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Norwegian sea-surface palaeoenvironments of marine oxygen-isotope stage 3: the paradoxical response of dinoflagellate cysts

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ABSTRACT: High-resolution marine palynological data have been obtained from two very long sediment cores (MD952009 and MD952010) retrieved from the southern Norwegian Sea. The dinoflagellate cyst assemblages show pronounced fluctuations in composition, which correlate strongly with magnetic susceptibility records and also mimic the δ^{18}O signal of the GISP2 Greenland ice-core. If focusing on the period from 48 to 30 cal. kyr BP, this correlation suggests a paradoxical response of the sea-surface environments to the atmospheric conditions over Greenland: when the Greenland δ^{18}O signal reflects warm interstadial conditions, the Norwegian Sea depicts cold sea-surface temperatures with quasi-perennial sea-ice cover (based on dinoflagellate cysts). In contrast, when the Greenland δ^{18}O records cold stadial periods, the Norwegian Sea-surface temperatures are warm (based on dinoflagellate cysts), probably linked to inflow of the North Atlantic Drift. These results, similar in both cores, are contrary to those of previous studies and shed light on a possible decoupling of Norwegian sea surface-water conditions and atmospheric conditions over Greenland. This decoupling could be linked to an atmosphere–ocean system behaving similar to that which the Northern Hemisphere is experiencing at present, i.e. strongly variable owing to the North Atlantic Oscillation. Copyright © 2002 John Wiley & Sons, Ltd.

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KEYWORDS: dinoflagellate cysts; Norwegian Sea; marine oxygen-isotope stage 3; sea-ice cover; North Atlantic Oscillation.

Introduction

The Norwegian–Greenland Sea is a high-latitude ocean that has been studied intensively over the past few decades. This region constitutes a key area for studying and understanding past climate variability. It is characterised by the inflow of North Atlantic surface waters, which largely contribute to the formation of North Atlantic Deep Water, the latter forming a major component of the global thermohaline circulation (e.g. Broecker *et al.*, 1990). The large-scale surface circulation is further dominated by the cold East Greenland Current (EGC), which carries low-salinity waters and sea-ice southward. This hydrographic setting has in the past been largely influenced by the expansion and retreat of adjacent continental ice-sheets, which consequently have played a crucial role in determining regional or even global climate.

The aim of this study is to reconstruct the palaeoceanographic changes in the Norwegian–Greenland Sea during marine oxygen-isotope stage 3 (MIS 3), a period punctuated by abrupt, suborbital discharges of icebergs into the North Atlantic Ocean (Heinrich events: Heinrich, 1988, Bond *et al.*, 1992; Paillard and Labeyrie, 1994). Various studies have shown that these Heinrich events occurred preferentially during times of cold atmospheric extremes, as recorded in the Greenland ice-sheets (e.g. Dansgaard *et al.*, 1993) and were associated with major drops in sea-surface temperatures (SST) of the adjacent temperate basins (Bond *et al.*, 1993; Grousset *et al.*, 1993; Bond and Lotti,

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1995; amongst others). In this paper, two cores (MD952009 and MD952010) located underneath the North Atlantic Drift (NAD) tongue were subjected to a high-resolution palynological study. Organic-walled dinoflagellate cysts (= dinocysts) can be regarded as satisfactory surface-water proxies of the palaeoenvironments of the Norwegian–Greenland Sea (see the special issue of Journal of Quaternary Science **16**, 2001). In high latitudes, dinocysts show a high species diversity in comparison to planktonic foraminifers, the classic method used in palaeoceanographic studies. This especially is true during glacial periods, where almost monospecific assemblages of *Neogloboquadrina pachyderma* sinistral limit qualitative or quantitative reconstructions of sea-surface parameters north of 60 °N using planktonic foraminifers alone. This problem may be amplified by dissolution, which can alter calcareous microfossil assemblages, particularly in cold environments.

This paper focuses on the variability of dinocyst assemblages through part of MIS 3, from 48 to 30 cal. kyr BP, a period during which the two cores studied depict high resolution and challenging palaeoclimatic signals. Our palynological results are discussed in the light of their correlation to the magnetic susceptibility records, which closely mimic the GISP2 Greenland ice-sheet δ^{18}O record (Dokken and Jansen, 1999; Kissel *et al.*, 1999; Rasmussen *et al.*, 1999). Comparison with other proxy records available on the two cores (planktonic δ^{18}O, ice-rafted detritus concentrations, percentages of *Neogloboquadrina pachyderma* sinistral) is also presented.

Material and methods

Hydrographic and sedimentary setting

Cores MD952009 (62°44.3′N, 03°59.9′W; 1027 m water depth) and MD952010 (66°41′N, 04°34′E; 1226 m water depth) were collected from the southern part of the Norwegian Sea during IMAGES (International Marine Past Global Changes Study) cruise MD 101 in May–July 1995 (Bassinot and Labeyrie, 1996); from the northeastern sector of the Faeroe Islands and from the Vøring Plateau, respectively (Fig. 1).

Core MD952009 consists of hemipelagic clays. As was shown previously from a twin core (ENAM93-21) by Rasmussen *et al.* (1996a,b, 1997), the magnetic susceptibility (MS) record of MD952009 closely matches the shape of the GISP2 Greenland ice-core δ^{18}O isotopic signal. It therefore has been assumed that the MD952009 records can be linked indirectly to atmospheric temperature oscillations over Greenland (Rasmussen *et al.*, 1999).

Core MD952010 has been retrieved from the same location as ODP Hole 644. This site is of great interest for palaeoceanographic and palaeoclimatic studies as it is located at the northern limit of North Atlantic Drift (NAD) influence, as well as being close to the glacial limit of the Fennoscandian ice-sheet. In fact, the Scandinavian ice-sheet extended as far offshore as the Vøring Plateau (Fig. 1) during the last glaciation (Mangerud, 1991). The extreme situations of the last glaciation have left a marked imprint in the local sedimentation, especially at the time when the Barents Sea was deglaciated (Bischof, 1994). In spite of the variation in glaciomarine sedimentation, Kissel *et al.* (1998, 1999) and Dokken and Jansen (1999) have shown that the MD952010 MS record presents analogies with the GISP2 record similar to the signal of MD952009.

