doi: 10.1046/j.1365-3121.2003.00488.x

Surface ocean temperatures in the north-east Atlantic during the last 500 000 years: evidence from foraminiferal census data

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ABSTRACT

Changes in North Atlantic sea surface temperature (SST) are regarded as a key element of the climate during the Quaternary. However, there are relatively few long-term records providing quantitative SST estimates from this region. Using planktic foraminiferal-derived SSTs together with changes on species level and iceberg-rafted debris, the last 500 ka were studied. Pronounced SST changes, as determined from the last glacial–interglacial cycle, characterize most colder periods. Peak interglacial temperatures were found for marine isotope stages (MIS) 1, 5e and 11, the latter two being the warmest. The warm substages within MIS 7 and 9 are marked by enhanced dissimilarity coefficients, indicating that SSTs obtained for these times appear to be overestimated. This is corroborated by differences within the species assemblage, which show enhanced cold water components. It is therefore concluded that detailed analysis down to species level is a crucial prerequisite to better reconstructions of SST.

Terra Nova, 15, 265–271, 2003

Introduction

Changes in North Atlantic sea surface properties have significant impact on the global Quaternary climate through variations in the thermohaline circulation (THC) (e.g. Rahmstorf, 1995; Broecker, 1997; Ganopolski and Rahmstorf, 2001). On glacial–interglacial timescales, sea surface temperature (SST) fluctuations exhibit large amplitudes in this area, making it particularly suitable for detailed investigation of SST–related ocean dynamics during different climatic modes, including peak interglacial conditions. Moreover, it is believed that numerous abrupt cooling events superimposed on the major glacial–interglacial trend originate in the North Atlantic region (Bond *et al.*, 1993; Dansgaard *et al.*, 1993). The most severe of these cooling events, so-called Heinrich events, appeared during glacial and interstadial periods and were associated with increased production rates of icebergs (Bond *et al.*, 1992; Broecker, 1994; van Kreveld *et al.*, 2000; Sarnthein *et al.*, 2001). Thus, they are recognizable in marine sediments not only by temperature and faunal changes but also by enormous input of iceberg-rafted debris (IRD) (Bond and Lotti, 1995; Elliot *et al.*, 1998). Some climate fluctuations have been recorded in peak interglacial periods too, but not within IRD-based records, as ice volume was usually low during these periods (Cortijo *et al.*, 1994; Bond *et al.*, 1997; Oppo *et al.*, 1998).

Thus far, SST estimates from the North Atlantic that cover more than the last two glacial–interglacial cycles have been rarely published. Such reconstructions, particularly when they are based on planktic foraminiferal diversities, seem quite adequate because results from other than conventional foraminiferal methods, e.g. UK′$_{37}$- and δ^{18}O-derived SSTs, are complicated by changes in productivity as well as salinity as a result of freshwater influence. However, the existing faunal SST reconstructions in the North Atlantic covering the last 500 ka (Ruddiman and McIntyre, 1976; Ruddiman *et al.*, 1986) need a detailed revision as they could not take account of more recent advances in the application and interpretation of certain potential proxies. Therefore, the objective of the present investigation was to study SST changes in the North Atlantic during the last 500 ka, using quantitative SST methods based on foraminiferal assemblages as well as faunal analysis down to species level.

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Materials and methods

Marine sediment core M23414 (53°32′N, 20°17′W, water depth 2200 m; Helmke and Bauch, 2001) was recovered from a site situated beneath the North Atlantic Drift, within the IRD belt (e.g. Ruddiman, 1977; Grousset *et al.*, 1993). This location is well suited to studying temporal changes in surface ocean properties because it should capture the dynamics of the THC. The stratigraphic subdivision of M23414 is based on a centimetre-sampled lightness record aligned to SPECMAP chronology (Helmke *et al.*, 2002), indicating that the record reaches back into marine isotope stage (MIS) 13 (Fig. 1). The chronology of the uppermost section of M23414 is supported by AMS ^{14}C age measurements and by assignment of the well-known ages of Heinrich events 1–6 to our core (Didié *et al.*, 2002; Fig. 1).

