accuracy of our calibration function lies within the range of the previous transfer function based on planktonic foraminifera for the South Atlantic. When we compare it with the transfer function developed by Niebler and Gersonde (1998), which only reconstructs summer SST, the F141-35-5 presents a similar multiple regression coefficient ($r = 0.98$ vs. $r = 0.99$), but a lower standard deviation ($\sigma = 0.52$ vs.

Table 2

Foraminiferal assemblages shown by the five varimax-rotated Q-mode principal component scores. Bold numbers correspond to those significant scores.

| Species | F1 | F2 | F3 | F4 | F5 | |
|---|---------------|---------------|---------------|---------------|---------------|--------|
| <i>O. universa</i> | 0.1581 | 0.1051 | -0.028 | 0.1145 | 0.1285 | |
| <i>G. conglobatus</i> | 0.1805 | 0.0054 | -0.0038 | -0.0419 | -0.103 | |
| <i>G. ruber</i> | 5.5572 | -0.3244 | 0.0437 | 0.2072 | -0.8552 | |
| <i>G. tenella</i> | 0.2333 | 0.0501 | -0.0171 | -0.0871 | -0.1464 | |
| <i>G. sacculifer</i> | 1.5172 | -0.086 | 0.1414 | 0.123 | 2.6106 | |
| <i>S. dehiscens</i> | 0.0189 | 0.021 | -0.0023 | -0.0291 | 0.0615 | |
| <i>G. adamsi</i> | 0.0009 | -0.0003 | 0 | 0.0001 | -0.0015 | |
| <i>G. siphonifera</i> | 0.4911 | 0.1074 | -0.0136 | -0.0924 | 0.2867 | |
| <i>G. calida</i> | 0.2763 | 0.1549 | -0.035 | -0.1055 | -0.0024 | |
| <i>G. bulloides</i> | -0.0132 | 1.2598 | 1.7287 | 0.8596 | -2.9043 | |
| <i>G. falconensis</i> | 0.4998 | 1.6849 | -0.4056 | -1.2699 | -2.7338 | |
| <i>G. digitata</i> | 0.0809 | 0.0437 | -0.0127 | -0.0249 | 0.0251 | |
| <i>G. rubescens</i> | 0.1624 | -0.0019 | 0.0007 | -0.0195 | -0.0546 | |
| <i>G. quinqueloba</i> | -0.0165 | 0.0819 | 0.2943 | 0.1419 | -0.2931 | |
| <i>N. pachyderma</i> (left) | -0.0666 | -0.3671 | 5.7052 | -0.2752 | 5.5784 | -0.007 |
| <i>N. pachyderma</i> (right) | -0.0332 | 1.5243 | -0.2752 | 5.5784 | -0.007 | |
| <i>N. dutertrei</i> | 0.2429 | 0.5102 | 0.009 | 0.4411 | 1.2847 | |
| <i>G. conglomerata</i> | 0.0012 | -0.0002 | 0.0002 | 0.0003 | 0.0037 | |
| <i>G. hexagona</i> | 0.0019 | 0.0014 | 0.0008 | 0.0019 | -0.0027 | |
| <i>P. obliquiloculata</i> | 0.24 | -0.0022 | 0.0585 | 0.0486 | 1.2887 | |
| <i>G. inflata</i> | 0.0086 | 5.246 | 0.2009 | -1.3332 | 1.6319 | |
| <i>G. truncatulinoides</i> (left) | 0.0987 | 0.7422 | 0.0459 | -0.248 | -1.0088 | |
| <i>G. truncatulinoides</i> (right) | 0.4126 | 0.3697 | -0.0985 | -0.4141 | -0.1756 | |
| <i>G. crassaformis</i> | 0.0649 | 0.0279 | 0.0039 | 0.0024 | 0.1738 | |
| <i>G. crassula</i> | 0 | 0.0007 | -0.0003 | -0.0006 | -0.0017 | |
| <i>G. hirsuta</i> | 0.1669 | 0.4649 | -0.1287 | -0.1778 | -0.2412 | |
| <i>G. scitula</i> | 0.162 | 0.3042 | -0.0921 | -0.3183 | -0.3636 | |
| <i>G. anfracta</i> | 0.0013 | -0.0003 | 0.0001 | 0.0003 | 0.0006 | |
| <i>G. menardii</i> | 0.6112 | 0.0505 | 0.0796 | 0.0548 | 2.0898 | |
| <i>G. tumida</i> | 0.1437 | 0.0091 | 0.0238 | 0.0073 | 0.6002 | |
| <i>G. menardii</i> var. <i>flexuosa</i> | 0.004 | -0.0017 | 0.0004 | 0.0019 | -0.0002 | |
| <i>C. nitida</i> | 0.0422 | -0.0133 | 0.0018 | 0.0087 | -0.0323 | |
| <i>G. glutinata</i> | 1.1531 | 0.3759 | 0.1449 | -0.2408 | 0.2625 | |
| <i>G. theyeri</i> | 0.0035 | -0.0012 | 0.0004 | 0.0016 | 0.0021 | |
| <i>G. iota</i> | 0.0008 | 0.0018 | -0.0001 | 0.0005 | -0.0042 | |
| Others | 0.1269 | 0.1494 | 0.0419 | -0.0522 | 0.0607 | |
| Variance (%) | 38 | 32 | 13 | 6 | 4 | |
| Cumulative variance (%) | 38 | 70 | 83 | 89 | 93 | |

