



A mid-Holocene climate reconstruction for eastern South America

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Abstract. The mid-Holocene (6000 calibrated years before present) is a key period in palaeoclimatology because incoming summer insolation was lower than during the late Holocene in the Southern Hemisphere, whereas the opposite happened in the Northern Hemisphere. However, the effects of the decreased austral summer insolation over South American climate have been poorly discussed by palaeodata syntheses. In addition, only a few of the regional studies have characterised the mid-Holocene climate in South America through a multiproxy approach. Here, we present a multiproxy compilation of mid-Holocene palaeoclimate data for eastern South America. We compiled 120 palaeoclimatological datasets, which were published in 84 different papers. The palaeodata analysed here suggest a water deficit scenario in the majority of eastern South America during the mid-Holocene if compared to the late Holocene, with the exception of northeastern Brazil. Low mid-Holocene austral summer insolation caused a reduced land–sea temperature contrast and hence a weakened South American monsoon system circulation. This scenario is represented by a decrease in precipitation over the South Atlantic Convergence Zone area, saltier conditions along the South American continental margin, and lower lake levels.

al., 2012; and others). The LGM and the MH, corresponding to 21 000 calibrated years before present (cal yr BP) and 6000 cal yr BP, respectively (Braconnot et al., 2007a), are usually chosen because of their different boundary conditions, if compared to the late Holocene (LH), that can be used to test the response of climatic models (Joussaume and Braconnot, 1997). During the LGM, Earth was covered by a larger amount of ice than during the LH, whereas the MH was characterised by increased (decreased) summer insolation in the Northern (Southern) Hemisphere if compared to modern conditions. The change in insolation, particularly, was due to a difference of ca. 101° between the MH longitude and the current longitude of the perihelion. As a consequence, the perihelion occurred at the austral spring equinox during the MH, whereas today it is reached at the austral summer solstice (Joussaume and Braconnot, 1997). This caused a MH insolation decrease of ca. 20 W m^{-2} in southern latitudes from January to March compared to pre-industrial values (Bosmans et al., 2012).

Data–model approaches require high-quality palaeoclimatic records and state-of-the-art climatic models. With this aim many projects have been carried out, such as the Climate: Long-range Investigation, Mapping, and Prediction (CLIMAP, CLIMAP Project Members, 1976, 1981, 1984), the Cooperative Holocene Mapping Project (COHMAP, COHMAP Members, 1988), and the Paleoclimate Modelling Intercomparison Project (PMIP, Braconnot et al., 2007a, b, 2012). PMIP is in its third phase, now part of the Coupled Model Intercomparison Project fifth phase (CMIP5, Taylor et al., 2012), and consists in evaluating the models' performance in reproducing the climate of the LGM, the MH, and the last millennium. One implication of these projects

1 Introduction

Recently, the Last Glacial Maximum (LGM) and the mid-Holocene (MH) have been the foci of numerous studies using data–model approaches (Pinot et al., 1999; Wainer et al., 2005; Kageyama et al., 2006; Braconnot et al., 2007a, b; Melo and Marengo, 2008; Silva Dias et al., 2009; Carré et

is that the better climate models are able to reproduce past climates, the more reliably these models will project future climates. Climatic changes have been observed throughout Earth's history, and the ability to project future climates has great importance for planning and implementing adaptation and mitigation policies (Jansen et al., 2007). Yet, as in the CLIMAP and COHMAP initiatives, the state-of-the-art models included in PMIP3 must also be evaluated with regard to palaeodata. Hence, gathering records in the form of palaeodata syntheses is imperative.

In their supplementary information, Braconnot et al. (2012) present a summary of the available global and regional datasets for the MH and the LGM, derived from different proxies and archives. These efforts (Prentice and Webb III, 1998; Kohfeld and Harrison, 2000, 2001; Harrison et al., 2003; Kucera et al., 2005; Power et al., 2008; MARGO Project Members, 2009; Leduc et al., 2010; Bartlein et al., 2011) have been motivated by PMIP and other modelling projects. Nevertheless, all of these efforts have included only a few records from the Southern Hemisphere. Records from the MH in South America are particularly sparse if compared to records from other locations in the Northern Hemisphere and with those from the LGM (see, e.g. MARGO Project Members, 2009). Thus, the uncertainties in the palaeoclimate record for this continent are still large.

In this study, we present a compilation of multiproxy palaeoclimatic data from the MH for eastern South America. This compilation includes data from land, cave, lake, river, and ocean archives. Our objectives were the following: (i) to provide a spatial reconstruction of the MH patterns of precipitation, (ii) to provide a spatial reconstruction of the MH temperature patterns, (iii) to provide information on the MH lake levels and ocean salinity, and (iv) to determine the MH climatic drivers in South America based on the palaeodata information. Section 2 reviews the main aspects of the climate of South America and the South Atlantic Ocean which are necessary to understand the palaeodata. Section 3 presents the proxies used in this compilation, how the spatial and temporal domains were determined, the limitations of each proxy, and a chronological reliability index developed to evaluate and compare different types of proxies. Section 4 is dedicated to the results, while the discussion and conclusions are presented in Sect. 5.

2 Climate of South America

2.1 South American monsoon system

The term “South American monsoon system” (SAMS, Garreaud et al., 2009; Vera et al., 2006) was first used after Zhou and Lau (1998) because the summer atmospheric circulation in South America does not agree with the classical monsoon definition. The classical monsoon is defined as a seasonal inversion of the large-scale surface circulation pattern due to

differential heating of the continents and the oceans. Zhou and Lau (1998) could not prove the existence of the South American monsoon by this criterion. Instead, they subtracted the annual wind from the winter and summer patterns and obtained a seasonal inversion of the easterlies anomalies. The result during austral summer is a circulation originating in the sub-Saharan region that crosses the equator and is driven southeastward by the Andes Cordillera (Fig. 1). In the Amazon Basin, a thermal low develops at the surface as a consequence of land heating. The winds of this circulation reach the Gran Chaco region in Paraguay and finally move clockwise, forming a low pressure system at the surface (Garreaud et al., 2009). Lenters and Cook (1995) identified five major regions of austral summer precipitation in South America: (1) the Amazon Basin; (2) the northern sector of the Andes, where precipitation is related to wind convergence at low levels and to the thermal low pressure at the surface; (3) the central sector of the Andes, where precipitation is due to the orography increase at the east side of the slope and to the meridional wind convergence; (4) the southern sector of the Andes, where precipitation is purely orographic; and (5) the South Atlantic Convergence Zone (SACZ, e.g. Carvalho et al., 2004), which is formed by wind convergence and moisture advection at low levels and by contribution of transient eddies moving equatorward. Another important circulation feature is the South American Low Level Jet (SALLJ, e.g. Marengo et al., 2004). It transports moisture from the Amazon Basin to the central southern South America. The SALLJ consists of a wind maximum at an altitude of 1 to 2 km and can influence the position and intensity of the SACZ (Marengo et al., 2004).

