Clim. Past Discuss., 8, 5925–5961, 2012
www.clim-past-discuss.net/8/5925/2012/
doi:10.5194/cpd-8-5925-2012
© Author(s) 2012. CC Attribution 3.0 License.

Climate
of the Past
Discussions

This discussion paper is/has been under review for the journal Climate of the Past (CP).
Please refer to the corresponding final paper in CP if available.

Mid-Holocene climate reconstruction for eastern South America

L. F. Prado[1], I. Wainer[1], C. M. Chiessi[2], M.-P. Ledru[3], and B. Turcq[4]

[1]Instituto Oceanográfico, Universidade de São Paulo, São Paulo, Brazil
[2]Escola de Artes, Ciências e Humanidades, Universidade de São Paulo, São Paulo, Brazil
[3]IRD UMR 226 Institut des Sciences de l'Evolution, IRD CNRS UM2, Montpellier, France
[4]IRD UMR 7159 Laboratoire d'Océanographie et du Climat: Expérimentations et approches numériques, Bondy, France

Received: 14 November 2012 – Accepted: 21 November 2012
– Published: 29 November 2012

Correspondence to: L. F. Prado (luciana.prado@usp.br)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Mid-Holocene (6 ka BP) is a key period to the study of climate, since it presented lower than present incoming summer insolation in the Southern Hemisphere, and the opposite in the Northern Hemisphere. This happened due to a different than present configuration of the orbital parameters. To investigate the effects of insolation on the Mid-Holocene climate, some global and regional multiproxy palaeodata compilations have been elaborated. However, few global studies have focused on the Southern Hemisphere, and none of the regional ones have characterized the Mid-Holocene climate in South America through a multiproxy approach. Here we present the first multiproxy compilation to the Mid-Holocene climate in eastern South America. We have compiled 120 palaeoclimatological data, published in 84 different papers. The palaeodata analyzed suggest a water deficit scenario in great part of eastern South America during Mid-Holocene, except for Northeastern Brazil. Nonetheless, further sampling is mandatory in South America and in the adjacent ocean basins.

1 Introduction

Recently, the Last Glacial Maximum (LGM) and the Mid-Holocene (MH) have been focused on numerous 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 al., 2012, and others). These specific periods in the past, corresponding to 21 000 yr before present (21 ka BP) and 6 ka BP, respectively, are usually chosen since they present some characteristics that can be used to test the climatic models response to different boundary conditions, compared to today. Whilst during the LGM the Earth was covered by a larger than present amount of ice, the MH was characterized by an increased (decreased) summer insolation in the Northern (Southern) Hemisphere, in relation to present conditions. This was due to a difference of about 101° between the MH and the current longitude of the perihelion. As a consequence,

cc BY

the perihelion occurred at the autumn equinox at the MH, whilst today it is reached at the winter solstice (Joussaume and Braconnot, 1997). This caused a MH insolation diminution of ca. 20 W m^{-2} in southern latitudes from January to March, comparing to Pre-Industrial values (Bosmans et al., 2012).

The data-model approaches require good quality palaeoclimatic records and state-of-the-art climatic models. Aiming this, some research projects were created. The LGM was the target of the Climate: Long-range Investigation, Mapping and Prediction research group (CLIMAP). The CLIMAP project consisted on the world ocean mapping, through marine records and comparison with numerical models outputs (CLIMAP Project Members, 1976, 1981, 1984). It was the first palaeoclimatic reconstruction and motivated further studies. The Cooperative Holocene Mapping Project (COHMAP, COHMAP Members, 1988) focused on the climate of the last 18 000 yr using palaeodata and global models results. The great advance in technology and computers through time has enabled the use of more complex numerical models in simulating the climate. Indeed, a variety of global models has become available, with different parameterizations and distinct outputs. Consequently, projects such as the Palaeoclimate Modelling Intercomparison Project (PMIP, Braconnot et al., 2007a, b, 2012) have been created, so as to evaluate the differences among the models, and the biases regarding the observations. The PMIP is on 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 (21 kyr), the MH (6 kyr) and the Last Millennium. The implication of this is that the best the reproduction of past climates, the more accurate the climate prediction. Climatic changes have been observed throughout the Earth's history, and knowing what is coming next has great importance for planning and implementing adaptation and mitigation policies. Yet, as the CLIMAP and COHMAP initiatives, the state-of-the-art models included on the PMIP3 must also be evaluated regarding observations. Hence, gathering records in the form of palaeodata synthesis is imperative.

In the supplementary information, Braconnot et al. (2012) present a summary of the available global and regional datasets, derived from different proxies and archives, to the MH and the LGM. These efforts have been motivated by the PMIP and other modeling projects. The BIOME 6000 (Prentice and Webb III, 1998) consists of past vegetation mapping, based on pollen and fossil-plant records, and so the research developed by Bartlein et al. (2011). Dust variations are reconstructed by the Dust Indicators and Records from Terrestrial and Marine Palaeoenvironments (DIRTMAP, Kohfeld and Harrison, 2001). Geomorphic and biostratigraphic data extracted from lakes constitute The Global Lake Status Data Base (GLSDB, Kohfeld and Harrison, 2000; Harrison et al., 2003), and contains records of changes in the water balance to the last 30 000 yr. Records of biomass burning extracted from sedimentary charcoal data inform changes in vegetation through wildfires; the Global Palaeofire Working Group (GPWP) has developed research within this area, to the LGM and the MH (Power et al., 2008). LGM global sea surface temperatures (SST) and seasonal sea-ice cover were reconstructed by the Multiproxy Approach for the Reconstruction of the Glacial Ocean project (MARGO, Kucera et al., 2005, 2009) using biological and geochemical palaeodata, whilst the GHOST project worked on the MH SST through alkenone and magnesium/calcium palaeothermometry (Leduc et al., 2010). Ice cores have been sampled mainly at the Antarctica (Vimeux et al., 2002; Kawamura et al., 2007; Jouzel et al., 2007; Masson-Delmotte et al., 2011; Stenni et al., 2011) and at the Greenland (Rasmussen et al., 2008; Kjaer et al., 2011; Steen-Larsen et al., 2011), with the purpose of complementing the land and ocean information. Conversely, all of these efforts denote few records in the Southern Hemisphere, mainly to the MH in South America, comparing to other locations in the Northern Hemisphere and to the LGM period. Thus, the uncertainties in this continent are large, and should be mitigated through efforts similar to the one presented here.

Here we present a multiproxy palaeoclimatic compilation to the MH in eastern South America. It includes data originated from land, caves, lakes, river and ocean archives. Our objective was to obtain a climatic scenario to the MH in eastern South America.

cc BY

Section 2 reviews the main aspects of the South American Monsoon System, which are necessary to interpret the palaeodata. Section 3 presents the proxies used in this compilation, how the spatial and time domains were estipulated, the limitations of each proxy and a quality index developed to evaluate and compare different types of proxy. Section 4 is dedicated to the results, whilst the discussion and some conclusions are presented in Sect. 5.

