A high-resolution radiolarian-derived paleotemperature record for the Late Pleistocene-Holocene in the Norwegian Sea

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[1] Polycystine radiolarians are used to reconstruct summer sea surface temperatures (SSSTs) for the Late Pleistocene-Holocene (600–13,400 ^{14}C years BP) in the Norwegian Sea. At 13,200 ^{14}C years BP, the SSST was close to the average Holocene SSST (~12°C). It then gradually dropped to 7.1°C in the Younger Dryas. Near the Younger Dryas-Holocene transition (~10,000 ^{14}C years BP), the SSST increased 5°C in about 530 years. Four abrupt cooling events, with temperature drops of up to 2.1°C, are recognized during the Holocene: at 9340, 7100 ("8200 calendar years event"), 6400 and 1650 ^{14}C years BP. Radiolarian SSSTs and the isotopic signal from the GISP2 ice core are strongly coupled, stressing the importance of the Norwegian Sea as a mediator of heat/precipitation exchange between the North Atlantic, the atmosphere, and the Greenland ice sheet. Radiolarian and diatom-derived SSSTs display similarities, with the former not showing the recently reported Holocene cooling trend. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3030 Marine Geology and Geophysics: Micropaleontology; 4267 Oceanography: General: Paleoceanography; 9325 Information Related to Geographic Region: Atlantic Ocean; *KEYWORDS:* Radiolarians, paleoclimate, Late Pleistocene-Holocene, Norwegian Sea

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1. Introduction

[2] High resolution sediment cores from the North Atlantic and Nordic Seas and ice core records from Greenland all document numerous rapid changes in ocean circulation and atmospheric conditions during the last 18,000 ^{14}C years BP. Marine sediment data and numerical computer models [*Ganopolski and Rahmstorf*, 2001; *Rahmstorf*, 2001; *Sarnthein et al.*, 2001] have identified three main modes of surface and deepwater circulation during this time period: 1) A warm or interglacial (Holocene) mode characterized by large amounts of heat transported by surface currents to higher latitudes (Figure 1) and North Atlantic Deep Water (NADW) formation present in the Nordic Seas. This mode is also found during the short and warm Dansgaard-Oeschger events; 2) A cold or stadial mode with highly reduced inflow of warm surface water into the Nordic Seas, resulting in ice-free conditions only during summers. The oceanic cooling effect was enhanced by the presence of an anticyclonic eddy west of Ireland. During this mode the NADW was formed in the North Atlantic south of the sill between Greenland, Iceland and Scotland; 3) A "switched off" or "Heinrich event" mode characterized by large amounts of meltwater derived from surging and calving ice sheets on surrounding continents. No deepwater (NADW) was then formed in the North Atlantic. The model simulations suggest that the current warm mode is stable during interglacials, while the cold stadial mode is the stable mode during glacial periods [*Ganopolski and Rahmstorf*, 2001; *Rahmstorf*, 2001]. When these modes become unstable, e.g., during Heinrich (associated with a "switched off" North Atlantic thermohaline circulation) and Dansgaard-Oeschger events (associated with a sudden incursion of warm Atlantic water and thereby a switch to warm mode circulation), the system will gradually try to reinforce the stable mode, in this case a cold glacial mode.

[3] There are contrasting views about what happened during the Younger Dryas cold period, and in spite of the number of models proposed to account for it, no consensus has yet been reached. Some of the current hypotheses are:

1. The Atlantic thermohaline circulation was shut down during this event [*Broecker*, 1992].
2. This period was characterized by an interglacial surface circulation that "switched off" only for a short time near the end of the Younger Dryas/early Preboreal [*Sarnthein et al.*, 2001], possibly initiated by an Arctic meltwater pulse from the Siberian rivers [*Spielhagen et al.*, 1998].

