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Southern Oscillation Signal in South American Palaeoclimatic Data of the Last 7000 Years

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During strong El Niño events, rainfall anomalies and changes in wind patterns are observed in different regions of South America. Along the central Brazilian coast, during the 1983 El Niño year, the frontal systems were blocked to the south, provoking a reversal of the longshore sand transport. Long-duration reversals of longshore transport were also recorded in Holocene beach-ridge terraces from the Rio Doce coastal plain. This led to the formulation of a model relating these reversals of longshore transport to El Niño-like conditions. El Niño-like conditions are past average climate situations that generate the same perturbations as the strong El Niño events observed during the last decade. They are likely to correspond to the long-duration low phase of the Southern Oscillation. To confirm this hypothesis we compared the Holocene beach-ridge record with other palaeoenvironmental records from regions where strong El Niño events would have a substancial signal as well: (1) water-level fluctuations of Lake Titicaca, (2) a pollen and sediment record in an eastern Amazonian lake, (3) changes of the Rio Xingu discharge in eastern Amazonia, and (4) variations of sand supply at the Rio Piura and Rio Chira outlets in the Sechura Desert. The occurrences of El Niño-like conditions were numerous before 3900–3600 yr B.P., absent between 3900–3600 and 2800–2500 yr B.P., and infrequent after 2800–2500 yr B.P. ©1993 University of Washington.

INTRODUCTION

The eastern margin of the Pacific Ocean, in the southern tropics, is characterized by relatively cold sea-surface temperature. These cold waters strongly influence the tropical continental climate. This climatic background pattern is drastically altered in the low phase of the Southern Oscillation (SO), defined by anomalously high/low pressure at Tahiti/Darwin. In the low SO phase, El Niño events may occur and the equatorial Pacific waters are warmer than usual (Philander, 1983; Enfield, 1989). This situation leads to large rainfall anomalies and changes in wind patterns in South America (Fig. 1). During strong El Niño events, the disturbances are generated by two main processes:

(1) a westward shift of the convection zone, normally centered on Amazonia (Fig. 1; Wyrtki, 1982). This shift promotes anomalously heavy rainfall in northern Peru and deficient rainfall in Amazonia and the Bolivian Altiplano.

(2) a blocking situation of polar frontal systems in a zone extending from southern Peru to southern Brazil, related to an enhancement of the subtropical jetstream (Kousky *et al.*, 1984). This situation is associated with anomalously high rainfall in the blocking zone and drought in the regions located northward, as well as modification of the wind patterns and, consequently, of the wind-driven littoral dynamics along the central part of the Brazilian coast.

Reversals of the longshore sand transport, with a duration of tens to hundreds of years, were evidenced in that region during the last 5100 yr. This suggests the possible existence of long-duration El Niño-like conditions. El Niño-like conditions likely correspond to a long-duration low SO phase. We propose here a conceptual model expounding climate anomalies in different regions of South America by long-term low phases of the Southern Oscillation. Studies conducted in the Bolivian Altiplano, eastern Amazonia, and northern Peru are used to confirm this hypothesis.

CHANGES IN BEACH-RIDGE FORMATION ALONG THE BRAZILIAN COAST

Evidence of reversals in longshore sand transport direction is found in the Rio Doce coastal plain (19°S; Dominguez *et al.*, 1983). However, no interpretation of this phenomenon had been proposed until such a reversal

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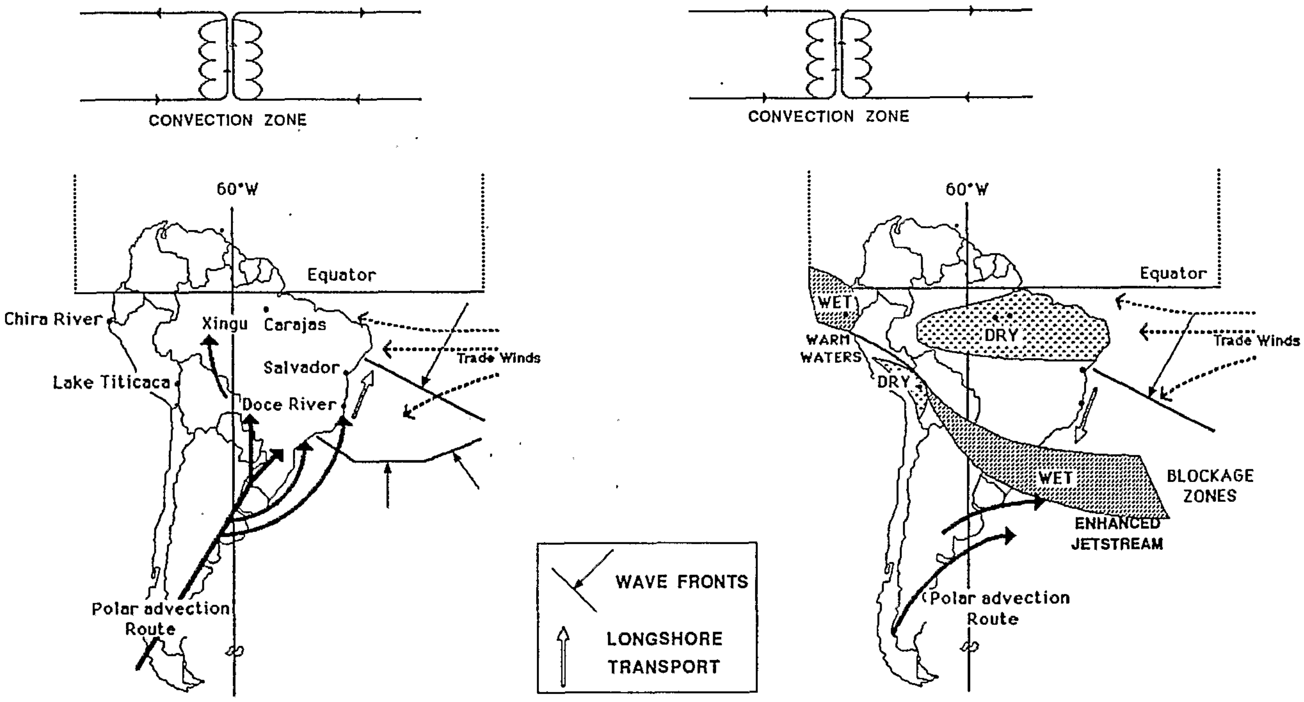

