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Short Paper

Paleoclimate changes during the last 100,000 yr from a record in the Brazilian Atlantic rainforest region and interhemispheric comparison

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Abstract

A long terrestrial record, Colônia CO-3, from the Atlantic rainforest region in Brazil (23°52′S, 46°42′20″W, 900 m a.s.l.) registrates variations in the forest expansion during the last 100,000 yr. The 780-cm depth core was analyzed at 2-cm intervals and arboreal pollen frequencies were compared to nearby speleothem stable isotope records and neighboring marine records from the tropical Atlantic. To evaluate regional versus global climate forcing, our record was compared with Greenland and Antarctic ice-core records. These comparisons suggest that changes in temperature seen in polar latitudes relate to moisture changes: e.g., to changes in the length of the dry season, in tropical and subtropical latitudes during glacial as well as interglacial times. These climatic changes result from changes in the frequency of polar air incursions to these latitudes inducing a permanent cloud cover and precipitation. This is an important result that should help define paleoclimatic features in the Southern Hemisphere for the last glaciation.

Keywords: Southern Hemisphere; Tropics; Paleoclimatology; Palynology; Rainforest; Long record; Interhemispheric comparison

Introduction

Southern Hemisphere paleoclimates derived from terrestrial paleoenvironmental records are often considered as responding to Northern Hemisphere climate-forcing parameters, such as changes in the intensity of the North Atlantic thermohaline circulation and changes in the extent of the Greenland ice sheet (Bard et al., 1997; EPICA, 2004; Lea et al., 2003; Steig et al., 1999). Also, because the Southern Hemisphere continental surfaces are much smaller than the Northern Hemisphere land areas, it might be difficult to detect typical Southern Hemisphere paleoclimate patterns. Paleoclimatic changes from a growing number of records throughout the American continent provide now an excellent network to test this paradigm as they link southern and northern hemispheres with comparable physiographic features (Markgraf et al., 2000). Generally speaking, it seems that these forcing parameters could affect changes in temperature gradients between pole and equator in both hemispheres which in turn appear to have had a strong impact on climate not just on high but also on low latitudes (Blunier and Brook, 2001; Broecker, 1998; Grimm et al., 2001; Ledru and Mourguiart, 2001; Ledru et al., 2002; Rind, 1998; Rind, 2000). However, Northern Hemisphere influence over South American paleoenvironmental changes continues to be strongly debated (Bennett et al., 2000; Heusser, 1989; Markgraf, 1989b; Moreno et al., 2001; Stieglitz, 2004). Latitudinal limits for Northern Hemisphere influence were proposed for the Younger Dryas climatic reversal (Ledru et al., 2002) and detailed climatological analysis of annual-scale climate variations showed fluctuations independent from the northern hemisphere (Garreaud, 1999; Garreaud and Aceituno, 2002; Marengo et al., 1997; Pezza and Ambrizzi, 2003). The recent increase of paleoenvironmental records from South

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America (Grimm et al., 2001; Ledru and Mourguiart, 2001; Markgraf, 1989a) and of ice-core records from Antarctica (Dansgaard et al., 1993; EPICA, 2004; Jouzel et al., 1995; Petit et al., 1999; Steig et al., 1999) resulted in a "southern approach" in the interpretation of Quaternary climatic changes. Comparisons of South American records with those from Australia and South Africa also contributed to define Southern Hemisphere climatic evolution since the Last Glacial Maximum (LGM) (Markgraf et al., 1992, 1995; Mc Glone et al., 1992). Intrahemispheric comparison of paleoclimate records spanning several continental glacial/interglacial cycles, however, has been hampered by the scarcity of long records in South America, although long records existed in great numbers in South Africa (Partridge and Scott, 2000; Scott, 1999) and Australia (Kershaw, 1974, 1978, 1994). Until now, in South America, the Funza I and II records from Colombia (4°50′N, 75°12′W) were the only ones dating back continuously 3.2 myr (Hooghiemstra, 1984; Hooghiemstra and Ran, 1994; Hooghiemstra and Van't Veer, 1999). In this paper, we present a new long terrestrial record located in Brazil in the Atlantic rainforest region that sheds new light on the question of interhemispheric paleoclimate linkages.