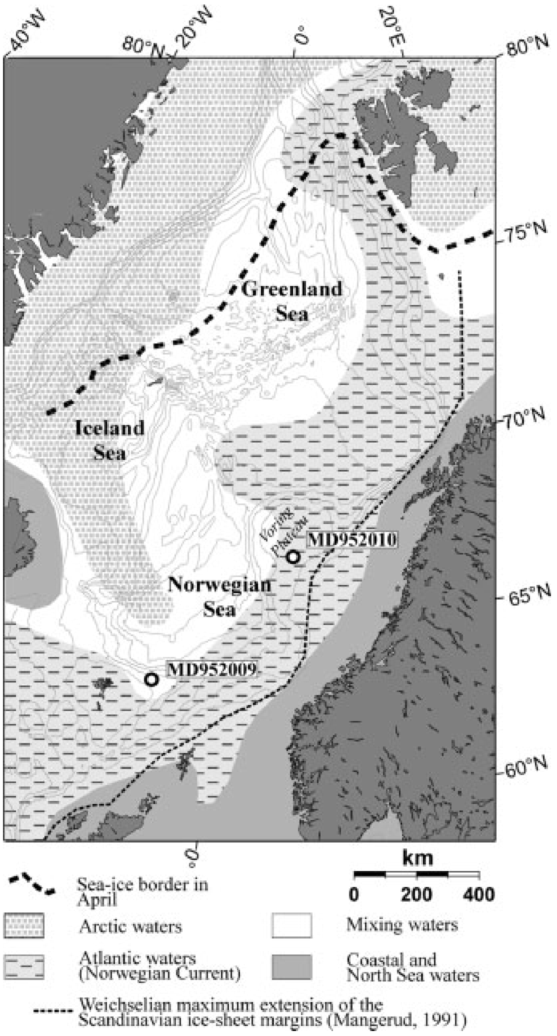

Figure 1 Map showing the distribution of the main surface-waters in the Norwegian Sea (slightly modified after Henrich *et al.*, 1989) with the location of the cores MD952009 and MD952010

Stratigraphy

The age models of core MD952009 and MD952010 (Fig. 2) conform strictly to the ones published by Kissel *et al.* (1999). Basically, these age models have been based on the fact that Atlantic marine sediment records can be tied to ice-core stratigraphies through regional climatic and ash-layer tie points (see Stoner *et al.*, in press). In the two cores, Heinrich layers and ash zone II, which previously have been identified unambiguously, and isotopically (δ^{18}O) and ^{14}C dated (Rasmussen *et al.*, 1996a,b, 1997; Dokken and Jansen, 1999; Balbon, 2000), coincide with magnetic minima. These minima were used as tie points. Independent support for this correlation was obtained from a palaeomagnetic study conducted on these cores (Laj *et al.*, 2000).

Dinocyst analysis

Dinocyst analysis was performed on the fraction <150 µm. Samples were taken every 10 cm (every 0.2 to 1 kyr) throughout both cores, or even at a higher resolution in key periods. The preparation technique followed the procedure described in Rochon *et al.* (1999).

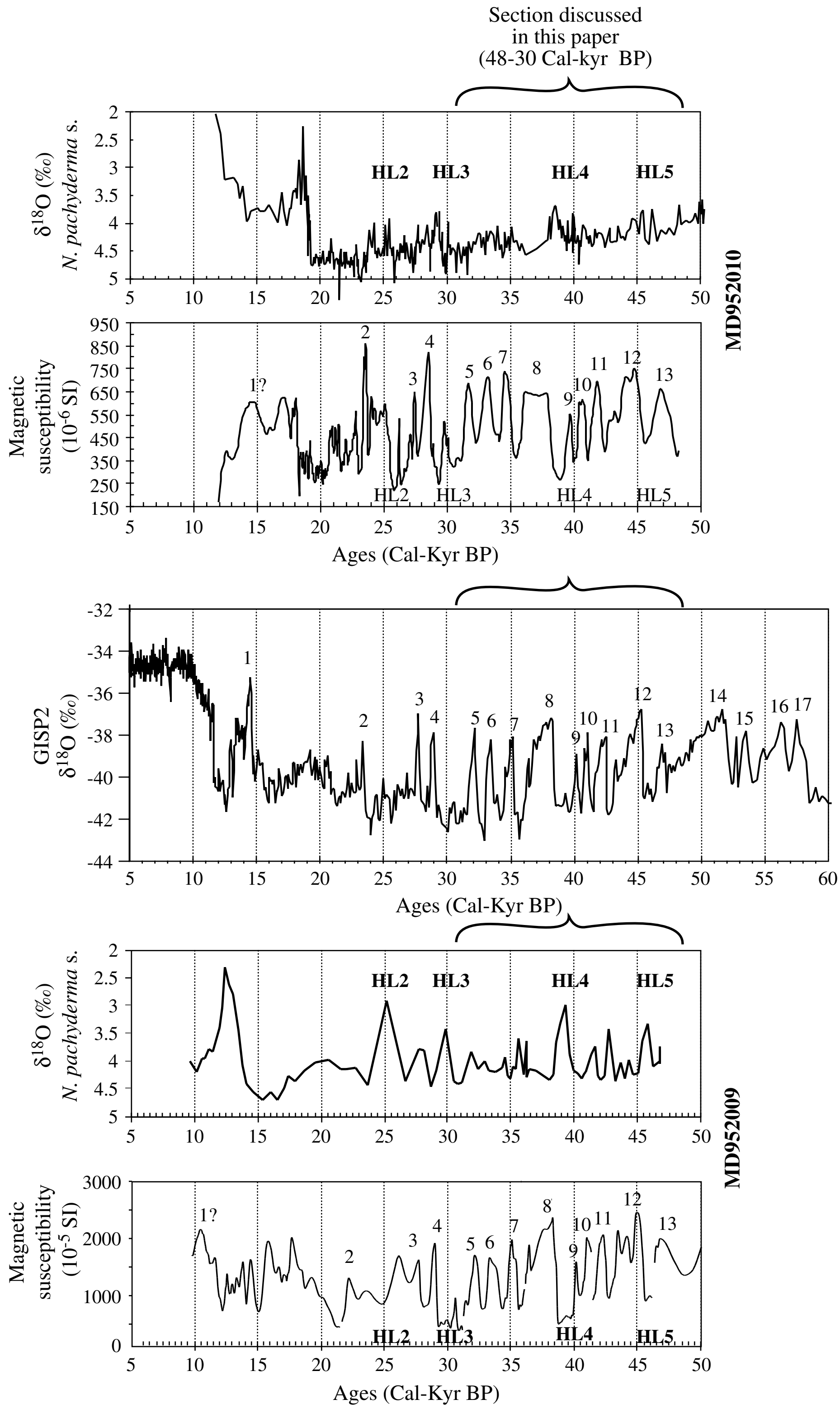

Figure 2 Comparison of the magnetic susceptibility and planktonic δ^{18}O records of cores MD952009 and MD952010 (Kissel *et al.*, 1999; Dokken and Jansen 1999; Balbon, 2000) with the GISP2 δ^{18}O record (Grootes and Stuiver, 1997). Interstadial events (From IE 1 to 13) and Heinrich events (HL1 to HL5) are marked in the cores according to Rasmussen *et al.* (1996a,b, 1997, 1999) and Kissel *et al.* (1998, 1999)