Sediment residues were derived from 1-cm-thick slab samples. IRD was counted in the > 250-μm size fraction at 2.5-cm depth intervals that correspond to 892 years on average. Faunal counts were executed in 5-cm steps that correspond to 1785 years on average. Samples were subdivided into two size fractions > 150 μm; a minimum of 300 specimens were counted for each size fraction per sample. To test the sensitivity of SST estimates, three different methods were applied and compared: the modern analogue technique (MAT) of Prell (1985), the revised analogue method (RAM) of Waelbroeck *et al.* (1998) and the transfer function technique (TFT) of

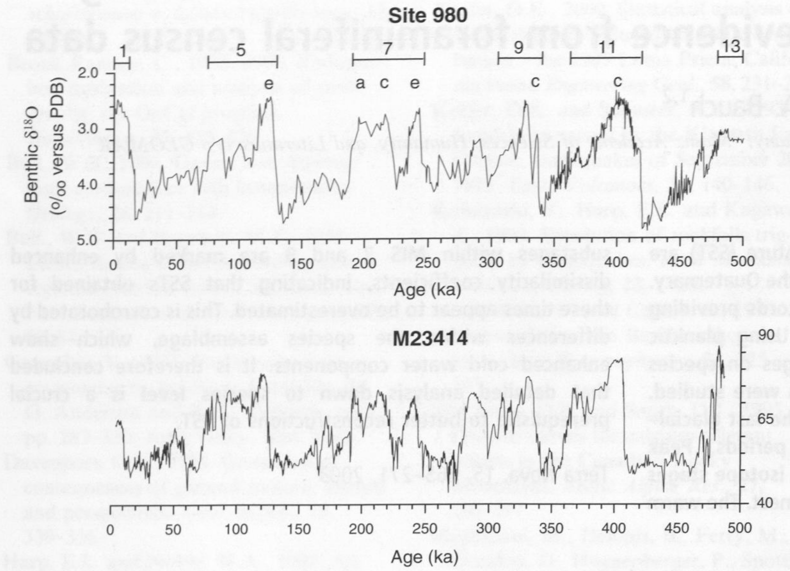

Fig. 1 Stratigraphic subdivision of core M23414 showing records of L^* (sediment reflectance percentage; from Helmke *et al.*, 2002) in comparison with benthic $\delta^{18}O$ (‰) of *Cibicidoides wuellerstorfi* from nearby ODP site 980 (55°29′N, 14°42′W, water depth 2179 m; from McManus *et al.*, 1999); marine isotope stage boundaries are indicated at the top.

Imbrie and Kipp (1971). A geographical section of the North Atlantic comprising 721 core top samples from the extended data base of U. Pflaumann ('ATL916Lc-epo' http://www.pangea.de/Institutes/IfG/) was used for comparison. To retrieve past SSTs, foraminiferal census counts were linked to the temperature data in the upper ocean 50-m layer (Levitus and Boyer, 1994). These were then related to the core top sediment sites by linear interpolation. The 10 best analogues (lowest dissimilarity) for every core sample were chosen for MAT calculations. The squared chord distance was used as an index to determine the dissimilarity coefficients (DCs) (Overpeck *et al.*, 1985).

Past SST estimates are based on the general assumption regarding an analogy between modern and past foraminiferal assemblages. This approach requires additional control on the reliability of the results obtained. Because communality, a statistical variable that controls TFT estimates, was revealed to be not a sensitive indicator of the no-analogue faunal assemblages (Mekik and Loubere, 1999), we used the DC computed with MAT and RAM because they directly compare foraminiferal relative abundances between subject samples and the reference database (Overpeck *et al.*, 1985; Waelbroeck *et al.*, 1998). The admissible value of the DC depends on the diversity of the fauna and is defined for every climate zone separately (Overpeck *et al.*, 1985; Waelbroeck *et al.*, 1998). In our case the lowest DC between the transitional core top assemblage of site M23414 and those from the neighbouring subpolar and subtropical zones is 0.14. Therefore, it can be concluded that a value such as this indicates significant differences in environmental conditions.