$\sigma = 1.26^{\circ}\text{C}$). This evidences that the selected model is robust enough to be used as a tool to estimate summer, and winter, Quaternary SST in the whole South Atlantic Ocean.

5.3. Application of the calibration function to core GeoB2806-4

Below 308 cm core depth, foraminifers were present in insufficient amount for statistical treatment or were completely absent. A total of 3031 planktonic foraminifera were recovered and 31 species identified. In most samples, the proportion of unidentified individuals mainly due to early ontogenetic stages was <5%.

The upper 300 cm of core GeoB2806-4 covers the last 12.5 cal kyr BP (Table 1). The application of the calibration function F141-35-5 yielded SSTs within the range of modern temperatures in the region (Levitus and Boyer, 1994) during the mid-late Holocene, but pronounced anomalies during the early Holocene prior to 8 cal kyr BP. At ~11.7 cal kyr BP, negative (summer and winter) SST anomalies of $\sim 5^{\circ}\text{C}$ were recorded, being coeval with the Northern Hemisphere Younger Dryas; whereas around 8.2 cal kyr BP, SSTs were $\sim 4^{\circ}\text{C}$ colder (Fig. 5). Then, during the last 8000 years, SST anomalies were lower than 2°C . Summer SST values oscillated between $\sim 15^{\circ}\text{C}$ and 19°C , with a mean value of $\sim 17^{\circ}\text{C}$, and winter SST values varied between $\sim 10^{\circ}\text{C}$ and 14°C , with a mean value of $\sim 12^{\circ}\text{C}$ (Fig. 5).

These results are partially consistent with other paleoceanographic reconstructions from both Northern and Southern Hemispheres in the sense that SST negative anomalies were recorded from the onset and during the early Holocene, peaking at 8.2 cal kyr BP (Farmer et al., 2005; Ellison et al., 2006; Pivell et al., 2013). In the western South

