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SHORT PAPER

Astronomical Forcing of Contrasting Rainfall Changes in Tropical South America between 12,400 and 8800 cal yr B.P.

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Today, precipitation over tropical South America is largely controlled by the seasonal movements of the Inter-Tropical Convergence Zone (ITCZ). During the summer, the ITCZ is shifted southward due to the warming of the continent. Paleoclimate data from southeastern Amazonia and the central Andes indicate that these two areas evolved similarly during the last 30,000 yr. However, between 12,400 and 8800 cal yr B.P., eastern Amazonia received substantial moisture whereas the Bolivian Altiplano was arid. This suggests that the ITCZ during summer was then farther north than it is today.

The quantity, distribution, and variation through space and time of precipitation are factors that contribute to the climatic differentiation of tropical regions. Thus, the reconstruction of precipitation patterns through time should provide a faithful image of climatic change in the tropics. Here, we reconstruct the rainfall regimes from two sedimentary records in South America that exhibit contrasting characteristics (i.e., southeastern Amazonia and the northern part of the Bolivian Altiplano). The paleoclimatic reconstructions are compared with present-day climatic conditions in the two regions and with other tropical South American records (Table 1).

Sedimentological (Sifeddine *et al.*, 1994b; Sifeddine *et al.*, 1994a) and palynological (Absy *et al.*, 1991) studies of a set of cores retrieved from lakes in the Serra dos Carajás in the southeastern part of Brazilian Amazonia (6°S; 50°W; Figs. 1a and 1b) yielded a precipitation record for the past 60,000 yr. The Serra dos Carajás is a narrow plateau about 800 m high, emerging above the Amazonian rainforest. The wet, tropical climate has two contrasting seasons. The dry season lasts for three months, from July to September (Fig. 1). During the past 60,000 yr, paleoenvironmental reconstructions reveal several wet and dry phases based on changes in the presence of forest around the plateau and on lake-level fluctuations. The pollen spectra and the extremely low percentage of detrital sediments in the record (Fig. 2) show that the 12,400–8800 cal yr B.P. (Stuiver and Reimer, 1993) period was characterized by maximum forest development (Absy *et al.*, 1991) and little erosion in the drainage basin. Furthermore, the good preservation of organic matter in the sediments confirms the presence of a permanent water

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TABLE 1
Location of the Records Used for Paleoclimatic Reconstructions

Site number (Fig. 1)	Name	Country	Latitude	W longitude
1	Serra dos Carajás	Brasil	6°S	50°
2	Lake Titicaca	Bolivia	16°S	69°
3	Lake Valencia	Venezuela	10°N	67°
4	São Gabriel da Cachoeira	Brasil	0°S	67°
5	Rio Caqueta	Colombia	1°S	72°
6	Upper Rio Doce	Brazil	17–18°S	42–43°
7	Brasilia	Brasil	16°S	48°
8	Atacama Desert	Chile	19–27°S	69°
9	Junin Plain	Peru	11°S	76°
10	Salitre	Brasil	19°S	47°

body. The climatic environment favorable for the development of the forest, which appeared about 15,500 cal yr B.P. (Van der Hammen and Absy, 1994; Markgraf, 1989), was still present between 12,400 and 8800 cal yr B.P. The full development of the tropical rainforest between 12,400 and 8800 cal yr B.P. implies that rainfall was abundant and that, like today, the dry season did not exceed three months. It can then be conjectured that, during this time interval, the