Sea surface temperatures

All three records of temperature results obtained by the different methods (MAT, RAM, TFT) are in close agreement with each other (Fig. 2). We will focus our discussion on the MAT records because this method yields better calibration results (standard deviation: winter = 1.02; summer = 1.06) than TFT (standard deviation: winter = 1.39; summer = 1.47). Moreover, in contrast to the RAM method, which has the best calibration (standard deviation: winter = 0.71; summer = 0.87) but includes artificial samples in the reference database (Waelbroeck *et al.*, 1998), MAT makes use of the actual foraminiferal communities. In addition, deviations of the calculated winter and summer SSTs from the modern data are: MAT, +0.4/+0.7; RAM, +0.9/+1.2; TFT, +1.2/+1.1.

The seasonal SST records deduced from the foraminiferal census counts show highly variable glacial–interglacial oscillations that reach up to 8–12 °C during transitional phases (Fig. 2). Superimposed on this are more rapid temperature decreases that punctuate the entire SST record. During glacial and interstadial periods these SST decreases were concurrent with increased IRD input and therefore correlate well with abundance peaks of the polar species *Neogloboquadrina pachyderma* sinistral (s) (Fig. 3). Such a relationship gives clear evidence that the type of climate system recognized for the last glacial period is a persistent feature of the cold climate in general. In most cases, these pronounced temperature falls reached 5–6 °C during glacial and interstadial phases whereas during peak interglacials, when IRD almost disappears, temperature fluctuations were diminished to 1–2 °C (Figs 2 and 3).

Although during all peak-interglacial intervals sea surface waters were of comparable warmth, average Holocene SSTs of about 14 °C during the summer were exceeded during MIS 5e and 11 by 1–2 °C (Fig. 2). DC records exhibit high values of up to 0.19 during warmer phases of MIS 7 and MIS 9c (Fig. 2). This exceeds the admissible value for our location, indicating that estimated SSTs may largely deviate from real values. Intriguingly, further north in the adjacent Nordic seas, enhanced oceanic heat received through the THC is recognized only for the Holocene, MIS 5e and MIS 11 (Bauch *et al.*, 1999, 2000), whereas MIS 7 and 9 appear to have been periods of much colder conditions (Bauch, 1997; Kandiano and Bauch, 2002). A more colder climate during MIS 7 in particular is also inferred from relatively high benthic $\delta^{18}O$ values recorded in the nearby ODP 980 core that indicate more increased glacial conditions as a result of enhanced ice volume when compared with the other interglacials (Fig. 1).

