

Planktonic Foraminiferal Sea Surface Temperature Variations in the Southeast Atlantic Ocean: A High-Resolution Record MD962085 of the Past 400,000 Years from the IMAGES II - NAUSICAA Cruise

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ABSTRACT

A high-resolution (~ 4 - 5cm/kyr) giant piston core record (MD962085) retrieved during an IMAGES II - NAUSICAA cruise from the continental slope of the southeast Atlantic Ocean reveal striking variations in planktonic foraminifer faunal abundances and sea-surface temperatures (SST) during the past 400,000 years. The location and high-quality sedimentary record of the core provide a good opportunity to assess changes in the intensity and position of the Benguela Current System and the Subtropical Convergence, two key features of the ocean-climate system in the south Atlantic. This record can be also used to evaluate the possible influence of Agulhas Current from the throughflow of the Indian Ocean into the South Atlantic. The planktonic foraminifer faunal abundances of the core are dominated by three assemblages: (1) *N. pachyderma* (right coiling) + *N. dutertrei*, (2) *G. bulloides*, and (3) *G. inflata*. The assemblage of *N. pachyderma* (right coiling) + *N. dutertrei* shows distinctive abundance changes which are nearly in-phase with glacial-interglacial variations. High abundances of this assemblage are associated with major glacial conditions, possibly representing low SST / high nutrient level conditions in the southwestern Africa margin. In contrast, the assemblages of *G. bulloides* and *G. inflata* show more high-frequency abundance change patterns, which are not well-parallel to glacial-interglacial changes. These patterns may indicate rapid oceanic frontal movements from the south, and a rapid change in the intensity of Benguela upwelling system from the east. A winter-season SST estimate using transfer function techniques for this record shows primarily

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glacial-interglacial variations. The SST reaches maxima during the transitions from the major glacial to interglacial stages (Termination II, III, IV), and is associated with the abundance maxima of a warm water species indicator *G. ruber*. The relationship shown by the SST and planktonic foraminifer $\delta^{18}\text{O}$ implies that the SST maxima lead the $\delta^{18}\text{O}$ minima by approximately 3-5 kyr.

(Key words: Paleoceanography, Late Quaternary, Micropaleontology, South Atlantic)

1. INTRODUCTION

In the southeast Atlantic Ocean, the northwest-directed Benguela Current System (BCS) and the Subtropical Convergence (STC) are two key components of the sensitive ocean-climate system (Figure 1). The BCS serves as a dominant control on the regional oceanography off South Africa, Namibia, and southern Angola and has been well-documented in many previous studies (Shannon, 1985; Lutjeharms and Meeuwis, 1987; Lutjeharms and Stockton, 1987; Summerhayes et al., 1995; Shannon and Nelson, 1997). The Benguela Oceanic Current is an oceanic component of the BCS and represents the equatorward drift of cold surface waters flowing from 34°C (Cape Town) past southwestern Africa to 23°S (Walvis Bay). Inside the shelf break, a component of the Benguela Oceanic Current moves equatorward and forms the Benguela Coastal Current, which energizes the strong coastal upwelling along the entire coastline of southwest Africa. To the south of the BCS, a component of the warm-water Agulhas Current enters from the Indian Ocean and forms a thermal barrier, which effectively limits the equatorward flow of cool, subantarctic surface water filaments into the BCS (Shannon et al., 1989). Movement of the thermal barrier, which is controlled by the relative position and intensity of the STC, creates a variable supply of cold subantarctic waters and warm Agulhas Current waters into the BCS (Gordon et al., 1992). The STC is an oceanic front which has distinct temperature and salinity characteristics due to the convergence of warm, saline subtropical and cool, low salinity subpolar waters. The location of this oceanic boundary or front marks the northerly extent of the west wind drift and the southern edges of the subtropical gyres, which are usually characterized as a zone of rapid sea-surface temperature (SST) changes. Monitoring past changes in SST and surface circulation of the southeast Atlantic Ocean is critical to understanding the history of Atlantic and global ocean-climate systems, because the major climatic features in this region are closely linked to high-latitude wind and sea ice fields and to the northern hemisphere climate through global thermohaline circulation (Gordon, 1986; Gordon et al., 1992; Broecker and Denton, 1989).

Assemblages of planktonic foraminifers represent useful tools for the reconstruction of past SST. Such reconstructions of past ocean variability rely on statistical relationships between Recent surface-sediment faunal distributions and compiled SST observations. The rationale of these reconstructions is based on many previous empirical observations (Bé and Tolderlund, 1971; Bé, 1977), in which the distribution of the Recent planktonic foraminifers is