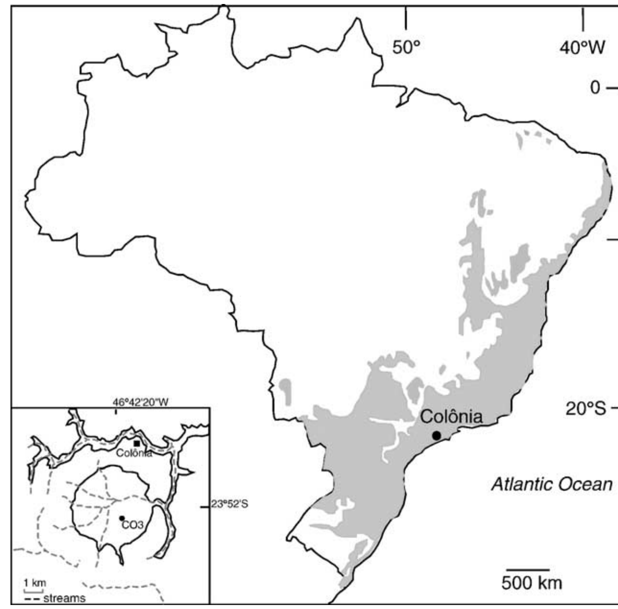

Figure 1. Map of Brazil showing the distribution of the Atlantic rainforest domain in grey with location of Colônia inside the city of São Paulo from Instituto Socio Ambiental (2001). Detail of the crater and location of core CO3 from Riccomini et al. (1991).

Material and settings

Colônia crater

Colônia is a meteor crater of 3.5 km width filled with 392 m of organic sediments, located in the city of São Paulo (23°52′S, 46°42′20″W, 900 m a.s.l.) (Riccomini et al., 1991). Its location, near the Atlantic Ocean in the Serra do Mar mountain range at an altitude of 900 m a.s.l., implies a strong sensitivity of vegetation to sea level and temperature changes. Five cores have been drilled in 1988 in the peat bog with a vibra corer (Martin et al., 1995) and preliminary sedimentologic results obtained on core CO5 showed marked environmental changes (Riccomini et al., 1991). In this paper, we present the results obtained on the 780-cm-long core CO3 located in the center of the crater (Fig. 1).

Atlantic rainforest

The Atlantic rainforest of Brazil has the second highest biodiversity in Brazil after the Amazonian rainforest (Fig. 1). Its expansion today is strongly reduced because of intensive deforestation and only 7% of its original distribution remains in ecological reserves. This domain includes different patches of forest with common ecological associations. Among them are the *Araucaria* forest which was recently included within the Atlantic rainforest domain, the semi-deciduous forest which develops inland at the latitude of São Paulo, and the coastal rainforest (Instituto Socio Ambiental, 2001; Oliveira Filho and Fontes, 2000).

The Atlantic rainforest covers a large territory in Brazil, from the Equator to 30°S, and consequently includes a wide range of climatic conditions. Climate is characterized by a lack of a dry season in the southern Brazil region and a more seasonal precipitation regime at the northern extension of this forest with the rainy season generally occurring during the austral summer. The climate in the region of the city of São Paulo, where the Atlantic rainforest is most extensive, is characterized by mean winter temperatures of 15°C and mean annual rainfall of 1700 mm. Rainfall is distributed evenly throughout the year as the 2-month dry season is attenuated by polar air incursions inducing frequent cloud cover and drizzle (Ledru, 1993).

A botanical survey was carried out in the region of Colônia (Garcia, 2003). On the peat bogs inside the crater, *Sphagnum*, *Baccharis* sp., *Tibouchina* sp, *Eriocaulon* sp, *Utricularia* sp, *Hyptis* sp., *Cuphea* sp., *Xyris* sp., *Drosera* sp. and the tree fern *Cyathea* were identified among the local plants. In the Atlantic rainforest, on the margins of the crater, the main tree species are Myrtaceae with 12 genera, *Myrsine* sp., *Alchornea* sp., *Podocarpus sellowii*, *Daphnopsis* sp., *Hedyosmum* sp., *Drymis winterii*, Rubiaceae with 16 genera, the palms *Bactris* sp., *Euterpe* sp. and *Geonoma* sp., and epiphytes of the Bromeliaceae and Orchidaceae families.

According to the first author's field observations, the region of São Paulo was classified as "degraded *Araucaria* forest" as single individuals of *Araucaria angustifolia* (Bert.) Kuntze can be found in shadowy ravines. *Podocarpus sellowii* Klotzsch ex Endl., another tropical conifer, is seldom found in this area although we observed this conifer growing inside a recently introduced *Eucalyptus* forest.