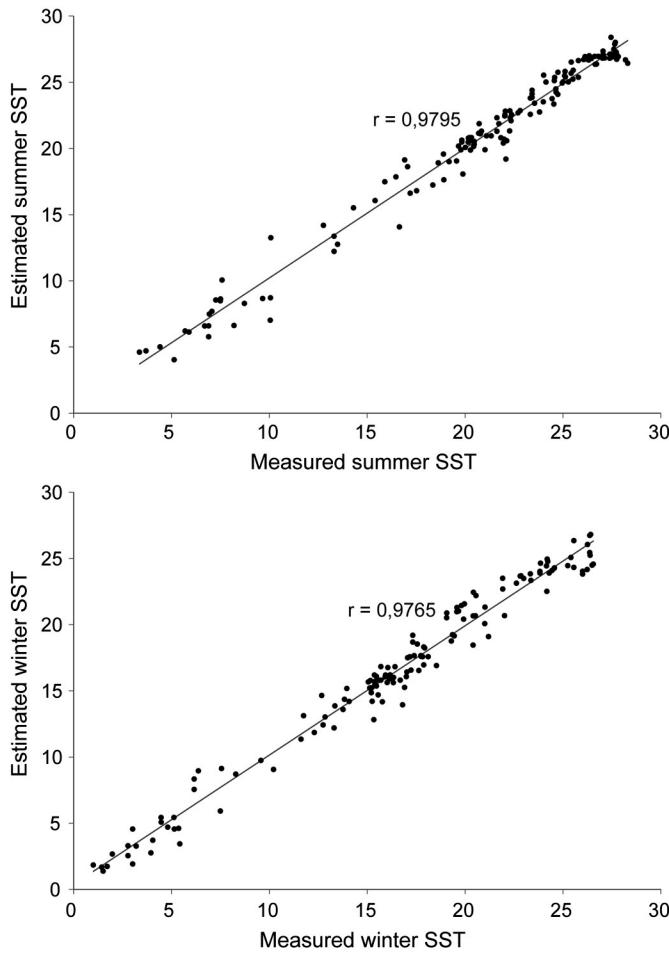


Fig. 3. Lineal regressions between measured and estimated temperatures (summer and winter), where r is the multiple correlation coefficient.

Atlantic, Pivel et al. (2013) documented strong SST changes in the Brazil Current ($25.84^{\circ}\text{S}/45.2^{\circ}\text{W}$) between the onset of the Holocene and ~ 8 cal kyr BP. As highlighted by the authors, what the record actually shows is a trend of decreasing SSTs for some millennia during the early Holocene ending abruptly with negative anomalies of $\sim 2^{\circ}\text{C}$ at around 8.2 cal kyr BP, evidencing that full interglacial conditions would only have started after that. However, independently of this particular event, Pivel et al. (2013) found positive SST anomalies along the entire Holocene. In contrast to this, core GeoB2806-4 recorded SST strong negative anomalies, not only during the 8.2 event but also during the onset of the Holocene, especially at ~ 11.7 cal kyr BP (Fig. 5). The difference between both reconstructions is most probably due to the fact that their record was exclusively under the influence of the Brazil Current, whereas our core was influenced by both, the Brazil and Malvinas Currents. However, we cannot rule out the use of different reconstruction techniques (Calibration Function – this study – vs. Artificial Neural Network Pivel et al., 2013), or even, the use of different calibration datasets as possible reasons for the differences observed between both records. It is important to highlight that the western South Atlantic is underrepresented in most of the calibration datasets (e.g., Niebler and Gersonde, 1998; Pflaumann et al., 2003; Kucera et al., 2005b). The lack of an adequate number of modern analogs in this region could be the reason of the observed differences between the reconstructed SST here and in other records (Toledo et al., 2007; Pivel et al., 2013).

The Younger Dryas ($\sim 12.9\text{--}11.5$ cal kyr BP sensu Alley (2000)) and the 8.2 event were large-scale general cooling and drying events of the Late Glacial and the early Holocene in the Northern Hemisphere. They presented similar geographical patterns, even though the 8.2