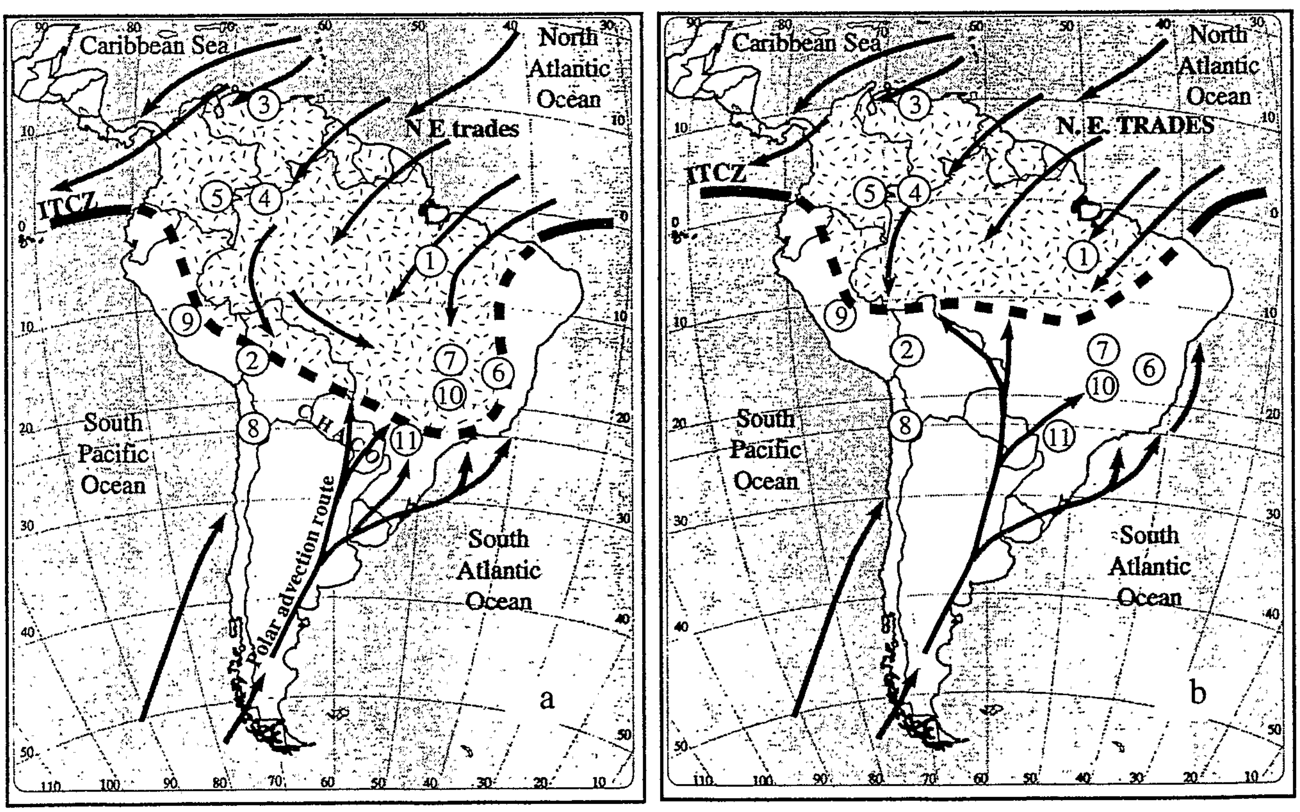

FIG. 1. Maps showing location of the various sites discussed in the text and mean position of the ITCZ during the austral summer today (a) and between 12,400 and 8800 cal yr B.P. (b), as reconstructed from paleo-precipitation records and from insolation data (Fig. 3). Sites are: (1) Serra dos Carajás, Brazil; (2) Lake Titicaca, Bolivia; (3) Lake Valencia, Venezuela; (4) São Gabriel da Cachoeira, Brazil; (5) Rio Caqueta, Colombia; (6) upper Rio Doce, Brazil; (7) Brasilia, Brazil; (8) Atacama Desert, Chile; (9) Junin Plain, Peru; (10) Salitre, Brazil; (11) *Araucaria* forest area, Brazil. The shaded continental area delimits the zone of influence of the moist equatorial air (northeast trades). The warming of the continent during the austral summer months induces an important southward migration of the ITCZ, east of the Andes.