NORMAL CONDITIONS **EL NIÑO CONDITIONS**

FIG. 1. Disturbances caused by strong El Niño phenomena in several countries of South America.

of the longshore transport was observed in 1983 (Farias *et al.*, 1985) on a beach from Salvador (Bahia State). During this year, southeastern swell that normally reaches the region during the austral autumn and winter and determines the longshore sand transport direction did not operate due to the blocking situation of frontal systems related to the 1982–1983 El Niño event. Therefore, over several months, a relation exists between longshore sand transport on the central Brazilian coast and the El Niño event. The mechanisms by which past longshore transport is generated and registered must be understood to make further interpretations.

Present Littoral Dynamics along the Central Brazilian Coast

The pattern of wave systems in the central part of the Brazilian coast is imperfectly known. However, observations are sufficient to identify two swell regimes, corresponding to the two wind systems active in the area: one from ENE and the other from S–SSE (Fig. 1). The ENE winds are related to the trades and are active throughout the year, particularly from October to March, whereas winds from the S–SSE sector correspond to cold frontal systems that periodically reach the region, mostly from April to September.

On a low coast, the longshore sand-transport direction depends on swell orientation (Fig. 2A). If the coast is submitted to diverse swell patterns, the efficient swells are defined as those that determine the resulting longshore transport direction. Such swells are not necessarily the most common ones. For instance, along the central Brazilian coast the southern sector waves, in spite of their infrequent occurrence, are much more powerful

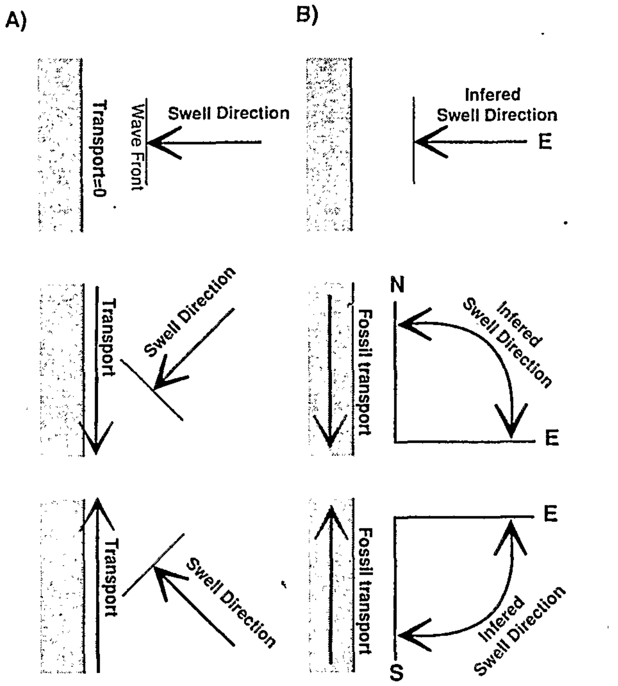

FIG. 2. Relations between swell and longshore transport direction. (A) Swell direction and resulting longshore transport. (B) Swell deduced from longshore transport direction.

than the northern sector waves and therefore generate a resulting longshore sand transport from south to north.

This pattern is altered during strong El Niño events (Fig. 1) when the polar frontal systems are blocked and the subtropical jet is enhanced (Kousky *et al.,* 1984). During these episodes, the frontal systems remain for an extended time in southern and southeastern Brazil. Consequently, the swells from the southern sector that are generated by these frontal systems do not reach the central part of the Brazilian coast. In such cases, the northern sector swell becomes the efficient one, driving the resulting longshore sand transport from north to south.

When fossil beach ridges exist, as along the central Brazilian coast, their geometry reflects the past directions of longshore sand transport. Thus, one can determine from which sector the past efficient swells came (Fig. 2B), thereby permitting the past atmospheric circulation to be characterized.