An average of 300 dinocysts per sample were identified and counted. The identification of dinocysts follows Turon (1984) and Rochon *et al.* (1999). The nomenclature conforms to Williams *et al.* (1998) and Head *et al.* (2001). *Brigantedinium* species were grouped together because of uncertain determination of many specimens owing to folding. Dinocyst concentrations were calculated using the marker grain method (de Vernal *et al.*, 1996).

To synthesise the empirical counts of dinocysts, sea-surface temperature (SST) calculations (February and August SST) and sea-ice cover durations were estimated according to the statistical procedure developed by de Vernal *et al.* (1993, 1997, 2001). The approach relies on the best analogue technique (Guiot, 1990) and the data base used for the calculation includes 677 surface sediment samples for a total of 30 selected dinocyst taxa (the data base can be found on the websites of GEOTOP (http://www.geotop.uqam.ca/) and the PANGAEA data bank of the Alfred Wegener Institute (http://www.pangaea.de)). The hydrographic data correspond to averages established following measurements made over the past few decades. Sea-ice cover was compiled mainly from data provided by the National Climate Data Center (NCDC) in Boulder, Colorado. The SST (0 m depth) are compiled from data published as CD-roms by the National Ocean Data Center (NODC, 1994).

The estimation procedure is adapted from the Guiot and Goeury (1996) 3P-Base software, and is described precisely in de Vernal *et al.* (2001). Basically, taxa relative abundances, expressed per thousand, are logarithmically transformed. One (1) is added to the frequency of each taxon in order to deal with values greater than zero, so the relative frequencies of taxa range from 1 to 1000. Another minor transformation consists of adjusting the frequency data ranging between 2 and 5 (i.e. 0.2 and 0.5%) to the value of 5 in order to make a better discrimination between absence (1) and presence (5). In a second step, fossil data are tested for the search of analogues in the modern data base. A set of five analogues is considered. The hydrographic data corresponding to these analogues are used to calculate an average that is weighted inversely to the index of similarity (distance) between the fossil and modern analogues. Validation exercises have revealed a degree of accuracy or prediction error established at ±1.3 °C and ±1.8 °C for the temperature of February and August respectively, and ±1.5 months yr^{-1} for the sea-ice cover. For this paper, we present only sea-ice cover duration and February SST reconstructions as August SST reconstructions are less useful with respect to these two parameters.

The dinocyst records of cores MD952009 and MD952010

Along-core fluctuations in dinocyst abundance

More than 30 taxa of dinocysts were recognised in each core studied (Eynaud, 1999). In the section corresponding to the last glacial period, dinocyst concentrations do not exceed 5000 cyst/cm^3. These values are low compared with those typical of neritic environments. Dinocyst assemblages are dominated by four species (Fig. 3): *Islandinium minutum*; Head *et al.*, 2001), *Operculodinium centrocarpum*, *Bitectatodinium tepikiense* and *Brigantedinium* spp. *Pentapharsodinium dalei* is a major subordinate species in some intervals.

Islandinium minutum is a subpolar to polar species, which today is associated with quasi-permanent sea-ice cover (>3 months · yr^{-1}: Dale, 1996; Rochon *et al.*, 1999; de Vernal and Hillaire-Marcel, 2000), whereas the species *O. centrocarpum* is at present distributed preferentially along the path of the NAD. *Bitectatodinium tepikiense*, *Brigantedinium* spp. and *P. dalei* currently are observed in surface sediments of the subpolar basins of the North Atlantic Ocean (Harland, 1983; de Vernal *et al.*, 1992; Dale, 1996; Rochon *et al.*, 1999). *Brigantedinium* spp. tolerates seasonal sea-ice cover but, as an heterotrophic species, is also linked to food availability (notably diatoms). Devillers and de Vernal (2000) have shown that no special relationship links the five species cited above to nutrient availability.

The relative abundances of the dominant species are different in the two cores (Fig. 3). For example, *O. centrocarpum* shows higher percentages in MD952010 (from 20 to 80%) than in MD952009 (maximum of 40% in the core section discussed). This difference displays the importance of the position of the two cores with regard to the surface circulation system that characterises the Norwegian Sea (see Fig. 1). This feature is also emphasised by the percentages of the subpolar to polar species *I. minutum*. This species occurs in quasi-monospecific percentages in core MD952009 but in lower percentages in core MD952010. Apart from these regionally marked differences, the dinocyst records display very similar changes through time.

Figure 4 illustrates the variation of *I. minutum* percentages with depth plotted versus MS and total dinocyst concentration data for both cores. The lower part of the record shows a clear covariation of the magnetic susceptibility record and the *I. minutum* percentages. Between the assumed interstadial events (IE) 12 and 3, and, despite the lower resolution in core MD952010 owing to the high compaction of sediments in this part of the record, the signals appear coherent in shape throughout both cores. Highest percentages of *I. minutum* correspond to high MS values, and *vice versa*. In contrast, between the assumed IE 3 and the tops of the cores, the signals have an opposite phasing, with minimal values of MS graphically corresponding to peaks in *I. minutum* percentages. The Last Glacial Maximum is identified between IE 3 and IE 2 (this last interstadial included) according to the age interval of 24–19 cal. kyr BP recommended by the EPILOG (Environmental Processes of the Ice Age: Land, Ocean and Glaciers) working group (Mix *et al.*, 2001; Schneider *et al.*, 2000). This period is characterised in both cores by the near disappearance of *I. minutum*. Thus, whatever part of the record is considered, a strong link seems to exist between the distribution of *I. minutum*, and therefore the dinocyst assemblages in surface waters, and the magnetic susceptibility record. The percentage abundances of *O. centrocarpum* also reflect major and rapid fluctuations in the 48 to 30 cal. kyr BP interval that closely match from core to core (Figs 5 and 6), but are inversely correlated with those of *I. minutum*.