2 Precipitation in South America

The terminology "South American Monsoon System" (SAMS) comes after Vera et al. (2006), and Zhou and Lau (1998) papers, since 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 surface circulation pattern in large scale, due to the 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, but by showing the seasonal inversion of the easterlies when subtracting the annual wind component from the winter and summer patterns. The result is a circulation originated at the subsaharian region that crosses the equator and is driven southeastward by the Andes Cordillera. In the Amazon Basin, a thermal low develops at the surface, as a consequence of land heating. These winds reach the Gran Chaco region, in Paraguay, and finally move clockwise, forming a low pressure at the surface. Lenters and Cook (1995) have found five major regions of summer precipitation in South America: (1) the Amazon Basin and (2) North of the Andes, related to wind convergence at low levels and to the thermal low pressure at the surface; (3) Center of the Andes, due to the orography increase at the east side of the slope and to the meridional wind convergence; (4) South of the Andes, purely orographic; and (5) South Atlantic Convergence Zone (SACZ), formed by wind convergence and moisture advection at low levels, and contributions of transient eddies moving equatorward.

cc BY

All these features correspond to surface patterns, but the high levels also present characteristics linked to the SAMS. The Bolivian High (BH) is the major summer feature at high levels and is a response to the latent heat released by the 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 the Northeast of Brazil. Both the BH and the Northeast trough, at high levels, are associated with the SACZ at the surface (Lenters and Cook, 1997). The SACZ is the main convective system in South America, and is responsible for most of the summer rain in Southeast and Central Brazil. It corresponds to a northwest-southeast oriented cloud band, and brings the moisture from the Amazon region to South and Southeast Brazil. The convergence zone couples with transient eddies from higher latitudes and can stay stationary for some days, characterizing the SACZ. The Atlantic Ocean SST can also influence the SACZ in intensity and position (Chaves and Nobre, 2004). Another important circulation feature is the South American Low Level Jet (SALLJ). It transports moisture from the Amazon Basin to the center-south of South America. The SALLJ consists of a wind maximum at 1 or 2 km high and can influence the position and intensity of the SACZ (Marengo et al., 2004). The transient systems are responsible for part of the precipitation in South America throughout the year, predominantly in Southern and Southeastern South America and also contribute to the SACZ. Reboita et al. (2010) have found three major areas of cyclones action over the Southern Atlantic Ocean, in the east coast of South America: Argentina (around 48° S), the La Plata river discharge in Uruguay (around 35° S), and the south/southeastern coast of Brazil. Nevertheless, they could not detect a preferential season for the occurrence of cyclones over the Southern Atlantic Ocean.

Great part of the interannual variability of the SAMS can be explained by the El Niño-Southern Oscillation (ENSO): its warm (cold) phase is responsible for decreased (increased) precipitation in the wet season of northern South America and above (below) average in Southeastern South America (Marengo et al., 2010, and references therein). The Southern Annular Mode (SAM) is also related to interannual oscillations in precipitation in Southeastern South America, but totally independent from the ENSO signal (Silvestri and Vera, 2003). At interdecadal timescales, there are evidences of effects induced by the Pacific Decadal Oscillation (PDO) and by the Atlantic Multidecadal Oscillation (AMO) on the SAMS variability (Garcia and Kayano, 2008; Chiessi et al., 2009).

An important problem found in palaeoclimatological studies is discussed by Vuille et al. (2012), related to differences and interaction between the SAMS and the Intertropical Convergence Zone (ITCZ). Both present seasonal variability, but the ITCZ is a permanent feature of the atmospheric circulation and follows the impacts of the annual cycle of insolation on SST, whereas the SAMS reflects the land-sea thermal gradient. Besides, at the American region, the ITCZ is essentially an oceanic phenomenon concentrated in the Northern Hemisphere, whilst the SAMS occurs basically over the South American continent. Moreover the SAMS moisture supply is strong in comparison to the easterlies and to the ITCZ, the SAMS is totally dependent on the land topography, what maintains this system over the continent whilst the ITCZ moves around the equator.

3 Proxy data

Palaeoclimatological information can be obtained from some natural elements that were influenced by past climate conditions. Still, we must assume that this climatic signal was attenuated by noise, what depends on the proxy chosen. Indeed, it is crucial to know the advantages and disadvantages of each kind of proxy, to avoid misinterpretation of the climatic imprint. The multiproxy compilation we present here contains a great diversity of proxy types, and we must take into account their limitations. Table 1 displays how we classified the palaeodata and the kinds of proxy included in each one of the subdivisions. It was based on Wirtz et al. (2010) proxy classification (see Table 1 in Wirtz et al. (2010) for more details). The oxygen and carbon stable isotopic ratios are the fractionation-depending proxies. The physic-chemical proxies comprise all geochemical ratios and physic-chemical approaches, whilst all information derived

CC BY

from organisms was classified as biological. We highlight that substantial part of the palaeodata analyzed is related with the latter type (ca. 83 %), essentially pollen assemblages.

3.1 Data limitations

Different proxies have distinct frequency dependence, due to their inherent sensibility to climate. Marine sediments are related to low frequency resolution (> 1 ka), because of the low sedimentation rate and bioturbation in non anoxic zones, whilst high frequency resolution can be found in corals or speleothems records, such as years or seasons (Bradley, 1999). Another consideration should be done in respect to different temporal responses from each type of proxy. The archives can be affected by climatic changes immediately after the event, or present a delayed reaction. Vegetational data, such as pollen assemblages, present climatic inertia, estimated in at least 25 ± 15 yr to abrupt climate changes, at the Cariaco Basin in tropical South America (Hughen et al., 2004). Moreover, Huntley (2012) discusses about the response of biological proxies to the bioclimatic variables instead of to the climate itself, and how this varies from one organism to another. This exemplifies the difficulty in comparing distinct types of proxies. Futhermore, not all records are continuous in time; in this case, it is essential to consider the greatest diversity of proxies available, by complementing the analysis. When dealing with biological records, one should also be aware of possible seasonal preferences. Planktonic foraminifera and coccolithophores are examples of organisms which carry the seasonal signal related to their biological cycles (Giraudeau and Beaufort, 2008).

3.2 Spatial and time domain

In this study, we used the ^{14}C ages published by the authors of each paper examined. So, calibrated ages will be expressed here as years Before Past (yr BP). Two main criteria were defined to select the papers included in our compilation. The first one is the definition of the MH period. The MH is referred to 6000 yr BP (e.g. Braconnot et

CC BY

al., 2012); however, the dating approach and the variable temporal resolution of the samples induce to uncertainties that should be taken into account. To solve this, we considered the range from 7000 to 5000 yr BP as the period corresponding to MH, and the aim is to characterize its mean climatic scenario.

Secondly, the spatial domain (Fig. 1) was defined based on physical aspects. The latitudinal limits comprise the equator and the westerlies mean high level latitude, around 40° S. 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 (Peixoto and Oort, 1992). The southwestern Atlantic Ocean (ca. 10° W) defines the eastern border of the domain, and the western one is limited by altitudes below 2300 m.

3.3 Quality control of the palaeodata

A thorough investigation of published studies containing MH climatic information in South America was organized. It resulted in the multiproxy palaeodata compilation presented here, summarized in Table 2, which contains location, proxy type and references of each paper examined. There were synthetized 120 palaeoclimatological information resulted from analysis of 84 studies. Some papers included different analyses, or an update of cores already examined previously. Figure 2 shows the spatial distribution of the records considered in this study. The numbers on the map identify each sample location, listed in Table 2. The data published in this paper will be available through Pangaea (http://www.pangaea.de) as soon as the manuscript is accepted for publication.

In order to evaluate the reliability of the palaeodata, we have created a quality index (Q), based on the sampling resolution and the sample age model:

$$Q = \frac{\mathrm{CA} + R + D}{3} \tag{1}$$

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

$$R = \begin{cases} 0.1 \text{ for ratio between } 0.01 \text{ and } 0.1 \\ 0.2 \text{ for ratio between } 0.11 \text{ and } 0.2 \\ \vdots \\ 11.0 \text{ for ratio between } 10.01 \text{ and } 11.00 \end{cases} \tag{2}$$

and so on. D (datings) is the number of datings within the interval 7–5 kyr divided by 10. The index is a semi quantitative approach that simply involves the computation of an arithmetic mean, giving the same weight to all parameters. Therefore, as Q encompasses a sum, the greater its value, the higher the quality of the palaeodata.

4 Results

The quality index Q described above was applied to the palaeodata in order to obtain their spatial distribution and subjective level of confidence. According to the description made, larger symbols on the figures refer to better quality data. Values of the Q index will be available on the supplementary table at http://www.pangaea.de, as soon as the manuscript is accepted for publication. It is important to mention that all the climatic information in we present here is based on the authors' conclusions contained in each paper used in this compilation and do not reflect any further interpretation.

Pollen assemblage records are of special importance because of their great amount. Figure 2 shows air temperature palaeodata to MH. The majority of samples were collected at the center-south of Brazil and Uruguay. Data of greater quality, according to index Q, can be found near the equator and in Southern Brazil. The records point to a warmer climate in the Southern Brazil and similar to present in northern Northeast Brazil.