Paleoenvironmental reconstruction of the Atlantic rainforest

Paleoenvironmental records from the area, nowadays covered by Atlantic rainforest, are rare mainly because permanent lakes in the coastal mountain slopes are few and difficult to access. The available paleodata from southern

Brazil indicate that the Atlantic rainforest expanded to its present potential distribution only 3000 yr ago (Behling, 1997). In northern Brazil, a pollen record located in the Cerrado vegetation domain shows an initial expansion of the rainforest ca 15,000 yr ago that lasted about 500 yr (Ledru et al., 2001). Considering the widespread distribution of the rainforest, these differences in timing of expansion attest to differences in the character and timing of climatic changes. In the southern region, forest distribution corresponds to a stabilization of the position of the winter polar fronts which apparently only became frequent between 25° and 23°S in the last 3000 yr (Ledru et al., 1998a,b). In the northernmost region, in contrast, forest expansion seems to relate to equilibrium between both hemispheres pole-equator temperature gradients, for example as inferred during the Antarctic Cold Reversal. At this time, weaker northern hemisphere than southern hemisphere gradient induced a complete reorganization in dominant southern air masses reducing the length of the dry season and the mean temperatures at low latitudes (Ledru et al., 2001, in press).

Pollen analysis

Methods

The core was sampled for pollen analysis at 2-cm intervals. Pollen samples were prepared following standard treatment (Faegri and Iversen, 1989) and mounted on microscope slides in silicon oil. Pollen counts were performed under 1000 × magnification and pollen was identified by comparison with our reference pollen collection. A total of 300 trees and herb pollen grains were counted for each sample. Fern spores and aquatic taxa were excluded from the total sum for percentage calculation. Arboreal Pollen frequencies (AP) are plotted in Figure 2, including all taxa characteristic of the Atlantic rainforest with conifers such as *Araucaria* and *Podocarpus* and a high diversity in angiosperms, which include pioneer species such as *Alchornea*, *Myrsine* and *Celtis*.

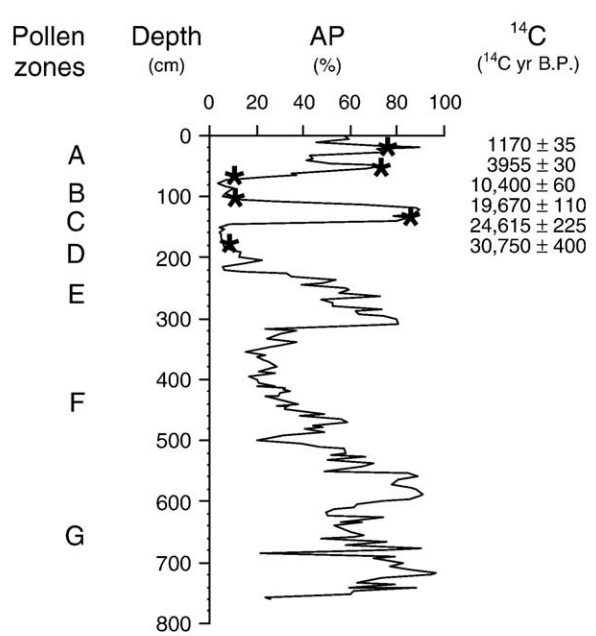

Figure 2. CO3 Arboreal Pollen percentages diagram plotted on a depth scale with indication of the radiocarbon dates and the pollen zones.

Chronology

The original chronology is based on six bulk ^{14}C ages measured on sediments from the uppermost 2 m of core CO3 (Table 1). The inclusion of the LGM time period (27,000–19,000 yr ago,) in the Colônia record is favorable for regular sedimentation with different features than other lacustrine records in Brazil (Ledru et al., 1998a,b). By extrapolation and comparison of some extreme and well-recognized changes in AP with extreme changes in stable isotope composition from polar, marine and speleothem records, we estimate an age of ~100,000 yr for the base of the Colônia record (Fig. 3).