The contrasting records of *O. centrocarpum* and *I. minutum* apparently illustrate variation in the influence of relatively warm and saline NAD water inflow, and, cold polar water intrusions in the Norwegian Sea, respectively. This interpretation is reflected in the estimations of February SST and sea-ice cover duration (reconstructed on the basis of the dinocyst whole assemblages with the modern analogue method—de Vernal *et al.*, 2001), which are positively correlated with *O. centrocarpum* and *I. minutum* percentages, respectively.

Between 48 and 30 cal. kyr BP, February SST and sea-ice cover duration were highly variable: February SST estimates range from −2 to 5.1 °C (±1.3 °C) for core MD952009, and from −1.5 to 5.7 °C (±1.3 °C) for core MD952010. The ice-cover duration varies between 0 and 11.3 months yr^{-1} (±1.8 months) in core MD952009 and between 0 and 5.7 months yr^{-1} (±1.8 months) in core MD952010. The sea-ice cover duration, estimated to be two times larger in core MD952009, emphasises the stronger NAD influence at the MD952010 site, which limited the expansion of the polar species *I. minutum*.

Comparison of *O. centrocarpum* and *I. minutum* records with the MS signal between 48 and 30 cal. kyr BP

When compared with the MS signal, assumed following Rasmussen *et al.* (1996a,b, 1997, 1999) and Kissel *et al.* (1998, 1999) to reflect variations of atmospheric conditions

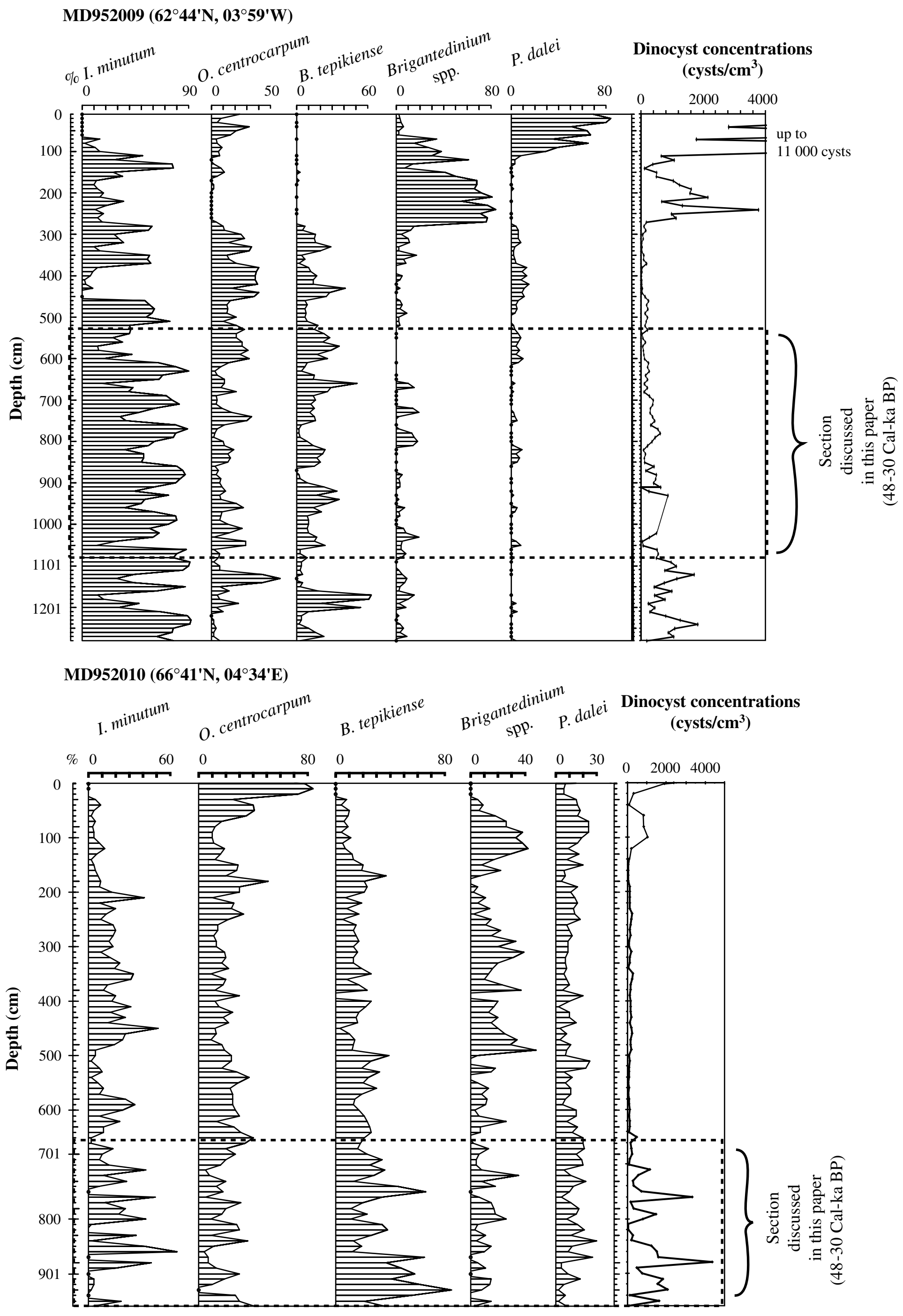

Figure 3 Percentage diagrams of the dominant dinocyst species in cores MD952009 and MD952010 compared with dinocyst total concentrations (cysts cm^{-3})

over Greenland, the succession of the *I. minutum* and *O. centrocarpum* peaks (Figs 5 and 6) closely follows the succession of interstadial and stadial periods of the Greenland isotopic records (Dansgaard *et al.*, 1993). This also appears to be true for the fluctuations of sea-ice cover duration and February SST. This good phasing of the atmospheric and oceanic signal should be questioned, however, owing to the fact that both qualitatively and quantitatively reconstructed sea-surface palaeoenvironments reveal temperature conditions strictly opposite to those recorded over Greenland at the same time. Notably, and despite a lower resolution of the dinocyst record in core MD952010, warm SST and only seasonal sea-ice cover are recorded in the Norwegian Sea during assumed stadial cold periods over Greenland, whereas cold SST and perennial sea-ice cover coincide with interstadial warm periods.