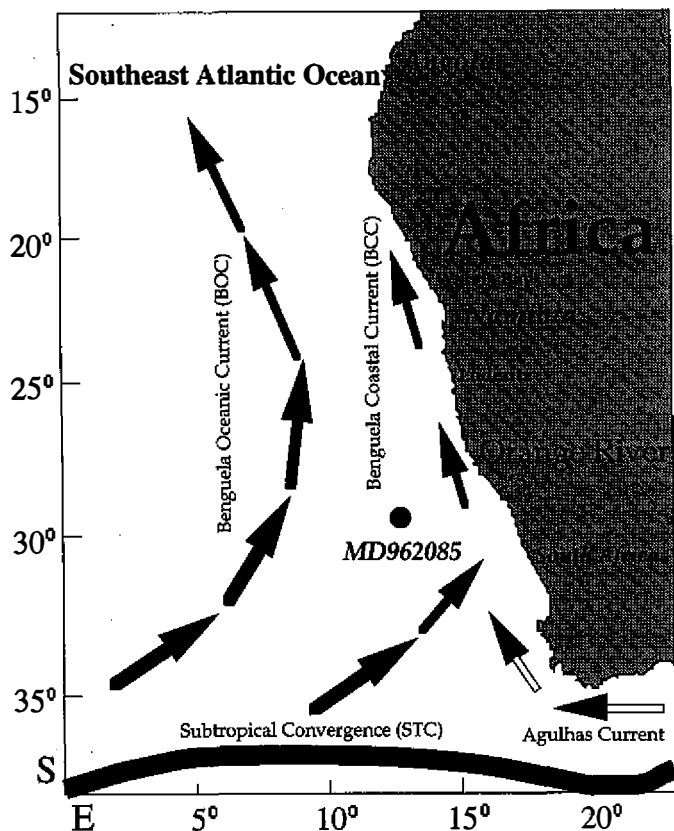


Fig. 1. Location map showing the position of IMAGES II core MD962085 and outlining the major oceanographic features of the Benguela Current and neighboring systems in the Southeast Atlantic Ocean.

thought to be closely related to the distribution of specific water masses, and hence to specific SST. Methods for quantitative estimates of SST on the basis of the Recent planktonic foraminifer assemblage distributions were first developed by using transfer function techniques (Imbrie and Kipp, 1971; Kipp, 1976). Since then these transfer function techniques have been applied in many other studies of Recent Atlantic Ocean planktonic foraminifers (Molfino et al., 1982; Mix et al., 1986; Pflaumann et al., 1996).

The giant piston core MD962085, taken during an IMAGES II - NAUSICAA (Namibia Angola Upwelling System and Indian Connection to Austral Atlantic) cruise (Scientific Report of the NAUSICAA-IMAGES II Coring Cruise, 1997; Chen et al., 1998), was obtained from a location in the lower slope of 30°S transect in the southeastern Atlantic, where the water depth is 3001 m. The core is 35.4 m long and is dominated by foraminifer-bearing nannofossil oozes. On-board analyses also indicated that the age of the base is at least as old as oxygen isotope stage 15. The study of this core thus provides an excellent opportunity to reconstruct the long-term history of oceanic and climatic change in the southeast Atlantic Ocean. The purpose of this paper is to use changes in planktonic foraminifer faunal assemblages and stable isotopes to document the amplitude and timing of SST variations in the southeast Atlantic Ocean. The specific objectives of this study are to: 1) document variations

in the relative abundance of planktonic foraminifer species in late Quaternary sediments (0-400 kya); 2) extract SST information from the faunal abundance changes by using transfer function techniques on the basis of an Atlantic coretop data base (N=661) ; and 3) determine the timing and magnitude of SST changes and identify the processes which affected the SST in this region.

2. DATA AND METHODS

The core MD962085 taken during the IMAGES II cruise was selected with sedimentation high enough that time resolution would be sufficient to detect any climatic signals caused by orbital variations (10^4 - 10^5 years). This core is located offshore the mouth of the Orange River, but is far away from the influence of cold Benguela coastal upwelling in one of the centers of strong intensity near Lüderitz. The annual range of SST variation at the core location is about 4°C , with summer SST of $\sim 20^{\circ}\text{C}$ and winter SST of $\sim 16^{\circ}\text{C}$ (Figure 2). On-board observation indicates that the sediments of this core are nearly-continuous without noticeable hiatus (Scientific Report of the NAUSICAA-IMAGES II Coring Cruise, 1997). Samples for shore-based research were taken at 5 cm intervals throughout the core, allowing micropaleontological and stable isotopic analyses to be carried out with the highest resolution possible. The samples used in this study are stored in the Institute of Applied Geophysics, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.. The archives and working halves of the core material are kept at the Department of Geology and Oceanography, University of Bordeaux, Bordeaux, France.

Freeze-dried raw samples were disaggregated in water and wet-sieved through $150\ \mu\text{m}$ mesh. Census counts of planktonic foraminifers were made from splits of the dried $>150\ \mu\text{m}$ fraction, such that at least 300 individual planktonic foraminifers were counted in each of the samples. Twenty seven species and morphotypes of Recent planktonic foraminifers were identified in this study, following established taxonomies (Parker, 1962; Kipp, 1976; Bé, 1977). Since the faunal data compiled here were to be compared to other various sources of works, we removed taxonomic inconsistencies by grouping all dextral neogloboquadrinid forms, including *Neogloboquadrina pachyderma* (right coiling) and *Neogloboquadrina dutertrei* into one category. Particularly, an old category "*Neogloboquadrina pachyderma-Neogloboquadrina dutertrei*" intergrade (P-D intergrade) that was unique to the work of Kipp (1976) was not considered in this study. The P-D intergrade was lumped into the category of all dextral neogloboquadrinids. Census counts were made in 228 downcore samples. In the top three meters of the core, the faunal abundance data were generated by 5 cm intervals. A interval of 10 cm was applied in the data generation for the core from 3 m depth to the bottom.