Precipitation or moisture are the variables with the greater number of palaeodata, for two reasons: these are the main information obtained from pollen assemblages, and this kind of archive constitutes the main proxy records found in eastern South America, related to the MH. The general scenario found through the palaeodata analyzed corresponds to a drier than present eastern South America, excepted by the Northeastern Brazil, which presents an unclear climate signal to MH. This scenario has already been discussed (Silva Dias et al., 2009; Cruz et al., 2009). Cruz et al. (2009) compared speleothem records and precipitation, vertical velocity, geopotential and oxygen isotopes fields simulated by a numerical model to characterize an east-west antiphasing. Higher quality palaeodata correspond to speleothems records. Oxygen isotopic ratio values capture the precipitation variability because the isotopic fractionation depends on the path the water takes from it source to its sink. The greater the distance, the greater the loss of heavier isotopes (Vuille et al., 2012). Thus, this ratio may have different interpretations depending on the site of the record. In South America, this ratio is related to the SAMS activity, in Southeastern Brazil, and in Northeastern Brazil it reflects the ITCZ activity.

In opposition to the precipitation/moisture data, salinity palaeorecords at the South America coast (Fig. 4) are fewer. This is due to the lesser amount of works related to this variable, caused by difficulties in collecting marine samples. However, all palaeodata but one show saltier conditions along the coast during MH. Better quality records, according to *Q* quality index, are situated at Northeastern Brazil and at the Argentinean coast.

Difficulties in collecting marine cores also reflect on the amount of SST proxy records (Fig. 5) to MH at the South America Coast. Even though, a spatial coherence is observed with the analyzed data: SST lower than present at the Southeastern Brazilian Coast, SST higher/similar to present in the Northeastern Brazil and SST higher than present at the southwestern Atlantic Ocean. The quality of these data, measured by *Q* index, however, is low.

Climatic information extracted from lake level proxies is showed in Fig. 5. Lake levels were lower than present in all sites analyzed, which corroborates with precipitation/moisture palaeodata (Fig. 3), characterizing a drier than present climate in eastern

cc BY

South America during MH. As to the SST proxy, the quality of lake levels proxy samples is low, being the best ones located in eastern Amazon.

5 Discussion and conclusions

The above-mentioned evidences revealed by the palaeodata lead to some key conclusions regarding the MH climate in eastern South America. The records suggest a large-scale drier than present MH climate in eastern South America, except for Northeastern Brazil. The drier areas are pointed mainly by high quality speleothem records; this pattern extends from 45° W to 60° W, and from 0° to 35° S. Wetter than present climate can also be found locally at the coast of Rio de Janeiro and São Paulo states (ca. 23° S, 43° W; Behling and Negrelle, 2001; Behling et al., 2007; Nagai et al., 2009), and in the Minas Gerais state (ca. 18° S, 43° W; Enters et al., 2010; Cassino, 2011).

Greater quality air temperature records indicate a warmer than present climate during MH in Southern Brazil, a mixed signal in Southeastern Brazil, and similar to present air temperature in Northeastern Brazil and west of 60° W. A drier than present climate during MH is portrayed in 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 listed in the present compilation). It can also be observed in lower than present lake levels all across the South America. SST proxy records are few and have intermediate quality when compared to land records. This decreases the accuracy of SST proxy records during MH. However, the existing records suggest warmer southern waters, and colder northern waters, at the Brazilian coast.

We suggest that lower than present values of summer insolation in the Southern Hemisphere during MH induced an ineffective land-sea contrast, the major mechanism responsible for the SAMS circulation. Less availability of energy at the surface diminished the ascendant motion, and so the formation of rain clouds, characterizing a drier than present climate at 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.

Consequently, the atmospheric circulation in high levels was also smoothed and the subsidence over the Northeastern Brazil was below the current average, generating more precipitation at this region. Diminished cloudiness and precipitation resulted in warmer air temperatures near the surface, as a consequence of higher ground albedo.

Regional circulation features such as land-sea breeze and winds associated with the position and intensity of the South Atlantic Subtropical High (SASH) can be related to the wetter than present regional areas. The land-sea breeze could also be enhanced by a higher sea level by this time (e.g. Bezerra et al., 2003). The climatic signal found in Northeastern Brazil is not very clear, since there are few records in this region. However, they correspond to speleothem records (Cruz et al., 2009; Barreto, 2010) and present good quality. Coastal palaeodata indicate wetter/similar to present conditions nearby (Behling and Negrelle, 2001; Behling et al., 2007; Nagai et al., 2009; Enters et al., 2010; Cassino, 2011).

When compared to present, the observed scenario points to a deficit in water balance: with precipitation diminished and evaporation enhanced (less cloudiness) the lake levels were below the current ones and air temperature near surface was above present values. Ocean proxy records revealed saltier than present waters at the South American Coast, mainly in river mouths, like Plata River (35° S, 57° W), in Argentina, and Doce River (20° S, 43° W), at Southeastern Brazil. Saltier waters near the coast are generally related to greater evaporation and/or smaller rivers discharge. These features are also related to a drier climate, corroborating with precipitation/moisture, lake levels and air temperature palaeodata.

The Brazil Current (BC) is a warmer southward current, and the Malvinas Current (MC) is a colder northward current, both at the South American Atlantic coast. Consequently, this situation could indicate an equatorward displacement of the Brazil-Malvinas Confluence (BMC) and a subsequent decrease in the SST gradient. With the insolation decrease in Southern Hemisphere during MH, the South Atlantic Ocean received and stored less energy, what could have reflected in colder SST values. Colder

SST at the subtropical Atlantic Ocean might have displaced the Subtropical Front towards north, and so the BMC.

Besides the comprehensive research on the palaeodata available to the MH presented here, it remains clear that further intensive sampling is mandatory in the South American region, and in the adjacent ocean basins. Still, the compilation elaborated here represents a new effort to the study of MH climate in South America.

Abbreviations

AMO	Atlantic Multidecadal Oscillation
BC	Brazil Current
BH	Bolivian High
CLIMAP	Climate: Long-range Investigation, Mapping and Prediction
CMIP	Coupled Model Intercomparison Project
COHMAP	Cooperative Holocene Mapping Projects
DIRTMAP	Dust Indicators and Records from Terrestrial and Marine Palaeoenvironments
ENSO	El Niño Southern Oscillation
GHOST	Global Holocene Spatial and Temporal Variability
GLSDB	Global Lake Status Data Base
GPWP	Global Palaeofire Working Group
ITCZ	Intertropical Convergence Zone
LGM	Last Glacial Maximum
MARGO	Multiproxy Approach for the Reconstruction of the Glacial Ocean
MC	Malvinas Current
MH	Mid-Holocene
PDO	Pacific Decadal Oscillation
PMIP	Palaeoclimate Modelling Intercomparison Project
SACZ	South Atlantic Convergence Zone
SALLJ	South American Low Level Jet
SAM	Southern Annular Mode
SAMS	South American Monsoon System
SASH	South Atlantic Subtropical High
SST	Sea Surface Temperature

Acknowledgements. This research was funded by FAPESP (grant 2011/06610-0), CNPq (grant 300223/93-5), and CNPq-MCTI/NCT-Criosfera (grant 573720/2008).

References

Absy, M. L., Cleef, A., Fournier, M., Martin, L. Servant, M., Sifeddine, A., Silva, M. F., Soubies, F., Suguio, K., Turcq, B., and Van Der Hammen, T.: Mise en évidence de quatre phases d'ouverture de la fôret dense dans de sud-est de l'Amazonie au cours des 60000 dernières années. Première comparaison avec d'autres regions tropicales, C. R. Acad. Sci. Paris, 312, II, 673–678, 1991.

Arz, H. W., Pätzold, J., and Wefer, G.: Correlated millennial-scale changes in surface hydrography and terrigenous sediment yield inferred from Last-Glacial marine deposits off Northeastern Brazil, Quaternary Res., 50, 157–166, 1998.

Arz, H. W., Gerhardt, S., Pätzold, and Röhl, U.: Millennial-scale changes of surface- and deepwater flow in the western tropical Atlantic linked to Northern Hemisphere high-latitude climate during the Holocene, Geology, 29, 239–242, 2001.

Barberi, M., Salgado-Labouriau, M. L., and Suguio, K.: Paleovegetation and paleoclimate of "Vereda de Águas Emendadas", central Brazil, J. S. Am. Earth Sci., 13, 241–254, 2000.

