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Correlated Millennial-Scale Changes in Surface Hydrography and Terrigenous Sediment Yield Inferred from Last-Glacial Marine Deposits off Northeastern Brazil

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The stable isotope composition of planktonic foraminifera correlates with evidence for pulses of terrigenous sediment in a sediment core from the upper continental slope off northeastern Brazil. Stable oxygen isotope records of the planktonic foraminiferal species *Globigerinoides sacculifer* and *Globigerinoides ruber* (pink) reveal sub-Milankovitch changes in sea-surface hydrography during the last 85,000 yr. Warming of the surface water coincided with terrigenous sedimentation pulses that are inferred from high XRF intensities of Ti and Fe, and which suggest humid conditions in northeast Brazil. These tropical signals correlate with climatic oscillations recorded in Greenland ice cores (Dansgaard-Oeschger cycles) and in sediment cores from the North Atlantic (Heinrich events). Trade winds may have caused changes in the North Brazil Current that altered heat and salt flux into the North Atlantic, thus affecting the growth and decay of the large glacial ice sheets. © 1998 University of Washington.

Key Words: **Northeast Brazil; Equatorial Atlantic; North Brazil Current; paleoceanography; stable oxygen isotopes; geochemical analyses; paleoclimate.**

INTRODUCTION

Rapid climatic oscillations, as reported from Greenland ice core records, occurred during the last glacial period (e.g., GRIP Members, 1993; Grootes *et al.*, 1993; Bender *et al.*, 1994). They produced cycles of high amplitude changes in dust content, methane and carbon dioxide concentration, and air temperature ($\delta^{18}O_{ice}$-record) that lasted several millennia. The short-term oscillations called Dansgaard-Oeschger cycles (ca. 24 recognized interstades) were part of longer term cooling cycles (Bond cycles) that culminated in massive iceberg discharges into the North Atlantic, the Heinrich events (e.g., Heinrich, 1988; Broecker *et al.*, 1992; Bond and Lotti, 1995), and were followed by abrupt shifts to warm interstades. Recent paleoceanographic work shows that these various cycles affected global climate (Behl and Kennett, 1996; McIntyre and Molfino, 1996; Bard *et al.*, 1997; Curry and Oppo, 1997; Little *et al.*, 1997).

Heat and moisture release from tropical areas may have forced some of the short-term climate changes. The sub-Milankovitch variations may represent a non-linear response of the low-latitude climate system to astronomical forcing (Pestiaux *et al.*, 1988; Hagelberg *et al.*, 1994). The cycles probably caused short-term variations of the wind field and moisture content in the tropical atmosphere that changed the upper level ocean (McIntyre and Molfino, 1996). For example, the southern trade winds may have had sub-Milankovitch variations in zonality and intensity (Little *et al.*, 1997).

As a strong, north-northwestward flowing boundary current of the western tropical Atlantic, the North Brazil Current (NBC) transports heat and salt into the North Atlantic (Peterson and Stramma, 1991; Stramma *et al.*, 1995). The NBC therefore contributes to the Atlantic conveyor circulation. Short-term changes in the flow pattern and intensity of the NBC during the last glacial period might therefore be related to global changes in climate and ocean circulation. Moreover, both the NBC and the continental climate of northeast Brazil are linked to annual and interannual changes in the southern trades (e.g., Philander and Pacanowski, 1986; Hastenrath and Merle, 1987; Nobre and Shukla, 1996).

To explore the paleoclimatic role of the NBC, we studied a sediment core from the upper continental slope off northeastern Brazil. We used radiocarbon dating and oxygen isotope data for age control. Variations in the carbonate content and the ratio between the elements Ti, Fe, and Ca were used as continental climate indicators. To reconstruct past hydrographic conditions, we measured the stable oxygen isotope ratios in the carbonate shells of two shallow-dwelling planktonic foraminifera. We found the last glaciation characterized by alternations in carbonate-dominated and terrigenous-dominated sedimentation. The stable isotope records suggest concurrent short-term changes in surface-water hydrography. Further correlations with northern hemisphere records suggest that variations in the low latitude atmospheric circulation contributed to millennial-scale shifts in global climate.

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PHYSIOGRAPHY AND OCEANOGRAPHICAL SETTING

The study area is located on the northeastern Brazilian continental margin near 4°S. The area has a narrow (on average 30 km wide), shallow (50 to 80 m) shelf and a steep continental slope (Fig. 1). Today, mainly biogenic carbonate is deposited on the shelf and the upper continental slope (Summerhayes *et al.*, 1975). Terrigenous sediments occur only on the inner shelf area. Small abandoned erosional channels on the shelf and incised valleys on the upper continental slope probably formed during low stands of the sea.

The core location is directly influenced by the NBC. North of 5°S the North Brazil Undercurrent (NBUC) rises to the surface and, together with the northern branch of the South Equatorial Current (SEC), produces northwestward surface flow up to 300 km wide (Da Silveira *et al.*, 1994; Schott *et al.*, 1995). The seasonal variability of the NBUC and NBC transport is related to the southeast trade winds, with a larger transport during austral spring and reduced transport in austral fall (Richardson and Walsh, 1986; Stramma *et al.*, 1995).