The isotopic composition of planktonic foraminifer *Globorotalia inflata* was analyzed in the size range 300 - $355\ \mu\text{m}$. In the top 18 m of the core, the isotopic data were generated by 5 cm intervals. Samples from the core depth of 18 m to the bottom were analyzed at 10 cm intervals. The isotopic composition of the foraminifers was measured on the CO_2 gas generated by treatment of the carbonate with pure phosphoric acid at a constant temperature of 75°C . The standard gas was calibrated against the international carbonate standard (Vienna

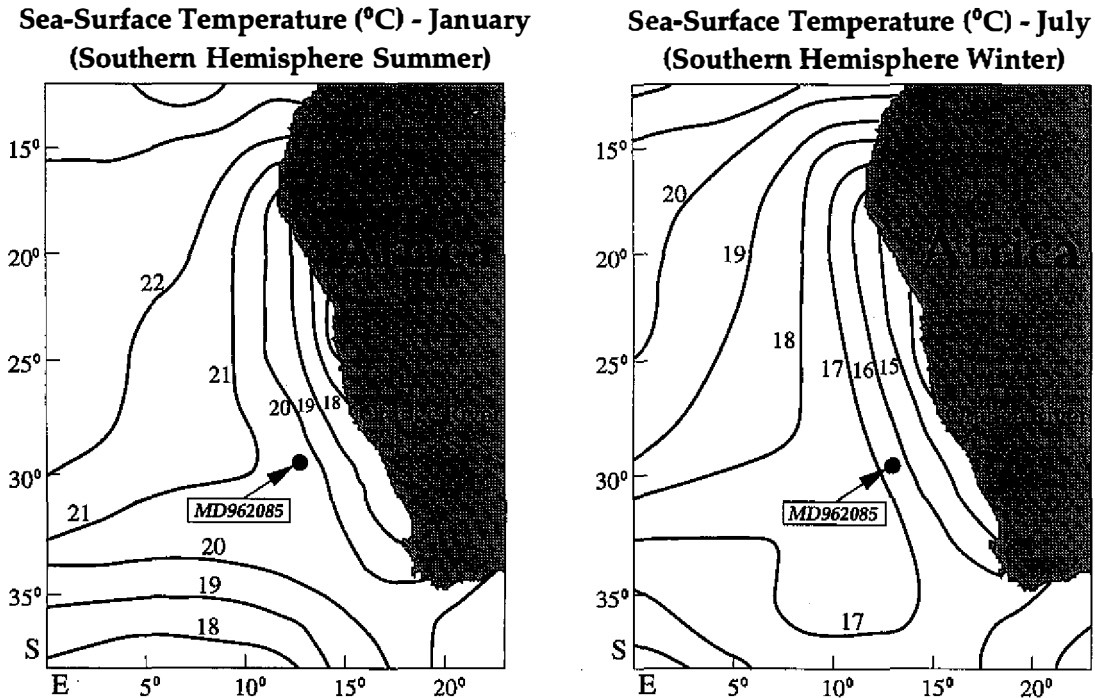


Fig. 2. Modern monthly mean sea-surface temperature of January and July in the Southeast Atlantic Ocean. Contoured using $1^\circ \times 1^\circ$ digital historical oceanographic data from NOAA (1994).

Pee Dee Belemnite [PDB]) using standard National Bureau of Standard 19 (NBS 19). The measurement precision for $\delta^{18}\text{O}$ on measurements of calcite standards was $\pm 0.08\text{‰}$ PDB. The faunal abundance and stable isotope data of core MD962085 are available electronically at Paleooceanographic Data Center of Core Laboratory - Center for Ocean Research, NSC, at the Institute of Applied Geophysics, National Taiwan Ocean University, Keelung, Taiwan, R.O.C. (Internet: <http://140.121.175.114>).

The oxygen isotope data of *Globorotalia inflata* were correlated with the SPECMAP stacked record (Imbrie et al., 1984) to obtain an age model for the core (Figure 3). Thirty six age control points were picked out to constrain the age of core MD962085 (Table 1). Five AMS ^{14}C datings were done for the samples from the very top part of the core (shown in ^{14}C ages): 3.5 cm ($3,996 \pm 57$ yrs B.P.), 18.5 cm ($5,011 \pm 57$ yrs B.P.), 73.5 cm ($11,405 \pm 59$ yrs B.P.), 83.5 cm ($12,494 \pm 80$ yrs B.P.), and 108.5 cm ($15,163 \pm 68$ yrs B.P.). These absolute dating ages were not taken into consideration in building up the age model that we presented in this study, but they demonstrated the good recovery of core top sediments of the core. In testing the validity of these age assignments, we have obtained an age-depth profile (Figure 4) constructed based on these age control points. From the Holocene down to stage 11, this record shows a