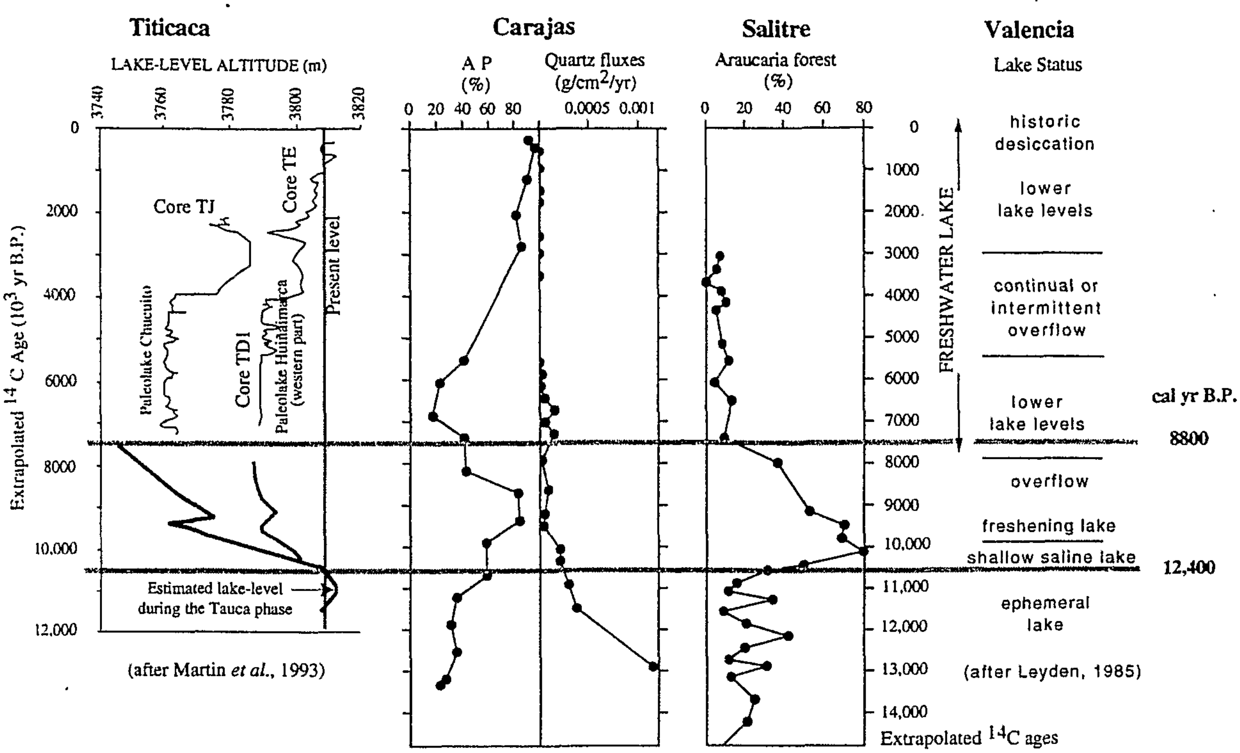

FIG. 2. Data from lake-level, pollen abundance, and sediment fluxes for some selected sites.

ITCZ reached the Carajás region during the austral summer, bringing moist equatorial air to the site (Fig. 1b).

The second key site in our study is Lake Titicaca (16°S, 69°W; Figs. 1a and 1b) in the northern part of the Bolivian Altiplano. Sedimentological and micropaleontological investigations (Wirrmann and Oliveira Almeida, 1987; Wirrmann and Mourguiart, 1995; Wirrmann *et al.,* 1992; Mourguiart and Carbonel, 1994) yielded a semi-quantitative record of lake-level variations for the past 29,000 yr. The Altiplano is a large endorheic drainage system at about 3650 to 3900 m altitude, bounded to the east and west by the oriental and occidental Andean cordilleras, respectively, which culminate at more than 6000 m. There is a steep rainfall gradient between the north (≥800 mm/yr) and the south (<200 mm/yr) (Roche *et al.,* 1992). This gradient is linked to the latitudinal movements of the ITCZ, which reaches the Andes from November to April. During this period, the warm, moist Amazonian air penetrates the Andes from the northeast (Grootes and Stuiver, 1989) bringing stormy rains. Based on a daily record spanning the past 80 years, it appears that fluctuations in the level of Lake Titicaca average 75 cm between the dry and wet seasons (Hastenrath and Kutzbach, 1985). Between 12,400 and 8800 cal yr B.P., the lake level dropped gradually to an altitude 60 m lower than that of today (Wirrmann and Mourguiart, 1995; Fig. 2), indicating a large deficit in rainfall over the Altiplano.