All mentioned features are present at low levels, but circulation at high levels in the atmosphere also shows characteristics linked to the SAMS (e.g. Marengo et al., 2012). The Bolivian High (BH) is the major summer feature at high levels and is a response to the latent heat released by rain clouds formed in the Amazon Basin. East of the BH, the Northeast Trough is observed as a return flux at high levels and is related to the subsidence over northeastern Brazil (Zhou and Lau, 1998). Both the BH and the Northeast Trough are associated with the SACZ at the surface (Lenters and Cook, 1997). The SACZ is the main convective system of South America, and is responsible for most of the austral summer precipitation in central and southeastern Brazil (Carvalho et al., 2004). It consists of a northwest–southeast-oriented cloud band that brings moisture from the Amazon region to central and southeastern Brazil. The SACZ is characterised by the coupling of the convergence zone with transient eddies from higher latitudes and can stay stationary for many days. Transient systems are responsible for a portion of precipitation in southeastern South America throughout the year, predominantly in southern and southeastern South America. Reboita et al. (2010) have found three major areas of cyclonic activity over the South Atlantic Ocean off eastern South America: Argentina (ca. 48° S), the La Plata

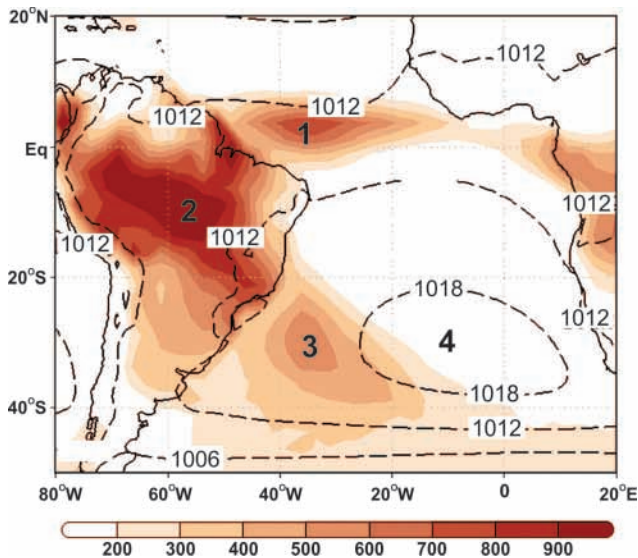


Fig. 1. Atmospheric mean circulation (1979–2010) at the surface level during austral summer (December to February), derived from ERA-Interim dataset (Dee et al., 2011). (1) Intertropical Convergence Zone (ITCZ); (2) and (3) South Atlantic Convergence Zone (SACZ), continental and oceanic components, respectively; (4) South Atlantic Subtropical High. Colours refer to mean precipitation during the December–January–February period, in millimetres (mm); dashed black lines refer to mean sea level pressure, in hectopascals (hPa). Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

river discharge between Argentina and Uruguay (ca. 35° S), and the south/southeastern coast of Brazil. Sea surface temperatures (SST) over the South Atlantic Ocean can influence the intensity and position of the SACZ (Chaves and Nobre, 2004).

A large portion of the interannual variability of the SAMS can be explained by the El Niño–Southern Oscillation (ENSO, e.g. Trenberth et al., 1997); its warm (cold) phase is responsible for decreased (increased) precipitation during the wet season of northern South America and above (below) average precipitation in southeastern South America (Marengo et al., 2012, and references therein). The Southern Annular Mode (SAM, Visbeck, 2009) is also related to interannual variability of precipitation in southeastern South America. At interdecadal timescales, there is evidence of effects induced by the Pacific Decadal Oscillation (PDO, Mantua et al., 1997) and by the Atlantic Multidecadal Oscillation (AMO, Enfield et al., 2001) on the variability of the SAMS (Garcia and Kayano, 2008; Chiessi et al., 2009; Silva et al., 2011).

An important issue found in palaeoclimatological studies pertains to the differences and interactions between the Intertropical Convergence Zone (ITCZ) and the SAMS (Vuille et al., 2012). Both the ITCZ and the SAMS exhibit seasonal variability, but the ITCZ is a permanent feature of at-

mospheric circulation affected by the annual cycle of insolation. This cyclicity impacts SST, whereas the SAMS reflects the land–sea thermal gradient. The ITCZ is essentially an oceanic phenomenon concentrated in the Northern Hemisphere (Takahashi and Battisti, 2007), whereas the SAMS occurs mainly over the South American continent. Furthermore, the SAMS is highly dependent on land topography, which keeps it over the continent, whereas the ITCZ moves around the equator (Vuille et al., 2012).

2.2 South Atlantic Ocean Circulation

The South Atlantic ocean circulation is part of the Atlantic Meridional Overturning Circulation (AMOC, e.g. Kuhlbrodt et al., 2007), which contributes to the global process of heat redistribution. The South Atlantic Ocean transports heat northward across the equator, and is therefore considered a particular basin (Srokosz et al., 2012). In the high latitudes of the North Atlantic, the surface ocean loses heat to the atmosphere. The result is the sinking of dense and cold waters, which are transported to the south at depth (Dickson and Brown, 1994).

In the South Atlantic Ocean, the surface currents found off eastern South America are the North Brazilian Current (NBC), South Equatorial Undercurrent (SEUC), South Equatorial Countercurrent (SECC), South Equatorial Current (SEC), Brazil Current (BC), and Malvinas Current (MC) (see Fig. 2a, after Peterson and Stramma, 1991).

Sea surface salinities (SSS) are strongly influenced by net precipitation/runoff. Accordingly, on the eastern South American continental margin, low SSS are found near the La Plata (ca. 35° S, 55° W) and Amazon (ca. 0°, 50° W) river mouths, and further offshore beneath the ITCZ. Maximum SSS are found in the subtropics, due to strong evaporation in the region of the subtropical high (ca. 25° S, 10–40° W) (Talley et al., 2012). SSTs have zonal distribution in the South Atlantic Ocean, with colder waters to the south and warmer waters to the north, ranging from 10 to 27 °C (Fig. 2b) (Locarnini et al., 2010). At ca. 36° S the confluence of the BC (warm surface current) and the MC (cold surface current) is characterised by densely spaced surface isotherms on the eastern South American continental margin (Wainer et al., 2000). The equatorial Atlantic presents a tongue-shaped pattern in the SST field known as the Atlantic Niño (Zebiak, 1993; Chang et al., 2006).