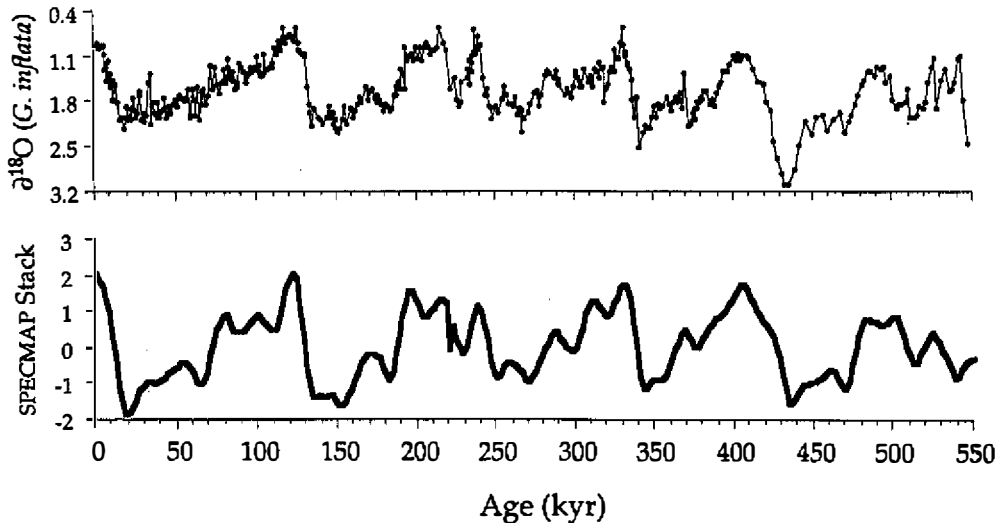


Fig. 3. Oxygen isotope stratigraphies for core MD962085. All oxygen isotope data are plotted relative to the PDB standard (‰) and are on the basis of analyses of planktonic foraminifer *G. inflata*. The age determination is carried out by matching the oxygen isotope record to the SPECMAP curve. Age control points selected for the correlation are shown in Table 1.

nearly-constant sedimentation rate (an average of ~4 - 5 cm/kyr) through time. The age model for the top part of the core from the Holocene through stage 3 certainly could be improved by independent methods such as AMS ^{14}C dating. Future works on refining and evaluating these age assignments must await our ongoing efforts of generating more AMS ^{14}C dating for the core.

3. RESULTS

The relative abundances of seven important planktonic foraminifer species are presented here in order to examine the changes in sea-surface conditions and climatic changes in the southeast Atlantic Ocean over the past 400,000 years (Figure 5). These seven species are: *Globigerinoides ruber*, *Globigerina bulloides*, *Neogloboquadrina pachyderma* (left coiling), *N. pachyderma* (right coiling) + *N. dutertrei*, *G. inflata*, and *Globigerinita glutinata*. We observed large downcore variations in the relative abundances of the dominant taxa. These may indicate that considerable past changes in surface waters occurred in this region during the late Quaternary.

The faunal abundance patterns shown in Figure 5 provide many interesting clues for interpreting the surface water condition changes in this region. For example, the abundance of a tropical water species *G. ruber* is noticeably increased during the transitions of major glacial

Table 1. Age control points of core MD962085 determined on the basis of oxygen isotope stratigraphic correlation with SPECMAP stack curve (Imbrie et al., 1984).

Depth (cm)	Age (kyr B.P.)	$\delta^{18}\text{O}$ Stage
0.0 (coretop)	0	
21.0	6	1.1
81.0	12	2.0
108.5	19	2.2
136.0	24	3.0
158.5	28	3.1
283.5	53	3.3
348.5	65	4.2
408.5	80	5.1
473.5	87	5.2
528.5	99	5.3
578.5	107	5.4
653.5	122	5.5
723.5	135	6.2
753.5	146	6.3
803.5	151	6.4
866.0	171	6.5
913.5	183	6.6
983.5	194	7.1
1023.5	205	7.2
1063.5	216	7.3
1098.5	228	7.4
1178.5	238	7.5
1238.5	249	8.2
1258.5	257	8.3
1313.5	269	8.4
1373.5	287	8.5
1428.5	299	8.6
1533.5	320	9.2
1583.5	331	9.3
1646.0	341	10.2
1758.5	375	11.2
1963.5	405	11.3
2098.5	434	12.2
2203.5	471	12.4
2298.5	491	13.1
2418.5	513	13.2