Sea-surface temperature (SST), evaporation, precipitation, and surface current intensity in this region are linked to seasonal and long-term changes in trade wind intensity (Hastenrath and Merle, 1987; Chang *et al.*, 1997). During austral spring the southeast trades reach maximum intensity and the SEC accelerates, deepening the mixed layer and accumulating salty, warm water masses off the South American continent. In austral fall, weak trade winds and reduced surface current intensity result in shallowing of the thermocline (Fig. 2). SST averages 27.3°C with seasonal variations of less than 2°C. Average sea surface salinity (SSS) is 36‰ with a seasonal amplitude of only 0.3‰. The top of the thermocline is characterized by a salinity maximum of 36.5‰ caused by the Subtropical Underwater (Schott *et al.*, 1995) (Fig. 2).

MATERIAL AND METHODS

We studied gravity core GeoB 3104-1 (03°40.0′S, 37°43.0′W), collected during a cruise on R/V Victor Hensen off Fortaleza (Ceará, NE-Brazil) from a water depth of 767 m (Fig. 1). During the Meteor cruise M 34/4 in spring 1996 a second sediment core (GeoB 3912-1) was retrieved at the same position, extending the sediment record from 523 to 674 cm. Detailed X-radiograph examination shows that the cores are generally undisturbed.

We measured bulk-sediment chemistry by means of profiling X-ray fluorescence. The measurements were made on the CORTEX scanner developed at the Netherlands Institute for Sea Research. This rapid, computer-controlled method (one measurement lasts about 1 min) allows qualitative determination of the geochemical composition of the sediment (Jansen *et al.*, 1992). The measurements were done at intervals of 3 cm or less.

Faunal and geochemical samples were taken every 2.5 cm. The geochemical samples were freeze-dried and ground prior to the measurements of total organic carbon (TOC) and carbonate content (Müller *et al.*, 1994). The results are expressed as weight percentages of dry, salt-free sediment. The faunal samples were wet-sieved and dried at 55°C. The foraminiferal fragmentation index was determined by counting whole planktonic foraminifera tests and test fragments in the dry-sieved fraction >250 μm (e.g., Metzler *et al.*, 1982). The samples were split as much as necessary to yield about 300 whole foraminiferal tests. The fragmentation index is given as % fragments = 100 * number of fragmented tests/total number of tests.

Eight specimens of 350 to 400 μm diameter (measured along the longest axis) of the species *Globigerinoides sacculifer* (without final chamber) and *Globigerinoides ruber* (pink) were used for stable isotope measurements on a Finnigan MAT 251 mass spectrometer. Samples were prepared on an automated line attached to the mass spectrometer. Analytical internal longtime precision is better than ±0.07‰, whereas the standard deviation of repeated measurements of foraminifera from several core depth intervals was less than ±0.1‰. Multiple measurements were averaged.

To prepare samples for ^{14}C AMS dating, about 700 individuals of the foraminiferal species *G. sacculifer* (250–400 μm) were hand picked. Carbonate hydrolysis and CO_2 reduction were done in Bremen, Germany. The AMS measurements were made at the Leibniz-Labor in Kiel, Germany (Nadeau *et al.*, 1997) and the Center for Isotope Research, Groningen, Netherlands.

RESULTS

Stratigraphy

The stratigraphy is composited from the gravity cores GeoB 3104-1 and GeoB 3912-1. The large size of the gravity corer for GeoB 3912-1 caused compaction and required a depth correction. Detailed comparisons of the core tops with undisturbed box core samples (box core GeoB 3912-2) show that no significant sediment disturbance occurred during core recovery.

In the upper 384 cm of GeoB 3104-1 the age/depth relation was inferred from linearly interpolated ^{14}C AMS ages (Table 1). We used the U–Th calibration of the ^{14}C ages from Bard *et al.* (1993) to convert the ^{14}C ages to calendar years. However, the calibration beyond 25,000 yr is based on so few data points that our age/depth estimates are tentative. For the core section older than 38,000 yr, the stable oxygen isotope record of the foraminifera *G. sacculifer* was correlated to the SPECMAP $\delta^{18}O$ stack (Imbrie *et al.*, 1984). In our age/depth model (Fig. 3), the composite core record extends to ~85,000 yr B.P. With an average sedimentation rate of 15 cm/1000 yr and an average sample interval of 3 cm, the resolution of our time series is ca. 200 yr.