During the extreme stadial periods of Heinrich events 5, 4 and 3, the Norwegian Sea records February SST that exceed 2 °C, or even 4 °C in the record of MD952010. Peaks of maximum sea-ice extension correspond with the Greenland interstadial events (IE). For core MD952009, each of the reconstructed peaks during the IEs depict a comparable amplitude, with sea-ice cover duration greater than 10 months yr^{-1}. The most prominent peaks reconstructed in MD952010 (up to 5 months yr^{-1}) are recorded during IE 10 and 7.

Detailed comparison of the micropalaeontological and the MS signals (Figs 5 and 6) shows that, although peaks broadly

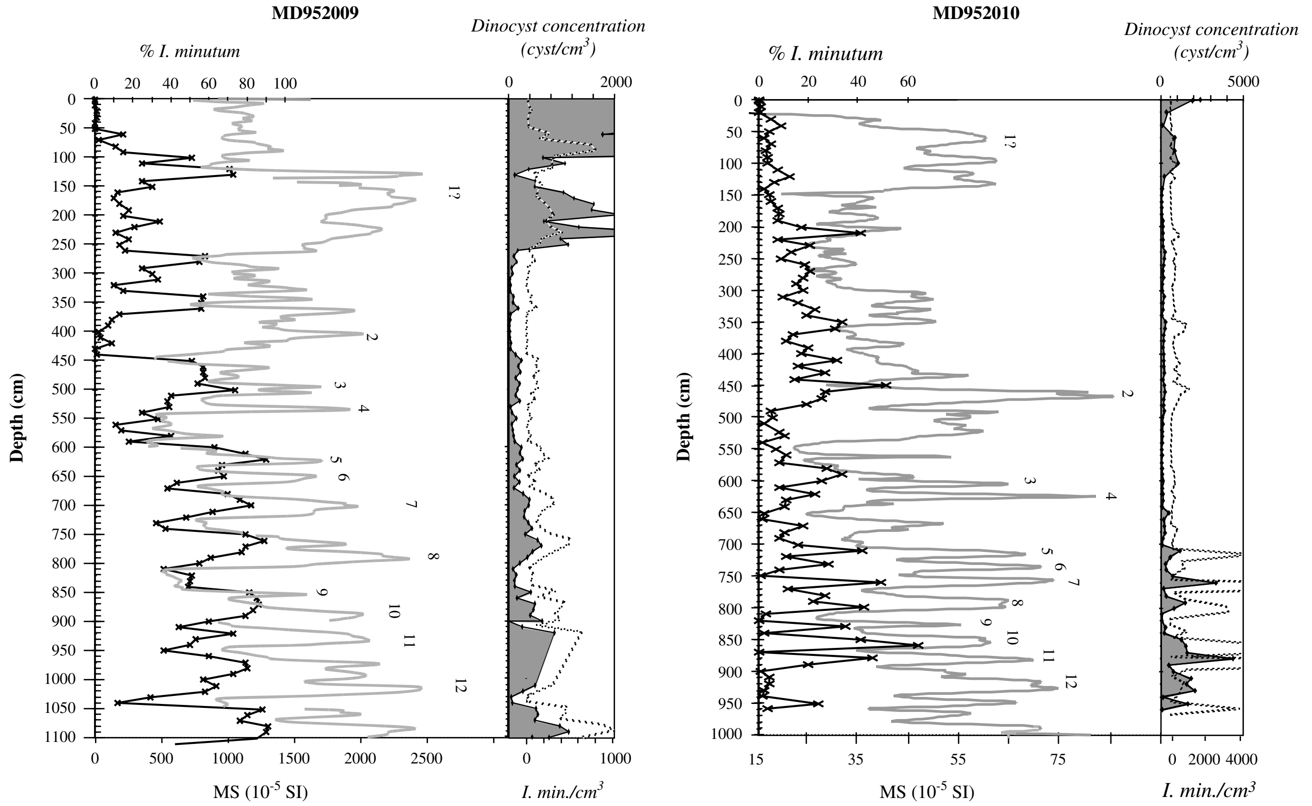

Figure 4 Variation of *I. minutum* percentages with depth plotted versus magnetic susceptibility and total dinocyst concentrations (cysts · cm^{-3}). Concentrations of *I. minutum* are superimposed on the total dinocyst concentration graph