Reversals of Longshore Sand Transport Direction during the Last 5000 yr in the Rio Doce Coastal Plain

The Rio Doce coastal plain, stretching in a nearly N–S direction, lies between 18°30′ and 19°45′ S. It is asymmetrical, crescent-shaped, and has a maximum width of about 38 km and a maximum N–S length of about 130 km (Fig. 3). Quaternary deposits are found seaward of an inactive cliff carved in Pliocene continental sediments. Detailed mapping showed the occurrence of sandy deposits associated with the last two transgressive episodes that exceeded present sea level (123,000 and 5100 yr B.P.; Suguio *et al.,* 1982).

Sea-level fluctuations during the last 7000 yr are well known for the central part of the Brazilian coast (Martin *et al.,* 1987). Three main episodes of submergence (7000–5100, 3900–3600, and 2700–2500 yr B.P.) alternating with three main episodes of emergence (5100–3900, 3600–2700, and after 2500 yr B.P.) can be identified (Fig. 4). A submerged coast does not exhibit the same morphological features as an emergent coast because relative sea-level changes play an essential role in coastal sedimentation. These changes have a double effect: they partially control sand supply and they determine the general form of deposition. Simultaneously, the shape of the deposits (geometry, location, and progradation direction of the beach ridges) is also controlled by the angle between a section of the beach and the efficient swell fronts. This beach-ridge formation is achieved by longshore sand transport process. Under favorable conditions, episodes of submergence and emergence, as well as past directions of the longshore sand transport, may be identified by a detailed study of beach-ridge geometry.

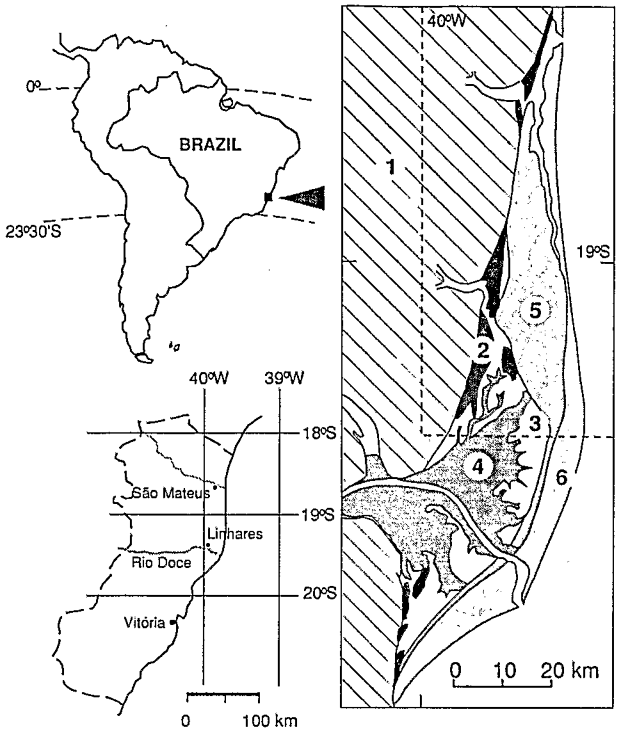

FIG. 3. Schematic geological map of the Rio Doce coastal plain showing (1) the Barreiras Formation, (2) Pleistocene marine terrace, (3) lagoonal deposits, (4) intralagoonal delta, (5) first generation Holocene marine terrace, and (6) second-generation Holocene marine terrace. The dashed line indicates area of Figure 5 (Martin and Suguio, in press).

The buildup of the Holocene part of the Rio Doce coastal plain began with the formation of a barrier island/lagoon system (Suguio and Martin, 1981, Dominguez *et al.,* 1987). Soon after lagoon formation, construction of a huge intralagoonal delta began. On the seaward side of the barrier island, a first generation of sandy terraces, covered by aligned beach ridges, developed (Fig. 3). The two regressive–transgressive episodes of the central Brazilian sea-level curve (Fig. 4) are well marked in the Doce River coastal plain by large-scale retreats of the coastline followed by a new generation of sandy terraces. On these terraces several marked truncations of the beach-ridge alignments correspond to changes in direction of longshore sand transport. In the northern part of the coastal

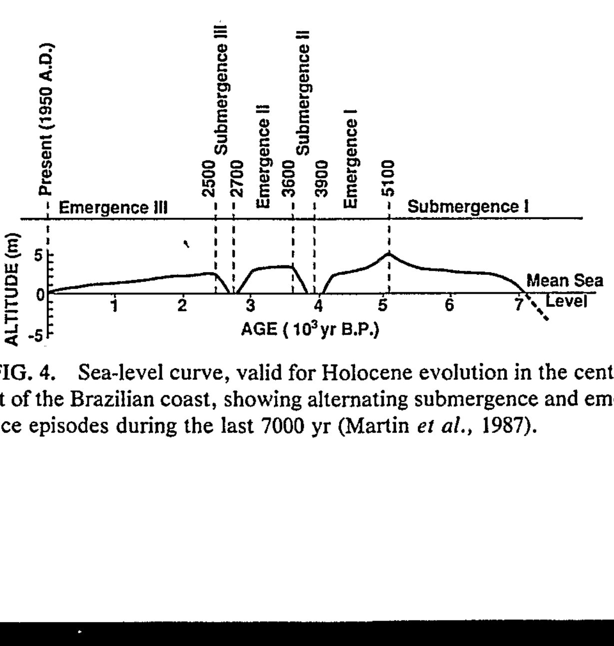

FIG. 4. Sea-level curve, valid for Holocene evolution in the central part of the Brazilian coast, showing alternating submergence and emergence episodes during the last 7000 yr (Martin *et al.,* 1987).

plain (Fig. 5), for instance, they are related to erosional periods caused by the northeastern swells alternating with depositional periods related to northward longshore sand transport (southern sector swells). Such reversals can be observed in all the beach-ridge systems of the Doce River coastal plain (Martin and Suguio, 1992). A detailed study of the whole sequence indicates the following:

(1) Absence of beach ridges older than 5100 yr B.P. (submergence episode) does not permit inferences to be made about longshore transport directions.