Results

Because the aim of this paper concerns the establishment of a chronological frame for extreme climatic events in Southern Hemisphere, only the tree pollen frequencies are discussed here in order to compare regional changes in vegetation to those in stable isotope records. Therefore, changes in moisture rates attested by changes in AP frequencies are related to changes in temperature characterized by values of δ^{18}O. Detailed palynological data will be presented in a future paper (M.-P. Ledru). In the low latitudes of the tropics, low arboreal pollen frequencies are associated with a long dry season and generally dry climatic conditions whereas high arboreal pollen frequencies are associated with a short dry season and moist climatic conditions (Ledru, 1993).

Seven zones, from G to A, were defined according to variations in AP frequencies (Fig. 2). They are interpreted as changes between more or less seasonal climatic conditions:

Zone G shows 2 peaks in AP between 550 and 720 cm depth: the first one reaches 96 % at 718 cm depth and the second one 89% at 559 cm depth. Between these high values, a sharp decrease to 50% is recorded between 680 and 590 cm depth.

In pollen zone F, between 550 and 320 cm depth, low AP frequencies are recorded with a minimum of 16% at 356 cm depth.

Zone E shows an expansion of the forest with the highest AP frequencies reaching 80% at 302 cm depth and 53% at the end of the pollen zone at 236 cm depth.

Zone D, between 232 and 140 cm depth, is characterized by an abrupt and strong decrease in AP frequencies, values varying between 14 and 4 %, 4% being recorded at 158 cm depth.

Zone C, between 140 and 110 cm depth, supports another forest expansion with frequencies ranging from 65 to 85 %.

Zone B, between 110 and 70 cm depth, is characterized by low AP frequencies, similar to those described in Zone D, ranging 3 to 14%. This zone is radiocarbon dated between 20,000 and 10,000 yr B.P. (Table 1).

Table 1
Radiocarbon ages of total organic matter from core CO3

Depth (cm)	Age (^{14}C yr B.P.)	Laboratory number	δ^{13}C	Age range (cal yr B.P.)[a]
21–23	1170 ± 35	LY 11500	−28.47	2980–2775
51–53	3955 ± 30	LY 11501	−27.6	4565–4350
71–73	10,400 ± 60	LY 11502	−23.11	12,885–11,980
101–103	19,670 ± 110	LY 11503	−23.48	25,200–23,615
129–131	24,615 ± 225	LY 11504	−28.72	30,400–28,225
181–183	30,750 ± 400	LY 11505	−24.27	36,700–33,150

Calibrated ages are calculated from Stuiver et al. (1998) and Jöris and Weninger (1998).

[a] range at two standard deviations with error multiplier of 1.0 ; cal. = calibrated.

Zone A between 70 and 0 cm depth represents the Holocene interval ^{14}C-dated between 10,000 and 0 cal yr B.P., and attest to forest expansion after ~8000 cal yr B.P. with millennial-scale fluctuations characterized by variations of tree-pollen content.

Comparison with other records

To confirm the chronology of our record and gain insight into the regional and local characters of paleoclimatic changes we correlate the AP percentages (changes in moisture rates) with the stable isotope from speleothem records from Santana cave (24°31′S; 48°43′W) close to São Paulo (Cruz, 2003). Chronologic control for the Santana record is from Uranium–Thorium ages and extends back 110,000 yr. First, we correlated both the AP pollen and speleothem isotope curves based on the ^{14}C dates. Second, we matched similar signals between both records. Although one must be aware and cautious about visual correlations, strong similarities appear between the different records.

The two AP peaks recorded in Zone G at Colônia are also recorded in the Santana speleothem record and are interpreted representing a more uniform rainfall regime, with a reduced or no dry season. Dates are estimated to be ~105,000 and ~85,000 yr, respectively. Pollen zone E is also represented in the speleothem record and dates back to between 60,000 and 50,000 yr ago. The increase in tree pollen recorded at 300 cm depth matches high δ^{18}O values in the Santana cave speleothem record, where it is dated at ~59,000 yr. Between 27,000 and 21,000 yr ago, an increase in AP frequencies to almost 100% is recorded. This peak in AP is more prominent than the variations observed in the stable isotopes of Santana speleothem.

