Response of the high-latitude Northern Hemisphere to orbital climate forcing: Evidence from the Nordic Seas

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ABSTRACT

Sediment cores from the Nordic (Greenland, Iceland, and Norwegian) seas provide evidence that this area acts as an initial responder to the forcing effect of orbitally driven changes in insolation on the climate system, as postulated by J. Imbrie et al. The $\delta^{18}O$ record of the cores documents a widespread initial deglacial signal in the area between 15 and 13 ka, ~1000 yr before other deglacial signals from other parts of the Northern Hemisphere. An even earlier meltwater event has been dated to 16,090 ±185 yr B.P. north of Iceland, at the initial rise of Northern Hemisphere insolation after the last glacial maximum. During the period with lowered surface salinities, the Nordic seas were still cold. Reconstructions of the surface-water conditions of the area show that, as the summer insolation values of the Northern Hemisphere reached half of maximum values, a sea-ice–free corridor opened along Norway at ~13.4 ka. Nearly contemporaneous fluctuations of the polar front and the sea-surface temperatures with the insolation changes indicate that the Nordic seas are very sensitive to insolation forcing, especially in regions close to the sea-ice margin. A decrease in sea-surface temperature and an increase in the areal extent of sea-ice cover since 7 ka indicate that the area is currently on the way to glacial conditions, supporting the predictions made earlier by J. Imbrie et al.

INTRODUCTION

A central element in the Milankovitch (orbital) theory of climate change is that the initial response of the climate system to orbital forcing must occur in the high latitudes of the Northern Hemisphere, as a result of orbitally derived changes in summer insolation. Imbrie et al. (1989, 1992) came to the same conclusion by investigating phase relations between the orbital-forcing function and the responses of different elements of the global climate system. Imbrie et al. postulated that the surface of the Nordic seas acts as an initial responder to the insolation forcing and transmits the response to the global climate system via ice-albedo feedbacks and effects on the thermohaline circulation, which transmits the signal to the southern ocean and the carbon cycle. It has been difficult to document this initial response clearly because of the scarcity of available unequivocal proxy data. Here we present new evidence in support of the early-response postulate, indicating a very early response of surface waters and ice sheets surrounding the Nordic seas when summer insolation is both rising and falling.

These seas currently comprise major oceanographic boundaries, seasonally variable sea-ice distribution, and deep-water formation, which is a driving element in the global thermohaline circulation. To test the postulate that the Nordic seas function as an early responder, we investigated evidence for initial responses to insolation changes in the surface conditions of these seas since the last insolation minimum at ~20 ka. We analyzed the *N. pachyderma* sinistral stable isotope record of five sediment cores dated by atomic mass spectroscopy (AMS)-^{14}C chronology to detect the first deglacial meltwater signal across the entire Nordic seas (Fig. 1). This provides an estimate of when the surrounding ice sheets started to shrink and melt away as insolation increased. We also used diatom assemblages and sea-surface temperature estimates derived from these assemblages to monitor changes in sea-surface temperature and sea-ice cover in the Nordic seas.

EARLIEST DEGLACIAL SIGNALS

Ice sheets contain water spiked with very low $\delta^{18}O$, which upon its release to the ocean in the form of meltwater and/or melting icebergs produces negative spikes in the surface-water $\delta^{18}O$. These are recorded by the calcite of planktonic foraminifers, which thus serve as a direct monitor of the melting of glacial ice. In the Nordic sea cores, the first major deglacial response to increasing insolation is recorded as a light isotopic meltwater spike between 15 and 13 ka, when June insolation values had risen by 63 W/m^2 to 42% of their maximum values, ~5 ka by