Barreto, E. A. S.: Reconstituição da pluviosidade da chapada diamantina (BA) durante o Quaternário tardio através de registros isotópicos (O e C) em estalagmites, Master Dissertation, Universidade de São Paulo, 2010.

Bauermann, S. G., Marques-Toigo, M., Behling, H., and Souza, P. A.: Análises palinológicas da turfeira de Águas Claras, planície costeira do Rio Grande do Sul, Brasil, 9°Congresso da Associação Brasileira de Estudos do Quaternário, 2003.

Behling, H.: Investigations into the Late Pleistocene and Holocene history of vegetation and climate in Santa Catarina (S Brazil), Veg. Hist. Archaeobot., 4, 127–152, 1995a.

Behling, H.: A high resolution Holocene pollen records from Lago do Pires, SE Brazil: vegetation, climate and fire history. J. Paleolimnol., 14, 253–268, 1995b.

Behling, H.: Late Quaternary vegetation, climate and fire history from the tropical mountain region of Morro de Itapeva, SE Brazil, Palaeogeogr. Palaeocli., 129, 407–422, 1997a.

Behling, H.: Late Quaternary vegetation, climate and fire history of the Araucaria forest and campos region from Serra Campos Gerais, Paraná State (South Brazil), Rev. Palaeobot. Palyno., 97, 109–121, 1997b.

Behling, H.: Late Quaternary environmental changes in the Lagoa da Curuça region (eastern Amazonia, Brazil) and evidence of Podocarpus in the Amazon lowland, Veg. Hist. Archaeobot., 10, 175–183, 2001.

Behling, H.: Late Quaternary vegetation and climate dynamics in southeastern Amazonia inferred from Lagoa da Confusão in Tocantins State, northern Brazil, Amazoniana, 17, 27–39, 2002.

Behling, H.: Late glacial and Holocene vegetation, climate and fire history inferred from Lagoa Nova in the southeastern Brazilian lowland, Veg. Hist. Archaeobot., 12, 263–270, 2003.

Behling, H.: Late Quaternary vegetation, fire and climate dynamics of Serra do Araçatuba in the Atlantic coastal mountains of Paraná State, southern Brazil, Veg. Hist. Archaeobot., 16, 77–85, doi:10.1007/s00334-006-0078-2, 2007.

Behling, H. and Costa, M. L.: Studies on Holocene tropical vegetation mangrove and coast environments in the state of Maranhão, NE Brazil, J. Quat. S. Am. A., 10, 93–118, 1997.

Behling, H. and Costa, M. L.: Holocene environmental changes from the Rio Curuá record in the Caxiuanã region, Eastern Amazon Basin, Quaternary Res., 53, 369–377, 2000.

Behling, H. and Costa, M. L.: Holocene vegetational and coastal environmental changes from the Lago Crispim record in northeastern Pará State, eastern Amazonia, Rev. Palaeobot. Palyno., 114, 145–155, 2001.

Behling, H. and Negrelle, R. B.: Tropical rain forest and climate dynamics of the Atlantic lowland Southern Brazil, during the Late Quaternary, Quaternary Res., 56, 383–389, doi:10.1006/qres.2001.2264, 2001.

Behling, H. and Safford, H. D.: Late-glacial and Holocene vegetation, climate and fire dynamics in the Serra dos Órgãos, Rio de Janeiro State, southeastern Brazil, Glob. Change Biol., 16, 1661–1671, doi:10.1111/j.1365-2486.2009.02029.x, 2010.

Behling, H., Bauermann, S. G., and Neves, P. C. P.: Holocene environmental changes in the São Francisco de Paula region, southern Brazil, J. S. Am. Earth Sci., 14, 631–639, 2001a.

Behling, H., Cohen, M. C. L., and Lara, R. J.: Studies on Holocene mangrove ecosystem dynamics of the Bragança Peninsula in north-eastern Pará, Brazil, Palaeogeogr. Palaeocl., 167, 225–242, 2001b.

Behling, H., Pillar, V. D., Orlóci, L., and Bauermann, S. G.: Late Quaternary Araucaria forest, grassland (Campos), fire and climate dynamics, studied by high-resolution pollen, charcoal and multivariate analysis of the Cambará do Sul core in southern Brazil, Palaeogeogr. Palaeocl., 203, 277–297, 2004.

Behling, H., Pillar, V. D. P., and Bauermann, S. G.: Late Quaternary grassland (Campos), gallery forest, fire and climate dynamics, studied by pollen, charcoal and multivariate analysis of the São Francisco de Assis core in western Rio Grande do Sul (southern Brazil), Rev. Palaeobot. Palyno., 133, 235–248, 2005.

Behling, H., Dupont, L., Safford, H. D., and Wefer, G.: Late Quaternary vegetation and climate dynamics in the Serra da Bocaina, southeastern Brazil, Quaternary Int., 161, 22–31, 2007.

Bezerra, F. H. R., Barreto, A. M. F., and Suguio, K.: Holocene sea-level history on the Rio Grande do Norte State coast, Brazil, Mar. Geol., 196, 73–89, 2003.

Bosmans, J. H. C., Drijfhout, S. S., Tuenter, E., Lourens, L. J., Hilgen, F. J., and Weber, S. L.: Monsoonal response to Mid-Holocene orbital forcing in a high resolution GCM, Clim. Past, 8, 723–740, doi:10.5194/cp-8-723-2012, 2012.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A., Laîné, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S. L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: experiments and large-scale features, Clim. Past, 3, 261–277, doi:10.5194/cp-3-261-2007, 2007a.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 2: feedbacks with emphasis on the location of the ITCZ and mid- and high latitudes heat budget, Clim. Past, 3, 279–296, doi:10.5194/cp-3-279-2007, 2007b.

Braconnot, P., Harrison, S. P., Kageyama, M., Bartlein, P. J., Masson-Delmotte, V., Abe-Ouchi, A., Otto-Bliesner, B., and Zhao, Y.: Evaluation of climate models using palaeoclimatic data, Nature Climate Change, 2, 417–424, doi:10.1038/nclimate1456, 2012.

Bush, M. B., Miller, M. C., De Oliveira, P. E., and Colinvaux, P. A.: Two histories of environmental change and human disturbance in eastern lowland Amazonia, The Holocene, 10, 543–553, doi:10.1191/095968300672647521, 2000.

Bush, M. B., Silman, M. R., De Toledo, M. B., Listopad, C., Gosling, W. D., Williams, C., De Oliveira, P. E., and Krisel, C.: Holocene fire and occupation in Amazonia: records from two lake districts, Phil. Trans. R. Soc. B., 362, 209–218, doi:10.1098/rstb.2006.1980, 2007.

Carré, M., Azzoug, M., Bentaleb, I., Chase, B. M., Fontugne, M., Jackson, D., Ledru, M.-P., Maldonado, A., Sachs, J. P., and Schauer, A. J.: Mid-Holocene mean climate in the south eastern Pacific and its influence on South America, Quaternary Int., 253, 55–66, doi:10.1016/j.quaint.2011.02.004, 2012.

Cassino, R. F.: Reconstituição da vegetação e do clima do Chapadão dos Gerais durante o Holoceno, a partir da análise palinológica da Vereda Laçador, Master Dissertation, Universidade Federal de Minas Gerais, 2011.

Chiessi, C. M., Mulitza, S., Pätzold, J., and Wefer, G.: How different proxies record precipitation variability over southeastern South America, IOP Conf. Series: Earth and Environmental Science, 9, 012007, doi:10.1088/1755-1315/9/1/012007, 2010.

Colinvaux, P. A., De Oliveira, P. E., Moreno, J. E., Miller, M. C., and Bush, M. B.: A long pollen record from lowland Amazonia: forest and cooling in glacial times, Science, 274, 85–88, 1996.

Cruz Jr., F. W., Burns, S. J., Karmann, I., Sharp, W. D., Vuille, M., Cardoso, A. O., Ferrari, J. A., Silva Dias, P. L., and Viana Jr., O.: Insolation-driven changes in atmospheric circulation over the past 116,000 years in subtropical Brazil, Nature, 434, 63–66, 2005.