(2) Between 5100 and 3900 yr B.P. (emergence episode), the longshore sand transport that is normally northward, reversed southward during seven separate episodes implying that during these intervals the southeastern swells did not reach the study area.

(3) Between 3900 and 3600 yr B.P., rising sea level did not permit beach-ridge formation which would have permitted the direction of longshore sand transport to be determined.

(4) Between 3600 and 288 yr B.P. (emergence episode), longshore transport was continuously northward; the southeastern swells were a permanent feature.

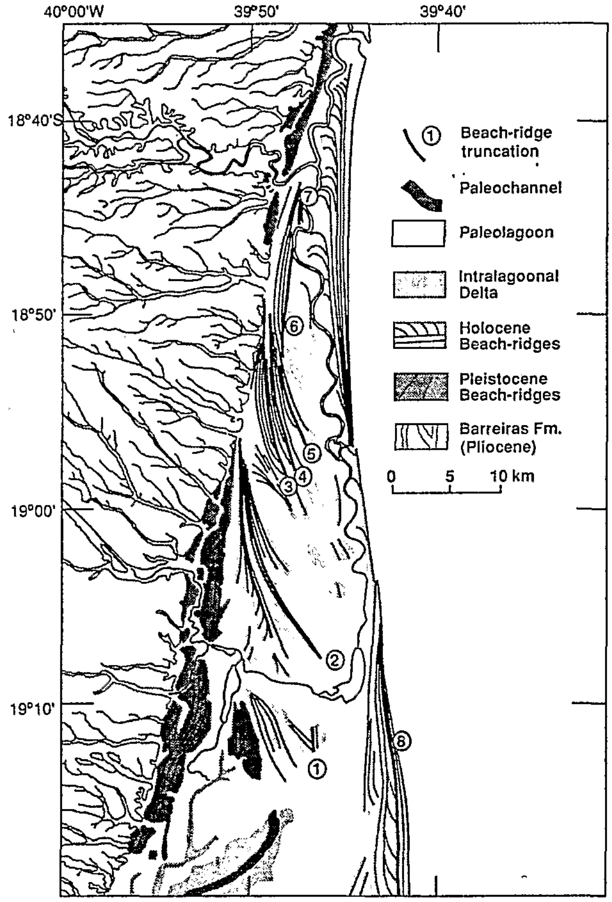

FIG. 5. Northern part of the Rio Doce coastal plain. Beach-ridge truncations are related to reversals in the direction of the longshore sand transport. See Figure 3 for location.

(5) Between 2800 and 2500 yr B.P., a relative sea-level rise prevented formation of beach ridges, making it impossible to determine the direction of longshore sand transport.

(6) Between 2500 yr B.P. and the present (emergence episode), the longshore transport reversed southward three times (at 2200 ± 200 and 1300 ± 200 yr B.P. and at an undefined recent time). During those three intervals, the southeastern swells did not reach this region.

These reversals can only be explained by changes in efficient swell direction and therefore in the wind regime (Martin *et al.*, 1984, 1991). As strong El Niño events are able to produce indirectly, over several months, the same kind of disturbance in longshore sand transport, we infer that the long periods of reversed longshore transport are associated with long periods of blocking conditions of frontal systems related to El Niño-like conditions.

CONCEPTUAL PALAEOCLIMATIC MODEL

Perturbations of few months duration of the longshore sand transport are easily observed on the present-day beaches but are not recorded in the geometry of past beach ridges. Indeed, the volumes of sand involved in the Holocene reversals of longshore transport along the Rio Doce coastal plain are considerably higher than volumes corresponding to a single El Niño event or mega-El Niño event. The size of the eroded zones (several kilometers of shoreline regression) imply persistence of the phenomenon during several tens of years. Therefore, the El Niño-like conditions recorded by the beach-ridge geometry are not palaeo-El Niño events (i.e., past occurrences of El Niño events similar to the present ones) but represent average palaeoclimate situations that generate the same kind of perturbations as strong El Niño events observed during the last decade. El Niño-like conditions are likely to correspond to phases with a low SO index. However, El Niño is an extreme event in the annual cycle, whereas the low SO mode may persist over longer time periods (Hastenrath, 1991, pp. 264–288). El Niño-like conditions may correspond to a single long-duration perturbation or to several repeated perturbations during a reasonably long time interval (a few decades). The resolution of geological records does not allow us to differentiate these two patterns.