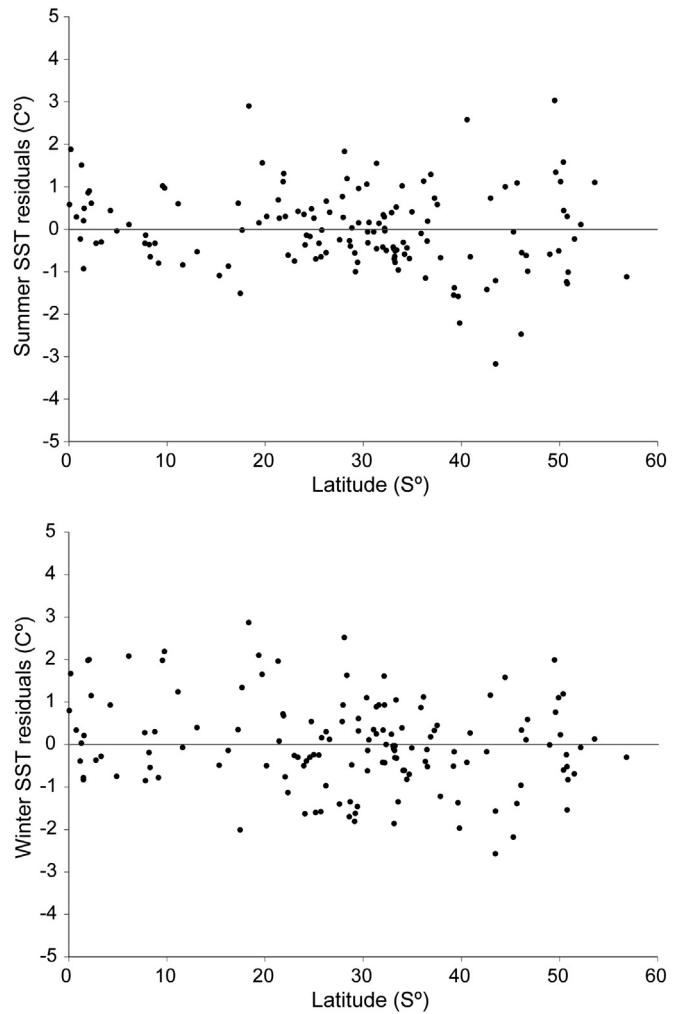


Fig. 4. Scatter diagrams of summer and winter residuals from the multiple regression. Positive values represent underestimated SSTs while negative values represent overestimated SSTs.

event hardly lasted 150–200 year (Alley et al., 1997; Maslin et al., 2001; Kobashi et al., 2007). Air temperature reconstructions based on methane, calcium, sodium, $\delta^{18}\text{O}$ and $\delta^{15}\text{N}$ records from GISP and GISP2 show up to 9°C of cooling during the Younger Dryas in Greenland, with summers $6\text{--}7^{\circ}\text{C}$ cooler than present (Alley, 2000; Kelly et al., 2008). Meanwhile, during the 8.2 event, the same records reflected a cooling half as severe in both Greenland and Antarctica (Alley et al., 1997; Jouzel et al., 2007; Kobashi et al., 2007). In the marine realm of both hemispheres, the 8.2 event showed a decrease in the SST (Farmer et al., 2005; Ellison et al., 2006; Pivel et al., 2013), but the Younger Dryas is more controversial. There are clear evidences of SST negative anomalies in the Northeast Atlantic, Gulf of Mexico and the western Subtropical North Atlantic (e.g. Bard et al., 2000; Flower et al., 2004; Carlson et al., 2008a), but SST records from the Southern Hemisphere are out-of-phase and show a warming of $0.3\text{--}1.9^{\circ}\text{C}$ from the southeast Atlantic to New Zealand (Lamy et al., 2004; Barrows et al.,

Table 3

Regression statistics for the model F141-35-5.

| Statistical value | Summer SST ($^{\circ}\text{C}$) | Winter SST ($^{\circ}\text{C}$) |
|--|-----------------------------------|-----------------------------------|
| Minimum of absolute residuals | -3.17 | -2.57 |
| Maximum of absolute residuals | 3.03 | 2.87 |
| Mean value of absolute residuals | -0.0004 | -0.0001 |
| Standard deviation of absolute residuals | 0.95 | 1.1 |