Cruz Jr., F. W., Burns, S. J., Karmann, I., Sharp, W. D., and Vuille, M.: Reconstruction of regional atmospheric circulation features during the late Pleistocene in subtropical Brazil from oxygen isotope composition of speleothems, Earth Planet. Sci. Lett., 248, 495–507, doi:10.1016/j.epsl.2006.06.019, 2006a.

Cruz Jr., F. W., Burns, S. J., Karmann, I., Sharp, W. D., Vuille, M., and Ferrari, J. A.: A stalagmite record of changes in atmospheric circulation and soil processes in the Brazilian subtropics during the Late Pleistocene, Quaternary Sci. Rev., 25, 2749–2761, doi:10.1016/j.quascirev.2006.02.019, 2006b.

Cruz Jr., F. W., Burns, S. J., Jercinovic, M., Karmann, I., Sharp, W. D., and Vuille, M.: Evidence of rainfall variations in Southern Brazil from trace element ratios (Mg/Ca and Sr/Ca) in Late Pleistocene stalagmite, Geochim. Cosmochim. Ac., 71, 2250–2263, doi:10.1016/j.gca.2007.02.005, 2007.

Cruz, F. W., Vuille, M., Burns, S. J., Wang, X., Cheng, H., Werner, M., Lawrence Edwards, R., Karmann, I., Auler, A. S., and Nguyen, H.: Orbitally driven east-west antiphasing of South American precipitation, Nat. Geosci., 2, 210–214, doi:10.1038/NGEO444, 2009.

De Oliveira, P. E.: A palynological record of Late Quaternary vegetational and climatic change in southeastern Brazil, PhD Dissertation, The Ohio State University, 1992.

De Oliveira, P. E., Barreto, A. M. F., and Suguio, K.: Late Pleistocene/Holocene climatic and vegetational history of the Brazilian caatinga: the fossil dunes of the middle São Francisco River, Palaeogeogr. Palaeocl., 152, 319–337, 1999.

De Toledo, M. B. and Bush, M. B.: A mid-Holocene environmental change in Amazonian savannas, J. Biogeogr., 34, 1313–1326, 2007.

Enters, D., Behling, H., Mayr, C., Dupont, L., and Zolitschka, B.: Holocene environmental dynamics of south-eastern Brazil recorded in laminated sediments of Lago Aleixo, J. Paleolimnol., 44, 265–277, doi:10.1007/s10933-009-9402-z, 2010.

Ferraz-Vicentini, K. R. and Salgado-Labouriau, M. L.: Palynological analysis of a palm swamp in Central Brazil, J. S. Am. Earth Sci., 9, 3/4, 207–219, 1996.

Garcia, M. J., DeOliveira, P. E., Siqueira, E., and Fernandes, R. S.: A Holocene vegetational and climatic record from the Atlantic rainforest belt of coastal State of São Paulo, SE Brazil, Rev. Palaeobot. Palyno., 131, 181–199, 2004.

Gouveia, S. E. M., Pessenda, L. C. R., Aravena, R., Boulet, R., Scheel-Ybert, R., Bendassoli, J. A., Ribeiro, A. S., and Freitas, H. A.: Carbon isotopes in charcoal and soils in studies of paleovegetation and climate changes during the late Pleistocene and the Holocene in the southeast and centerwest regions of Brazil, Global Planet. Change, 33, 95–106, 2002.

Groeneveld, J. and Chiessi, C. M.: Mg/Ca of Globorotalia inflate as a recorder of permanent thermocline temperatures in the South Atlantic, Paleoceanography, 26, PA2203, doi:10.1029/2010PA001949, 2011.

Harrison, S. P., Kutzbach, J E., Liu, Z., Bartlein, P. J., Otto-Bliesner, B., Muhs, D., Prentice, I. C., and Thompson, R. S.: Mid-Holocene climates of the Americas: a dynamical response to changed seasonality, Clim. Dynam., 20, 663–688, doi:10.1007/s00382-002-0300-6, 2003.

Hassan, G. S., Espinosa, M. A., and Isla, F. I.: Diatom-based inference model for paleosalinity reconstrctions in estuaries along the northeastern coast of Argentina, Palaeogeogr. Palaeocl., 275, 77–91, 2009.

Hughen, K. A., Eglinton, T. I., Xu, L., and Makou, M.: Abrupt tropical vegetation response to rapid climate changes, Science, 304, 1955–1959, doi:10.1126/science.1092995, 2004.

Iriarte, J.: Vegetation and climate change since 14,810 14C yr B.P. in southeastern Uruguay and implications for the rise of early Formative societies, Quaternary Res., 65, 20–32, 2006.

Iriarte, J., Holst, I., Marozzi, O., Listopad, C., Alonso, E., Rinderknecht, A., and Montaña, J.: Evidence for cultivar adoption and emerging complexity during the mid-Holocene in the La Plata Basin, Nature, 432, 614–617, 2004.

Irion, G., Bush, M. B., Nunes de Mello, J. A., Stüben, D., Neumann, Müller, G., Morais de, J. O., and Junk, J. W.: A multiproxy palaeoecological record of Holocene lake sediments from the Rio Tapajós, eastern Amazonia, Palaeogeogr. Palaeocl., 240, 523–535, doi:10.1016/j.palaeo.2006.03.005, 2006.

Jacob, J., Disnar, J.-R., Boussafir, M., Sifeddine, A., Turcq, B., and Albuquerque, A. L. S.: Major environmental changes recorded by lacustrine sedimentary organic matter since the last glacial maximum near the equator (Lagoa do Caçó, NE Brazil), Palaeogeogr. Palaeocl., 205, 183–197, doi:10.1016/j.palaeo.2003.12.005, 2004.

Jaeschke, A., Rühlemann, C., Arz, H., Heil, G., and Lohmann, G.: Coupling of millennial-scale changes in sea surface temperature and precipitation off northeastern Brazil with high-latitude climate shifts during the last glacial period, Paleoceanography, 22, PA4206, doi:10.1029/2006PA001391, 2007.

Joussaume, S. and Braconnot, P.: Sensitivity of paleoclimate simulation results to season definitions, J. Geophys. Res., 102, 1943–1956, 1997.

Kohfeld, K. E. and Harrison, S. P.: How well can we simulate past climates? Evaluating the models using global palaeoenvironmental datasets, Quaternary Sci. Rev., 19, 321–346, 2000.

Kohfeld, K. E. and Harrison, S. P.: DIRTMAP: the geological record of dust, Earth Sci. Rev., 54, 81–114, 2001.

Kucera, M., Rosell-Melé, A., Schneider, R., Waelbroeck, C., and Weinelt, M.: Multiproxy approach for the reconstruction of the glacial ocean surface (MARGO), Quaternary Sci. Rev., 24, 813–819, 2005.

Leal, M. G. and Lorscheitter, M. L.: Plant succession in a forest on the Lower Northeast Slope of Serra Geral, Rio Grande do Sul, and Holocene palaeoenvironments, Southern Brazil, Acta Bot. Bras., 21, 1–10, 2007.

Ledru, M.-P.: Late Quaternary environmental and climatic changes in central Brazil, Quaternary Res., 39, 90–98, 1993.

cc BY

Ledru, M.-P., Mourguiart, P., and Riccomini, C.: Related changes in biodiversity, insolation and climate in the Atlantic rainforest since the last interglacial, Palaeogeogr. Palaeocl., 27, 140–152, 2009.

Ledru, M.-P., Cordeiro, R. C., Dominguez, J. M. L., Martin, L., Mourguiart, P., Sifeddine, A., and Turcq, B.: Late-glacial cooling in Amazonia inferred from pollen at Lagoa do Caçó, Northern Brazil, Quaternary Res., 55, 47–56, doi:10.1006/qres.2000.2187, 2001.

Ledru, M.-P., Mourguiart, P., Ceccantini, G., Turcq, B., and Sifeddine, A.: Tropical climates in the game of two hemispheres revealed by abrupt climatic change, Geology, 30, 275–278, 2002.

Ledru, M.-P., Rousseau, D.-D., Cruz Jr., F. W., Riccomini, C., Karmann, I., and Martin, L.: Paleoclimate changes during the last 100,000 yr from a record in the Brazilian Atlantic rainforest region and interhemispheric comparison, Quaternary Res., 64, 444–450, 2005.