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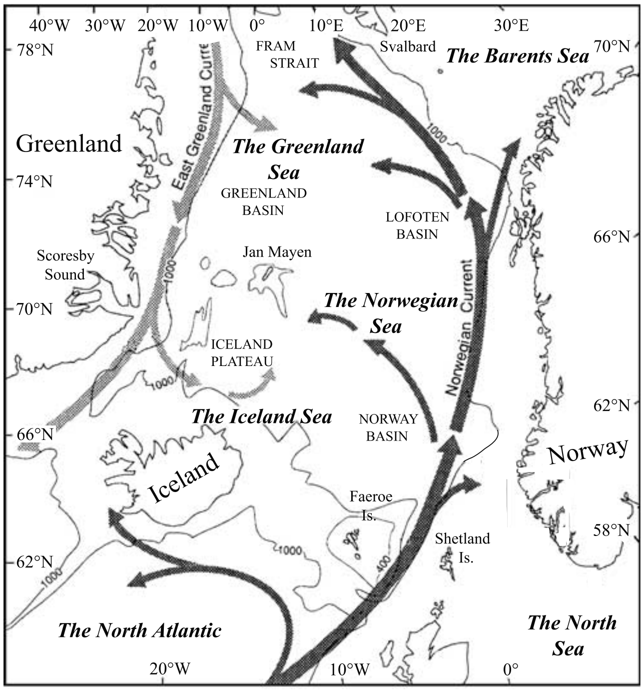

Figure 1. Map of the Nordic Seas and North Atlantic with the main surface currents (modified from *Sejrup et al.* [1995]).

3. The Younger Dryas could have been the last stadial period of the glacial following a temporary Dansgaard-Oeschger event [*Sarnthein et al.*, 1994; *Rahmstorf*, 2001].

4. Rerouting of the continental runoff from the Mississippi River during deglaciation, along with the sudden drainage of Lake Agassiz waters into the North Atlantic, preconditioned this ocean for a reduced NADW formation [*Fanning and Weaver*, 1997; *Manabe and Stouffer*, 1997].

[4] Holocene climate itself appears not to be as stable as previously believed. *Bond et al.* [1997] showed, from their study of ice-rafted debris (IRD), that the Holocene climate varies with a cyclicity close to 1470 ± 500 years. There seems to be a close correlation between these IRD cycles and change in production rates of the cosmogenic nuclides ^{14}C (measured in tree rings) and ^{14}Be (measured in ice cores), both proxy data closely related to solar winds and solar activity [*Bond et al.*, 2001]. This suggests that the variation in solar input is an important factor influencing the Holocene climate.

[5] Many paleoclimatic reconstructions are based on knowledge about living, marine, fossilizable microorganisms (e.g., coccolithophorids, diatoms, foraminifers, radiolarians) and their response to prevailing oceanographic conditions. *Cortese et al.* [2002] used *Imbrie and Kipp*'s [1971] Q-mode factor analysis to define a relationship between radiolarian faunas and summer sea surface temperatures (SSSTs) in the Nordic Seas. This technique is widely used among micropaleontologists, and its application to polycystine radiolarians has proved to be very useful [*Morley*, 1979; *Pisias et al.*, 1997; *Bjørklund et al.*, 1998; *Hass et al.*, 2001; *Cortese and Abelmann*, 2002]. One hundred and sixty surface sediment samples were used to develop the SSST transfer function [*Cortese et al.*, 2002]. Four assemblages were thus identified, and named after the oceanographic region (the North Atlantic, the Norwegian Sea, the Iceland Plateau, the Greenland Sea) where they were found to be important.

[6] The aim of this study is to reconstruct Late Pleistocene and Holocene SSST variations, by studying radiolarian assemblages in two sediment cores from the southeastern part of the Norwegian Sea. The results are compared to SSST diatom data from the same area [*Birks and Koç*, 2002] and to δ^{18}O data from the GISP2 Greenland ice core [*Stuiver et al.*, 1995].

2. Material and Methods

2.1. Core Samples and Data Handling

[7] Two cores were used in this study: core HM79-4 (63°06'N, 02°33'E) and core MD95-2011 (66°58'N, 07°38'E) (Figure 2). The former core was collected on the R/V *Håkon Mosby* cruise arranged by the Geological Institute at the University of Bergen, and the latter on the IMAGES cruise 101 with the R/V *Marion Dufresne*. In core HM79-4 we collected 64 samples spanning a section of 1.85 m (55.5–240.5 cm) and a time frame of 9880–13,400 ^{14}C years BP. This results in an average sedimentation rate of 52 cm/1000 years, and an average sampling resolution of 55 years. We also analyzed older samples (between 240.5 and 255.5 cm), but these did not contain significant amounts of biogenic opal. In core MD95-2011 we studied 126 samples from a 6.40 m long section (15.5–655.5 cm) given a time frame of about 600–9770 ^{14}C years BP. The average sedimentation rate for the studied section was 70 cm/1000 years, and the average sampling resolution was 73 years. Each sample was prepared following the procedure described by *Goll and Bjørklund* [1974]. Mesh size used for the sieving was 45 μm. Between 374 and 555 radiolarian specimens were counted in each sample, and a minimum of 300 of these were identified to the species or genus level. The raw data (including counted values of both known and unknown taxa) were calculated into percentage and log transformed, before applying Q-mode factor analysis.