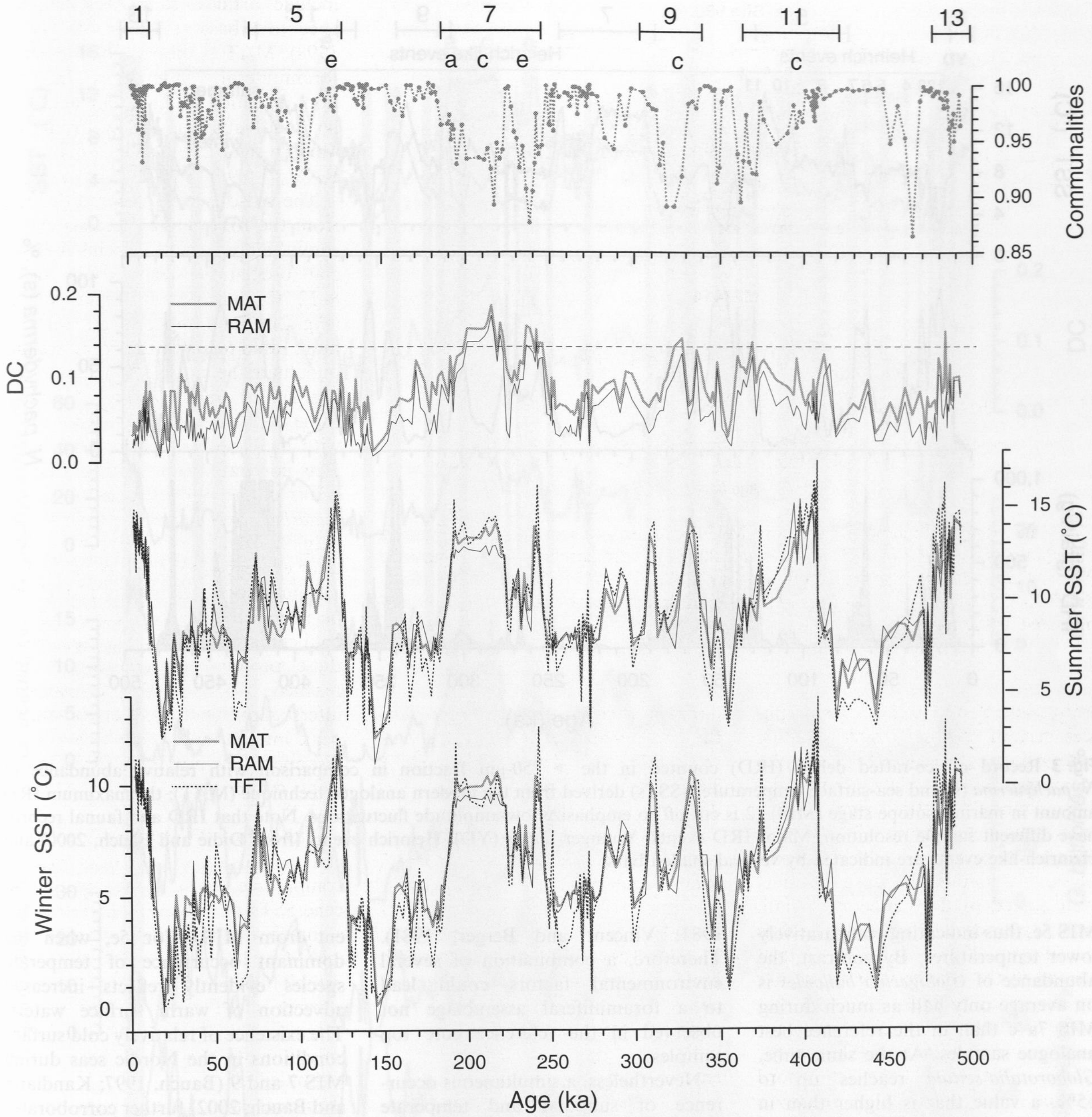

Fig. 2 Summer and winter sea-surface temperature (SST) estimates calculated with the modern analogue technique (MAT), revised analogue technique (RAM) and transfer function technique (TFT) together with dissimilarity coefficients (DCs) provided by MAT and RAM, and communalities derived from TFT. The admissible value of 0.14 for DC is indicated by the dashed line.

Foraminiferal assemblages

Despite some important recent advances in the understanding of THC dynamics during the late Quaternary, most of these new studies were based upon relative SST estimates using only the polar species *N. pachyderma* (s). Thus, faunal analysis down to species level may provide a better insight into the different climatic conditions, also when dealing with quantitative SSTs as a summarized signal of the entire assemblage. A closer look at the foraminiferal fauna from warm substages MIS 7 and MIS 9c, corresponding to the best analogue fauna with high dissimilarity index, reveals typical transitional and subpolar features (Fig. 4). Along with rather high abundances of relatively warm-water species such as *N. pachyderma* dextral (d) and *Globorotalia inflata*, the polar foraminifera *N. pachyderma* (s) still reaches values of 12–16% and subpolar species *Turborotalita quinqueloba* yields its maximum of 30% during MIS 7e and MIS 9c (Fig. 4). This value of the former is twice as high as during interglacials MIS 1 and