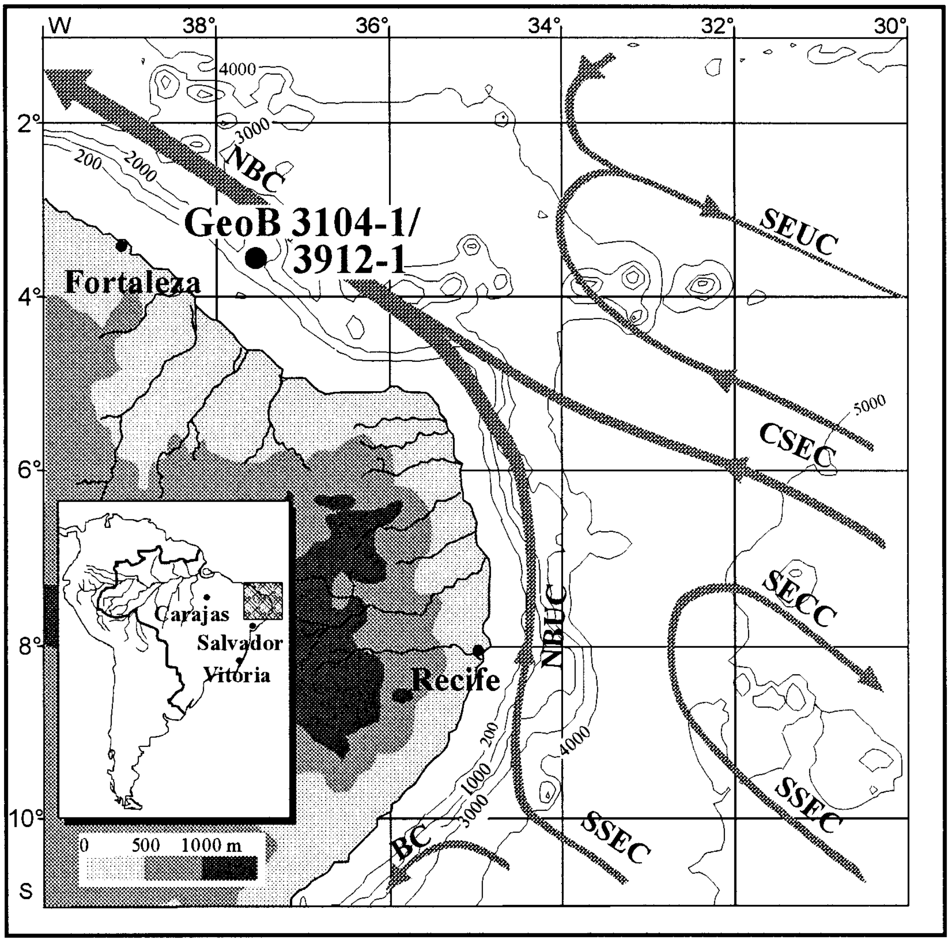

FIG. 1. Schematic view of surface circulation patterns in the western equatorial Atlantic. S/C-SEC, Southern/Central-South Equatorial Current; SECC, South Equatorial Counter Current; SEUC, South Equatorial Undercurrent; NBC, North-Brazil Current; NBUC, North-Brazil Undercurrent; BC, Brazil Current (Peterson and Stramma, 1991; Da Silveira *et al.,* 1994). Large dot shows location of cores.

Carbonate Preservation and XRF-Measurements

The Holocene section and isotope stage 5 of the cores are characterized by a carbonate content of 65–70 wt% (Fig. 4a). Intermediate carbonate contents of 35–45 wt% for isotope stages 2–4 are episodically interrupted by sections with very little carbonate ($<$10 wt%) dominated by terrigenous components. These oscillations in isotope stages 2–4 are more apparent in the better resolved XRF-intensities of the elements Ca, Fe, and Ti (Fig. 4b). High Ca intensities are related to low Ti and Fe intensities and correlate well with the carbonate content. As a component of calcite and aragonite, Ca mainly reflects the marine carbonate content in the sediment. Ti and Fe, however, are related to siliciclastic components and especially clay minerals. They vary directly with the terrigenous fraction of the sediment (Jansen *et al.,* 1992).

The fragmentation index is 20% on average. The exceptionally good preservation of the aragonitic pteropod shells precludes major dissolution of primary carbonate. Smear slide analysis shows that siliceous organisms contributed little to the sediment.

Oxygen Isotope Records

The main features of the marine oxygen isotope records as known from the last glacial/interglacial cycle (e.g., Imbrie *et al.,* 1984) are reproduced in our stable isotope measurements of planktonic foraminifera. The $\delta^{18}O$ values vary between -1.7 and $+0.49$‰ for *G. sacculifer* and -1.79 and $+0.04$‰ for *G. ruber* (pink) with an average isotope composition of -0.34‰ and -0.69‰, respectively (Fig. 4d).

Isotope stages 2, 3, and 4 are marked by several distinct, short-term oscillations of the $\delta^{18}O$ records with average amplitudes of around 0.6‰ in the isotope records of both *G. sacculifer* and *G. ruber* (pink). Several rather abrupt excursions to isotopically light values occur between 72,000 and 23,000 cal yr B.P. Each peak is followed by a decrease to heavy $\delta^{18}O$ values over several millennia, resulting in a somewhat sawtooth-shaped curve for the last glaciation. The average