Other paleoenvironmental records show a similar regional contrast during the same period. Records from northern South America indicate high moisture levels. Lake Valencia, north of Carajás (10°N, 67°W: Figs. 1a and 1b), was overflowing (Bradbury *et al.,* 1981: Leyden, 1985), pollen spectra from lake sediments in the São Gabriel da Cachoeira region (0°S, 67°W; Figs. 1a and 1b), northwest of Carajás, indicate full development of rainforests (Oliveira, 1995), and to the west in the Colombian Amazon, sediments in the Rio Caqueta basin (Urego, 1991) (1°S, 72°W; Figs. 1a and 1b) reflect a wet phase. In contrast, geomorphic studies in the upper Rio Doce region (17–18°S, 42–43°W; Figs. 1a and 1b), southeast of Carajás, identified alluvial cones that date from this period (Servant *et al.,* 1989). At present, the ITCZ reaches this region during the austral summer (Fig. 1a), fostering the growth of a semi-deciduous mesophilous forest. The intensive gullying in this region between 12,400 and 8800 cal yr B.P. necessary to provide material for the alluvial cones implies degradation of the forest cover, linked to a precipitation deficit. Similarly, in the Brasilia area (16°S, 48°W: Figs. 1a and 1b), cores retrieved from swamps (Barbieri-Ribeiro, 1994) indicate that organic sedimentation, which began 30,000 yr ago, ceased between 25,000 and 7500 cal yr B.P., implying drier conditions than today. Apparently, between 12,400 and 8800 cal yr B.P., these last two sites were not as much (if at all) affected by the equatorial air mass, indicating that the ITCZ did not move