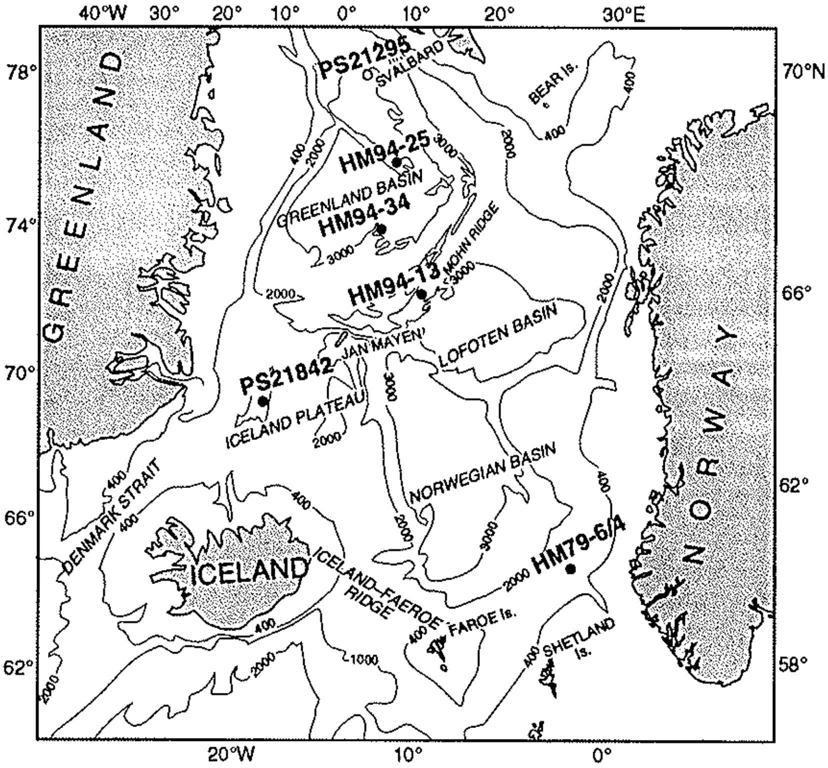

Figure 1. Bathymetry of Nordic (Greenland, Iceland, and Norwegian) seas and location of cores mentioned in text. Cores investigated in this study are HM94-25 (lat 75°36'N, long 01°18'E, depth 2469 m), HM94-34 (73°46'N, 02°23'W, depth 3004 m), HM94-13 (71°37'N, 01°37'W, depth 1946 m), PS21842 (69°27'N, 16°31'W, depth 968 m) and HM79-6/4 (see Koç Karpuz and Jansen, 1992).

^{14}C dating (6 ka by the calendar) after the last insolation minimum (Fig. 2). The light isotopic peaks have been radiocarbon dated by AMS to 14,695 ±125 yr B.P. (reservoir corrected age) in core HM94-25 and 14,580 ±165 yr B.P. in core HM94-34 from the Greenland Basin (Table 1). The first meltwater spike for the Iceland and Norwegian seas has been dated to 14,090 ±125 and 14,100 ±155 yr B.P. (Koç Karpuz and Jansen, 1992) or somewhat earlier (Fig. 2). We cannot determine whether there is a real time difference of a few hundred years from north to south, because of the combined errors of the dating and the bioturbation. In sum, we take this evidence to indicate that meltwater inputs to the entire Nordic sea area reached a maximum before 14,000 yr B.P. These dates correlate well with the meltwater peak of 14,480 yr B.P. previously recorded from the Fram Strait core PS21295 (Jones and Keigwin, 1988).

Comparison with similar meltwater events from areas south of the Nordic seas, reflecting meltwater coming from the southern flank of the Laurentide ice sheet, indicates that the earliest deglaciation response happened in the Nordic seas (Fig. 2). Planktonic oxygen isotope records from the Gulf of Mexico, Bermuda Rise, and North Atlantic all indicate the first deglacial meltwater spike after 14,000 yr B.P., ~1000 yr after that of the Nordic seas, documenting that deglaciation of this region began as a precursor to the main deglaciation of the Laurentide ice sheet.