The proposed conceptual model suggests the existence of El Niño-like conditions, with effects similar to strong present-day El Niño events, occurring more or less repeatedly during the last 5100 years. If El Niño-like conditions occurred during the last 5100 years, they should produce in Amazonia, on the Bolivian Altiplano, and in northern Peru the same types of perturbations as those exhibited by modern strong El Niño events (Fig. 1):

(1) Prior to 3900–3600 yr B.P., numerous occurrences of blocking situations suggest a series of drier periods in

Amazonia and the Bolivian Altiplano, as well as a series of wetter periods in the Sechura Desert of northern Peru.

(2) Between 3900–3600 and 2800–2500 yr B.P., when no blocking situations occurred, the climate must have been, on average, wetter in Amazonia and the Bolivian Altiplano and drier in the Sechura desert.

(3) Between 2800–2500 and 0 yr B.P., the three recorded occurrences of blocking situations suggest at least three drier periods in Amazonia and the Bolivian Altiplano and at least three wetter periods in the Sechura Desert about 2200 and 1300 yr B.P. and in the recent past.

CONFIRMATION OF THE MODEL

Palaeoclimatic information from a record of water-level fluctuations of Lake Titicaca, from a pollen and sediment record in an eastern Amazonian lake, from a record of changes in the Rio Xingu discharge in eastern Amazonia, and from past variations of sand supply at Rio Piura and Rio Chira outlets in the Sechura Desert support our palaeoclimatic inferences derived from beach-ridge observations.

Fluctuations in the Level of Lake Titicaca during the Last 7000 yr

In a normal year, the water level of Lake Titicaca drops ca. 75 cm during the dry season between May and October and rises by a similar amount during the rainy season from November to March (Fig. 6; Carmouze and Aquize Jaen, 1981). During El Niño events (Lamb, 1977; Quinn *et al.*, 1987), or more generally during low SO phase, precipitation is greatly reduced and during the rainy season the rise is markedly weaker or the water level may even drop (Francou and Pizarro, 1985). Inversely, during anti-El Niño years or, more generally, during high SO phase, rainfall is enhanced and the lake-level rise is consistently higher (ca. 190 cm in 1986). As an example, during the interval between 1936 and 1943, marked by repeated occurrences of El Niño events, the reduction of the lake-level rises lead to a net lowering of 3 m. During the "normal" years of 1944, 1945, and 1946, the lake level remained in that low position. Then, between 1947 and 1963, an interval marked by four occurrences of anti-El Niño events, the increased austral summer precipitation provoked a 3 m net increase of lake level (Fig. 6).

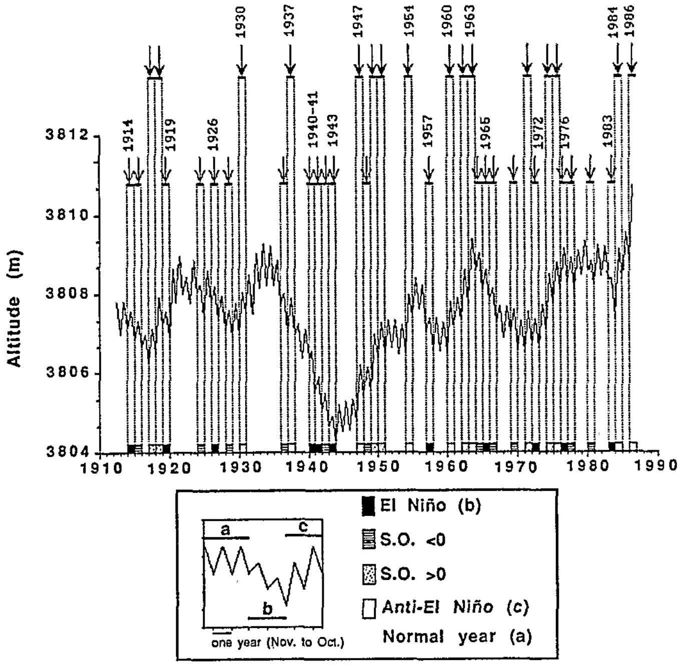

FIG. 6. Annual water-level fluctuations in the Lake Titicaca showing relation to the Southern Oscillation (SO).

The last 7000 yr of water-level fluctuations of Lake Titicaca were reconstructed using a transfer function based on modern ostracod fauna (Mourguiart and Roux, 1990). The data indicate that Lake Titicaca, which had rapidly reached its lowest level around 7500 yr B.P., did not rise regularly afterwards (Fig. 7).

Prior to 3900 yr B. P., water levels fluctuated around a position considerably lower than the present one (−18 m for the small southeastern subbasin and −48 m for the large northwestern one). At the time Rio Doce data indicate several periods of El Niño-like conditions. Because lake levels remained around the same mean position, it is likely that the climate was not permanently dry, but instead there was a succession of droughts.

Between 3900 and 3000 yr B.P. (no period of El Niño-like conditions at Rio Doce), the water level rose markedly (up to −6 m in the small subbasin and ca. −25 m in the large one) as a consequence of a wetter climate.