The variability of the South Atlantic Ocean comprises time frequencies ranging from interannual to multidecadal periods (Enfield and Mayer, 1997; Venegas et al., 1998; Czaja and Frankignoul, 2002; Wainer et al., 2008).

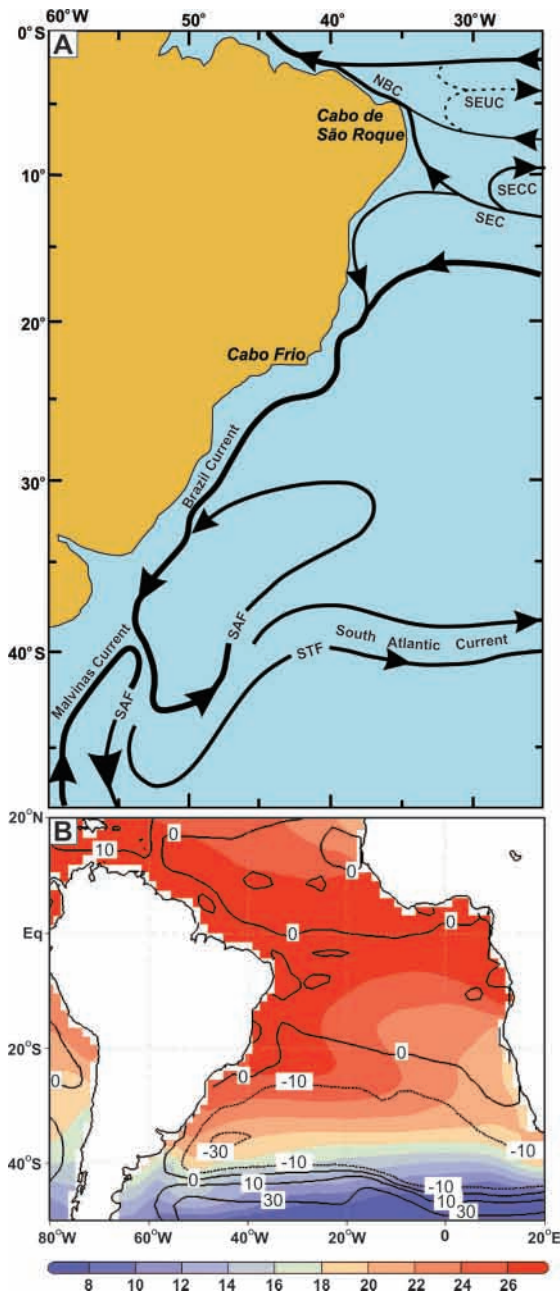


Fig. 2. The South Atlantic Ocean. **(a)** Upper-level barotropic currents and fronts on the Brazilian continental margin, western South Atlantic Ocean: NBC – North Brazilian Current; SEUC – South Equatorial Under Current; SECC – South Equatorial Countercurrent; SEC – South Equatorial Current; SAF – Subantarctic Front; STF – Subtropical Front; adapted from Peterson and Stramma (1991). **(b)** Austral summer (December to February) barotropic stream function in sverdrup (Sv) (dashed and solid lines, Salas-Melia et al., 2005), and Era-Interim sea surface temperature in degrees Celsius (°C) (shaded colours, Dee et al., 2011).

Table 1. Description of proxy types used in this study (modified from Wirtz et al., 2010).

| Code | Proxy type | Description |
|------|--|---|
| IF | Isotopic oxygen and carbon fractionation | $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ |
| PC | Physico-chemical | Mg/Ca, Ti/Ca, Fe/Ca, Fe/Sr, Al/Si, Si/Ca, C/N, $\delta^{15}\text{N}$, grain size, petrography, alkenone, thermoluminescence, mineralogy, pH, Eh, magnetic susceptibility |
| BI | Biological | Pollen, diatoms, spores, algae, molluscs, sponge, organic matter, charcoal, relative abundance |

3 Proxy data

Our multiproxy compilation contains a large variety of archive and proxy types, and one must consider their limitations. Table 1 displays the classification of the palaeodata and the types of proxy used in our compilation. Our classification was based on Wirtz et al. (2010) (see Table 1 in Wirtz et al. (2010) for more details). The oxygen and carbon stable isotopic ratios are the fractionation-dependent proxies. The physico-chemical proxies comprise all geochemical ratios and physico-chemical approaches, whilst all information derived from organisms is classified as biological. We highlight that a substantial part (ca. 83 %) of the palaeodata analysed is classified as the latter type, with most being pollen assemblages. Pollen data mainly reflect temperature changes, but can also reveal changes in the rainfall regime, particularly in the tropics. The *Araucaria* forest is related to wet and cold climate (e.g. Behling, 1997), whereas the dominance of Poaceae and Asteraceae in the pollen spectra may correspond to dry and cold climate (e.g. Ledru et al., 2009).

3.1 Data limitations

Different proxies have distinct frequency dependence due to their inherent sensitivity to climate. Deep marine sediments typically have low resolution (> 1 ka) because of their low sedimentation rate and bioturbation in non-anoxic zones, whereas high resolution, such as years or seasons, can be typically found in corals (Bradley, 1999). Another consideration should be made in respect to the different temporal responses from each type of proxy. The archived proxies can be affected by climatic changes immediately after the event, or they can have a delayed reaction. Vegetational data, such as pollen assemblages deposited in the Cariaco Basin (located off northern South America), show climatic inertia and tend to take at least 25 ± 15 yr to respond to

abrupt climate changes (Hughen et al., 2004). Moreover, Huntley (2012) discussed the biological response of proxies to bioclimatic variables instead of to the climate itself, and argued that this response varies from one organism to another. This complicated relationship between biological proxies and climate exemplifies the difficulties in comparing different types of proxies. Furthermore, not all records are continuous in time. When dealing with biological records, one should also be aware of possible seasonal preferences. Planktonic foraminifera and coccolithophores are examples of organisms that carry a seasonal signal related to their biological cycles (Giraudeau and Beaufort, 2008).

3.2 Temporal and spatial domains

In this study, we used the ^{14}C ages as published by the authors of each examined paper. Thus, non-calibrated ages are expressed as yr BP, while calibrated ages are expressed as cal yr BP. Two main criteria were used to select the papers included in our compilation. The first one is the temporal definition of the MH period. The MH is usually referred to as 6000 cal yr BP (e.g. Braconnot et al., 2012); however, sampling errors related to the dating approach and the variable temporal resolution of the samples introduce uncertainties that should be taken into account. To account for these uncertainties, we considered the interval from 7000 to 5000 cal yr BP as the period corresponding to the MH.