This early melting of the Nordic seas region happened before significant warming of the surface ocean took place (Koç Karpuz and Jansen, 1992; Lehman and Keigwin, 1992), indicating calving of marine-based ice sheets as the main mechanism for the initial destruction of the ice sheets. As noted by others, the calving probably resulted from destabilization of marine-based parts of the ice sheets by an initial sea-level rise (Jones and Keigwin, 1988; Lehman et al., 1991; Veum et al., 1992) or by thinning due to ablation caused by the rising insolation. An early melting of the Barents ice sheet was suggested by Jones and Keigwin (1988) as a main feature of the initial deglaciation process. Our documentation of correlative early meltwater spikes from the whole Nordic seas area, both in the north, west, and southeast, points to contemporaneous calving as a general process affecting the marine-based ice sheets in the whole region in the initial deglaciation. However, the most active transfer of meltwater to these seas during the first deglacial phase apparently took place west of the Barents Sea (Sarnthein et al., 1992).

We find evidence for an even earlier meltwater spike in the oxygen isotope record of core PS21842 from north of Iceland (Figs. 1 and 2). This peak is radiocarbon dated to 16,090 ±185 yr B.P., i.e., during the initial rise of Northern Hemisphere insolation after the last insolation minimum, and at the start of the sea-level rise, ~1500 yr (by radiocarbon dating) earlier than the major deglacial event noted above in the Nordic seas. Although replicate measurements (plotted as circles) of this level show some scatter, possibly due to bioturbation or the fact that the sampling interval was of longer duration than the event, all values are more negative than the base level, which gives credibility to the signal. Other isotope records from the Iceland Sea and the Vøring Plateau (T. Fronval, 1994, personal commun.) also show similar evidence. Flanks of the Greenland, Scandinavian, British, or Iceland ice sheets can be envisaged as a possible source for this meltwater signal, which is situated right at the start of the insolation and sea-level rise.

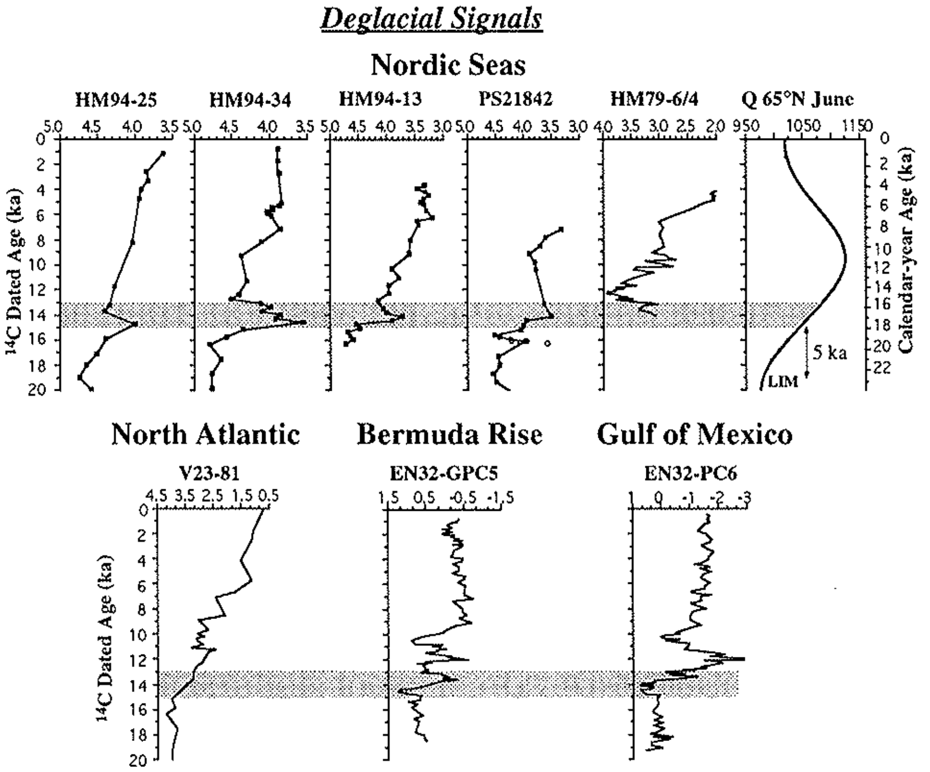

Figure 2. Time series of planktonic $\delta^{18}O$ in cores from Nordic seas, North Atlantic, Bermuda Rise, and Gulf of Mexico. Data for core HM79-6/4 are from Koç Karpuz and Jansen (1992); for core V23-81 from Jansen and Veum (1990); for core EN32-GPC5 from Keigwin et al. (1991); and for core EN32-PC6 from Leventer et al. (1982). Q is June insolation at lat 65°N from Berger (1978). Isotope data are plotted in ^{14}C dated years, by using age models from Table 1 and published age models. Also shown is time scale in calendar years, based on U/Th correction to radiocarbon time scale proposed by Bard et al. (1990). Shaded area indicates time of major meltwater peaks in Nordic seas. LIM—last insolation minimum.