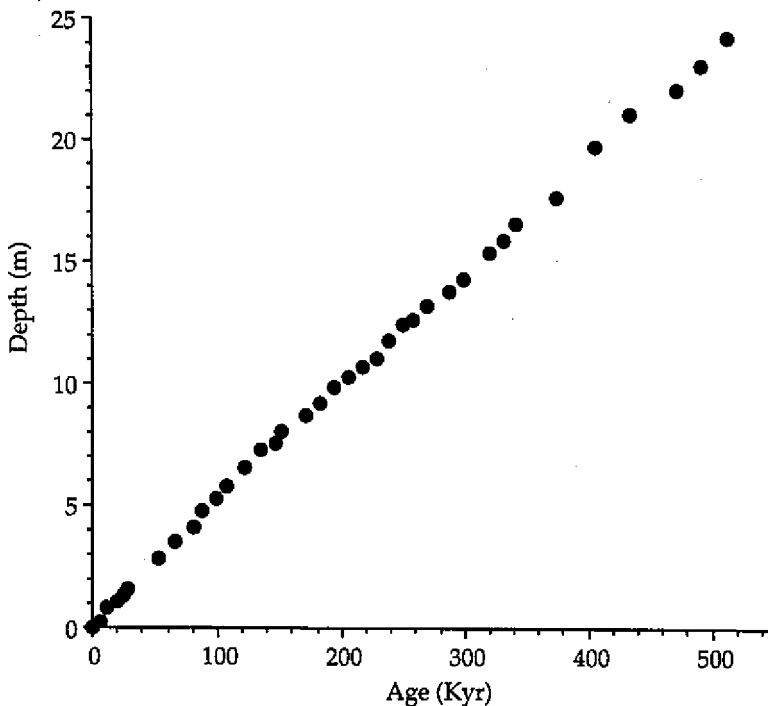


Fig. 4. Age-depth relationship in core MD962085. Age control points are given in Table 1.

to interglacial stages. During the transitions of stage 12 to 11 (Termination V), stage 6 to 5 (Termination II), and stage 2 to 1 (Termination I), this species shows maximum abundances of ~10%, while in intervals other than the major transition stages, the species abundances remain low (~3%). The faunal assemblage *N. pachyderma* (right coiling) + *N. dutertrei* which may represent cold and high-nutrient surface water conditions, reaches maximum abundances during major glacial stages 2-4, 6, 8, and 10. The abundances of this assemblage exhibit large-amplitude and low-frequency variabilities which are well-parallel to glacial-interglacial cycles. On the other hand, *G. bulloides* and *G. inflata*, species that are representative of the subpolar and transitional zones in the Atlantic Ocean (Bé and Tolderlund, 1971; Bé, 1977), show abundance maxima in both glacial and interglacial stages. The abundances of these two species seem to fluctuate in a mode of higher frequency. More interestingly, the abundances of *G. glutinata* show much higher frequency modes of variability and fluctuate between a range of 0% and 10%. The abundances of this species seem not to respond to glacial-interglacial changes. Particularly noteworthy among the trends shown in Figure 5 is that a polar water species *G. pachyderma* (left coiling) shows unique episode of maximum abundances (~20%) during the beginning of stage 9 (~330 kya). The coretop sediment distribution of this species was found to be closely associated with strong coastal upwelling environments along the southwest African continental margin (Giraudeau, 1993; Giraudeau and Rogers, 1994), and to be overwhelmingly