Stable isotope records from polar ice cores from Antarctica (Vostok) (Petit et al., 1999) and Greenland (GRIP) (Johnsen et al., 2001) reflect changes in air temperature; similar records from marine sediment cores reflect changes in sea-surface temperature. These data were plotted in order to compare the

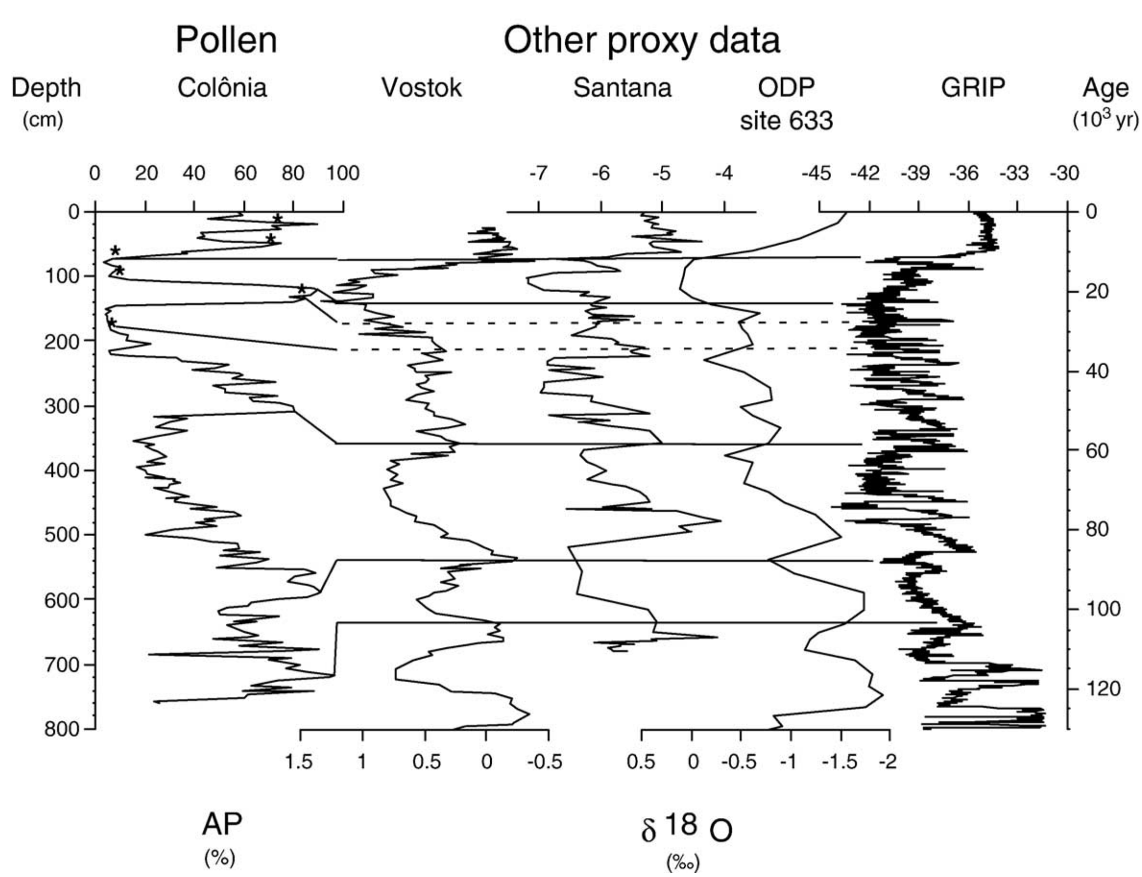

Figure 3. Comparison between GRIP (Johnsen et al., 2001), Vostok (Petit et al., 1999), speleothem Santana (Cruz, 2003), and marine ODP site 633 isotope records (deMenocal et al., 1993) and CO3 Arboreal Pollen frequencies. The dotted line indicates similar extreme patterns between the different records.

signals obtained in Brazil to global climatic changes. First comparisons with marine and ice cores show that global climatic changes in climate are well-recorded in the stable isotopes of speleothems from subtropical Brazil (Fig. 3). Both the Colônia tree-pollen frequencies and ice-core stable-isotope variations show similar patterns in changes although their amplitudes suggest differences in signal expression during certain periods.

Data from Vostok and GRIP were downloaded from the NOAA web site (http://www.ngdc.noaa.gov). Considering the lack of long and continuous marine records on western South Atlantic, we selected a record located within the equatorial divergence zone, ODP site 663 (1°11,9′S 11°52,7′W water depth 3708 m) (deMenocal et al., 1993). The oxygen isotope stratigraphy was analyzed on planktonic foraminifers. The marine core dates back 900,000 yr, but only the last 130,000 yr will be discussed in this paper (Fig. 3).