2.2. Factor Analysis

[8] The Nordic Seas radiolarian transfer function (SSST = −7.64 * F1 − 8.68 * F2 + 0.04 * F3 + 5.52 * F4 + 13.66) developed by *Cortese et al.* [2002] was applied to the down core data (Figure 3). The Regress and Thread routines [*Imbrie and Kipp*, 1971] were performed using the Palaeo-ToolBox computer package [*Sieger et al.*, 1999]. The transfer function is based on SSST data from *Dietrich* [1969], and 34 radiolarian taxa (Table 1) counted in 160 core top stations in the Nordic Seas. Table 1 also shows which taxon defines each factor [*Cortese et al.*, 2002]. The multiple correlation coefficient is 0.88 and the standard error of estimate for the regression equation is ± 1.2°C (see *Cortese et al.* [2002] for more details). The communality for core HM79-4 is in average 0.81, with 13 samples showing nonanalog conditions with the surface sediment

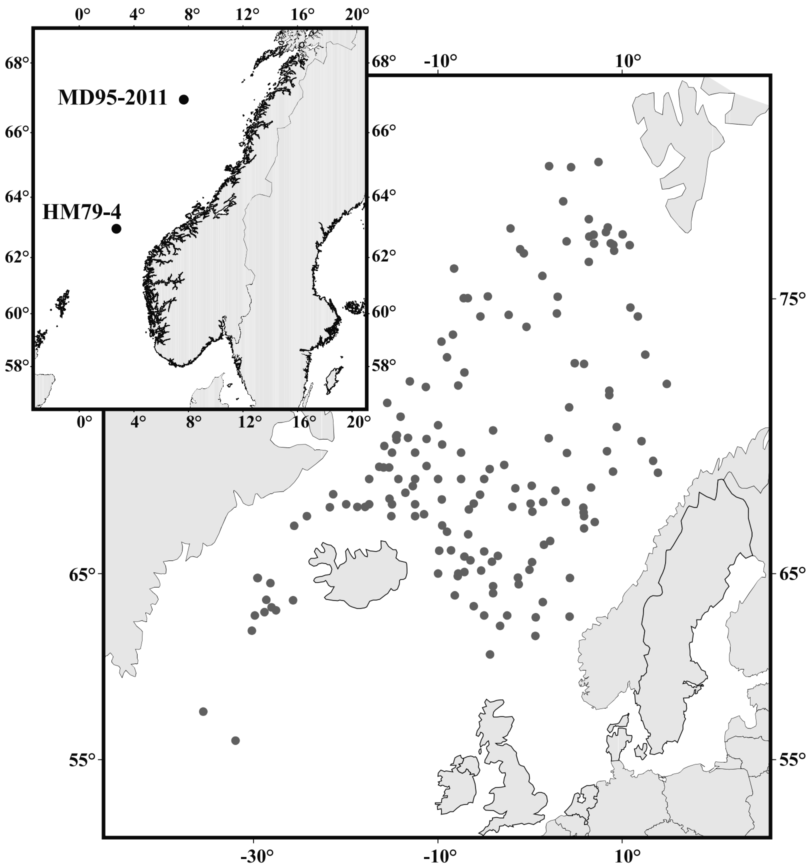

Figure 2. Surface sediment sample locations [from *Cortese et al.*, 2002] used for the radiolarian temperature equation (main map). Core locations for MD95-2011 and HM79-4, used for paleoclimatic reconstructions (inset map).

sample (reference) data set (Table 2). The average communality for core MD95-2011 is 0.88, with a nonanalog situation in 4 samples (Table 3). Nonanalog conditions (samples marked with an asterisk in Tables 2–3) are usually caused by only one species, whose down core abundance does not exceed substantially its maximum abundance in the reference data set.