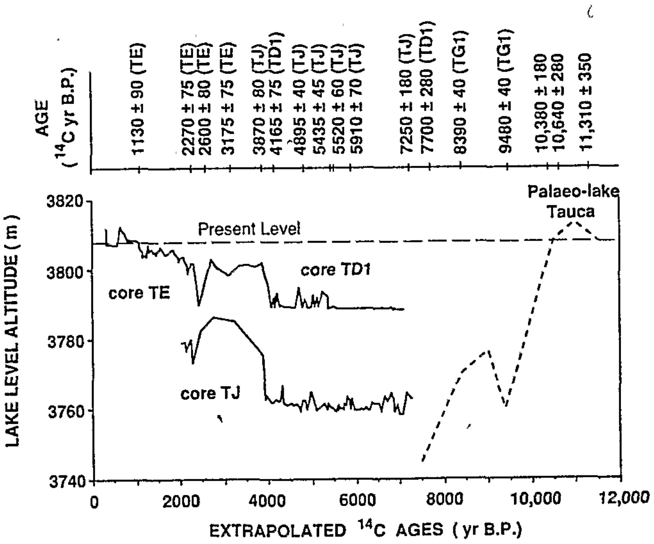

FIG. 7. Water-level fluctuations in Lake Titicaca during the last 12,000 yr.

TABLE 1

January–May Rainfall Anomalies (mm) for Selected Stations during the Last Three El Niño Events

Station	January–May rainfall (mm) 1972 Anomaly	1976 Anomaly	1983 Anomaly	Mean normal
São Gabriel do Cachoeira (0°8'S, 67°5'W)	−6	−93	−407	1394
Manaus (3°7'S, 60°1'W)	−78	−19	−416	1334
Belém (1°28'S, 48°29'W)	−224	−168	−387	1808
Barra do Corda (5°30'S, 45°16'W)	−92	−42	−133	796
Conceicão do Araguaia (8°16'S, 49°17'W)	−189	−234	−178	978

Note. The 5-month normal rainfall (mm) is given in the last column on the right (from Kousky *et al.*, 1984).

After 3000 yr B.P. (at least three periods of El Niño-like conditions at Rio Doce) the water level remained lower than at present, with 4 to 5 episodes of abrupt water level drop, corresponding to drier episodes. One is dated about 2300 yr B.P. and another about 1300 yr B.P.

Variations in Pollen Assemblages and Sedimentary Fluxes in a Lake Core from the Serra dos Carajas (Eastern Amazonia)

The Carajas region is located in an elongated NW–SE zone where precipitation is relatively low for a rain-forest region (1500–2000 mm; RADAM Projeto 1974, 1975, 1976). Thus, its vegetation probably is sensitive to changes in rainfall. As explained earlier, El Niño events are marked by a westward shift of the convection zone, normally centered on Amazonia, toward the Pacific Ocean, which leads to a rainfall decrease in Amazonia (Table 1). During the 1983 El Niño year, annual rainfall in the Carajas region decreased, lengthening the dry season from 3 to 5 months.

The Southern Serra dos Carajas (6°20'S, 50°25'W) is a 700- to 800-m-high narrow plateau developed on a banded iron formation and surrounded by the Amazonian rain forest. The plateau surface is covered by more or less dense scrub savannas with small tress. Palynological (Absy *et al.*, 1991) and sedimentological (Sifeddine, 1991) analyses were made of a core collected on the plateau, in the center of a former lake now filled with sediment. Palynological data (Fig. 8) reveal that during the last 60,000 yr four periods of forest decline occurred, evidenced by a strong decrease in arboreal pollen percentages. The last interval, between 7000 and 4000 yr B.P., is different from the previous dry phases inasmuch as savanna pollen was absent and sedimentary fluxes were low (Fig. 8). Moreover, between 6000 and 4000 yr B.P., the arboreal pollen is dominated by *Piper*, a pioneer element of the rain forest median strata, which reaches 40% of the total pollen sum. During the Pleistocene dry phases, *Piper* is represented only by low percentages. The absence of savanna pollen, the low levels of erosion revealed by low sedimentary fluxes, and the permanence of rain forest pioneers indicate somewhat wetter climates than during the Pleistocene dry periods. The great abundance of charcoal microfragments in the sediment of this interval, corresponding to the highest carbon fluxes registered in the core (Fig. 8), suggests repeated fires.

This evidence leads to the conclusion that the forest regression is not due to permanent dryness but to a series of dry periods alternating with slightly wetter periods. After 4000 yr B.P., the percentage of *Piper* and of nonarboreal pollen decreased drastically. The succession of upper strata pioneer arboreal elements after this time suggests further climatic fluctuations, but the low sedimentation rate precludes their detailed study.