TABLE 1. AGE MODELS FOR THE CORES

Core	Depth (cm)	Lab. reference	Corrected age (yr)
HM94-25	17.5	TUa-379	4715 ±90
	23.5	TUa-378	11,710 ±90
	29.5	TUa-377	14,695 ±125
	35.5	TUa-376	17,095 ±130
HM94-34	14.5	TUa-362	5095 ±85
	32.5	TUa-363	6090 ±105
	38.5	TUa-364	12,375 ±110
	41.5	TUa-365	12,765 ±125
	47.5	TUa-366	14,580 ±165
	50.5	TUa-375	16,335 ±120
	59.5	TUa-367	19,840 ±125
HM94-13	1.5	TUa-350	3650 ±60
	12.5	TUa-354	5150 ±70
	17.5	TUa-353	6505 ±75
	20.5	TUa-351	6840 ±90
	27.0	Vedde Ash	10,600 ±60
	38.5	TUa-352	14,125 ±110
PS21842	12.0	Vedde Ash	10,600 ±60
	19.5	TUa-410	14,090 ±125
	27.5	TUa-406	15,595 ±175
	33.5	TUa-407	16,090 ±185
	35.5	TUa-457	17,340 ±175
	45.5	TUa-408	20,705 ±230

Note: Atomic mass spectroscopy ages are measured on the planktonic foraminifer *Neogloboquadrina pachyderma* (sinistral form) and are corrected for the reservoir effect of 440 yr.

SEA-SURFACE TEMPERATURE, POLAR FRONT FLUCTUATIONS, AND INSOLATION CHANGES

During the intense meltwater flux (15–13 ka by ^{14}C dating), the Nordic seas were still cold with extensive sea-ice cover, similar to the well-known "Heinrich layers" documented from the North Atlantic (Bond et al., 1992). Toward the end of the period with lowered salinities, as insolation values reached halfway to maximum values, a sea-ice–free corridor opened along Norway at 13.4 ka, indicating substantial northward flow of the North Atlantic drift (Koç et al., 1993) (Fig. 3). The presence of diatoms and the low loadings of diatoms indicative of the sea-ice margin (*Nitzschia grunowii*, *N. cylindrica*, *Thalassiosira hyalina*, *Bacterosira fragilis*, and *Porosira glacialis*–sea-ice factor) (Fig. 4) indicates open-water conditions in the eastern Nordic seas after 13.4 ka. That no diatom record is available from the western Nordic seas before ~9 ka (Fig. 4) implies that the area in the west was under the influence of heavy sea-ice cover, reducing biological productivity before that time. After this initial warming, in spite of the increasing insolation, we observe an increase in the seasonal sea-ice cover and a series of subsequent sea-surface temperature coolings of this corridor, culminating in the Younger Dryas (Fig. 4).