2.3. Age Models

[9] The Vedde Ash (10,310 years BP [*Birks et al.*, 1996]), sixteen AMS ^{14}C-datings of *Neogloboquadrina pachyderma* [*Dreger*, 1999; *Koç Karpuz and Jansen*, 1992; N. Koç, personal communication, 1999] and the peak occurrence of the radiolarian species *Rhizoplegma boreale* [*Dolven and Bjørklund*, 2001] were used to develop the chronology of core HM79-4 and core MD95-2011 (Table 4). The ^{14}C-age model is based on linear interpolation between datum points and 400 years have been subtracted from all dates to account for the ocean-reservoir effect. Calendar years were calculated, from the ^{14}C-dated samples, by using the CALIB 4.3 program made by Stuiver and Reimer (available at http://depts.washington.edu/qil/dloadcalib/) with data from *Stuiver et al.* [1998]. Calendar ages for the remaining samples were assigned by linear interpolation.

[10] When comparing our radiolarian SSST data to diatom SSST data from core MD95-2011 and core HM79-6, we used the age model (and SSST data) given by *Birks and Koç* [2002]. For the GISP2 δ^{18}O record we used the Meese/Sowers timescale based on annual layer counting and volcanic markers [*Meese et al.*, 1994, 1997] (see also ftp://ftp.ngdc.noaa.gov/paleo/icecore/greenland/summit/gisp2/depthage/gisp2age.txt). Note that ages in Figure 3 are expressed in ^{14}C years BP while in Figures 4–6 they are expressed in calendar years BP.

2.4. Cross-Spectral Analysis

[11] Cross-spectral analysis was carried out with the Arand Software package [*Howell*, 2001] (available online at http://www.ngdc.noaa.gov/paleo/arand/). The MD95-2011/HM79-4 age model was, for the purpose of cross-spectral analysis only, synchronized to the GISP2 age model by peak to peak correlation (Table 5) and linear interpolation between these points. This was possible due to the close similarity between the two records (the correlation coefficient between the two curves was 0.9), with close matches even in several fine structures and events within the Younger Dryas (Figure 4). The GISP2 and MD95-2011/HM79-4 time series were then equally resampled (at 0.05 ka steps) between 1 and 14.6 ka. The