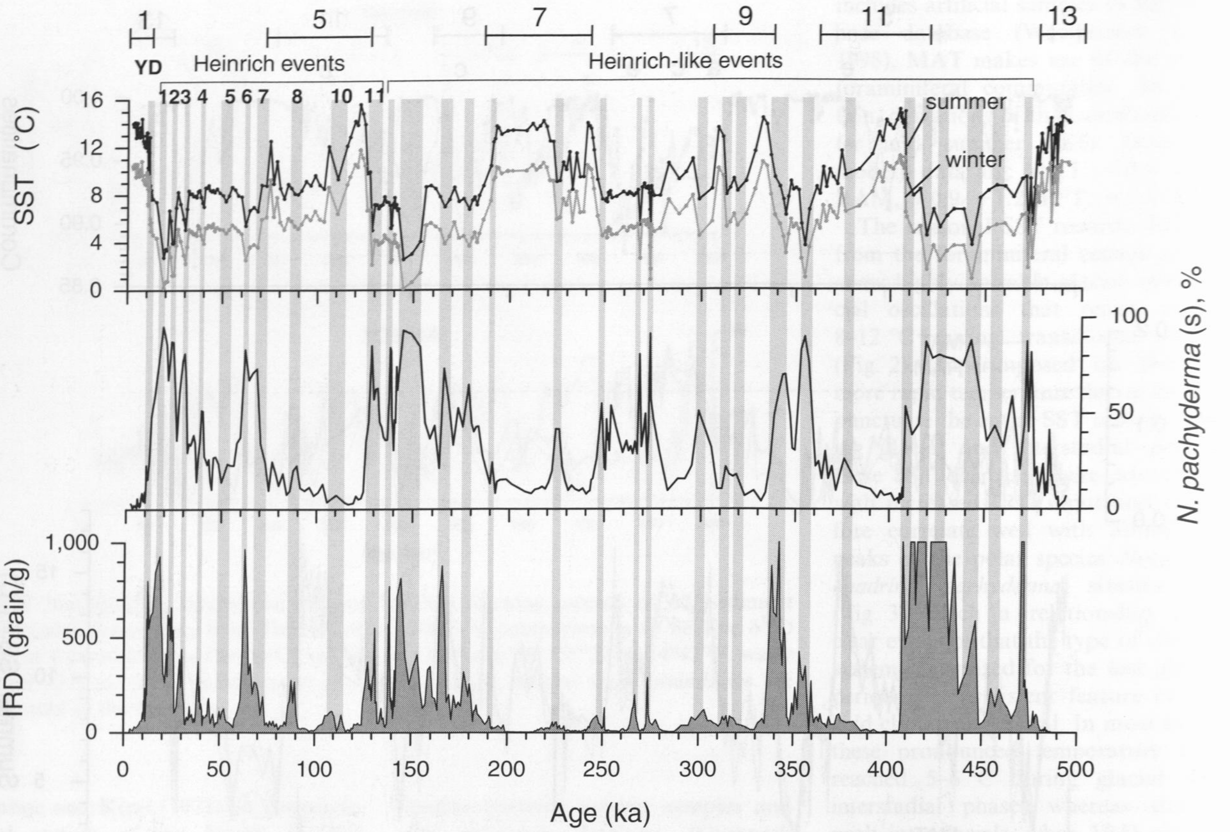

Fig. 3 Record of ice-rafted debris (IRD) counted in the > 250-μm fraction in comparison with relative abundance of *N. pachyderma* (s) and sea-surface temperatures (SSTs) derived from the modern analogue technique (MAT); the maximum IRD amount in marine isotope stage (MIS) 12 is cut off to emphasize low-amplitude fluctuations. Note that IRD and faunal records have different sample resolution. Major IRD events, Younger Dryas (YD), Heinrich events (from Didié and Bauch, 2000) and Heinrich-like events are indicated by vertical shaded bars.

MIS 5e, thus indicating comparatively lower temperatures. By contrast, the abundance of *Globigerina bulloides* is on average only half as much during MIS 7a–c than in the reference best analogue samples. At the same time, *Globorotalia scitula* reaches up to 15%, a value that is higher than in the reference database (Fig. 4).

The no-analogue situations within MIS 7 and 9c, in particular, may be caused by complex environmental circumstances, for which temperature is important but by no means the sole factor controlling foraminiferal species abundance. For instance, Loubere (1981) found that *G. inflata* shows a strong relationship to seasonality, becoming more abundant as annual thermal contrast increases; the distribution of *G. bulloides* seems strongly related to the particular upper ocean density structure and/or to phytoplankton productivity (Loubere, 1981; Vincent and Berger, 1981). Therefore, a combination of several environmental factors could lead to a foraminiferal assemblage not observed in the reference core top samples.