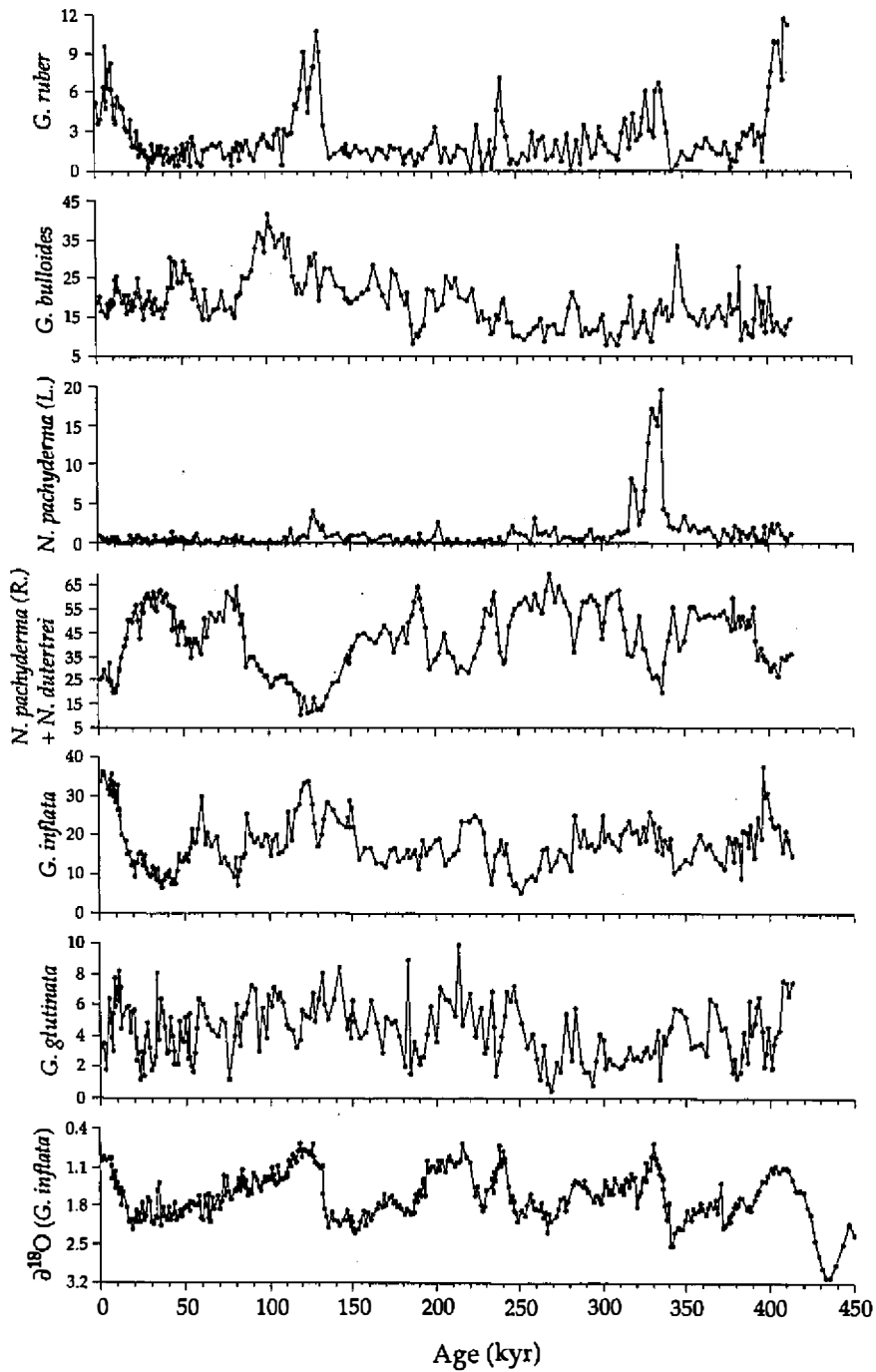


Fig. 5. Relative abundances of six dominant species of planktonic foraminifers for core MD962085 plotted against age and compared to oxygen isotope stratigraphies (*G. inflata*).

abundant in south of Antarctic polar front zone (Niebler and Gersonde, in press) in the South Atlantic Ocean. A complete description of the faunal variations in core MD962085 is presented by Yuan-Pin Chang (1998).

Quantitative estimates of sea-surface temperature (SST) based on the faunal data from core MD962085 were derived using the widely applicable transfer function method (Imbrie and Kipp, 1971). This statistical approach utilizes regression equations that relate the modern sea floor distribution of various plankton groups to overlying surface water properties (e.g., SST). In the Atlantic Ocean, estimates of SST were based on an early version of a foraminifer transfer function, FA-12, which was developed using curvilinear terms of five foraminiferal factors determined from a 365 coretop data set (Molfinio et al., 1982). This set of transfer functions were applied in a project for reconstructing the last glacial maximum conditions of the Atlantic Ocean (CLIMAP, 1981). A methodologically different technique (SIMMAX) used to estimate SST in the Atlantic Ocean has been recently tested and compared to the CLIMAP transfer functions (Pflauman et al., 1996).

In this study we used a newly developed transfer function to estimate SST from core MD962085 (Figure 6). This transfer function was written based on 661 coretop data from the Atlantic Ocean (Prell, 1985; Pflauman et al., 1996) (Figure 7). This transfer function incorporates all available coretop data and thus provides a better overall representation of the diverse fauna and environments of the Atlantic Ocean. Moreover, testing the transfer function against coretop SST observations demonstrated that this equation is able to produce reliable estimates by showing high correlation ($r = 0.98$) and a small value of standard deviation ($\pm 1.59^\circ\text{C}$). For a more in-depth discussion of the application of this transfer function to Atlantic Ocean fora-

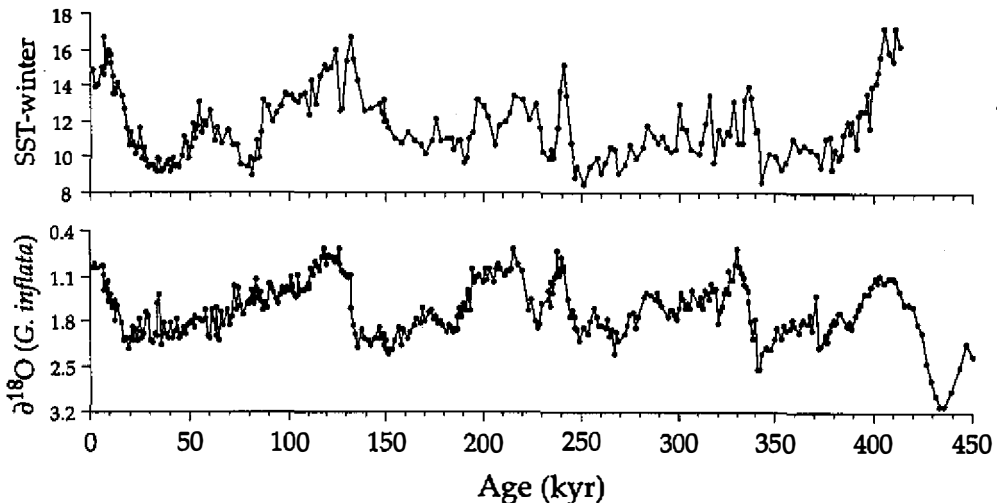


Fig. 6. Core MD962085 planktonic foraminiferal sea-surface temperature estimates (winter season) calculated by a transfer function developed by Cheng-Chieh Chang (1998). The sea-surface temperature estimates are compared to oxygen isotope stratigraphies (*G. inflata*).

miniferal assemblages see Cheng-Chieh Chang (1998).

