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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.

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 conglomerata*, *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).