Ledru, M.-P., Ceccantini, G., Gouveia, S. E. M., López-Sáez, J. A., Pessenda, L. C. R., and Ribeiro, A. S.: Millenial-scale climatic and vegetation changes in a northern Cerrado (Northeast, Brazil) since the Last Glacial Maximum, Quaternary Sci. Rev., 25, 1110–1126, 2006.

Lenters, J. D. and Cook, K. H.: On the origin of the Bolivian High and related circulation features of the South American climate, J. Atmos. Sci., 54, 656–677, 1997.

Lorente, F. L., Meyer, K. E. B., and Horn, A. H.: Análise palinológica de vereda da Fazenda Urbano, município de Buritizeiro, Minas Gerais, Brasil, Geonomos, 18, 57–72, 2010.

MARGO Project Members: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum, Nat. Geosci., 2, 127–132, doi:10.1038/NGEO411, 2009.

Mayle, F. E., Burbridge, R., and Killeen, T. J.: Millennial-scale dynamics of southern Amazonian rain forests, Science, 290, 2291–2294, doi:10.1126/science.290.5500.2291, 2000.

Melo, M. L. D. and Marengo, J. A.: The influence of changes in orbital parameters over South American climate using the CPTEC AGCM: simulation of climate during the mid-Holocene, The Holocene, 18, 501–516, 2008.

Moro, R. S., Bicudo, C. E. M., Melo, M. S., and Schmitt, J.: Paleoclimate of the late Pleistocene and Holocene at Lagoa Dourada, Paraná State, southern Brazil, Quaternary Int., 114, 87–99, 2004.

Nagai, R. H., Sousa, S. H. M., Burone, L., and Mahiques, M. M.: Paleoproductivity changes during the Holocene in the inner shelf of Cabo Frio, southeastern Brazilian continetal margin: benthic foraminífera and sedimentological proxies, Quaternary Int., 206, 62–71, doi:10.1016/j.quaint.2008.10.014, 2009.

CC BY

Oliveira, M. A. T., Behling, H., and Pessenda, L. C. R.: Late-Pleistocene and mid-Holocene environmental changes in highland valley head áreas of Santa Catarina State, Southern Brazil, J. S. Am. Earth Sci., 26, 55–67, 2008a.

Oliveira, M. A. T., Behling, H., Pessenda, L. C. R., and Lima, G. L.: Stratigraphy of near-valley head quaternary deposits and evidence of climate-driven slope-channel processes in Southern Brazilian highlands, Catena, 75, 77–92, 2008b.

Parizzi, M. G., Salgado-Labouriau, M. L., and Kohler, H. C.: Genesis and environment history of Lagoa Santa, southeastern Brazil, The Holocene, 8, 311–321, 1998.

Parolin, M., Medeanic, S., and Stevaux, J. C.: Registros palinológicos e mudanças ambientais durante o Holoceno de Taquarussu (MS), Rev. Bras. Paleontol., 9, 137–148, 2006.

Pessenda, L. C. R., Aravena, R., Melfi, A. J., Telles, E. C. C., Boulet, R., Valencia, E. P. E., and Tomazello, M.: The use of carbono isotopes (13C, 14C) in soil to evaluate vegetation changes during the Holocene in Central Brazil, Radiocarbon, 38, 191–201, 1996.

Pessenda, L. C. R., Gouveia, S. E. M., Aravena, R., Boulet, R., and Valencia, E. P. E.: Holocene fire and vegetation changes in southeastern Brazil as deduced from fossil charcoal and soil carbono isotopes, Quaternary Int., 114, 35–43, doi:10.1016/S1040-6182(03)00040-5, 2004a.

Pessenda, L. C. R., Ribeiro, A. S., Gouveia, S. E. M., Aravena, R., Boulet, R., and Bendassolli, J. A.: Vegetation dynamics during the late Pleistocene in the Barreirinhas region, Maranhão State, northeastern Brazil, based on carbon isotopes in soil organic matter, Quaternary Res., 62, 183–193, doi:10.1016/j.yqres.2004.06.003, 2004b.

Pessenda, L. C. R., Ledru, M.-P., Gouveia, S. E. M., Aravena, R., Ribeiro, A. S., Bendassolli, J. A., and Boulet, R.: Holocene palaeoenvironmental reconstruction in northeastern Brazil inferred from pollen, charcoal and carbono isotope records, The Holocene, 15, 812–820, doi:10.1191/0959683605hl855ra, 2005.

Pessenda, L. C. R., De Oliveira, P. E., Mofatto, M., Medeiros, V. B., Garcia, R. J. F., Aravena, R., Bendassoli, J. A., Leite, A. Z., Saad, A. R., and Etchebehere, M. L.: The evolution of a tropical rainforest/grassland mosaic in southeastern Brazil since 28,000 14C yr BP based on carbon isotopes and pollen records, Quaternary Res., 71, 437–452, doi:10.1016/j.yqres.2009.01.008, 2009.

Pivel, M. A. G., Toledo, F. A. L., and Costa, K. B.: Foraminiferal record of changes in summer monsoon precipitation at the southeastern Brazilian continental margin since the Last Glacial Maximum, Rev. Bras. Paleontol., 13, 79–88, doi:10.4072/rbp.2010.2.01, 2010.

cc BY

Power, M. J., Marlon, J., Ortiz, N., Bartlein, P. J., Harrison, S. P., Mayle, F. E., Ballouche, A., Bradshaw, R. H. W., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P. I., Prentice, I. C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A. A., Anderson, R. S., Beer, R., Behling, H., Briles, C., Brown, K . J., Brunelle, A., Bush, M., Camill, P., Chu, G. Q., Clark, J., Colombaroli, D., Connor, S., Daniau, A.-L., Daniels, M., Dodson, J., Doughty, E., Edwards, M. E., Finsinger, W., Foster, D., Frechette, J., Gaillard, M.-J., Gavin, D. G., Gobet, E., Haberle, S., Hallett, D. J., Higuera, P., Hope, G., Horn, S., Inoue, J., Kaltenrieder, P., Kennedy, L. Kong, Z. C., Larsen, C., Long, C. J., Lynch, J., Lynch, E. A., McGlone, M., Meeks, S., Mensing, S., Meyer, G., Minckley, T., Mohr, J., Nelson, D. M., New, J., Newnham, R., Noti, R., Oswald, W., Pierce, J., Richard, P. J. H., Rowe, C., Sanchez Goñi, M. F., Shuman, B. N., Takahara, H., Toney, J., Turney, C., Urrego-Sanchez, D. H., Umbanhowar, C., Vandergoes, M., Vanniere, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., and Zhang, J. H.: Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data, Clim. Dynam., 30, 887–90, doi:10.1007/s00382-007-0334-x, 2008.

Prieto, A. R.: Late Quaternary vegetational and climatic changes in the Pampa grassland of Argentina, Quaternary Res., 45, 75–88, 1996.

Prieto, A. R., Blasi, A. M., De Francesco, C. G., and Fernández, C.: Environmental history since 11,000 14C yr B.P. of the northeastern Pampas, Argentina, from alluvial sequences of the Luján River, Quaternary Res., 62, 146–161, 2004.

Reboita, M. S., Rocha, R. P., Ambrizzi, T., and Sugahara, S.: South Atlantic Ocean cyclogenesis climatology simulated by regional climate model (RegCM3), Clim. Dynam., 35, 1331–1347, doi:10.1007/s00382-009-0668-7, 2010.

Rezende, A. B.: Espículas de esponja em sedimentos de lagoa como indicador paleoambiental no NW do Estado do Paraná, Master Dissertation, Universidade de Guarulhos, 2010.

Salgado-Labouriau, M. L., Casseti, V., Ferraz-Vicentini, K. R., Martin, L., Soubiès, F., Suguio, K., and Turcq, B.: Late Quaternary vegetational and climatic changes in cerrado and palm swamp from Central Brazil, Palaeogeogr. Palaeocl., 128, 215–226, 1997.