Nevertheless, a simultaneous occurrence of subpolar and temperate planktic foraminiferal species, for which a water mass relationship is relatively well known, may still allow us to make some profound palaeoceanographic assumptions. For *T. quinqueloba*, a close association with Arctic water–mass fronts is inferred from core top sediments of the North Atlantic and the Nordic seas (Barash, 1988; Johannessen *et al.*, 1994). If the high abundance of *T. quinqueloba* during the climate peaks of MIS 7 and 9 resulted from a proximity of site M23414 to polar waters, then the water–mass configuration during these periods was significantly different from MIS 1 or 5e, when the dominant occurrence of temperate species evidently reflects increased advection of warm surface waters. The existence of relatively cold surface conditions in the Nordic seas during MIS 7 and 9 (Bauch, 1997; Kandiano and Bauch, 2002) further corroborates our conclusion based on the various faunal evidence of less benign SSTs in the north-east Atlantic at these times. Isotopic SST estimations derived from benthic and plankic foraminiferal $\delta^{18}O$, however, would indicate surface temperatures for MIS 7 and 9 comparable to those for MIS 5e and 1, but with global ice volumes larger than during the latter two periods (McManus *et al.*, 1999).

Foraminiferal species changes during other peak interglacial periods resemble each other in a general way. Special emphasis has recently been given to climate dynamics of MIS 11,