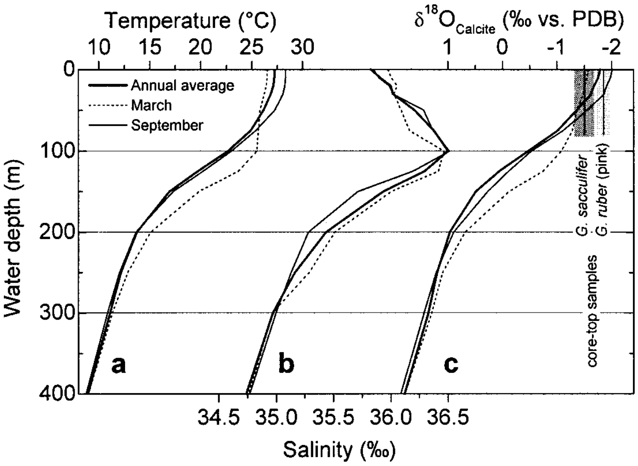

FIG. 2. Seasonal temperature (a) and salinity (b) distribution in the uppermost 400 m of the water column next to our core location (Levitus *et al.*, 1994; Levitus and Boyer, 1994); and (c) calculated $\delta^{18}O_{Calcit}$ equilibrium values and average $\delta^{18}O$ values measured on surface samples of the planktonic foraminifera *G. sacculifer* and *G. ruber* (pink) from the study area. Vertical range of gray bands denotes the depth range of the live foraminifera, and band width represents the standard deviation of the averaged isotope value.

$\delta^{18}O$ offset between *G. ruber* and *G. sacculifer* ($\Delta\delta^{18}O$) is about −0.35‰. Downcore, however, the $\Delta\delta^{18}O$ values vary between −0.1 to −0.5‰ and correlate well to changes in $\delta^{18}O$. Low $\Delta\delta^{18}O$ values correspond to light $\delta^{18}O$ values and vice versa (Fig. 4e). Changes in the planktonic foraminiferal assemblage are also evident. The assemblage is dominated by the two tropical species *G. ruber* (white) and *G. sacculifer*. Low *G. ruber* (white) contents are correlated to high *G. sacculifer* concentrations, and together the two species account for more than 60% of foraminiferal tests. At the previously mentioned intervals of light isotopic values the content of *G. ruber* (pink) increases at the expense of *G. ruber* (white) (Fig. 4c).

DISCUSSION

Continental Climate Indicators

In the oligotrophic western tropical Atlantic, carbonate accumulation was nearly constant during the last glacial/interglacial transition (Rühleman *et al.*, 1996). Because dissolution had little effect on our cores, the carbonate content variability in the cores for isotope stages 2–4 is mainly due to dilution by terrigenous sediment. To quantify terrigenous sedimentation we used the ratios of XRF intensities of Ti and Ca and of Fe and Ca (Fig. 5).

The episodically increased accumulation of terrigenous sediment may have been caused by climatic changes in the coastal areas of northeast Brazil (Rao *et al.*, 1993). Slightly increased humidity and higher precipitation rates in the drainage basins of the coastal rivers would increase land erosion, river runoff, and thus increase the supply of terrigenous sediment to the upper continental slope. Clay-mineralogic and palynologic study of our sediment cores confirms the occurrence of more humid phases in northeastern Brazil during the isotope stages 2 to 4 (H. Behling, personal communication, 1997; Tintelnot, 1997). In palynologic records from lake sediments in the northeastern Brazilian hinterland (Serra dos Carajas), several shifts from dry to more humid conditions were also recognized for the last 60,000 yr (Absy *et al.*, 1991). However, the resolution and the stratigraphic control of those records are insufficient for direct comparison.

The variations in the terrigenous sediment supply may additionally result from resedimentation processes related to

TABLE 1
^{14}C Ages obtained by Accelerator Mass Spectrometry Dating of Monospecific Carbonate Samples (*G. sacculifer* in the Fraction of 250–500 μm) in Core GeoB 3104-1

Laboratory number[a]	Depth in core (cm)	Age (^{14}C yr B.P.)	Error (yr)	Calibrated age (cal yr B.P.)
KIA 653	8	2660	±50	2880
KIA 1857	20	5740	±60	6450
KIA 1856	52	9660	±50	11,140
GrA 3719	87	12,580	±100	14,760
KIA 1855	97	12,960	±90	15,230
GrA 3720	172	16,120	±160	19,150
KIA 651	209	20,540	+350/−330	24,280
GrA 3721	274	25,050	±200	29,340
KIA 1853	292	27,820	+290/−280	32,340
KIA 1852	337	31,690	+450/−420	36,370
KIA 650	384	33,400	+1840/−149	38,100
GrA 3722	462	38,600	+900/−800	43,130

Note. Ages were corrected for a reservoir effect of 400 yr (Bard, 1988) and calibrated using the method of Bard *et al.* (1993). For the deglacial, we conservatively estimate the calendar year chronology to be good to within ±500 yr. Before about 25,000 cal yr B.P. there are only a limited number of calibration points, so the assumed correction is uncertain (probably at least ±1500 yr).

[a] GrA, Groningen; KIA, Kiel.