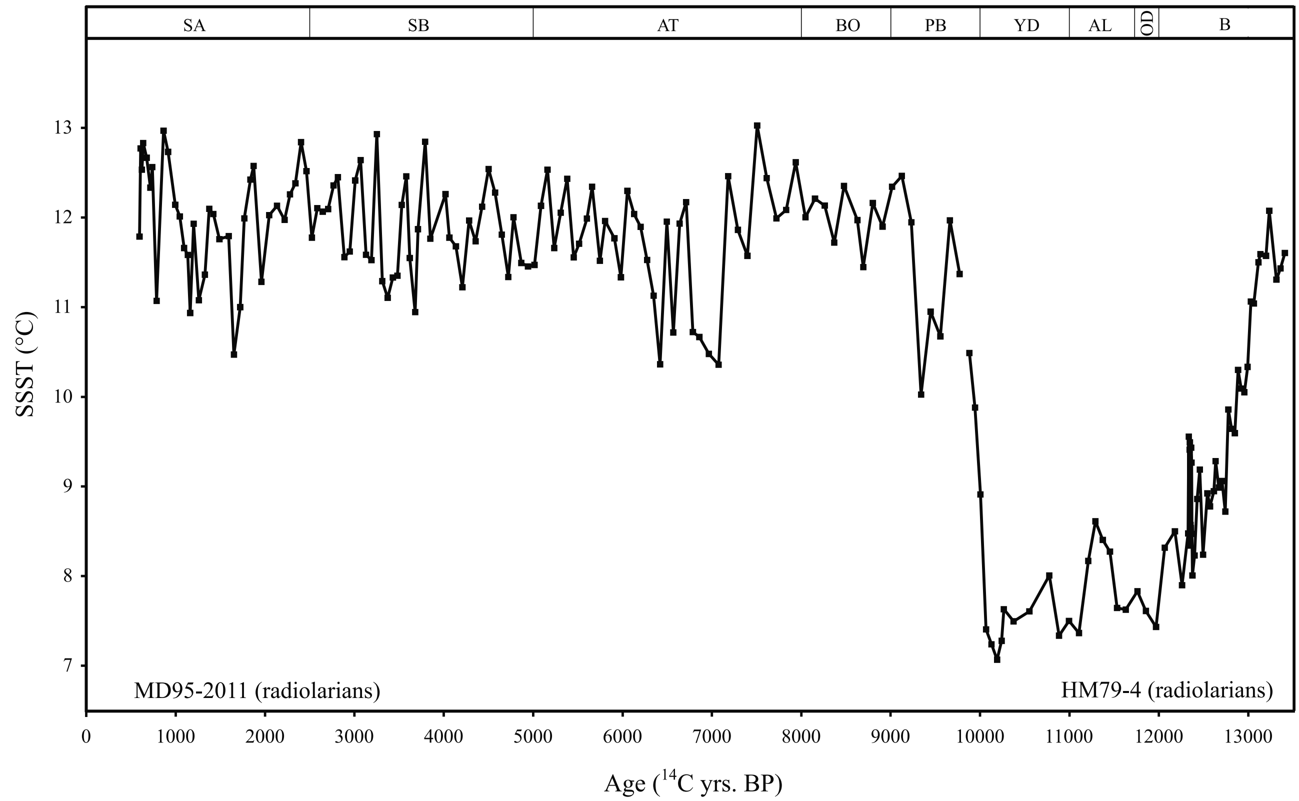

Figure 3. Radiolarian summer sea surface temperature (SSST) record for the late Pleistocene (HM79-4) and the Holocene (MD95-2011). Ages in ^{14}C years BP and chronozones after *Mangerud et al.* [1974]. B = Bølling, OD = Older Dryas, AL = Allerød, YD = Younger Dryas, PB = Preboreal, BO = Boreal, AT = Atlantic, SB = Subboreal, SA = Sub-atlantic.

series were fully detrended before calculating their autospectra and coherency. We used a confidence level of 80% and 90 lags.

3. Results

3.1. Paleotemperature Estimates for Cores MD95-2011 and HM79-4

[12] The application of the temperature transfer function developed by *Cortese et al.* [2002] to the down core radiolarian assemblages in core MD95-2011 and core HM79-4 gives us a high-resolution record for the last 13,400 ^{14}C years BP. The paleotemperature reconstruction (Figure 3) shows relatively high temperatures (close to 12°C) before the onset of Bølling. The temperature then drops by more than 4°C, from 12°C at ~13,200 ^{14}C years BP to 7.4°C at ~12,000 ^{14}C years BP, and stays low (close to 7.5°C) until the end of the Younger Dryas (10,000 ^{14}C years BP), except for a small warm peak (~1°C) between 11,100 and 11,530 ^{14}C years BP in the Allerød chronozone, where the temperature reaches 8.6°C. At the Pleistocene-Holocene transition, a rapid warming takes place, and the temperature increase from 7 to 12°C in less than 530 years. The early Preboreal temperature peak (12°C) is followed by an abrupt cooling to 10°C at 9340 ^{14}C years BP, before the temperature rebounds to 12.5 at 9125 ^{14}C years BP. During the rest of the Holocene the temperature ranges between 10.4°C and 13°C, with an average of 11.9°C. These small-scale fluctuations are interrupted by a cooling at about 7100 ^{14}C years BP (Atlantic chronozone), where temperature decreases by 2.1°C in only 100 radiocarbon years. Similar temperature drops are found at 6400 ^{14}C years BP and 1650 ^{14}C years BP.

3.2. Cross-Spectral Analysis

[13] Cross-spectral analysis of the GISP2 δ^{18}O and our radiolarian-derived SSST estimates (Figure 5) indicates that these two records are coherent, at the 80% level of confidence, for frequencies of 0.90 and 1.35 cycles/kyr (corresponding to periods of 1.11 and 0.74 kyr, respectively). The phase relationship between the two records is generally positive for periods shorter than 2.5 kyr, indicating that, at these periodicities, the reference record (the GISP2 δ^{18}O curve) usually leads the other series (the SSST estimates from cores MD95-2011/HM79-4). The lead of the GISP2 record is always shorter than ca. 260 years, and the maximum lead value (256 years) is obtained for a period of 1.67 kyr, where the phase angle is 55 degrees. In particular, for the significant frequencies (0.90 and 1.35 cycles/kyr), the phase angles are 12 and 7 degrees (corresponding to a lead of the GISP2 record by ca. 37 and 14 years, respectively).