Scheel-Ybert, R., Gouveia, S. E. M., Pessenda, L. C. R., Aravena, R., Coutinho, L. M., and Boulet, R.: Holocene palaeoenvironmental evolution in the São Paulo State (Brazil), based on anthracology and soil d13C analysis, The Holocene, 13, 73–81, doi:10.1191/0959683603hl596rp, 2003.

cc BY

Servant, M., Maley, J., Turcq, B., Absy, M. L., Brenac, P., Fournier, M., and Ledru, M.-P.: Tropical forest changes during the Late Quaternary in African and South American lowlands, Global Planet. Change, 7, 25–40, 1993.

Sifeddine, A., Bertrand, P., Fournier, M., Martin, L., Servant, M., Soubies, F., Suguio, K., and Turcq, B.: La sédimentation organique lacustre en milieu tropical humide (Carajas, Amazonie orientale, Brésil): relation avec les changements climatiques au cours des 60,000 dernières années, Bull. Soc. Géol. France, 165, 613–621, 1994.

Sifeddine, A., Martin, L., Turcq, B., Volkmer-Ribeio, C., Soubiès, F., Cordeiro, R. C., and Suguio, K.: Variations of the Amazonian rainforest environment: a sedimentological record covering 30,000 years, Palaeogeogr. Palaeocl., 168, 221–235, 2001.

Sifeddine, A., Wirrmann, D., Albuquerque, A. L. S., Turcq, B., Cordeiro, R. C., Gurgel, M. H. C., and Abrão, J. J.: Bolk composition of sedimentary organic matter used in palaeoenvironmental reconstructions: examples from the tropical belt of South America and Africa, Palaeogeogr. Palaeocl., 214, 41–53, doi:10.1016/j.palaeo.2004.06.012, 2004.

Silva Dias, P. L., Turcq, B., Silva Dias, M. A. F., Braconnot, P., and Jorgetti, T.: Evaluation of model simulation of 6ka BP and present climate in tropical South America, in: Past climate variability from the Last Glacial Maximum to the Holocene in South America and Surrounding regions, edited by: Vimeux, F., Sylvestre, F., and Khodri, M., Springer Verlag, 259–281, 2009.

Smith, C. B, Cohen, M. C. L., Pessenda, L. C. R., França, M. C., Guimarães, J. T. F., Rossetti, D. F., and Lara, R. J.: Holocene coastal vegetational changes at the mouth of the Amazon River, Rev. Palaeobot. Palyno., 168, 21–30, doi:10.1016/j.revpalbo.2011.09.008, 2011.

Stevaux, J. C.: Climatic events during the Late Pleistocene and Holocene in the Upper Parana River: correlation with NE Argentina and South-Central Brazil, Quaternary Int., 72, 73–85, 2000.

Stríkis, N. M., Cruz, F. W., Cheng, H., Karmann, I., Lawrence Edwards, R., Vuille, M., Wang, X., De Paula, M. S., Novello, V. F., and Auler, A. S.: Abrupt variations in South American monsoon rainfall during the Holocene based on a speleothems record from central-eastern Brazil, Geology, 39, 1075–1078, doi:10.1130/G32098.1, 2011.

Toledo, F. A. L., Costa, K. B., and Pivel, M. A. G.: Salinity changes in the western tropical South Atlantic during the last 30 kyr, Global Planet. Change, 57, 383–395, 2007.

Toledo, F. A. L., Costa, K. B., Pivel, M. A. G., and Campos, E. J. D.: Tracing past circulation changes in the western South Atlantic based on planktonic foraminifera, Rev. Bras. Paleontol, 11, 169–178, doi:10.4072/rbp.2008.3.03, 2008.

Turcq, B., Pressinotti, M. M. N., and Martin, L.: Paleohydrology and paleoclimate of the past 33,000 years at the Tamanduá River, Central Brazil, Quaternary Res., 47, 284–294, 1997.

Turcq, B., Albuquerque, A. L. S., Cordeiro, R. C., Sifeddine, A., Simões Filho, F. F. L., Souza, A. G., Abrão, J. J., Oliveira, F. B. L., Silva, A. O., and Capitâneo, J.: Accumulation of organic carbono in five Brazilian lakes during the Holocene, Sediment. Geol., 148, 319–342, 2002.

Vera, C., Higgins, W., Amador, J., Ambrizzi, T., Garreaud, R., Gochis, D., Gutzler, D., Lettenmaier, D., Marengo, J., Mechoso, C. R., Nogues-Paegle, J., Silva Dias, P. L., and Zhang, C.: Toward a unified view of the American Monsoon Systems, J. Climate, 19, 4977–5000, 2006.

Vilanova, I., Prieto, A. R., and Espinosa, M.: Palaeoenvironmental evolution and sea-level fluctuations along the southeastern Pampa grasslands coast of Argentina during the Holocene, J. Quaternary Sci., 21, 227–242, doi:10.1002/jqs.953, 2006b.

Vuille, M., Burns, S. J., Taylor, B. L., Cruz, F. W., Bird, B. W., Abbott, M. B., Kanner, L. C., Cheng, H., and Novello, V. F.: A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia, Clim. Past, 8, 1309–1321, doi:10.5194/cp-8-1309-2012, 2012.

Wainer, I., Clauzet, G., Ledru, M.-P., Brady, E., and Otto-Bliesner, B.: Last Glacial Maximum in South America: Paleoclimate proxies and model results, Geophys. Res. Lett., 32, L08702, doi:10.1029/2004GL021244, 2005.

Wang, X., Auler, A. S., Lawrence Edwards, R., Cheng, H., Ito, E., and Solheid, M.: Interhemispheric anti-phasing of rainfall during the last glacial period, Quaternary Sci. Rev., 25, 3391–3403, doi:10.1016/j.quascirev.2006.02.009, 2006.

Whitney, B. S., Mayle, F. E., Punyasena, S. W., Fitzpatrick, K. A., Burn, M. J., Guillen, R., Chavez, E., Mann, D., Pennington, R. T., and Metcalfe, S. E.: A 45 kyr Palaeoclimate record from the lowland interior of tropical South America, Palaeogeogr. Palaeocl., 307, 177–192, doi:10.1016/j.palaeo.2011.05.012, 2011.

Wang, X., Auler, A. S., Edwards, R. L., Cheng, H., Ito, E., Wang, Y., Kong, X., and Solheid, M.: Millennial-scale precipitation changes in southern Brazil over the past 90,000 years, Geophys. Res. Lett., 34, L23701, doi:10.1029/2007GL031149, 2007.

Weldeab, S., Schneider, R. R., and Kölling, M.: Deglacial sea surface temperature and salinity increase in the western tropical Atlantic in synchriny with high latitude climate instabilities, Earth Planet. Sci. Lett., 241, 699–706, 2006.

Wirtz, K. W., Lohmann, G., Bernhardt, K., and Lemmen, C.: Mid-Holocene regional reorganization of climate variability: analyses of proxy data in the frequency domain, Palaeogeogr. Palaeocl., 298, 189–200, doi:10.1016/j.palaeo.2010.09.019, 2010.

Zech, W., Zech, M., Zech, R., Peinemann, N., Morrás, H. J. M., Moretti, L., Ogle, N., Kalim, R. M., Fuchs, M., Schad, P., and Glaser, B.: Late Quaternary palaeosol records from subtropical (38° S) to tropical (16° S) South America and palaeoclimatic implications, Quaternary Int., 196, 107–120, doi:10.1016/j.quaint.2008.01.005, 2009.

Zhou, J. and Lau, K.-M.: Does a monsoon climate exist over South America?, J. Climate, 11, 1020–1040, 1998.

cc BY

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

Code	Proxy type	Description
IF	Isotopic oxygen and carbon fractionation	$\delta^{18}O$, $\delta^{13}C$
PC	Physico-chemical	Mg/Ca, Ti/Ca, Fe/Ca, Fe/Sr, Al/Si, Si/Ca, C/N, $\delta^{15}N$, Grain size, Petrography, Alkenone, Thermoluminescence, Mineralogy, pH, Eh, Magnetic susceptibility
BI	Biological	Pollen, Diatoms, Spores, Algae, Molluscs, Sponge, Organic Matter, Charcoal, Relative abundance

Table 2. Location and reference of the palaeoclimatic records used in this study. Abbreviations: Site: Lk = lake, Cv = cave, Rv = river; Proxy type: IF = Isotopic Fractionation, PC = Physico-Chemical, BI = Biological. Numbers within parenthesis in "Site column", to 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 on Table 1.