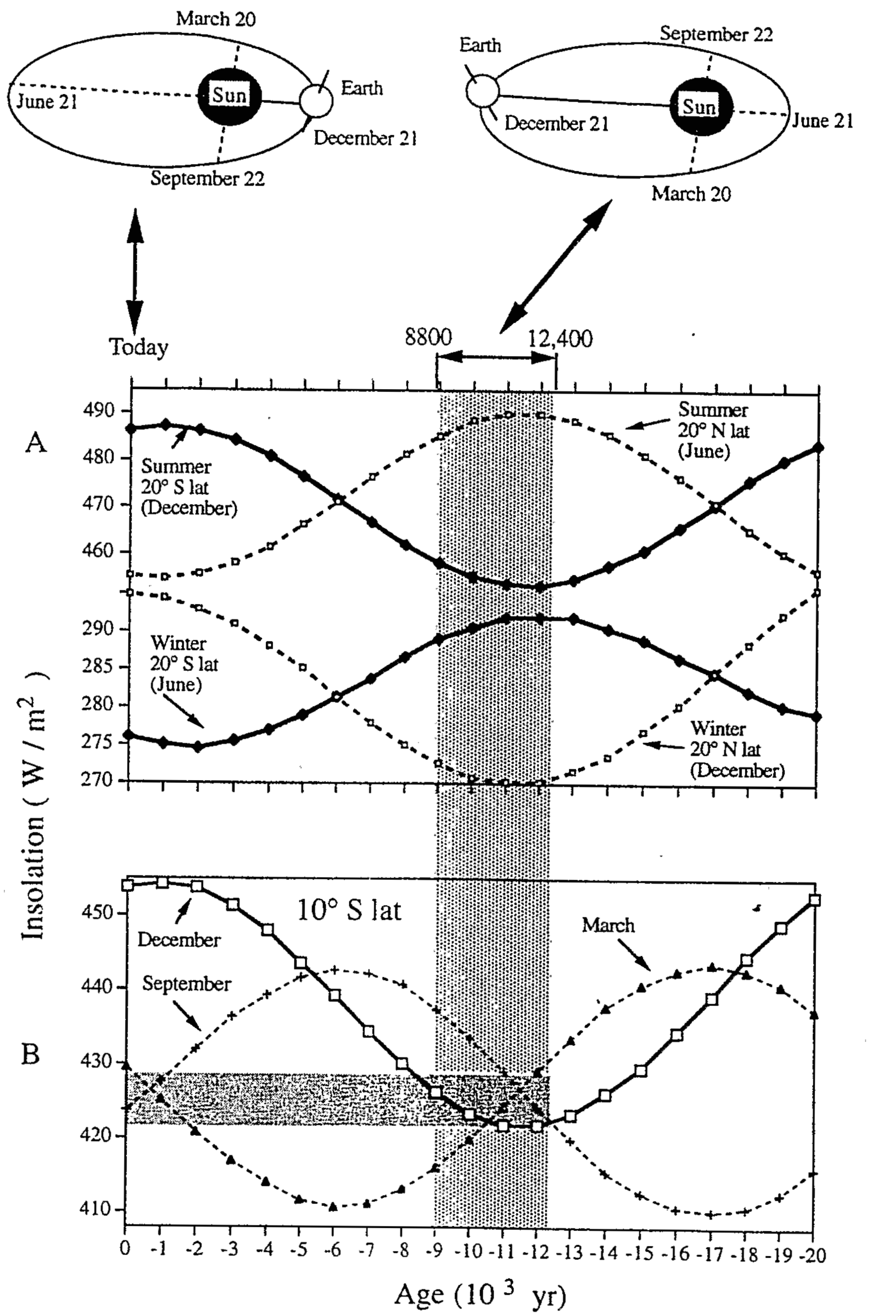

FIG. 3. Position of the Earth on December 21 relative to the Sun (upper figures) and insolation data for the past 20,000 yr (lower figures; data from Berger and Loutre, 1991). Upper: Present-day conditions (left) and conditions at 11,000 cal yr B.P. (right). Today, the Earth is close to the perihelion, giving warm summers, whereas at 11,000 cal yr B.P., it was close to the aphelion, inducing colder summers. Lower: (A) Today, the seasonal contrast in insolation is much larger at 20°S (close to the southernmost summer position of the ITCZ) than at 20°N, while it was the opposite 11,000 years ago. (B) Insolation values for a spring month (September), a summer month (December), and an autumn month (March) at 10°S. The horizontal shaded bar emphasizes the fact that between 12,400 and 8800 cal yr B.P. the insolation value varied very little from September to March and was similar to the present-day value for early spring or early autumn. As a consequence, the South American continent was not able to warm significantly during the summer months, and the ITCZ was blocked in a position similar to the one it reaches today in spring or autumn. The position of the ITCZ shown in Fig. 1b is that encountered today around October.

as far south as today during the austral summer (Fig. 1b). The lowering of Lake Titicaca, which began ca. 12,400 cal yr B.P., also supports this hypothesis because the deficit in rainfall was the consequence of the moist Amazonian air no longer reaching the Altiplano (Fig. 1b). Paradoxically, in the Atacama desert (19–27°S; Figs. 1a and 1b), south of Lake Titicaca where extremely rare rain showers also originate from the Amazon lowlands (Messerli *et al.*, 1993); the period 12,400–8800 cal yr B.P. was marked by an environment wetter than today (Grosjean, 1994; Grosjean *et al.*, 1995). North of Lake Titicaca, in the central Andes of Peru, pollen spectra from lake sediments in the Junin area (Hansen *et al.*, 1994) (11°S, 76°W; Figs. 1a and 1b) do not record any major change in precipitation during this period.

Today, orbital parameters (Berger and Loutre, 1991) are such that the Earth is far from the Sun in June and closest in December (Berger, 1992) (Fig. 3). As a consequence, in the Southern Hemisphere, seasonal differences are strong, with warm summers, cold winters, and strong seasonal shifts of the ITCZ (Fig. 1a). In contrast, around 11,000 cal yr B.P., the Earth was closer to the Sun in June and farther from it in December (Fig. 3), resulting in colder summers, warmer winters, and reduced seasonality in the Southern Hemisphere. The continent was not warming as much as today during the austral summer, and the ITCZ likely was located farther north (Fig. 1b), probably close to the position it occupies today during the austral late spring and early autumn when the Atlantic high pressure cell located on the eastern margin of the continent blocks the equatorial continental air to the northwest (Andrade, 1972; Niemer, 1989). Today, polar advections penetrate the continent from the south mainly in winter (Andrade, 1972). A weaker ITCZ ca. 11,000 cal yr B.P. would have helped polar advections to penetrate farther north in spring and autumn, and maybe even in summer. Support for this comes from the 800 km northward expansion of *Araucaria* forests (Fig. 1a) into the Salitre area about that time (Niemer, 1989; Ledru, 1993) (19°S, 47°W; Figs. 1a, 1b, and 2). Modern *Araucaria* forests are closely linked to precipitation occurring in the frontal zone of polar advections and cannot tolerate more than one month of drought. In addition, a strengthening of polar advections would increase snowfall in the south of the Altiplano (as can be exceptionally observed today in the Atacama Desert) without significantly affecting Lake Titicaca to the north.

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