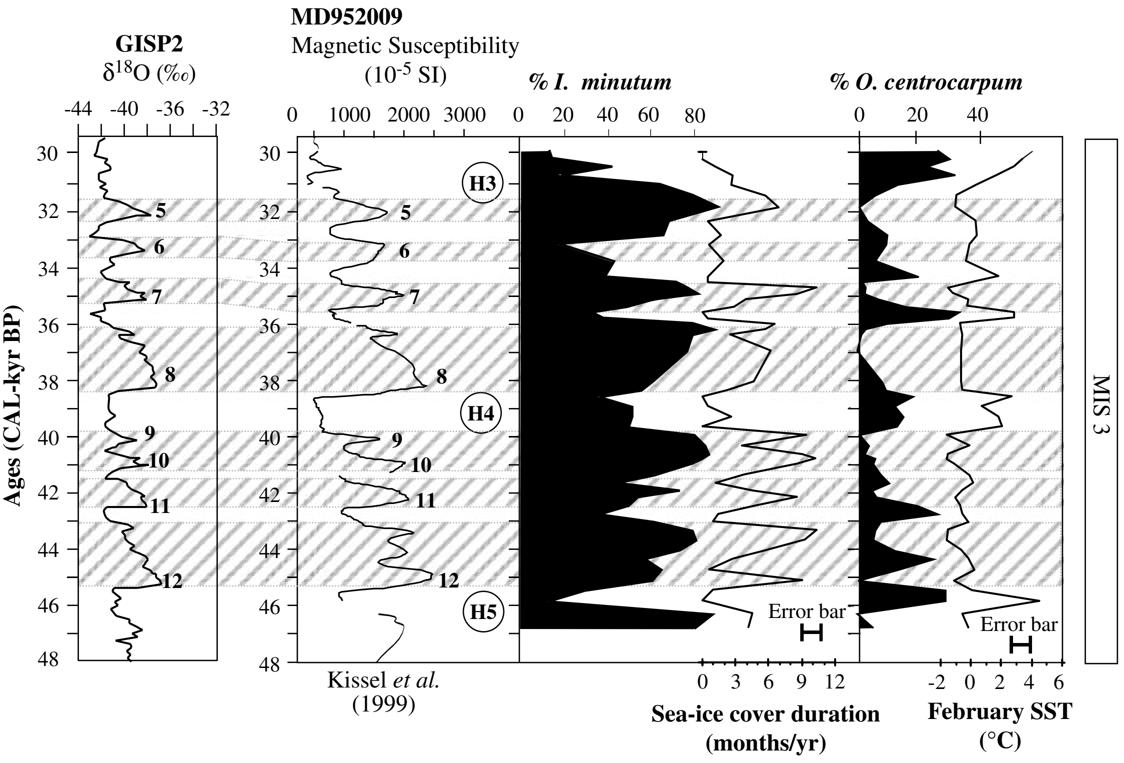

Figure 5 Comparison of the GISP2 δ^{18}O profile with the magnetic susceptibility record of core MD952009 from 48 to 30 cal. kyr BP with selected dinocyst species percentages (*I. minutum, O. centrocarpum*) and reconstructed annual sea-ice cover and February SST (based on modern analogue method—de Vernal *et al.*, 2001)

suggest synchronous development, the maximum values of the respective signals do not coincide systematically. In fact, in the high-resolution record of MD952009, high MS values characterise the onset of the interstadial periods, whereas maximum sea-ice cover occurred at the end of these interstadials. In comparison, the relatively low resolution of MD952010 does not allow us to clearly identify such a trend.

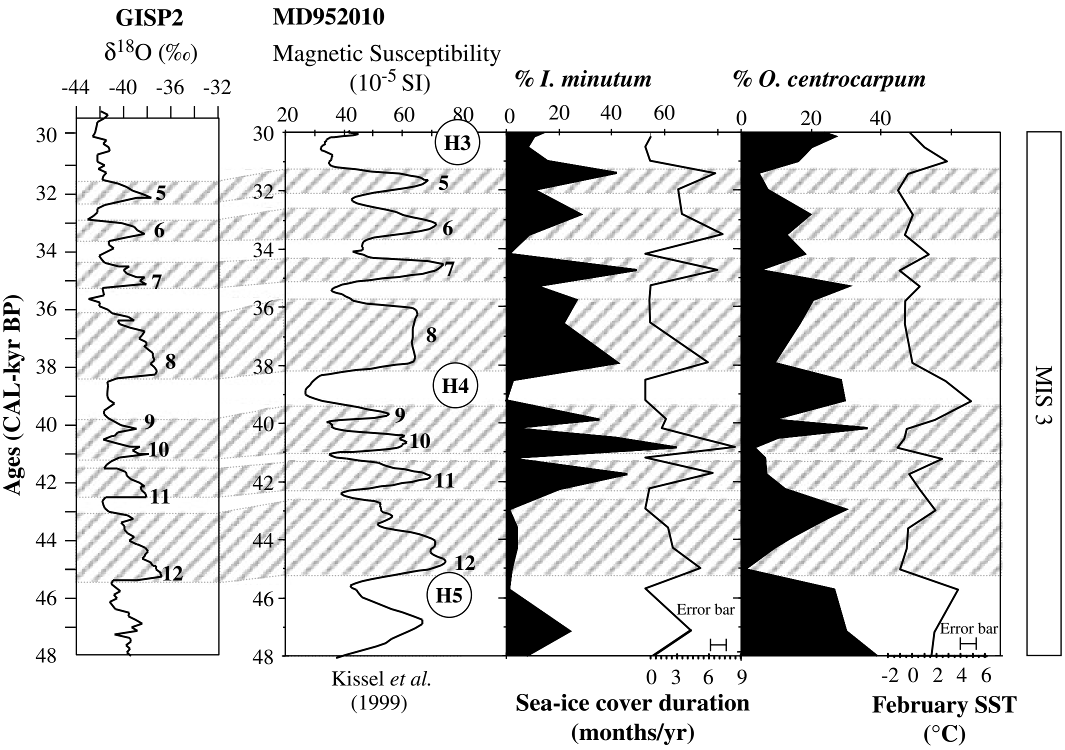

Figure 6 Comparison of the GISP $\delta^{18}O$ profile with the magnetic susceptibility record of core MD952010 from 48 to 30 cal. kyr BP with selected dinocyst species percentages (*I. minutum, O. centrocarpum*) and reconstructed annual sea-ice cover and February SST (based on modern analogue method—de Vernal *et al.*, 2001)

A paradoxical response?

The major observation that emerges from the detailed analysis of the interval from 48 to 30 cal. kyr BP is that each interstadial event of the Greenland glaciological record seems to correspond to a maximum duration of the sea-ice cover in the Norwegian Sea, whereas each stadial period is reflected in the Norwegian Sea by minimum duration of sea-ice cover. If we assume the global relevance of the Greenland $\delta^{18}O$ record for the Northern Hemisphere (Dansgaard *et al.*, 1993), their furthermore means that, during this period, ice-cover duration in the Norwegian Sea varied in opposite phasing with the mean atmospheric temperature of the Northern Hemisphere.

The first argument that one can pose against these conflicting results is that, considering the mean size of dinocysts (silt size), the assemblages may not result from *in situ* deposition but rather the lateral advection of cysts. In this case, our reconstructions would not mirror the sea-surface parameters, but a combination of allochthonous and autochthonous parameters. However, when considering the present biogeographical distribution of the dominant dinocyst species that occur in both cores, and especially the distribution of the cyst species *I. minutum*, two observations tend to support our interpretation:

1 The species *I. minutum* presently occurs in high percentage abundances in surface sediments off the eastern Greenland coast north of 65 °N (Rochon *et al.*, 1999), precisely along the path of the East Greenland Current (EGC). The EGC carries Polar Water from the Arctic Ocean southwards along the East Greenland continental shelf with an annual mean transport of 21 ± 3 Sv (up to 37 Sv in winter, Woodgate *et al.*, 1999). It also carries a steady stream of multiyear pack ice throughout the year (up to 0.14 Sv in late autumn and late winter, Martin and Wadhams, 1999). Moored current meters in the abyssal depths (Woodgate and Fahrbach, 1999) have shown episodic bottom current activity directly under the EGC, but also in the centre of the cyclonic Greenland Sea gyre. Such a hydrodynamic scheme should affect the present distribution of *I. minutum*, leading to transport downslope into the basin. However, mapping of its maximum percentages in surface sediments revealed well delimited patches on the East Greenland shelf that show a strong gradient across the continental slope (Rochon *et al.*, 1999).