[14] The first peak in all three curves (coherency and autospectra for GISP2 and cores MD95-2011/HM79-4),

Table 1. Scaled Varimax Factor Score Matrix (Taxa Versus Factor Scores) for the 34 Taxa Used in the Reference Data Set [*Cortese et al.*, 2002][a]

Scaled Varimax Factor Scores	Factor 1	Factor 2	Factor 3	Factor 4
Actinomma leptoderma/boreale group	**1.615**	**4.588**	**−1.661**	0.721
Actinomma leptoderma longispina	−0.240	**1.861**	−0.823	−0.284
Actinomma medianum	0.019	−0.038	0.234	−0.074
Actinomma sp. 1	−0.022	−0.017	−0.050	0.177
Actinomma sp. 2	0.083	−0.188	**1.091**	−0.327
Amphimelissa setosa	**4.732**	**−1.252**	0.967	**−1.310**
Artobotrys borealis	0.072	−0.521	−0.221	**2.388**
Artostrobus joergenseni	0.897	−0.419	0.144	0.507
Ceratocyrtis galeus	0.026	0.026	−0.058	0.244
Ceratocyrtis histricosus	0.001	−0.053	−0.078	0.366
Corocalyptra craspedota	−0.196	−0.162	0.020	**1.036**
Drift fauna	−0.043	−0.037	0.225	0.132
Eucyrtidium calvertense	0.008	−0.058	0.271	−0.025
Larcospira minor	−0.409	**1.798**	**3.421**	0.015
Larcoidea sp. 1	−0.189	−0.270	**1.086**	0.990
Lipmanella xiphephorum	−0.054	−0.041	−0.058	0.380
Lithelius spiralis	−0.064	−0.105	0.032	0.408
Lithocampe platycephala	**1.731**	0.563	−0.273	0.865
Lithomelissa hystrix	−0.144	−0.237	0.020	**1.124**
Lithomelissa setosa	−0.040	−0.929	0.045	**3.683**
Lithomelissa sp. aff. *L. stigi*	−0.046	−0.023	−0.073	0.227
Lithomelissa thoracites	−0.056	−0.057	−0.056	0.374
Lithomitra lineata	0.145	−0.377	0.020	**1.217**
Phorticium pylonium (clevei)	−0.284	**1.477**	**1.956**	**1.273**
Phorticium sp. 1	0.015	−0.034	0.160	−0.046
Plagiacantha arachnoides	0.033	−0.053	−0.013	0.123
Plectacantha oikiskos	0.135	−0.110	−0.029	0.331
Pseudodictyophimus gracilipes group	**2.034**	−0.207	0.376	**1.577**
Sethoconus (Artostrobus) tabulatus	0.025	−0.014	−0.001	0.034
Spongotrochus glacialis group	−0.068	0.624	**3.294**	−0.296
Streblacantha circumtexta	−0.128	0.149	0.394	0.150
Streblacantha sp. 1	−0.110	−0.184	0.076	0.777
Stylatractus sp. 1	0.014	−0.089	0.398	−0.038
Tholospyris gephyristes	0.747	−0.078	−0.199	0.900

[a] Absolute values higher than 1.000 are in boldface.

exceeding the 80% confidence level, is centered at a period higher than 2 ka (Figure 5). This is to be expected, as it represents the main signal of the records, which are highly coherent (and very similar) at the glacial-interglacial level, and down to supra-millennial scale periodicities.

[15] The second peak in the coherency curve is not significant, as there are no corresponding peaks in the two series autospectra. The same holds true for almost all the other peaks in the coherency curve, with the exception of the two peaks discussed in detail above.