Secondly, the spatial domain (Fig. 3) was defined based on physical parameters. The latitudinal limits used are the equator, and the mean latitude of the high-level westerlies (ca. 40°S) (Peixoto and Oort, 1992). The westerlies can vary in latitudinal position throughout the year, from 30 to 60°S at the surface, and from 30 to 50°S at high levels in the atmosphere (Peixoto and Oort, 1992; Garreaud et al., 2009). None of the palaeorecords used in this compilation were under the direct influence of the westerlies. The longitudinal limits used are the 10°W meridian in the western South Atlantic Ocean for the eastern border of the domain, and the western border is characterised by altitudes below 2300 m.

Considering the temporal and spatial domains defined above, we conducted a thorough investigation of published studies containing MH climatic information from South America. Table 2 contains the location, proxy type, and reference for each paper examined. We compiled 120 palaeoclimatological datasets from the analysis of 84 studies using the original published chronologies. Some papers included different analyses or an update of cores examined previously. Figure 3 shows the spatial distribution of the records included in this study. The numbers on the map identify each sample location as listed in Table 2.

3.3 Dating uncertainty

To evaluate the dating uncertainty of the palaeodata, we have created a chronological reliability index (Q) based on the

sampling resolution and the sample age model:

$$Q = \frac{CA + R + D}{3}. \quad (1)$$

CA (calibration) equals 1 if ages are calibrated, or 0 if they are not calibrated. R (resolution) refers to the mean number of samples per core length ratio, where

$$R = \left\{ \begin{array}{l} 0.1 \text{ for ratio between } 0.01 \text{ and } 0.1 \\ 0.2 \text{ for ratio between } 0.11 \text{ and } 0.2 \\ \vdots \\ 11.0 \text{ for ratio between } 10.01 \text{ and } 11.00 \end{array} \right\} \quad (2)$$

D (dating) is the number of datings within the interval 7000–5000 cal yr BP, divided by 10. This index is a semi-quantitative approach that simply involves the computation of an arithmetic mean, where the same weight is given to all parameters. Therefore, because Q encompasses a sum, the greater its value, the higher the chronological reliability of the palaeodata.

4 Results

Figures 4 to 8 show results of the Q index applied to the compiled palaeodata. Larger symbols refer to data with a higher chronological reliability. It is important to note that all of the climatic information we present is based on the authors' conclusions in each paper used in this compilation and do not imply any further interpretation.

4.1 Precipitation

Precipitation and moisture are the most abundant variables in the palaeodata for two reasons: (i) these variables are the main type of information obtained from pollen assemblages, and (ii) pollen assemblages constitute the main type of proxy records found in eastern South America during the MH (Fig. 4). The general MH scenario corresponds to a drier eastern South America than during the LH, except for northeastern Brazil, which exhibits an unclear climate signal during the MH. A similar climatic scenario has already been discussed (Valdes, 2000; Cruz et al., 2009; Silva Dias et al., 2009). Valdes (2000) described drier conditions in South America (except for northeastern Brazil) during the MH austral summer (from December to February), derived from the first phase of PMIP data models. Cruz et al. (2009) compared speleothem-based precipitation records to vertical velocity, geopotential, and oxygen isotopes fields simulated by a numerical model and obtained an east–west antiphase of these variables over tropical South America. Oxygen isotopic values capture the precipitation variability because the isotopic fractionation in the area depends on the path the water takes from its source to its sink; the greater the distance, the greater the loss of the heavier isotopes (Vuille et al., 2012). Thus, this



Fig. 3. Spatial distribution of the 120 palaeorecords (from 84 studies) used in this study. Vertical axis refers to latitude, and horizontal values correspond to longitude. Details for each record are found in Table 2.

ratio may have different interpretations depending on the site of the record. In southeastern South America the oxygen isotopic ratio is related to the SAMS activity versus moisture derived from the adjacent subtropical South Atlantic Ocean (e.g. Cruz Jr. et al., 2005). Silva Dias et al. (2009) have examined two MH numerical runs: the first one only considered variations in the orbital parameters, and the second one included changes in vegetation. The former run presented results very similar to Valdes (2000) and Cruz et al. (2009), characterised by a drier-than-modern MH climate in South America during the wet season (December to February), except for northeastern Brazil. The latter run resulted in a northward displacement of the SACZ and a southward migration of the ITCZ during the MH austral summer when compared to the run without changes in vegetation.

Climatic information extracted from lake level proxies is shown in Fig. 5. Lake levels were lower than modern levels for all analysed sites, which corroborates the precipitation/moisture palaeodata (Fig. 4). This characterises a drier climate in eastern South America during the MH compared

to the LH. Q -index values of the lake level proxy records are low, with the highest ones located in the eastern Amazon.

Palaeorecords of SSS from the South American continental margin (Fig. 6) are scarce. There are few salinity palaeorecords mainly because of the difficulties in collecting appropriate marine sediment cores. However, all records but one show saltier conditions along the South American continental margin during the MH if compared to the LH. Higher Q -index values are found off northeastern Brazil and on the Argentinean continental margin.

4.2 Temperature

Figure 7 shows air temperature palaeodata for the MH. The majority of samples were collected in Uruguay and central-southern Brazil. High Q -index data can be found near the equator and in southern Brazil. The records depicted in Fig. 7 indicate a warmer climate in southern Brazil and a climate similar to the LH in the north-northeastern Brazil.

Difficulties in collecting marine sediment cores also affect the amount of SST proxy records (Fig. 8) for the MH off

Table 2. Locations and references of the palaeoclimatic records used in this study*. Abbreviations are as follows. Site: Lk = lake, Cv = cave, Rv = river; proxy type: IF = isotopic fractionation, PC = physico-chemical, BI = biological. Numbers within parentheses in the “Site” column – in records 72, 77, 90, 95, 112, and 113 – refer to total of samples collected at the referred site. More details of proxy type can be found in Table 1.