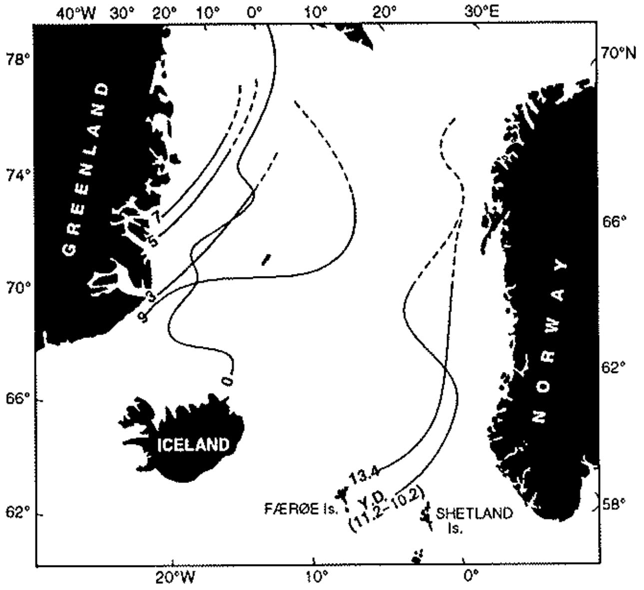

Figure 3. Spatial variation of polar front and accompanying sea-ice edge in Nordic seas through past 13.4 ka (as compiled from Koç et al., 1993). Numbers indicate ages (in ka) and dashed lines indicate assumed position of polar front. Y.D. is Younger Dryas.

A drastic change of climatic conditions occurred in the Nordic seas as summer insolation reached its maximum between 10 and 9 ka (by ^{14}C dating). Within <50 yr the sea-surface temperature rose 9 °C from the very cold Younger Dryas values to Holocene values (Koç Karpuz and Jansen, 1992) (Fig. 4). The seasonal maximum sea-ice margin and the polar front, which had been positioned in the eastern Nordic seas through the deglaciation period, suddenly retreated to a northwestern position off Greenland, documenting a strong influx of warm Atlantic waters (Koç et al., 1993) (Fig. 3). In step with the high insolation values, the Nordic seas underwent warmest climatic conditions between 8 and 5 ka, as depicted by the warm Atlantic diatom factor (Fig. 4). This is only 1–2 ka after the insolation maximum, and the delay was probably caused by the influence of the remnants of the Laurentide ice sheet. During this interval the Atlantic diatom factor, which at present is mapped in the mid-latitude Atlantic Ocean and consists mainly of *Thalassiosira oestrupii* (Koç Karpuz and Schrader, 1990), was dominating the Nordic seas, and the areas off Greenland were much less influenced by sea ice (low loadings of the diatom sea ice factor) than today (Figs. 3 and 4). Surface waters of these seas were as much as 6 °C warmer than at present, in particular in the areas that today are seasonally influenced by sea-ice cover.

A gradual cooling in the Holocene is observed in step with decreasing summer insolation in the Northern Hemisphere. We also observe an increase in the extent of seasonal sea-ice cover of the western Nordic