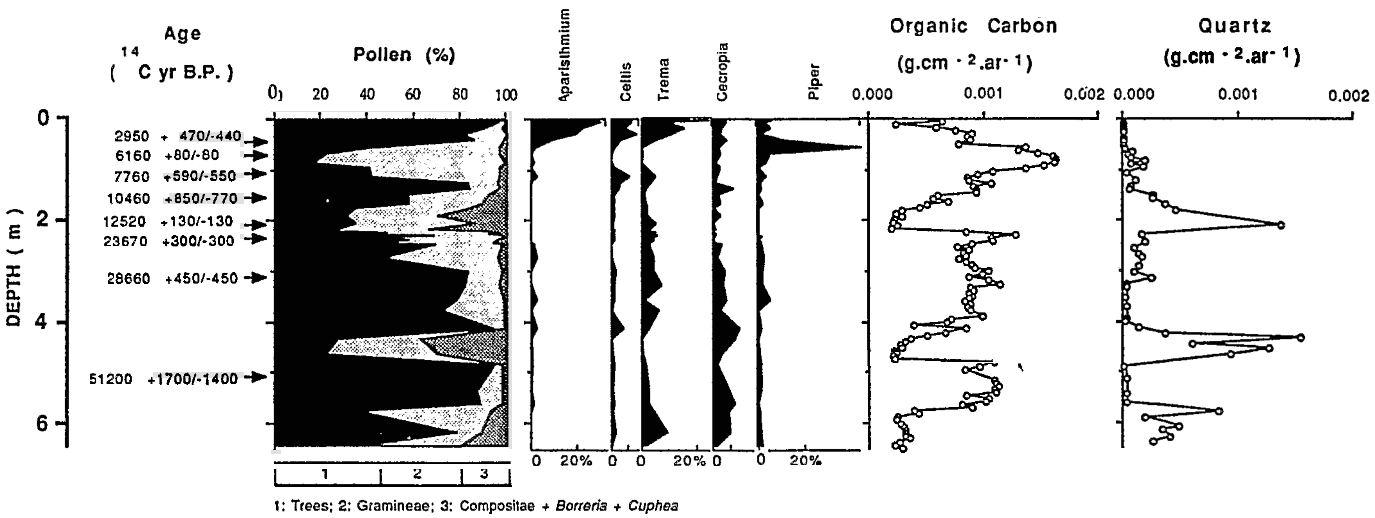

FIG. 8. Summary pollen diagram and quartz and organic carbon fluxes in the CSS2 core, Serra Sul dos Carajas, Eastern Amazonia, Brazil.

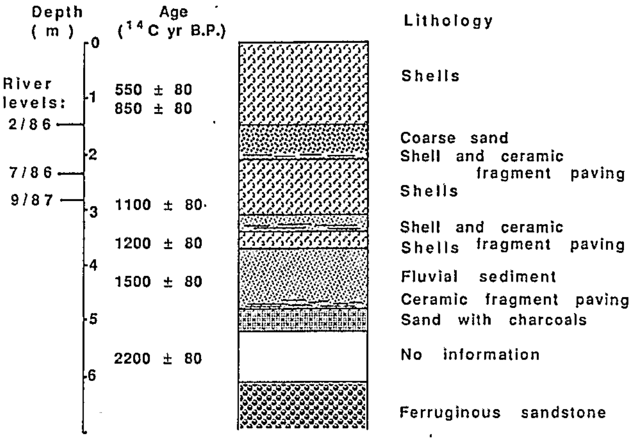

FIG. 9. Section of the anthropogenic accumulation Guara-I (Rio Xingu). Modified from Perota and Botelho (1990).

Rio Xingu (Eastern Amazonia) Discharge Variations during the Last 2500 yr

The palaeoclimatic information from the Carajas record is complemented by archaeological data from a shell midden in eastern Amazonia (Perota and Botelho, 1990). The base of this shell midden lies 4 m below the mean level of Rio Xingu (Fig. 9). The data show that three periods of settlement occurred when the river level was low. These periods, lasting for decades, were interrupted by episodes of flooding about 2200, 1200, and 850 yr B.P. (Table 2). These data indicate the existence of three dry periods, corresponding to the settlement phases, before 2200 yr B.P., before 1200 yr B.P., and before 850 yr B.P.

TABLE 2.

Radiocarbon Ages Data and Occupation Phases in the Archeological Site Guara-I on the Rio Xingu (from Perota and Botelho, 1990)

Radiocarbon ages (yr B.P.)	Laboratory number	Site history	River level
550 ± 80	Beta 17125	Occupation	Low
		Submergence	High
840 ± 60	Si 7142		
850 ± 85	Si 7143		
860 ± 55	Si 7149		
870 ± 85	Si 7145		
920 ± 80	Beta 21769		
940 ± 130	Si 7148	Occupation	Low
1000 ± 55	Si 7141		
1050 ± 60	Si 7174		
1060 ± 70	Beta 21770		
1080 ± 80	Beta 27429		
1090 ± 60	Beta 27025		
		Submergence	High
1200 ± 80	Beta 21768		
1255 ± 70	Si 7150		
1370 ± 80	Beta 27023	Occupation	Low
1480 ± 120	Beta 27027		
1485 ± 75	Si 7144		
		Submergence	High
2255 ± 55	Si 7146	Occupation	Low

Variation of Sand Deposition by the Rio Piura and Rio Chira (Northern Peru)

The climate of northern Peru is normally desertic. However, during several episodes within the 1982–1983 El Niño event, repeated heavy convective rainfalls occurred. The Sechura Desert was transformed into a region of extensive and raging flash floods. In the Chulucanas region, the yearly rainfall (mean = ca. 250 mm) reached 4000 mm in 1983 (Fig. 10; Goldberg and Tisnado, 1987).