4. Discussion

4.1. Presence of Radiolarians

[16] Our data show that the first significant amounts of biogenic opal in the Nordic Seas after the last glacial maximum are found at about 13,400 ^{14}C years BP. This has also been confirmed by diatom studies [*Koç Karpuz and Jansen*, 1992]. The fact that biogenic opal is not an important component of the glacial sediments may be due to: (1) low production in the water masses, (2) high biogenic opal dissolution in the water masses/sediments, or (3)

Table 2. Data From 64 Samples in HM79-4[a]

Depth, cm	14C-age, yrs. BP −400	Calendar age, yrs. BP	Comm.	SSST, °C	NA
55.5	9881	11155	0.851	10.5	
60.5	9943	11275	0.849	9.9	
65.5	10005	11394	0.806	8.9	
70.5	10067	11514	0.868	7.4	*
75.5	10129	11633	0.889	7.2	
80.5	10191	11753	0.895	7.1	
84.5	10241	11849	0.834	7.3	*
86.5	10266	11896	0.888	7.6	*
91.5	10376	12066	0.870	7.5	
95.5	10553	12297	0.823	7.6	
100.5	10774	12584	0.747	8.0	
103.0	10885	12728	0.855	7.3	
105.5	10995	12872	0.837	7.5	
108.0	11106	13016	0.847	7.4	
110.5	11211	13146	0.839	8.2	
113.0	11291	13218	0.801	8.6	
115.5	11372	13290	0.849	8.4	*
118.0	11453	13363	0.796	8.3	*
120.5	11534	13435	0.857	7.6	
123.5	11630	13522	0.852	7.6	
127.5	11760	13638	0.866	7.8	
130.5	11856	13724	0.835	7.6	
134.0	11969	13826	0.861	7.4	*
137.0	12066	13913	0.876	8.3	
140.5	12179	14014	0.838	8.5	*
143.0	12260	14086	0.854	7.9	
146.5	12327	14151	0.865	8.5	*
150.0	12334	14167	0.851	9.6	
153.0	12339	14180	0.838	8.3	*
155.5	12344	14192	0.830	9.4	
158.0	12348	14203	0.803	9.5	
160.5	12353	14214	0.840	8.6	
163.0	12358	14226	0.851	8.5	
165.5	12362	14237	0.820	9.4	
168.0	12367	14248	0.839	9.3	
170.5	12371	14260	0.861	8.5	
173.0	12376	14271	0.838	8.0	
176.5	12401	14319	0.857	8.2	
178.5	12430	14371	0.844	8.9	
180.5	12458	14422	0.847	9.2	
183.0	12494	14487	0.842	8.2	
186.5	12544	14577	0.869	8.9	
188.5	12572	14629	0.838	8.8	
191.5	12615	14707	0.832	8.9	
193.0	12636	14745	0.801	9.3	
195.5	12672	14810	0.818	9.0	
198.0	12708	14875	0.811	9.1	
200.5	12744	14939	0.817	8.7	
203.0	12779	15004	0.845	9.9	
205.5	12815	15069	0.828	9.6	
208.0	12851	15133	0.826	9.6	*
210.5	12886	15198	0.790	10.3	
213.0	12922	15263	0.807	10.1	
215.5	12958	15327	0.826	10.1	
218.0	12993	15392	0.811	10.3	
220.5	13029	15456	0.735	11.1	
223.0	13065	15521	0.765	11.0	
226.5	13115	15612	0.744	11.5	
228.0	13136	15650	0.773	11.6	
231.5	13200	15743	0.665	11.6	
233.0	13235	15783	0.673	12.1	
236.5	13316	15878	0.556	11.3	*
238.5	13363	15932	0.616	11.4	*
240.5	13410	15986	0.708	11.6	*

[a] Shown is HM79-4 depth (cm), ^{14}C age (years BP, reservoir-corrected), calendar age (years BP = 1950), communality values obtained from the factor analysis, and summer sea surface temperature (°C); nonanalog samples (NA) are marked by an asterisk.

Table 3. Data From 126 Samples in MD95-2011[a]