Downcore winter SST variations from core MD962085 are presented against age (Figure 6). Only winter SST is presented because the temperature reconstruction of this season in this record exhibits changes of larger amplitude than summer SST. The coretop value of the winter SST estimate is about 15°C, in agreement with the range of modern temperature in this season (Figure 2). The consistency between the observed and estimated coretop SST values indicates the reliability of SST estimates made by our newly-written transfer functions. The downcore SST pattern is strikingly similar to that of $\delta^{18}\text{O}$, which indicates the glacial-interglacial ice volume changes. The range of the downcore SST fluctuations is approximately 8°C, with a maximum interglacial value of ~17°C and a minimum glacial value of ~7°C. This glacial-interglacial SST amplitude observed in the southeast Atlantic Ocean is similar to those estimated in deep-sea core from the mid-latitude North Atlantic Ocean (Imbrie *et al.*, 1989; McIntyre *et al.*, 1989). The amplitude of SST increase associated with major terminations is

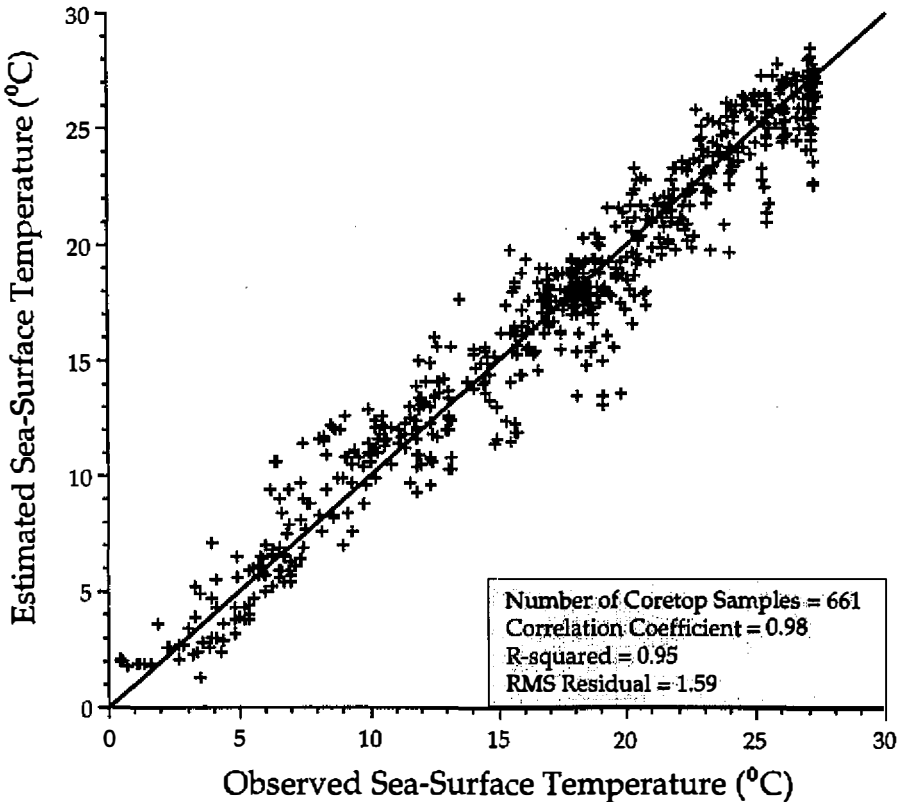


Fig. 7. Scatter diagram showing the observed winter season sea-surface temperature vs. estimated sea-surface temperature by a planktonic foraminiferal transfer function for the Atlantic Ocean on the basis of 661 coretop data (Cheng-Chieh Chang, 1998).

about 4° to 6°C, and that seems to reach maximum during Termination V (from stage 12 to 11). Small amplitude fluctuations of about 3° to 4°C are apparently distinguishable in peak interglacial stages. This type of fluctuation is noticeable in the early intervals of stage 9, 7, and 5, indicating a general instability of surface water conditions during interglacial stages in the southeast Atlantic Ocean. When examining the record in detail, we found that the temperature changes precede the glacial-interglacial changes. This leading of temperature changes to the $\delta^{18}\text{O}$ variations is especially noticeable in the intervals of major terminations. In general, a lead of 3 to 5 kyrs of maximum SST to minimum $\delta^{18}\text{O}$ can be easily observed from the time series of this record.

4. DISCUSSION

Planktonic foraminifer assemblages are sensitive tracers of environmental changes in the layer of surface waters in which they live. In the southeast Atlantic Ocean area, the surface water layer is today influenced by the BCS, an important eastern boundary current driven primarily by atmospheric conditions controlling trade wind intensity and zonality. The atmospheric circulation is internally linked to the north-south gradient of SST in the Southern Hemisphere oceans, and also responding to the strength of northwestern African monsoon winds. The ecological influences of the BCS originate either from the coastal branch, the Benguela Coastal Current, or from the Benguela Oceanic Current, a geostrophic current flowing seaward from the divergence around the Antarctic. It is important to distinguish coastal upwelling faunal assemblages from open ocean ones in the core MD962085, since the identification of different faunal assemblages may imply different sources of climatic signals which can be recovered from this record.