These heavy rainfalls related to strong El Niño events washed a large amount of loose sediment into the Rio Piura and Rio Chira while, simultaneously, stream competency increased. The fluxes of sediment at the river outlets were redistributed northward by the longshore

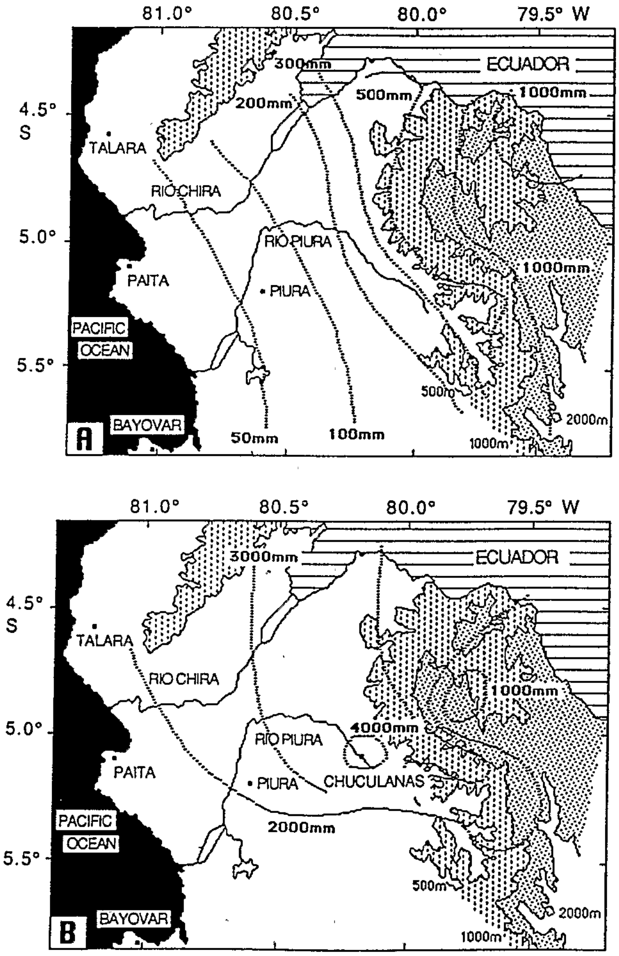

FIG. 10. Contours of mean rainfall in northern Peru, (A) for a typical non-El Niño year and (B) for the 1983 El Niño year (after Goldberg and Tisnado, 1987)

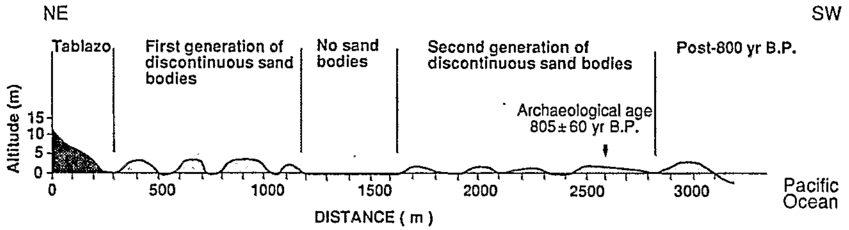

FIG. 11. Discontinuous sandy sedimentation in the north of Rio Chira outlet (northern Peru) related to discontinuous sediment supplies by the river. Modified from Richardson (1983).

current. These supplies of sediment ceased as soon as the abnormal rainfalls ended (Sandweiss *et al.*, 1983).

During the last 5000 yr, a sequence of sand ridges was deposited close to the Rio Piura and Rio Chira outlets. However, the sand volume involved was too substantial to be transported during only a few months, even by strong floods. The transport can only be explained by rainy periods of longer duration or repeated occurrences of rainy periods. Studies of these geomorphological features reveal the presence of two generations of deposits separated by a zone without any sand bodies (Fig. 11; Richardson, 1983). Despite the absence of a precise chronology, it seems possible to relate the sand ridges to periods of El Niño-like conditions. The first generation of sandy deposits, therefore, may date to the period before 3900 yr B.P. when several El Niño-like conditions occurred; the zone without sand bodies to the interval between 3900–3600 and 2800–2500 yr B.P., when no El Niño-like conditions occurred; and the second generation of sand deposits to the interval after 2800–2500 yr B.P., when few periods of El Niño-like conditions occurred.

The outermost sand body, bordering the ocean, is morphologically different from the others. Archaeological data revealed that it developed after 805 ± 60 yr B.P. (SI 1457). The historical El Niño events are not individually represented by specific sand ridges. Instead, the outermost sand body represents the cumulative supplies of all these events. This seems to indicate that the present climatic pattern, with episodic El Niño events as described since the Spanish occupation, may have become established only after 805 yr B.P.

CONCLUSION

Palaeoclimatic information, obtained separately in different regions of South America, point to the existence of periods of long-duration low SO phase during the last 7000 yr. In all regions considered, they represent average palaeoclimatic situations that generate the same perturbations as strong El Niño events. Their duration is believed to last several decades. These occurrences were numerous before 3900–3600 yr B.P., absent between 3900–3600 and 2800–2500 yr B.P., and rare after 2800–2500 yr B.P. They promoted marked climatic variations in the regions considered.

Occurrences of such short-term events have considerable importance for the tropical palaeoclimate. Their short duration implies that they are not easily registered in the geological records and cannot be defined by palaeoclimatic simulations (COHMAP Members, 1988). This kind of short-term event may be, in part, responsible for the enhanced Holocene seasonality observed in the tropical zones, particularly in South America (Markgraf, 1989).

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