| No. | Site | Proxy type | Reference | Lat. (°) | Long. (°) |
|-----|---------------------------|------------|---------------------------------|----------|-----------|
| 1 | Salitre de Minas | BI | Ledru (1993) | −19.00 | −46.77 |
| 2 | Morro de Itapeva | BI | Behling (1997a) | −22.78 | −45.53 |
| 3 | Curuçá Lk | BI | Behling (2001) | −0.77 | −47.85 |
| 4 | São Francisco de Paula | BI | Behling et al. (2001a) | −29.24 | −50.57 |
| 5 | Jacareí peat | BI | Garcia et al. (2004) | −23.28 | −45.97 |
| 6 | Nova Lk | BI | Behling (2003) | −17.97 | −42.20 |
| 7 | Volta Velha | BI | Behling and Negrelle (2001) | −26.07 | −48.63 |
| 8 | Crispim Lk | BI/PC | Behling and Costa (2001) | −0.59 | −47.65 |
| 9 | São Francisco de Assis | BI | Behling et al. (2005) | −29.59 | −55.22 |
| 10 | Caçó Lk | IF/BI | Ledru et al. (2006) | −2.96 | −43.42 |
| 11 | Serra da Bocaina | BI | Behling et al. (2007) | −22.71 | −44.57 |
| 12 | Marcio Lk | BI | De Toledo and Bush (2007) | −0.13 | −51.08 |
| 13 | Tapera Lk | BI | De Toledo and Bush (2007) | −0.13 | −51.08 |
| 14 | Aleixo Lk | IF/PC/BI | Enters et al. (2010) | −17.99 | −42.12 |
| 15 | Fazenda Lk | BI | Resende (2010) | −23.51 | −52.45 |
| 16 | Saquinho Rv | BI/PC | De Oliveira et al. (1999) | −10.40 | −43.22 |
| 17 | Serra Campos Gerais | BI | Behling (1997b) | −24.40 | −50.13 |
| 18 | Colônia | BI | Ledru et al. (2009) | −23.87 | −46.71 |
| 19 | Pires Lk | BI | Behling (1995a) | −17.95 | −42.22 |
| 20 | Águas Claras | BI | Bauermann et al. (2003) | −30.10 | −50.85 |
| 21 | Serra da Boa Vista | BI | Behling (1995b) | −27.70 | −49.15 |
| 22 | Morro da Igreja | BI | Behling (1995b) | −28.18 | −49.87 |
| 23 | Serra do Rio Rastro | BI | Behling (1995b) | −28.38 | −49.55 |
| 24 | Cambará do Sul | BI | Behling et al. (2004) | −28.95 | −49.90 |
| 25 | Serra do Araçatuba | BI | Behling (2007) | −25.92 | −48.98 |
| 26 | Cerro do Touro | IF/PC/BI | Oliveira et al. (2008a) | −26.25 | −49.25 |
| 27 | Serra dos Órgãos | BI | Behling and Safford (2010) | −22.46 | −43.03 |
| 28 | Aquiri Lk | BI/PC | Behling and Costa (1997) | −3.17 | −44.98 |
| 29 | Calado Lk | BI/PC | Behling et al. (2001b) | −3.27 | −60.58 |
| 30 | Curuá Rv | BI/PC | Behling and Costa (2000) | −1.74 | −51.46 |
| 31 | Serra Sul de Carajás – Lk | BI | Absy et al. (1991) | −6.33 | −50.42 |
| 32 | Pata Lk | BI | Colinvaux et al. (1996) | 0.27 | −66.68 |
| 33 | Caçó Lk | BI | Ledru et al. (2002) | −2.96 | −43.42 |
| 34 | Caçó Lk | IF/BI | Ledru et al. (2006) | −2.96 | −43.42 |
| 35 | Águas Emendadas | BI | Barberi et al. (2000) | −15.57 | −47.58 |
| 36 | Confusão Lk | BI | Behling (2002b) | −10.63 | −49.72 |
| 37 | Santa Lk | BI | Parizzi et al. (1998) | −19.63 | −43.90 |
| 38 | Geral Lk | BI/PC | Bush et al. (2000) | −1.80 | −53.53 |
| 39 | Comprida Lk | BI/PC | Bush et al. (2000) | −1.86 | −53.98 |
| 40 | Arr. Las Brusquitas – Rv | BI | Vilanova et al. (2006b) | −38.23 | −57.77 |
| 41 | Bella Vista Lk | BI | Mayle et al. (2000) | −13.62 | −61.55 |
| 42 | Chaplin Lk | BI | Mayle et al. (2000) | −14.47 | −61.55 |
| 43 | Colônia | BI | Ledru et al. (2005) | −23.87 | −46.71 |
| 44 | Dourada Lk | IF/PC/BI | Moro et al. (2004) | −25.24 | −50.04 |
| 45 | Cromínia | BI | Salgado-Labouriau et al. (1997) | −17.28 | −49.42 |
| 46 | India Muerta | BI | Iriarte (2006) | −33.70 | −53.95 |
| 47 | Puente de la Tropa – Rv | BI/PC | Prieto et al. (2004) | −34.58 | −59.14 |
| 48 | Paso de Corro – Rv | BI/PC | Prieto et al. (2004) | −34.55 | −59.12 |
| 49 | Serra Geral | BI | Leal and Lorscheitter (2007) | −29.60 | −51.65 |
| 50 | Arr. Sauce Chico – Rv | BI | Prieto (1996) | −38.08 | −62.26 |
| 51 | Empalme Querandies | BI | Prieto (1996) | −37.00 | −61.11 |
| 52 | Arari Lk | BI | Smith et al. (2011) | −0.60 | −49.14 |

Table 2. Continued.