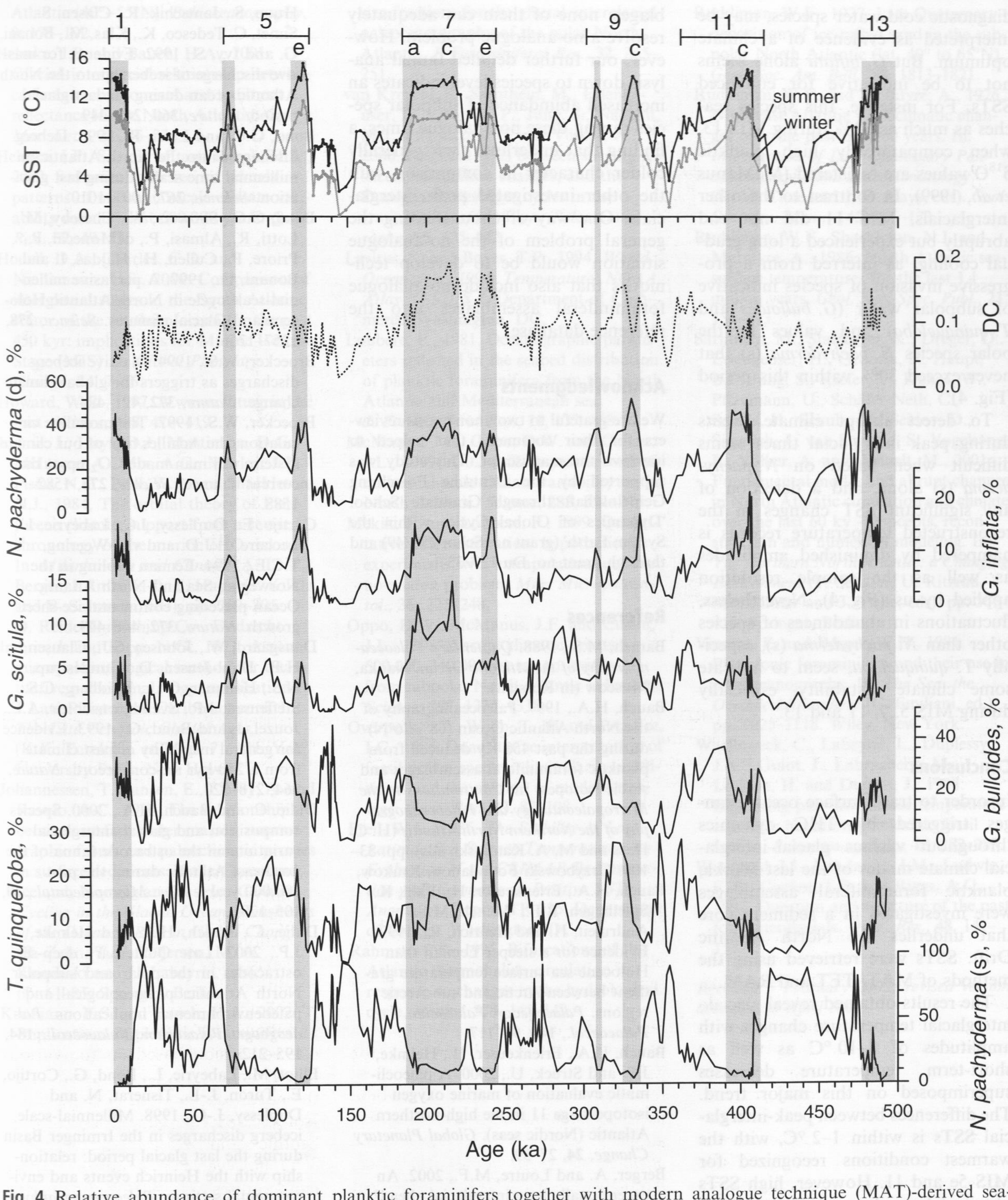

Fig. 4 Relative abundance of dominant planktic foraminifers together with modern analogue technique (MAT)-derived sea-surface temperatures (SSTs) and dissimilarity coefficients (DCs); shaded areas indicate climatic maxima as recognized on the basis of SST estimates.

which was indicated as a period with very prolonged peak interglacial conditions (Imbrie *et al.*, 1984; Winograd *et al.*, 1997) and proposed to be the closest analogue to the Holocene future on the basis of similarity in their orbital geometry (Howard, 1997; Hodell *et al.*, 2000; Berger and Loutre, 2002). Immediately after deglaciation of MIS 12, a very prominent excursion of the transitional species *G. inflata* and *N. pachyderma* (d) is observed (Fig. 4). Their relative abundances of 22% and 52%, respectively, along with diminished abundances of diagnostic cold-water species, may be interpreted as evidence of a climate optimum. But *G. inflata* alone seems not to be indicative for enhanced SSTs. For instance, this species reaches as much as 23% during MIS 13, when comparatively high planktic $\delta^{18}O$ values are registered (McManus *et al.*, 1999). In contrast to the other interglacials, MIS 11 did not end abruptly but experienced a long gradual cooling, as inferred from a progressive invasion of species indicative of subpolar water (*G. bulloides* and *T. quinqueloba*) and values in the polar species *N. pachyderma* (s) that never exceed 30% within this period (Fig. 4).

To detect abrupt climate events during peak interglacial times seems difficult when based on *N. pachyderma* (s) alone, and a detection of any significant SST changes in the reconstructed temperature records is hampered by diminished amplitudes as well as the sample resolution applied by us (Fig. 4). Nevertheless, fluctuations in abundances of species other than *N. pachyderma* (s), especially *T. quinqueloba*, seem to indicate some climate instability, especially during MIS 5, 7, 11 and 13.

Conclusions

In order to trace surface ocean changes triggered by THC dynamics throughout various glacial–interglacial climate modes of the last 500 ka, planktic foraminiferal assemblages were investigated in a sediment core that underlies the North Atlantic Drift. SSTs were retrieved using the methods of MAT, TFT and RAM.

The results obtained reveal glacial–interglacial temperature changes with amplitudes of 8–10 °C as well as short-term temperature decreases superimposed on this major trend. The differences between peak-interglacial SSTs is within 1–2 °C, with the warmest conditions recognized for MIS 5e and 11. However, high SSTs obtained for warm substages MIS 7 and 9c are questionable because of enhanced DCs between down-core and reference samples indicating no-analogue situations. Because all conventional faunal SST methods are based on the general assumption regarding a correspondence between modern and past foraminiferal assemblages, none of them can adequately resolve a no-analogue problem. However, our further detailed faunal analysis down to species level indicates an increased abundance of subpolar species during these no-analogue times, a finding that underlines their generally colder character in comparison with the other investigated peak interglacials. One way of circumventing the general problem of the no-analogue situation would be to develop techniques that also include no-analogue foraminiferal assemblages into the reference database.

Acknowledgments

We are grateful to two anonymous reviewers for their comments that helped to improve the manuscript. This study was supported by the Deutsche Forschung Gemeinschaft through Graduate School 'Dynamics of Global Cycles within the System Earth' (grant no. Schm 250/49) and through grant no. Du 129/33-1.

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Received 5 February 2002; revised version accepted 26 April 2003