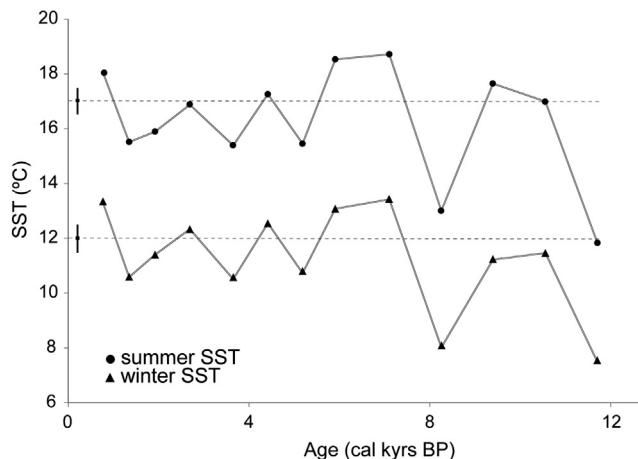


Fig. 5. Correlation function based summer and winter SST estimates at the location of core GeoB2806-4. Error bars on the left correspond to $\sigma = 0.52$ for summer SSTs and $\sigma = 0.58$ for winter SSTs. Dotted lines represent the modern SSTs of the core location after Levitus and Boyer (1994).

2007; Carlson et al., 2008b; Barker et al., 2009) along with Antarctica (EPICA, 2004). Core GeoB2806-4 reveals an important decrease in SST at 8.2 cal kyr BP and 11.7 cal kyr BP, coevals with the 8.2 event and the Younger Dryas respectively. However, due to the low resolution of our SST record, it is difficult to define whether these cooling periods were directly related to global events, or if they are a result of local oceanographic conditions such as increased upwelling of colder subsurface waters related to local.

These results corroborate that the developed calibration function here is useful for Quaternary paleotemperature reconstruction in sediment cores of the whole western South Atlantic Ocean.

6. Conclusions

We provide a new calibration function (F141-35-5) that integrates assemblages from the Antarctic Circumpolar Current to the Subtropical Gyre and tropical warm waters from the South Atlantic (60° S to 0° S). The derived IKM foraminiferal calibration function, based on 141 surface samples, 35 taxonomic groups and 5 factors, evidences a very strong correlation with Southern Hemisphere summer and winter SSTs. It provides a useful tool for paleotemperature reconstruction from sediment cores of the whole South Atlantic Ocean during the Quaternary. Its calibration exhibits similar standard deviations, correlation coefficients and deviation in residuals for both seasons. Sigmas lower than 1° C were obtained, revealing summer $\sigma = 0.52^{\circ}$ C and winter $\sigma = 0.58^{\circ}$ C. The factors are interpreted as representing the main oceanographic fronts in the South Atlantic: the Subtropical Gyre (Factor 1/Tropical Factor) characterized by *G. ruber*, *G. sacculifer* and *G. glutinata*; the Subtropical Front (Factor 2/Subtropical Factor) characterized by *G. inflata*, *G. falconensis*, *N. pachyderma* (dextral) and *G. bulloides*; the Subpolar Front (Factor 4/Subpolar Factor) characterized by *N. pachyderma* (dextral) and *G. bulloides*; the Polar Front (Factor 3/Polar Factor) characterized mostly by *N. pachyderma* (sinistral); and the Angola Dome/Angola-Benguela Front (Factor 5/Marginal Gyre Factor) defined by *G. sacculifer*, *G. inflata*, *P. obliquiloculata* and *N. dutertrei*. This suggests that the calibration function correctly models not only the assemblages of planktonic foraminifera but also the current hydrographic features of the region. Estimated summer and winter SSTs for the late Holocene show average SST that coincides with the modern SST at the site. However, Late Glacial and early Holocene SST reconstructions reveal strong negative anomalies of the SST with minima at 8.2 and 11.7 cal kyr BP, which could be coeval with the 8.2 and Younger Dryas events, respectively. The calibration function F141-35-5 presents better statistical accuracy than other transfer functions developed for

the South Atlantic. In consequence, it results useful as a tool for SST reconstruction from sediment cores of the western South Atlantic Ocean and, probably, for Quaternary records from the Atlantic sector of the Southern Ocean.

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