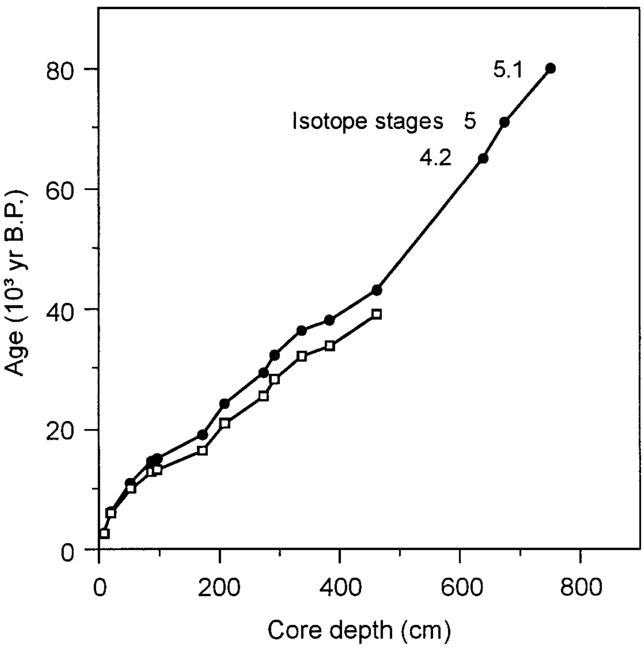

FIG. 3. Age–depth relation for core GeoB 3104-1/3912-1, from 12 calibrated radiocarbon AMS ages (Table 1). Labeled open squares show ^{14}C ages corrected by a 400 yr reservoir effect (Bard, 1988). For ages >40,000 yr we used three SPECMAP age-control points. Age-control points in calendar years (after Bard *et al.,* 1993) are shown by black dots.

short-term sea-level changes. In this case, however, such millennial scale variations should also be found in records from other areas off Brazil, with similar shelf and continental slope morphologies. Sediment cores retrieved off Salvadore and Vitoria from the continental margin of eastern Brazil, do not show comparable short-term changes in the sediment composition during the last glaciation (H. Arz, T. Jennerjahn, unpublished data).

Evidence of Hydrographic Changes

High-amplitude oscillations in the $\delta^{18}O$ records of the planktonic foraminiferas *G. sacculifer* and *G. ruber* (pink) (0.5 to 0.8‰) indicate short-term changes in the surface water hydrography off northeastern Brazil during isotope stages 2 to 4. Variations in the $\delta^{18}O$ are generally attributed to both the changes in the local temperature and salinity of the surface water, and to global changes in ice volume (e.g., Shackleton *et al.,* 1987; Wefer and Berger, 1991). Short-term global sea-level changes in the order of 10 to 20 m were proposed to accompany the massive iceberg surges which occurred during the last glaciation in the North Atlantic region (Heinrich events) (Bond and Lotti, 1995; Broecker, 1994). If the ice-released $\delta^{18}O$ mixed with the tropical surface waters in less than 400 yr, nearly synchronous signals should be recorded at our site. However, if a change in global marine $\delta^{18}O$ of 0.1‰ corresponds to a sea-level change of 10 m, global ice volume explains only about one-third of the observed amplitude.

The remaining two-thirds probably reflects local changes in temperature and salinity. If the $\delta^{18}O$ changes were caused entirely by salinity, SSS would have changed as much as 2‰. But little SSS variation was proposed for the last glacial/interglacial cycle in the study area by Dürkoop *et al.* (1997). If salinity was stable throughout the glaciation, light $\delta^{18}O$-levels imply higher SST. High SST is also implied by the peaks in the abundance of *G. ruber* (pink) (Fig. 4c); as pointed out by Hemleben *et al.* (1989), *G. ruber* (pink) prefers warmer surface waters than *G. ruber* (white). However, local salinity changes due to fresh-water input by rivers should be taken into consideration.

Variations in the local hydrography are also implied by the difference in $\delta^{18}O$ between *G. ruber* (pink) and *G. sacculifer* ($\Delta\delta^{18}O$). The vital effect, temperature sensitivity, habitat depth, and temporal distribution pattern of these species are well known from culture experiments and analysis of plankton-tow and core-top samples (e.g., Erez and Luz, 1982; Fairbanks *et al.,* 1982; Deuser and Ross, 1989; Mulitza *et al.,* 1998). Both species have been described as shallow dwelling, tropical taxa that live in the uppermost 50 to 80 m of the water column (e.g., Ravelo and Fairbanks, 1992). Nevertheless, the $\Delta\delta^{18}O$ measured on core-top samples and especially the down-core variation in $\Delta\delta^{18}O$ show that the species record different isotopic signals (Fig. 2c and 4e); *G. ruber* (pink) tends to record lighter values and *G. sacculifer* rather lower values than the average annual $\delta^{18}O$ signal of the mixed layer. This difference may indicate a different seasonal distribution pattern of the species, with the $\Delta\delta^{18}O$ depending on the seasonal amplitudes in SST (Mulitza *et al.,* 1998). However, the $\delta^{18}O$ of *G. sacculifer* is altered by secondary calcification in subsurface waters (Duplessy and Blanc, 1981; Lohmann, 1995). Therefore its isotope signal might show a mixed signal of surface and subsurface water. The $\Delta\delta^{18}O$ signal could consequently also reflect changes in the vertical $\delta^{18}O$ gradient. Finally, *G. sacculifer* generally shows higher amplitudes in the $\delta^{18}O$ signal than *G. ruber,* consistent with the generally weak SST seasonality in the western tropical Atlantic and the greater inter-annual changes in the subsurface layer (Hastenrath and Merle, 1987).