In pollen zone G, the two peaks estimated at 105,000 and 85,000 yr ago are also well recognized in the GRIP and Vostok records (first peak) and the marine record of site 663. They are associated with the end of the last interglaciation and named 5c and 5a respectively. The decrease in AP and in δ^{18}O of the next phase shows the beginning of he last glaciation which lasted until 11,000 yr ago. The extreme signal observed between 27,000 and 21,000 yr ago, during the last glaciation, and interpreted as high moisture rates at 23°S near the Atlantic, is not recorded in any of the other records shown in Figure 3. It is interpreted as a local feature.

The beginning of the Holocene is well-recorded in all the records showing the same pattern of changes: at Colônia, an increase of AP frequencies is associated to a reduced seasonal rainfall regime or more permanent rainfall. Numerous fluctuations in AP frequencies are related to abrupt changes in seasonality as observed during the entire Holocene.

Implications for Southern hemisphere paleoclimatology

Southern hemisphere paleoclimate changes are interpreted to reflect Northern Hemisphere influences and synchrony or asynchrony between both hemispheres is often debated (Bard et al., 1997; Blunier et al., 1998; EPICA, 2004; Grootes et al., 2001; Lea et al., 2003). Recently, a possible specific control of the Southern Hemisphere on global glaciations and deglaciations was emphasized (Knorr and Lohmann, 2003; Lamy et al., 2004; Stocker, 2003). On the other hand, correlations between mid-latitude South American and South African sedimentological records support peculiar paleoclimatic patterns for Southern Hemisphere that are not recorded in high-latitude ice cores, especially during the LGM time period (Bradbury et al., 2001; Meadows and Baxter, 1999). The high moisture levels inferred for the base of the record of Colônia are well-recorded in ice cores such as GRIP (Johnsen et al., 2001) and Vostok (Petit et al., 1999) where they are attributed to global warm air temperatures.

The decrease in AP corresponds to the beginning of the last glaciation at the marine oxygen isotope stage (MIS) 5–4 boundary, at about 74,000 yr ago, and is dated between 74,000 and 60,000 yr ago in marine and ice-core records, a period during which a decrease in both air and sea surface temperatures is recorded (Kukla et al., 1997).

MIS 2 is characterized by low temperatures in all ice and marine records. One of the most striking results in Colônia record is the strong increase in arboreal pollen frequencies during the LGM, reflecting high moisture rates at this latitude. High lake levels were also recorded in northern Patagonia (Bradbury et al., 2001), and relatively moist climatic conditions in Bolivia at the Salar de Uyuni (Sylvestre, 2002), South Africa (Meadows and Baxter, 1999) and New Zealand (R.M. Newnham, personal communication, 2005). This points out the presence of a latitudinal band of moisture throughout the Southern Hemisphere subtropics between ~24,000 and ~21,000 yr ago, when global air and sea surface temperatures were extremely low. These LGM high moisture rates are interpreted to reflect an equatorward displacement of the circum-polar vortex, inducing a northward shift of the westerlies on the Pacific side of South America, and of the polar jets on the Atlantic side (Markgraf et al., 1992; Wainer et al., 2005). Although not yet proven, differences in climate trends between the two hemispheres may also exist during less extreme events such as interstades or even the previous interglaciation, which shows a different climate amplitude between North and South (Cruz et al., 2005; Jouzel et al., 1994). To characterize these paleoclimatic differences better, detailed analysis of several specific indicator taxa such as the tropical conifers in the Colônia record will be necessary and will greatly improve the understanding of how the Southern Hemisphere might affect global climates.

Conclusion

The Colônia Crater record confirms that the Atlantic rainforest experienced global climatic changes during the Quaternary. Comparison with the speleothem stable-isotope records of Santana cave show that distribution of moisture throughout the year and changes in the length of the dry season had a strong impact on the rainforest distribution during the last glaciation. These climatic changes result from changes in the incursion frequency of polar air to these latitudes and the related permanent cloud cover and precipitation. Comparisons with ice cores from Antarctic and Greenland suggest that changes in temperature characterized from stable isotopes ratios are related to changes in moisture rates in the tropics. This is an important result that should help define paleoclimatic features in the Southern Hemisphere for the last glaciation. Detailed comparisons of the available proxies are now needed, specially between δ^{13}C and individual taxa of the Colônia record to characterize these climatic changes better.

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