No	Site	Proxy type	Reference	Lat (°)	Lon (°)
1	Salitre de Minas	BI	Ledru (1993)	−19.00	−46.77
2	Morro de Itapeva	BI	Behling (1997a)	−22.78	−45.53
3	Curuça 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

Table 3. Continued.

No	Site	Proxy type	Reference	Lat (°)	Lon (°)
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
53	Tapajós Lk	BI/PC	Irion et al. (2006)	−2.79	−55.08
54	Santa Maria Lk	BI	Bush et al. (2007b)	−1.58	−53.60
55	Saracuri Lk	BI	Bush et al. (2007b)	−1.68	−53.57
56	Geral Lk	BI	Bush et al. (2007b)	−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

cc BY

Table 4. Continued.

No	Site	Proxy type	Reference	Lat (°)	Lon (°)
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	Anhembi	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

Table 5. Continued.

No	Site	Proxy type	Reference	Lat (°)	Lon (°)
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	Anhembi	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	India 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
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

Fig. 1. Spatial distribution of the 120 palaeorecords (at 84 locations) used in this study. Vertical axis refers to latitude, and horizontal values correspond to longitude. Details for each record are found in Table 2.

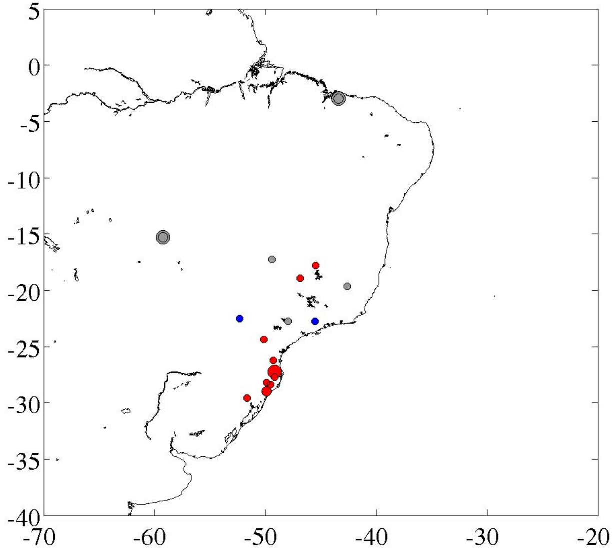

Fig. 2. MH air temperature palaeodata in South America. Symbol colors: blue, colder than present; red, warmer than present, grey, similar to present. Size refers to palaeodata quality: larger symbols means better quality data. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

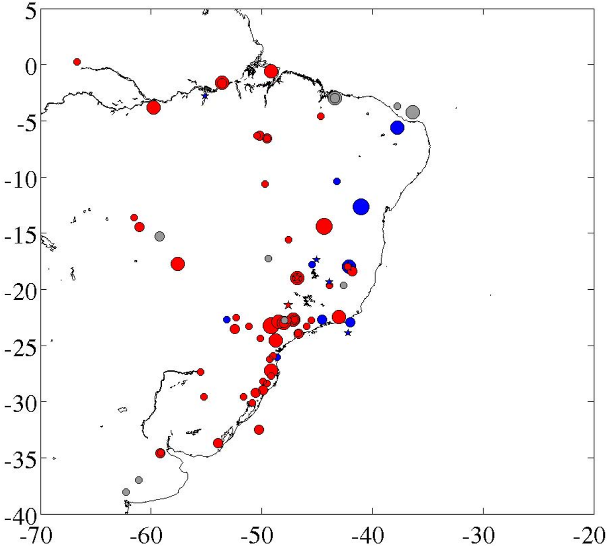

Fig. 3. MH precipitation/moisture palaeodata in South America. Symbol colors: blue circles, wetter than present; red circles, drier than present, grey circles, similar to present; blue stars, dry-to-wet transition; red stars, wet-to-dry transition. Size refers to palaeodata quality: larger symbols means better quality data. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

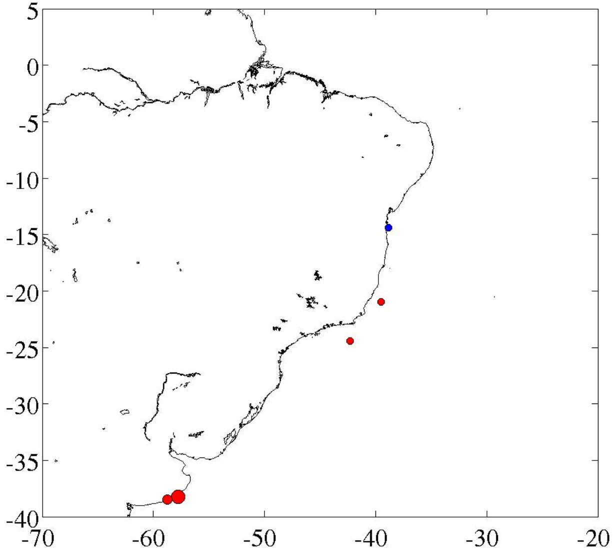

Fig. 4. MH salinity palaeodata in South America eastern coast. Symbol colors: blue circle, fresher than present; red circles, saltier than present. Size refers to palaeodata: larger symbols means better quality data. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

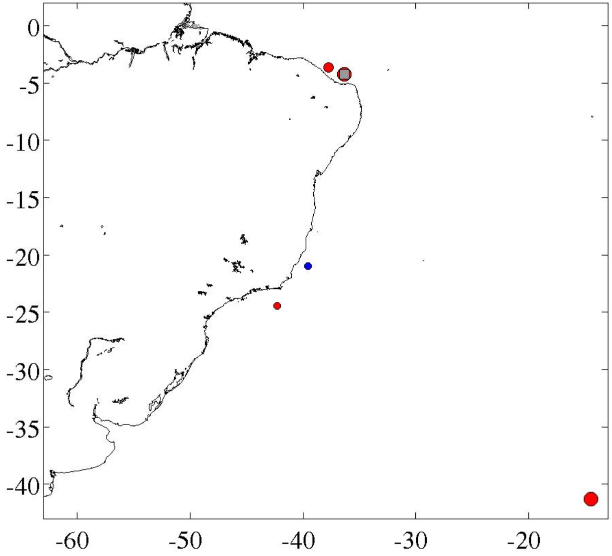

Fig. 5. MH sea surface temperature palaeodata in South America eastern coast. Symbol colors: blue circles, colder than present; red circles, warmer than present; grey circles, similar to present; grey squares, warmer-colder oscillation. Size refers to palaeodata quality: larger symbols means better quality data. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

cc BY

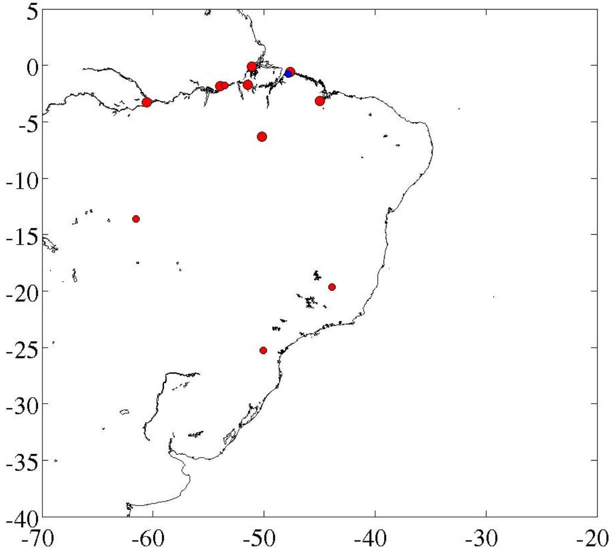

Fig. 6. MH lake level palaeodata in South America. Symbol color: red, lower than present; blue, higher than present. Size refers to palaeodata quality: larger symbols means better quality data. Vertical axis refers to latitude values, and horizontal axis refers to longitude values.

cc BY