| No. | Site | Proxy type | Reference | Lat. (°) | Long. (°) |
|-----|------------------------------|------------|-------------------------------|----------|-----------|
| 53 | Tapajós Lk | BI/PC | Irion et al. (2006) | -2.79 | -55.08 |
| 54 | Santa Maria Lk | BI | Bush et al. (2007) | -1.58 | -53.60 |
| 55 | Saracuri Lk | BI | Bush et al. (2007) | -1.68 | -53.57 |
| 56 | Geral Lk | BI | Bush et al. (2007) | -1.65 | -53.59 |
| 57 | Quequén Grande Rv | BI/PC | Hassan et al. (2009) | -38.50 | -58.75 |
| 58 | South Atlantic Oc | IF/BI | Toledo et al. (2007) | -24.43 | -42.28 |
| 59 | South Atlantic Oc | IF/BI | Toledo et al. (2007) | -14.40 | -38.82 |
| 60 | South Atlantic Oc | IF/BI | Toledo et al. (2007) | -20.95 | -39.53 |
| 61 | South Atlantic Oc | IF | Arz et al. (1998) | -3.67 | -37.72 |
| 62 | South Atlantic Oc | IF/PC | Arz et al. (1998) | -3.67 | -37.72 |
| 63 | South Atlantic Oc | IF/PC | Arz et al. (2001) | -4.25 | -36.35 |
| 64 | South Atlantic Oc | BI | Toledo et al. (2008) | -24.43 | -42.28 |
| 65 | South Atlantic Oc | BI/PC | Nagai et al. (2009) | -22.94 | -41.98 |
| 66 | South Atlantic Oc | IF | Pivel et al. (2010) | -24.43 | -42.28 |
| 67 | South Atlantic Oc | IF/PC | Weldeab et al. (2006) | -4.61 | -36.64 |
| 68 | South Atlantic Oc | PC | Chiessi et al. (2010) | -32.50 | -50.24 |
| 69 | South Atlantic Oc | PC | Jaeschke et al. (2007) | -4.25 | -36.35 |
| 70 | South Atlantic | IF/PC | Groeneveld and Chiessi (2011) | -41.27 | -14.49 |
| 71 | Botuverá Cv | IF | Cruz et al. (2005) | -27.22 | -49.15 |
| 72 | Lapa Grande Cv (2) | IF | Stríkis et al. (2011) | -14.42 | -44.36 |
| 73 | Botuverá Cv | IF | Wang et al. (2007) | -27.22 | -49.15 |
| 74 | Santana Cv | IF | Cruz et al. (2006a) | -24.53 | -48.72 |
| 75 | Botuverá Cv | IF | Cruz et al. (2006b) | -27.22 | -49.15 |
| 76 | Botuverá Cv | IF/PC | Cruz et al. (2007) | -27.22 | -49.15 |
| 77 | Rio Grande do Norte – Cv (2) | IF | Cruz et al. (2009) | -5.60 | -37.73 |
| 78 | Botuverá Cv (2) | IF | Wang et al. (2006) | -27.22 | -49.15 |
| 79 | Taquarussu – Rv | BI | Parolin et al. (2006) | -22.50 | -52.33 |
| 80 | Buritizeiro | BI | Lorente et al. (2010) | -17.41 | -45.06 |
| 81 | Vereda Laçador | BI | Cassino (2011) | -17.81 | -45.43 |
| 82 | Salitre de Minas | IF/PC/BI | Pessenda et al. (1996) | -19.00 | -46.77 |
| 83 | Londrina | IF/PC/BI | Pessenda et al. (2004a) | -23.30 | -51.17 |
| 84 | Piracicaba | IF/PC/BI | Pessenda et al. (2004a) | -22.77 | -47.63 |
| 85 | Botucatu | IF/PC/BI | Pessenda et al. (2004a) | -23.00 | -48.00 |
| 86 | Anhemi | IF/PC/BI | Pessenda et al. (2004a) | -22.75 | -47.97 |
| 87 | Jaguariúna | IF/PC/BI | Pessenda et al. (2004a) | -22.67 | -47.02 |
| 88 | Salitre de Minas | IF/PC/BI | Pessenda et al. (2004a) | -19.00 | -46.77 |
| 89 | Misiones | IF/PC | Zech et al. (2009) | -27.39 | -55.52 |
| 90 | Tamanduá Rv (17) | PC | Turcq et al. (1997) | -21.45 | -47.60 |
| 91 | Serra Sul de Carajás – Lk | BI | Servant et al. (1993) | -6.30 | -50.20 |
| 92 | Salitre de Minas | BI | Servant et al. (1993) | -19.00 | -46.77 |
| 93 | Serra Sul de Carajás – Lk | IF/PC | Sifeddine et al. (1994) | -6.58 | -49.50 |
| 94 | Serra Sul de Carajás – Lk | IF/PC/BI | Sifeddine et al. (2001) | -6.58 | -49.50 |
| 95 | Caçó Lk (2) | IF/PC/BI | Jacob et al. (2004) | -2.96 | -43.42 |
| 96 | Serra Sul de Carajás - Lk | IF/PC/BI | Sifeddine et al. (2004) | -6.58 | -49.50 |
| 97 | Dom Helvécio Lk | IF/PC/BI | Sifeddine et al. (2004) | -19.68 | -42.63 |
| 98 | La Gaiba Lk (2) | BI | Whitney et al. (2011) | -17.75 | -57.58 |
| 99 | Paraná Rv (25) | BI/PC | Stevaux (2000) | -22.72 | -53.17 |
| 100 | Botucatu | IF/PC/BI | Gouveia et al. (2002) | -23.00 | -48.00 |
| 101 | Anhemi | IF/PC/BI | Gouveia et al. (2002) | -22.75 | -47.97 |
| 102 | Jaguariúna | IF/PC/BI | Gouveia et al. (2002) | -22.67 | -47.02 |
| 103 | Pontes e Lacerda | IF/PC/BI | Gouveia et al. (2002) | -15.27 | -59.22 |
| 104 | Índia Muerta | BI | Iriarte et al. (2004) | -33.70 | -53.95 |
| 105 | Campo Alegre | IF/PC/BI | Oliveira et al. (2008b) | -26.25 | -49.25 |
| 106 | Serra Norte Carajás – Lk | BI/PC | Turcq et al. (2002) | -6.30 | -50.20 |

Table 2. Continued.

| No. | Site | Proxy type | Reference | Lat. (°) | Long. (°) |
|-----|------------------------|------------|---|----------|-----------|
| 107 | Caracarana Lk | BI/PC | Turcq et al. (2002) | -3.84 | -59.78 |
| 108 | Água Preta de Baixo Lk | BI/PC | Turcq et al. (2002) | -18.42 | -41.83 |
| 109 | Dom Helvécio Lk | BI/PC | Turcq et al. (2002) | -19.68 | -42.59 |
| 110 | Feia Lk | BI/PC | Turcq et al. (2002) | -15.57 | -47.30 |
| 111 | Caçó Lk | IF/BI | Pessenda et al. (2005) | -2.96 | -43.42 |
| 112 | Botucatu (2) | IF/BI | Scheel-Ybert et al. (2003) | -22.85 | -48.48 |
| 113 | Jaguariúna (2) | IF/BI | Scheel-Ybert et al. (2003) | -22.67 | -47.17 |
| 114 | Anhembi | IF/BI | Scheel-Ybert et al. (2003) | -22.75 | -47.97 |
| 115 | Barreirinhas | IF/PC | Pessenda et al. (2004b) | -3.03 | -44.65 |
| 116 | Curucutu | IF/PC/BI | Pessenda et al. (2009) | -23.93 | -46.65 |
| 117 | Serra Negra Lk | BI | De Oliveira (1992) | -18.95 | -46.83 |
| 118 | Olhos Lk | BI | De Oliveira (1992) | -19.38 | -43.90 |
| 119 | Cromínia | BI | Ferraz-Vicentini and Salgado-Labouriau (1996) | -17.28 | -49.42 |
| 120 | Paixão Cv | IF | Barreto (2010) | -12.63 | -41.02 |

* The data published in this paper will be available through Pangaea (<http://www.pangaea.de>) as soon as the manuscript is accepted for publication. The available information on Pangaea include publication details, core details (name, location, latitude, longitude, elevation, coring device, core length), sample details (analytical method, samples treatment, sample interval, number of samples), dating details (number of datings within MH, calibration), climatic information (period, description, and evidences of changes observed), and values of the Q index.