Climate Implications

Several studies showed that a nonlinear response to the precessional forcing may be responsible for sub-Milankovitch changes (periods of 9500 to 12,000 yr) in low latitude climate (Pestiaux *et al.,* 1988; Short *et al.,* 1991; Hagelberg *et al.,* 1994). Such millennial periods (semi-precessional periods) are thought to be a complex climatic response to insolation forcing in equatorial regions, where they are reflected in the variation of SST, moisture content, and the wind field (Short *et al.,* 1991; Grimm *et al.,* 1993; Curry and Oppo, 1997).

Using the relative abundance of the sub-thermocline coccolithophoridae *Florisphaera profunda,* McIntyre and Molfino (1996) showed that changes in the equatorial wind-field are a plausible cause for the low and high latitude short-term climatic oscillations during the last 60,000 yr. They proposed that the intensity of the tropical easterlies controls the release of

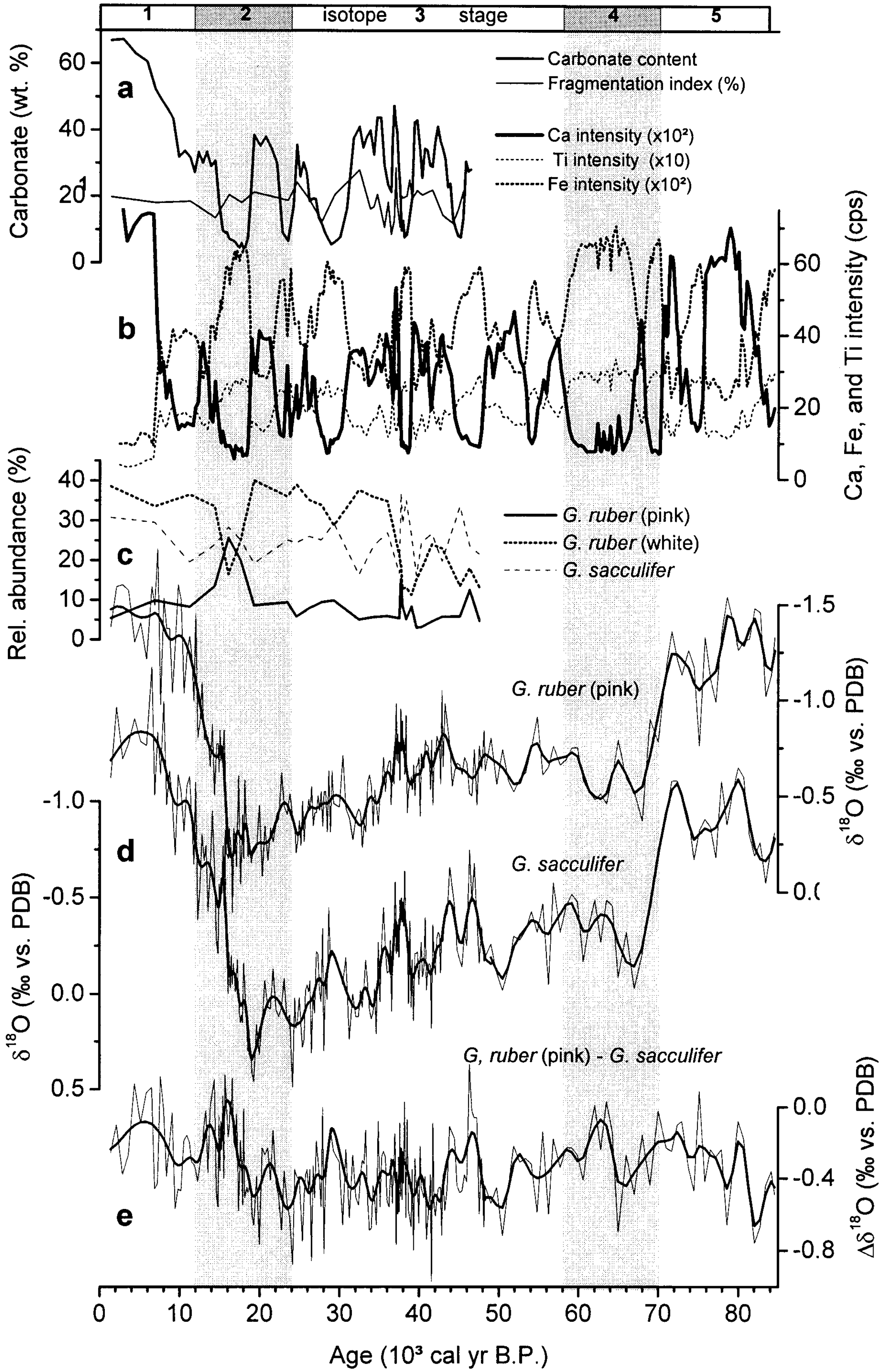

FIG. 4. (a) Carbonate content and foraminiferal fragmentation index of core GeoB 3104-1. (b) XRF intensity in counts/second (cps) of the elements Ca, Fe, and Ti from core GeoB 3912-1 (for Ca and Fe the intensity is divided by 100, for Sr and Ti, by 10). (c) Relative abundance of the foraminifera *G. sacculifer* and *G. ruber* (white and pink variety). (d) Composite $\delta^{18}O$ records of the foraminifera *G. sacculifer* and *G. ruber* (pink) from cores GeoB 3104-1 and GeoB 3912-1. (e) Difference ($\Delta\delta^{18}O$) between the records in (d); thin lines represent isotope data and thick lines a smoothed signal.