The three dominant species of planktonic foraminifers in this record are *N. pachyderma* (right coiling) + *N. dutertrei*, *G. bulloides*, and *G. inflata*. *N. dutertrei* is closely associated with the surface water upwelling during the summer monsoon season in the Arabian Sea (Cullen, 1981; Duplessy et al., 1981) and in the Panama Basin (Fairbanks et al., 1982). Sediment trap results from the Panama Basin (Thunell and Reynolds, 1984) indicate that *N. dutertrei* has a pronounced abundance peak between 25 to 50 m depth, which corresponds to the steep thermocline, the highest productivity, and the associated chlorophyll maximum. In open oceans, *N. dutertrei* is also abundant in major divergence regions of equatorial current systems (Bé and Tolderlund, 1971; Bé, 1977). In the Bay of Bengal (Cullen and Prell, 1984) and the western continental margin of India (Divakar Naidu, 1993), *N. dutertrei* has been identified as an index of low salinity waters. In the record of core MD962085, the abundances of *N. pachyderma* (right coiling) + *N. dutertrei* are well-parallel to $\delta^{18}\text{O}$ variations, namely, the high abundances of this species are associated with glacial stages and the low abundances are associated with interglacial stages (Figure 5). This relationship may imply a general relatively high nutrient and/or productivity level of glacial oceans (Sarnthein et al., 1988; Lyle et al., 1988; Mix, 1989), and a more nutrient supply and/or high productivity condition occurring in the glacial southeast Atlantic Ocean. In fact, the low-frequency, glacial-interglacial components of estimated SST changes (Figure 6) are primarily driven by the abundance changes of

this species assemblage: high abundances of *N. pachyderma* (right coiling) + *N. dutertrei* representing relatively low SST and low abundances of the assemblage representing high SST conditions.

G. bulloides and *G. inflata* are representatives for the subpolar and transitional zones in the Atlantic Ocean (Bé and Tolderlund, 1971). The distributions of these two species were investigated in detail by faunal factor analyses in the Benguela upwelling zone (Giraudeau, 1993; Giraudeau and Rogers, 1994), in which *G. bulloides* was reported as an "intermediate factor" which has a distribution between an "upwelling factor" *G. pachyderma* (left coiling) and an "offshore factor" *G. inflata*. The ecological roles of these two species seem to reflect different nutrient / temperature conditions. The temporal patterns of these two species in the core MD962085 seem not to be well-parallel to $\delta^{18}\text{O}$ variations (Figure 5), but rather show a relationship of negatively-correlated. High abundances of *G. bulloides* are associated with low abundances of *G. inflata*, and vice versa. This relationship may indicate a change of dominant faunal assemblages associated with frontal movements of the subpolar and transitional belts from the south, or of a change of dominance of the "intermediate" and "offshore" factors in the Benguela upwelling zone from the east.

One noticeable pattern downcore is that the high abundances of *G. ruber* occur during the major transition of glacial to interglacial stages (Figure 5). In general, previous studies in other regions revealed *G. ruber* to be a typical tropical species preferring the environment of warm surface water and deep DOT (Bé, 1977, Fairbanks et al., 1982; Ravelo et al., 1990). It is quite obvious that the warm SST estimates during major Termination stages are derived from the high abundances of *G. ruber*. It is very unlikely that this species was coming from the tropical / subtropical waters in the north, because this spatial change of faunal assemblages involves drastic climatic and oceanographic changes, which are not seen in the studies on cores from the north (Little et al., 1997a; b). We speculate that the high abundances of *G. ruber* can be caused by more thermocline or intermediate water transfers from the Indian Ocean via Agulhas Current, such conditions implying a more vigorous thermohaline circulation in the "Global Conveyor Belt" model proposed by Broecker and Denton (1989). In fact, recent investigations (Little et al., 1997a) on the cores collected from the Cape Basin from Cape Point to the Walvis Ridge suggest more warmer conditions in the surface waters as compared to the north for the past 200,000 years. At this stage we do not have firm evidence indicating that the high abundances of *G. ruber* reflect more surface water communication from the Agulhas Current to the BCS. Further studies on cores from more southern locations as well as from the southwest Indian Ocean are necessary for better interpretation.

5. CONCLUSIONS

This study of planktonic foraminifer faunal and stable isotope records for the core MD962085 of the past 400,000 years has yielded the following conclusions:

1. Over the past 400,000 years, the relative abundances of planktonic foraminifers in the core MD962085 are dominated by three assemblages: (1) *N. pachyderma* (right coiling) + *N. dutertrei*, (2) *G. bulloides*, and (3) *G. inflata*. The assemblage of *N. pachyderma* (right coil-

ing) + *N. dutertrei* shows distinctive abundance changes which are closely associated with glacial-interglacial variations; in contrast, the assemblages of *G. bulloides* and *G. inflata* show more high-frequency abundance change patterns, which are not well-parallel to glacial-interglacial changes.

2. A winter-season SST estimate using transfer function techniques for this record shows primarily glacial-interglacial variations. The range of the downcore SST fluctuations is approximately 8°C, with a maximum interglacial value of ~ 17°C and a minimum glacial value of ~ 7°C. The SST variations seem to be primarily driven by the abundance changes of *N. pachyderma* (right coiling) + *N. dutertrei*.

3. The SST reaches maxima during the transitions from the major glacial to interglacial stages (Termination II, III, IV), and is associated with the abundance maxima of a warm water species indicator *G. ruber*. The average leads of the SST maximum to the $\delta^{18}\text{O}$ minimum are approximately 3-5 kyr.

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