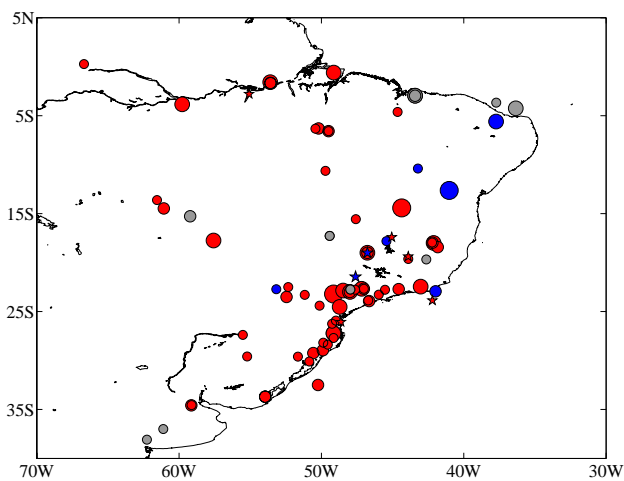


Fig. 4. MH precipitation/moisture palaeodata in eastern South America. Symbol colours: blue circles, wetter than modern; red circles, drier than modern; grey circles, similar to modern; red stars, dry-to-wet transition; and blue stars, wet-to-dry transition. Symbol size refers to palaeodata Q -index (a chronological reliability index; see text for more information) values; larger symbols indicate higher Q -index values. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

eastern South America. Despite the scarcity of SST records, the following pattern stands out: SST was lower than during the LH on the southeastern Brazilian continental margin, SST was higher/similar to the LH in the northeastern Brazilian continental margin, and SST was higher than during the LH over the Mid-Atlantic Ridge. However, Q -index values from these data are generally low.

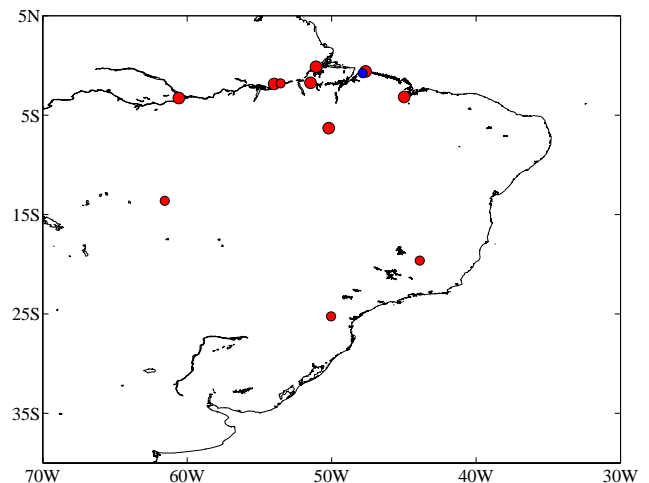


Fig. 5. MH lake level palaeodata in eastern South America. Symbol colours: red, lower than present; and blue, higher than present. Symbol size refers to palaeodata Q -index (a chronological reliability index; see text for more information) values; larger symbols indicate higher Q -index values. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

5 Discussion and conclusions

The evidence mentioned above indicates a significantly different scenario regarding MH precipitation over eastern South America if compared to the LH. The summarised records suggest an overall drier MH climate than during the LH in eastern South America, with the exception of northeastern Brazil (Figs. 4, 5). This pattern extends from 45 to 60° W, and from 0 to 35° S. Wetter climate than during the LH can be found locally on the coast of the states of São

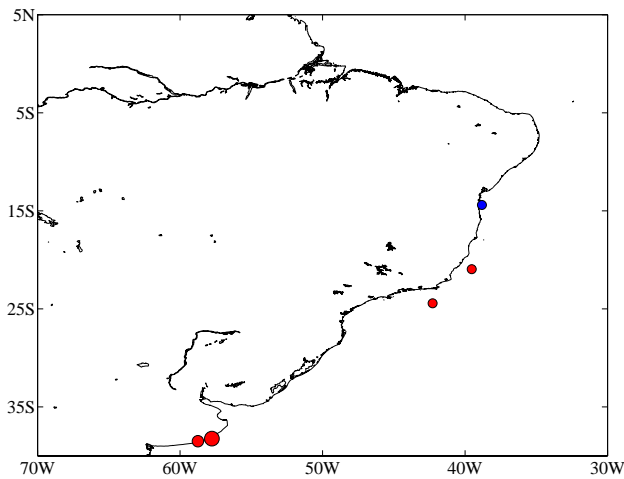


Fig. 6. MH salinity palaeodata off eastern South America. Symbol colours: blue circle, fresher than present; and red circles, saltier than present. Symbol size refers to palaeodata Q -index (a chronological reliability index; see text for more information) values; larger symbols indicate higher Q -index values. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

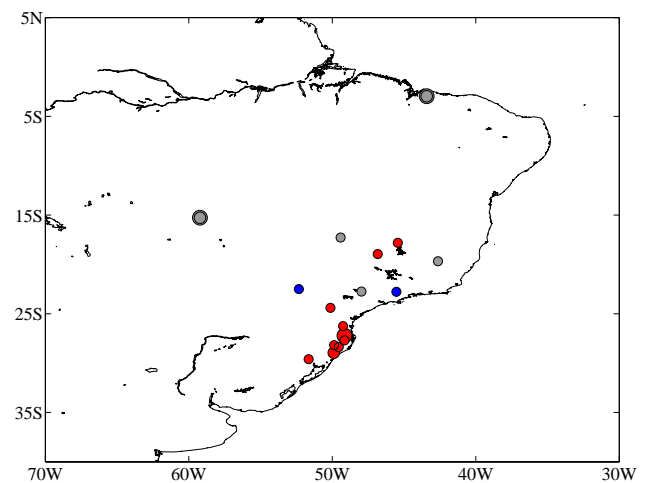


Fig. 7. MH air temperature palaeodata in eastern South America. Symbol colours: blue, colder than present; red, warmer than present; and grey, similar to present. Symbol size refers to palaeodata Q -index (a chronological reliability index; see text for more information) values; larger symbols indicate higher Q -index values. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

Paulo (ca. 23° S, 43° W; Nagai et al., 2009) and in the state of Minas Gerais (ca. 18° S, 43° W, e.g. Cassino, 2011).