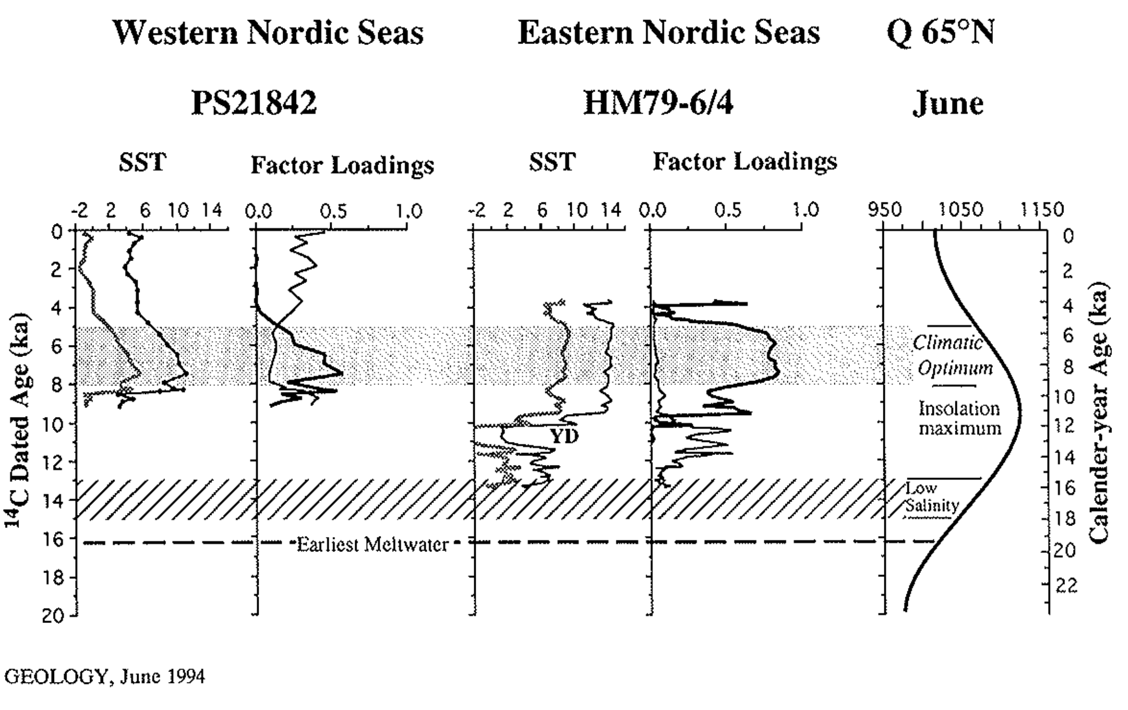

Figure 4. Diatom-based winter (gray lines) and summer (black lines) sea-surface temperature estimates (SST), factor loadings of diatom factors typical of warm Atlantic waters (thick black lines), and waters with seasonal sea-ice cover (thin black lines) in Nordic seas, compared with June insolation at lat 65°N. Age scales are same as in Figure 2. Higher factor loadings mean that influence of specific water masses associated with factors is higher. YD = Younger Dryas. Shaded area indicates period of climatic optimum; diagonal-rule area is interval of major deglacial signal in Nordic seas. Data for core HM79-6/4 are from Koç Karpuz and Jansen (1992).

seas, indicated by the increasing loading of the sea-ice factor in core PS21842 (Fig. 4). This happened as early as 7 ka, documenting that the western Nordic seas responded very early to the falling summer insolation, in the manner seen by Imbrie et al. (1992) as a "preglacial state," by a spread of sea-ice cover that increased the albedo of the region. In the eastern part of these seas, which today is still influenced by advection of warm Atlantic water, the climatic optimum lasted until ~5 ka. Here, the amplitude of sea-surface temperature change was smaller than in the west.

DISCUSSION

Our results demonstrate that surface-ocean conditions in the Nordic seas are very sensitive to insolation changes, in particular regions close to the sea-ice margin. The spread of sea-ice cover has profound influence on both the albedo and the ocean-atmosphere heat flux. Heat fluxes decrease by 400 to 800 W/m^2 in areas with thick ice cover compared to open waters along sea-ice margin (Häkkinen and Cavalieri, 1989). The most intensive heat transfer occurs today in open waters along the ice margin, and diminishing these would decrease the ocean-atmosphere heat exchange and promote cooling.

The presence of a meltwater spike right at the start of the sea-level rise at 16 ka in the southern Nordic seas and the documentation of a widespread deglaciation signal at 15–13 ka in these seas show that the surrounding ice sheets deglaciated rapidly in response to increased insolation. The major meltwater flux from this event led to diminished deep-water formation and thermohaline overturning in these seas (Veum et al., 1992). The thermohaline cell was turned on after this intermittent reduction of overturning, in line with major melting of the Laurentide ice sheet and the main eustatic sea-level rise (Fairbanks, 1989; Charles and Fairbanks, 1992).

Although changes in thermohaline circulation can be envisaged as a feasible mechanism for transmitting insolation forcing to the global climate system, including the carbon cycle, there is no clear evidence to document that overturning in the Nordic seas diminished as insolation minima drove the world into a glacial period. Available observations document persisting ventilation through the Holocene, and proxy data in the form of benthic and planktonic $\delta^{13}C$ show an increase rather than the expected decrease in $\delta^{13}C$ values at glacial onsets (I. Beyer, 1994, personal commun.). This may indicate that it is not a simple switch in overturning that takes place at the onset of ice ages, but more subtle changes which current proxy methods have not been able to capture, that reduce overflows, in addition to effects originating in other parts of the climate system. More detailed three-dimensional reconstructions of the thermohaline circulation in the Nordic seas and the North Atlantic are needed before we can clarify how the surface-ocean changes, which closely follow the falling summer insolation, were transmitted by the deep-ocean circulation.

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