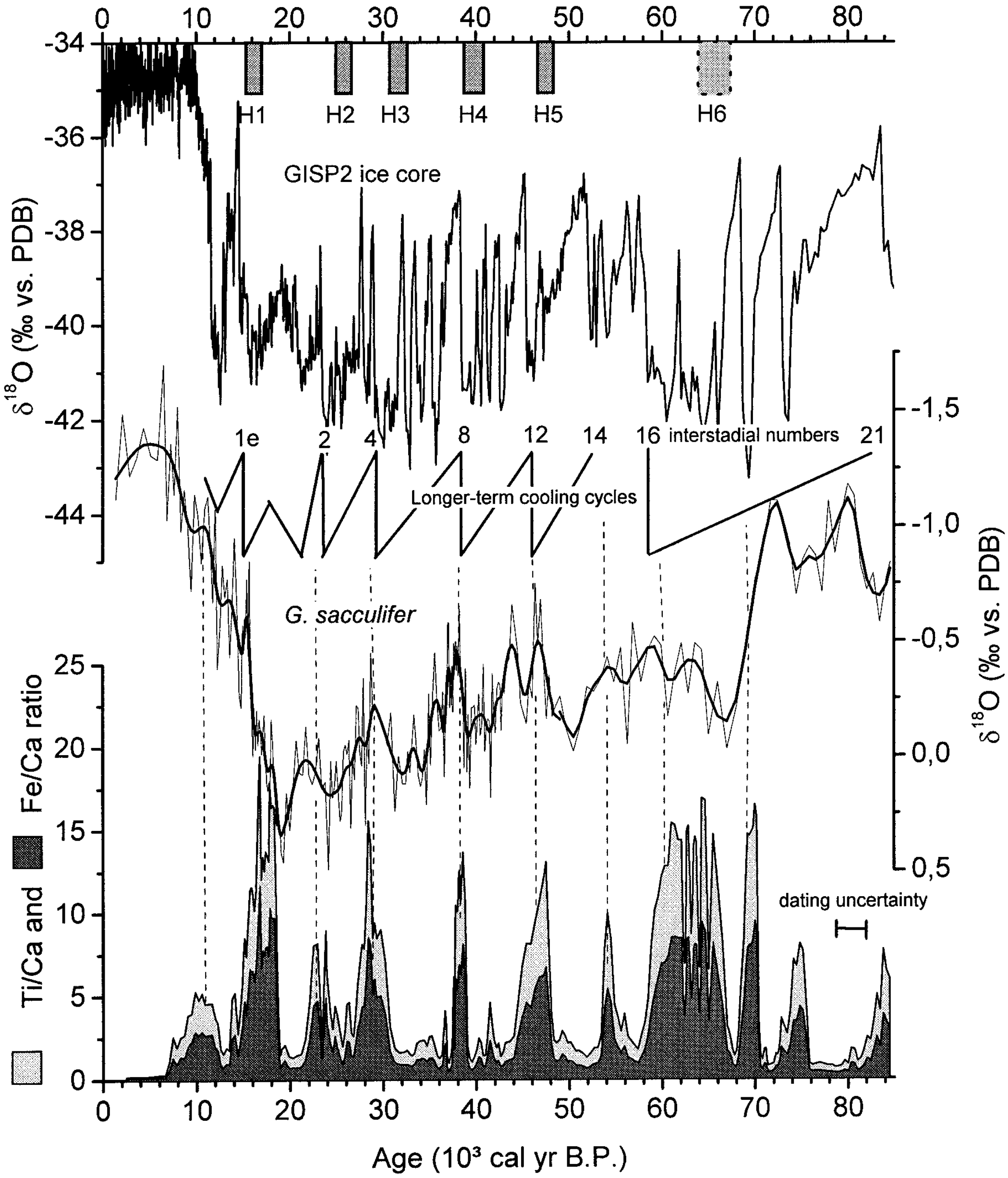

FIG. 5. Comparison of the $\delta^{18}O$ *G. sacculifer* record and the Ti–Ca and Fe–Ca ratio (Ti-Ca record scaled up fourfold) of cores GeoB 3104-1/3912-1 with the $\delta^{18}O$ record of the GISP2 ice core (Grootes *et al.*, 1993), the Heinrich events (ages from Vidal *et al.*, 1997), and the schematic longer term cooling cycles (after Bond *et al.*, 1993). Records tentatively correlated by vertical dashed lines.

Carribbean warm water into the high northern latitudes. A somewhat modified mechanism was suggested by Little *et al.* (1997). From short-term changes in the upwelling intensity recorded in glacial sediments off Walvis Bay, they deduced variations in the zonality of the SE trade winds. The variation in the SE trades in turn should have forced SEC and NBC intensities, thus affecting the interhemispheric heat exchange on a sub-Milankovitch time-scale.