2 In the case of transport, maxima of *I. minutum* should reflect advection from cold waters, supposedly deriving from subpolar/polar latitudes: the transport therefore should include a marked southward component. In contrast, maxima of *O. centrocarpum*, a cosmopolitan species having its centre of distribution in warm-temperate regions (Harland, 1983; Turon, 1984; Rochon *et al.*, 1999), should then be driven by a poleward flow. When compared with the MS maxima and minima in both cores (Rasmussen *et al.*, 1996a,b, 1997; Kissel *et al.*, 1999), this would mean that Greenland IEs should coincide with southward cold polar flows, whereas stadial periods should coincide with northward warm surface currents.

We therefore assume a paradoxical response of the proxies to palaeoenvironmental change. According to Kissel *et al.* (1999), maxima of MS are indicative of a change in the amount of magnetite deposited with time. These authors state that this change could just be assumed to reflect a modification in the intensity of the deep-sea circulation but do not indicate how the circulation may have been modified.

A third point supports the validity of the dinocyst signal: the fact that this signal is coherent on a regional scale, occurring in both cores MD952009 and MD952010.

If we assume that our records are not affected by lateral advection of cysts, cyst dissolution could have biased the dinocyst signal. In particular, preferential dissolution of *I. minutum* cysts during stadial conditions (corrosive properties of cold waters) could lead to the artificial dominance of *O. centrocarpum* and therefore to a 'warm signal'. However, this appears unlikely as high percentages of *I. minutum* are at present preferentially recorded in polar sediments under the pathway of cold corrosive waters. Such dissolution processes should, furthermore, affect the whole community, and therefore be recorded in the dinocyst total concentrations. We should then record a covariation of these concentrations and *I. minutum* percentages, a pattern that is not observed in the cores studied (see Fig. 3). The opposite relationship is true in the upper part of the cores, where very low dinocyst concentrations are recorded during periods of high *I. minutum* percentages.

Sea-ice cover duration (dinocyst-based), planktonic δ^{18}O record, ice-rafted detritus (IRD) concentrations, and percentages of *Neogloboquadrina pachyderma* sinistral have been correlated between cores MD952010 and MD952009 (Fig. 7). The correlation reveals an ambiguous response of the tracers, as the signals appear to be coherent only during Heinrich events. Major features are depicted throughout δ^{18}O light peaks during Heinrich events and especially during H4. These light peaks, which, in the Nordic seas, have been interpreted as large melt-water releases (Cortijo *et al.*, 1997) are in good agreement with the dinocyst reconstruction of sea-ice cover, showing minimum duration at this time. A coherent scheme is, however, more difficult to construct from the comparison of the δ^{18}O and dinocyst-based sea-ice cover records during the Dansgaard–Oeschger cycles. The IRD concentration peaks seem to recurrently precede ice-cover peaks, showing a global anti-phased response. Event H4 is worthy of note because it is represented by low IRD concentrations in the two cores, whereas this event is marked in the southern part of the North Atlantic Ocean by one of the largest IRD discharges (Cortijo *et al.*, 1997).

Only the composition of planktonic foraminiferal assemblages from core MD952009 (Manthé, 1998) clearly supports our interpretations. These high-resolution foraminiferal studies reflect similar palaeoenvironmental conditions as depicted by the dinocysts from Heinrich events 5 to 3: *N. pachyderma* s. relative abundance peaks (up to 100%) are associated with sea-ice cover duration maxima and vice versa. According to dinocyst and planktonic foraminifer data, this implies that cold SST occurred in the Norwegian Sea during the warm Greenland interstadials, and that warm SST occurred during the cold Greenland stadials. Such a result cannot be observed so unambiguously in the planktonic foraminiferal data of core MD9520010, as only Heinrich periods seems to offer a coherent response (SST warming). Higher resolution micropalaeontological data are required to definitively support the proposed correlation.

These controversial dinocyst results shed light on the link existing in high latitudes between the atmospheric circulation pattern and sea-surface conditions of the subpolar/polar basins. They underline the fact that the Greenland δ^{18}O record cannot be systematically interpreted as a global intrahemispheric temperature signal but rather as a mean atmospheric temperature signal over Greenland, that seems, in the light of our results, not systematically in phase with sea-surface temperatures of the southern Norwegian Sea. To explain this situation, we assume that these periods of decoupling mirror a climatic situation comparable to the one that prevails at present in the North Atlantic Ocean, indicated by the balance of a positive versus a negative North Atlantic Oscillation (NAO) index. The NAO index is defined as the difference in sea-level pressure between two stations close to the low over Iceland and the high over the Azores. During the last century, high winter/spring indices were caused by a net displacement of air from over the Arctic and Icelandic regions towards the subtropic belt near the Azores and the Iberian Peninsula causing stronger westerlies over the North Atlantic Ocean. Stronger westerlies bring warm, moist air over the European continent and lead to rather mild maritime winters. A low winter/spring index reflects weaker mean westerlies over the North Atlantic Ocean, with corresponding colder European winters.

Oceanographic studies have shown that the NAO also leaves a marked imprint on sea-surface parameters: cold SST and more saline waters characterised the Norwegian–Greenland Sea when the NAO index was low, whereas, at the same time, warm SST and low salinities marked the upper layers of the Labrador Sea (Dickson, 1997; Blindheim *et al.*, 2000). Primarily, the NAO leads to climatic conditions over the Canadian provinces and the Labrador Sea that are opposite to those over the European provinces and Norwegian Sea. The Danes have noticed that a 'severe' winter in Denmark occurred simultaneously with a 'mild' winter in Greenland and vice versa. Greenland climate therefore seems to respond in phase with the Canadian and Labrador part of the system. It has been shown that the NAO circulation mode was coherent with the periodic behaviour in the most recent part of the stable isotope record from the GISP2 ice-core (White *et al.*, 1997).

If the NAO is characterised by a seasonal response, long-term periods of positive or negative indexes could affect temperature and salinity in the Norwegian–Greenland Sea, e.g. during the 'Great Salinity Anomaly' (Dickson *et al.*, 1988). Predominance of one of these opposite NAO conditions over several centuries could well be recorded in marine sediments. On the other hand, the climatic situation that characterised the Norwegian–Greenland Sea during MIS 3, might have been significantly different from that at present. We infer, therefore, that our records might be caused by a climate situation comparable to the NAO but do not know if, during glacial times, the atmospheric circulation operated in a 'modern' mode or if this mode differed significantly.