Drier climatic conditions during the MH compared to the LH are portrayed by the replacement of wet forests by shrubs and grasslands in some regions, as suggested by pollen analyses (e.g. Behling and Safford, 2010, and others in Fig. 4). A drier MH climate can also be observed in proxies indicating lower lake levels than during the LH all across eastern South America (Fig. 5).

The land–sea temperature gradient is the major driver of the SAMS circulation (e.g. Vera et al., 2006). During the MH, lower than LH values of austral summer insolation in the Southern Hemisphere induced a less effective land–sea contrast. Less energy was available at the surface and diminished the ascendant motion. Rain cloud formation was impaired, characterising a drier climate if compared to the LH in the SAMS area. The release of latent heat by these clouds is responsible for the establishment of the BH, which is linked to the Northeast Trough (e.g. Marengo et al., 2012). Consequently, high-level atmospheric circulation was also smoothed, and the subsidence over northeastern Brazil was below modern average, generating more southern incursions of the ITCZ and precipitation in this region.

Coastal palaeodata indicate wetter/similar conditions to the LH (Fig. 4) (e.g. Nagai et al., 2009). Regional circulation features such as the land–sea breeze and winds associated with the position and intensity of the South Atlantic subtropical high can be related to the coastal areas that were wetter during the MH if compared to the LH. The land–sea breeze may have also been enhanced by a higher sea level during the MH (e.g. Angulo et al., 2006). It is noteworthy that the

MH climatic signal described for northeastern Brazil is based on a few records. However, these records show high Q -index values (Cruz et al., 2009; Barreto, 2010).

Air temperature records with high Q -index values indicate a warmer climate during the MH if compared to the LH in southern Brazil, a mixed signal in southeastern Brazil, and similar to LH air temperatures in northeastern Brazil and to the west of 60° W (Fig. 7). Proxy records of SST are very few and have intermediate Q -index values when compared to land records (Fig. 8). Their scarcity and intermediate Q -index values hamper the delivery of a clear scenario for the MH. The only relatively clear scenario can be observed at the NBC, which probably showed warmer SST during the MH if compared to the LH.

When compared to modern climate, our compilation indicates a deficit in the water balance in eastern South America during the MH. With diminished precipitation and enhanced evaporation (less cloudiness), the lake levels were below their modern levels, and air temperatures near the surface were above modern values. These higher air temperatures can be related to less vegetation and to a higher surface albedo. Ocean proxy records revealed saltier waters for the MH than during the LH off eastern South America, mainly close to river mouths such as the La Plata River (35° S, 57° W) in northern Argentina and the Doce River (20° S, 43° W) in southeastern Brazil (Fig. 6). Saltier waters near the coast are generally related to enhanced evaporation and/or reduced river discharge. These features are also related to a drier climate, corroborating the precipitation/moisture, lake levels, and air temperature palaeodata, as well as previous

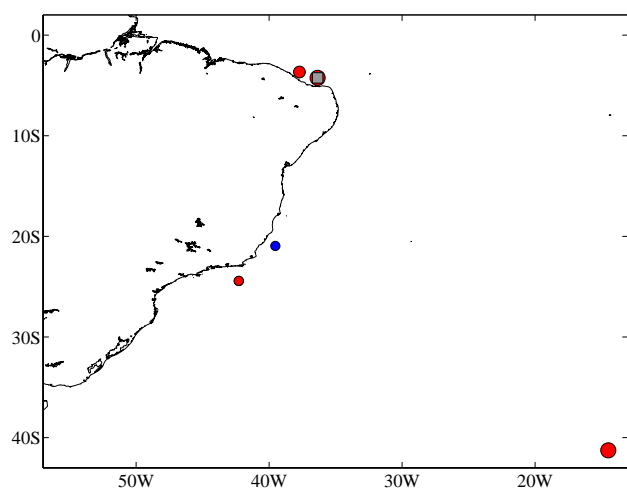


Fig. 8. MH sea surface temperature palaeodata off eastern South America. Symbol colours: blue circles, colder than present; red circles, warmer than present; grey circles, similar to present; and grey squares, warmer–colder oscillation. Symbol size refers to palaeodata Q -index (a chronological reliability index; see text for more information) values; larger symbols indicate higher Q -index values. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

studies (Valdes, 2000; Cruz et al., 2009; Silva Dias et al., 2009).

The BC transports warm waters southward, while the MC transports cold waters northward, and both are located off eastern South America (e.g. Goni et al., 1996). Consequently, the drier climatic scenario presented here could indicate an equatorward displacement of the Brazil–Malvinas Confluence (BMC) or a decrease in the meridional SST gradient in the western South Atlantic. With the decrease in summer insolation in the Southern Hemisphere during the MH, the South Atlantic Ocean received less energy, which could have been responsible for colder SSTs.

Our methodology points to the speleothem records to be the palaeodata with the highest Q -index values. However, as speleothem $\delta^{18}\text{O}$ does not always reflect the precipitation amount, multiproxy compilations are needed to reconstruct clearer past climate signals. Finally, we have identified precipitation as the climatic parameter that shows the most robust MH scenario in eastern South America, mainly because of the large availability and diversity of proxies and palaeo-records related to this variable.

Appendix A

Abbreviations

| | |
|------|---|
| AMO | Atlantic Multidecadal Oscillation |
| AMOC | Atlantic Meridional Overturning Circulation |

| | |
|--------|--|
| BC | Brazil Current |
| BCF | Brazil Current Front |
| BH | Bolivian High |
| CLIMAP | Climate: Long-range Investigation, Mapping, and Prediction |
| CMIP | Coupled Model Intercomparison Project |
| COHMAP | Cooperative Holocene Mapping Projects |
| ENSO | El Niño–Southern Oscillation |
| ITCZ | Intertropical Convergence Zone |
| LGM | Last Glacial Maximum |
| LH | Late Holocene |
| MC | Malvinas Current |
| MH | Mid-Holocene |
| NBC | North Brazilian Current |
| PDO | Pacific Decadal Oscillation |
| PMIP | Paleoclimate Modelling Intercomparison Project |
| SACZ | South Atlantic Convergence Zone |
| SALLJ | South American Low Level Jet |
| SAM | Southern Annular Mode |
| SAMS | South American monsoon system |
| SEC | South Equatorial Current |
| SECC | South Equatorial Countercurrent |
| SEUC | South Equatorial Undercurrent |
| SSS | Sea surface salinity |
| SST | Sea surface temperature |

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