Periods of enhanced upwelling in the eastern Atlantic should be accompanied by a deepening of the mixed layer and an increased storage of warm water in the western tropical South Atlantic, because both eastern Atlantic upwelling and western Atlantic mixed layer depth are directly linked to changes in the intensity of the SE trade winds (Hastenrath and Merle, 1987; Peterson and Stramma, 1991). In fact, our $\delta^{18}O$ records imply repeated increase in SST that coincided with reduced vertical $\delta^{18}O$ gradients in the water column.

The amount of precipitation received by the coastal area of northeastern Brazil is also connected to the southern trades. At present, maximum precipitation occurs during the austral winter, when the trade winds gain their maximum intensities and humid air masses reach the coastal mountains. Consequently, a moisture supply that increases during periods of more zonal and intensified trade winds may explain the terrigenous pulses in our cores.

Short-term variations recorded in our cores may correlate with the $\delta^{18}O$ record of the GISP2 ice core (Grootes *et al.,* 1993; Meese *et al.,* 1994) (Fig. 5). The Heinrich events (as dated by Vidal *et al.,* 1997), and the longer term cooling cycles (Bond cycles) in the ice core records line up with excursions in the Ti/Ca ratio and the isotopic records. These findings accord with correlations between Greenland and Antarctic ice core $\delta^{18}O$ records (Bender *et al.,* 1994; Jouzel *et al.,* 1994) and with paleoceanographic evidence from tropical areas (Curry and Oppo, 1997; McIntyre and Molfino, 1996; Bard *et al.,* 1997). Our light $\delta^{18}O$ values and high Ti/Ca ratios probably mark major interstades and may record lesser interstades as well (Fig. 6).

Our data thus suggest that high latitude warming generally coincides with warm SSTs in the western tropical Atlantic. Furthermore, our data suggest that short-term variations in trade winds are responsible for changes in the intensity of the NBC, and thus, for the magnitude of warm water storage and release from the western tropical Atlantic. In that case, the NBC's heat flux to high latitudes may have contributed to the growth and decay of northern hemisphere ice sheets during the last glaciation.

However, uncertainty in the stratigraphic control of our records also permits the alternative interpretation that increases in SST off Brazil slightly preceded the ice core interstades. Thermohaline circulation was reduced during the North Atlantic cold periods and the related Heinrich events (e.g., Bond *et al.,* 1993; Vidal *et al.,* 1997). Ocean modeling implies that the Atlantic equatorial regions may have become warmer during periods of reduced thermohaline overturning (e.g., Paillard and Labeyrie, 1994; Manabe and Stouffer, 1997). Maximum warming at the end of each Bond cycle could make northern high-latitude warming occur slightly later than SST maxima at the low latitudes of the southern hemisphere.

CONCLUSIONS

Variations in the stable isotope records, carbonate content, and XRF intensities of Ca, Fe, and Ti in a sediment core from the upper continental slope of northeastern Brazil imply linkage between marine and continental climate signals. Periods of more humid continental conditions, as indicated by high Fe and Ti XRF-intensities, coincide with warm SST, as shown by light values in the $\delta^{18}O$ signal of planktonic foraminifera. The difference between the $\delta^{18}O$ of *G. ruber* (pink) and that of *G. sacculifer* also indicates change in seasonality and vertical $\delta^{18}O$ gradients in the mixed layer.

These findings suggest short-term variations in the SE trade wind intensity that may correlate with short-term climatic variations recorded in Greenland ice cores. The correlations are most simply explained by synchronous response to sub-Milankovitch low latitude climate forcing.

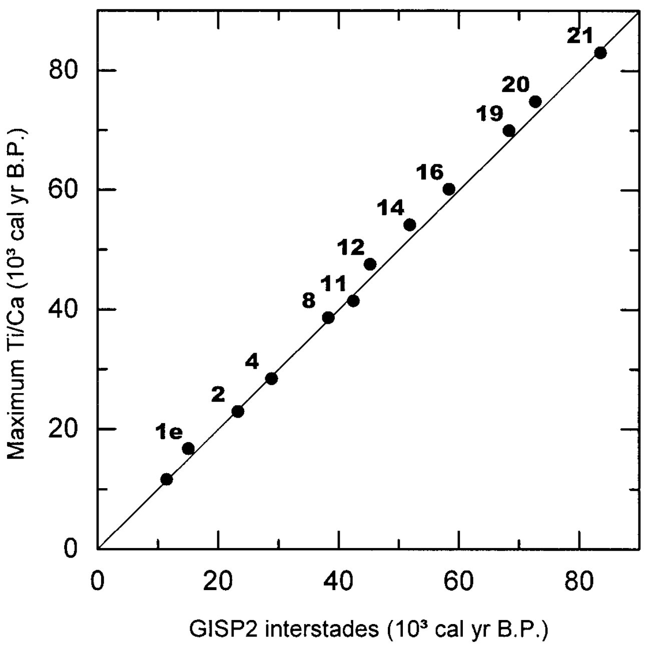

FIG. 6. Age comparison of the GISP2 ice core interstades with the terrigenous pulses (Ti/Ca and Fe/Ca ratio) recorded in core GeoB 3104-1/3912-1 for the last 85,000 yr; average age deviation from the ice core signals is less than 3%.

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