Despite these limitations in our interpretations, our results point to heterogeneous climate situations in polar environments during the last glacial period, at least between 48 and 30 cal. kyr BP. More studies are, however, needed to test our hypothesis and to assess the exact behaviour of Norwegian versus Greenland palaeoenvironments. Considering the recent work of Blindheim *et al.* (2000), this heterogeneity could involve more complicated processes than a simple 'bipolar seesaw' between the eastern and western part of the North Atlantic Ocean. In fact, Blindheim *et al.* (2000) have shown that a positive link exists between NAO indexes and the NAD penetration into the Norwegian Sea. High NAO indices imply that only a narrow NAD extended northward of the Faeroe–Iceland Strait. This results in a SST cooling at the scale of the Greenland and Norwegian basins, owing to the spreading of polar waters eastward. Simultaneously, NAD flow is intensified in the narrow band along the Norwegian shelf northwards towards Svalbard. However, the various hydrographical systems of the Norwegian–Greenland Sea should be studied in more detail on a regional scale to test the validity of our interpretations, implying the analysis of a large number of cores because of the complex hydrographical conditions of the Norwegian–Greenland Sea.

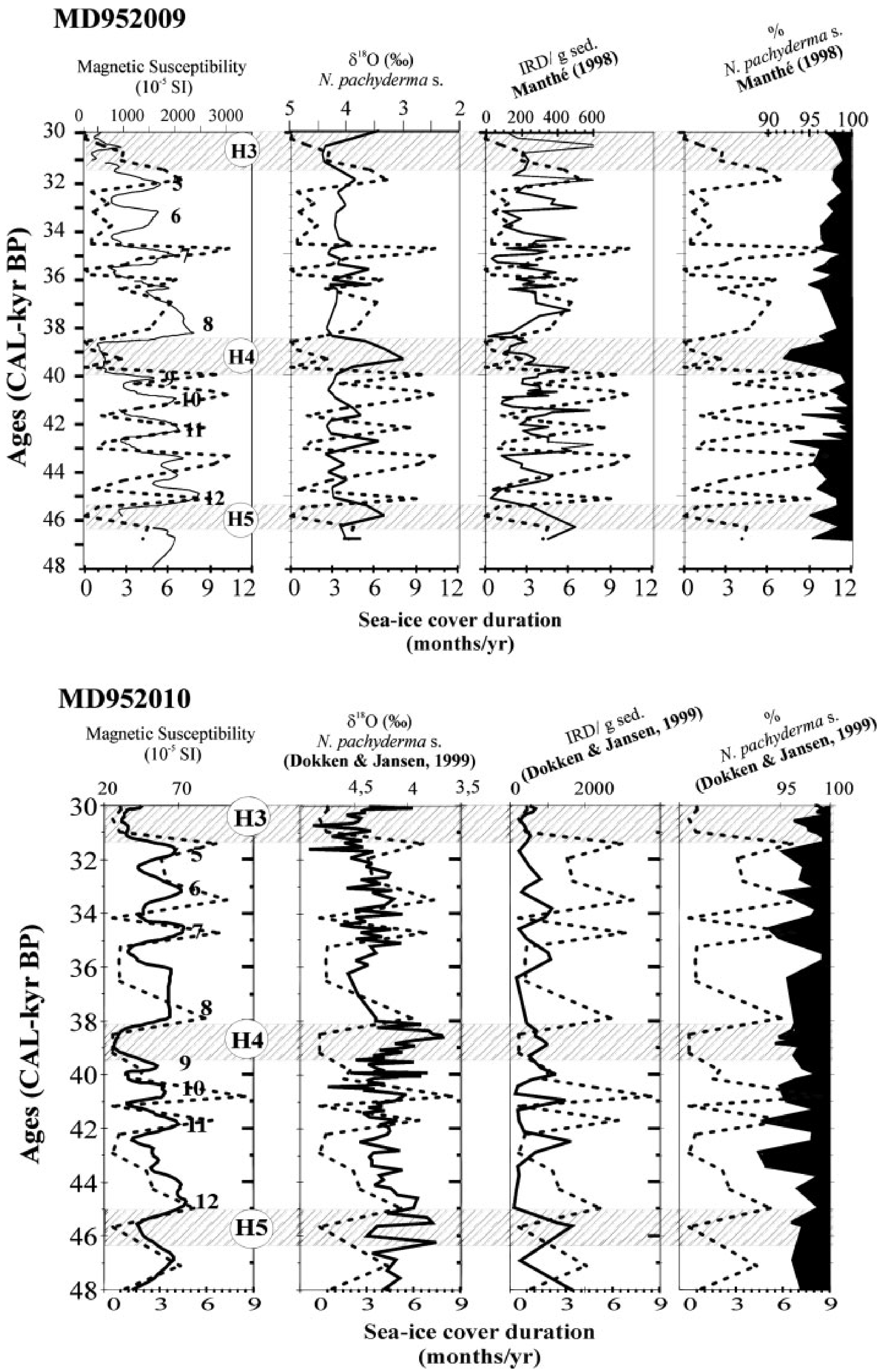

Figure 7 Comparison of the sea-ice cover duration reconstructions (dinocyst-based) (dotted curve) with the planktonic $\delta^{18}O$ record, ice-rafted detritus (IRD) concentrations and percentages of *Neogloboquadrina pachyderma* sinistral from cores MD952010 and MD952009 from 48 to 30 cal. kyr BP

Conclusions

The investigation of the dinocyst assemblages of cores MD952009 and MD952010, retrieved from the Southern Norwegian Sea and covering the past 50 000 yr, has demonstrated the potential of this specific surface-water proxy for palaeoenvironmental studies in cold-water environments. The species diversity and the high variability of the dinocyst record in both cores have enabled us to reconstruct palaeoenvironmental changes that affected the southern Norwegian Sea.

Our study has shown that a direct positive correlation exists between the magnetic susceptibility signal of the sediments of the cores, assumed to reflect atmospheric conditions over Greenland (Rasmussen *et al.*, 1996a,b, 1997, 1999; Kissel *et al.*, 1998, 1999), and the proxy of sea-surface parameters that dinocysts potentially represent (relative abundances, SST, sea-ice cover). This correlation is observed on a regional scale, as it has been demonstrated in two cores separated by more than 500 nautical miles. The correlation suggests a complex response of Nordic palaeoenvironments to climate changes, possibly involving an atmospheric mechanism comparable to that which at present drives the North Atlantic Oscillation.

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