Depth, cm	14C-age, yrs. BP −400	Calendar age, yrs. BP	Comm.	SSST, °C	NA
15.5	595	567	0.944	11.8	
19.5	607	581	0.907	12.8	
24.5	622	600	0.938	12.5	
29.5	637	618	0.921	12.8	
35.5	675	641	0.896	12.7	
41.5	718	663	0.936	12.3	
44.5	739	674	0.892	12.6	
49.5	786	711	0.929	11.1	
55.5	864	788	0.935	13.0	
59.5	917	839	0.925	12.7	
65.5	995	917	0.882	12.1	
69.5	1047	968	0.910	12.0	
75.5	1094	1026	0.923	11.7	
81.5	1135	1080	0.904	11.6	
85.5	1163	1116	0.896	10.9	
90.5	1202	1164	0.877	11.9	
95.5	1259	1225	0.920	11.1	
101.5	1329	1298	0.899	11.4	
105.5	1375	1347	0.896	12.1	
109.5	1421	1395	0.921	12.0	
115.5	1490	1468	0.872	11.8	
124.5	1594	1578	0.919	11.8	
129.5	1652	1639	0.940	10.5	
135.5	1721	1712	0.944	11.0	
139.5	1768	1761	0.903	12.0	
145.5	1837	1834	0.880	12.4	
148.5	1871	1870	0.862	12.6	
155.5	1961	1971	0.895	11.3	
160.5	2047	2082	0.923	12.0	
165.5	2134	2194	0.866	12.1	
170.5	2220	2306	0.908	12.0	
175.5	2281	2379	0.913	12.3	
180.5	2341	2452	0.893	12.4	
185.5	2402	2526	0.909	12.8	
190.5	2462	2599	0.920	12.5	
195.5	2523	2672	0.878	11.8	
200.5	2584	2745	0.909	12.1	
205.5	2644	2818	0.883	12.1	
210.5	2705	2891	0.854	12.1	
215.5	2765	2965	0.875	12.4	
219.5	2814	3023	0.877	12.5	*
225.5	2887	3111	0.921	11.6	
230.5	2947	3184	0.817	11.6	
235.5	3008	3257	0.909	12.4	
240.5	3068	3331	0.862	12.6	
245.5	3129	3404	0.904	11.6	
250.5	3190	3477	0.927	11.5	
255.5	3250	3550	0.907	12.9	
260.5	3311	3623	0.863	11.3	
265.5	3372	3696	0.860	11.1	
270.5	3430	3768	0.900	11.3	
275.5	3480	3834	0.900	11.4	
280.5	3530	3900	0.905	12.1	
285.5	3580	3966	0.887	12.5	
289.5	3620	4019	0.867	11.5	
295.5	3680	4099	0.882	10.9	*
298.5	3710	4138	0.903	11.9	
306.5	3790	4244	0.885	12.8	
312.5	3850	4323	0.883	11.8	
326.5	4018	4527	0.879	12.3	*
329.5	4062	4576	0.886	11.8	
334.5	4135	4657	0.881	11.7	
339.5	4208	4739	0.886	11.2	
344.5	4282	4820	0.871	12.0	
349.5	4355	4902	0.886	11.7	
354.5	4428	4984	0.850	12.1	
359.5	4501	5065	0.864	12.5	
364.5	4575	5147	0.877	12.3	
369.5	4648	5228	0.883	11.8	
374.5	4721	5310	0.859	11.3	
378.5	4780	5375	0.869	12.0	
384.5	4868	5473	0.844	11.5	
389.5	4941	5554	0.832	11.5	
394.5	5014	5636	0.832	11.5	
399.5	5087	5717	0.820	12.1	
404.5	5161	5799	0.856	12.5	
409.5	5234	5881	0.847	11.7	
414.5	5307	5962	0.862	12.1	
419.5	5380	6044	0.846	12.4	
424.5	5454	6125	0.870	11.6	
428.5	5512	6190	0.841	11.7	
434.5	5600	6288	0.872	12.0	
438.5	5659	6354	0.894	12.3	
444.5	5747	6451	0.821	11.5	
448.5	5805	6517	0.826	12.0	
455.5	5908	6631	0.848	11.8	
460.5	5981	6712	0.884	11.3	
465.5	6054	6794	0.882	12.3	*
470.5	6128	6876	0.905	12.0	
475.5	6201	6957	0.827	11.9	
480.5	6274	7039	0.860	11.5	
485.5	6347	7120	0.891	11.1	
490.5	6421	7202	0.856	10.4	
495.5	6494	7283	0.861	12.0	
500.5	6567	7365	0.903	10.7	
505.5	6640	7446	0.853	11.9	
510.5	6714	7528	0.836	12.2	
515.5	6787	7609	0.822	10.7	
520.5	6860	7691	0.881	10.7	
525.5	6968	7819	0.835	10.5	
530.5	7076	7948	0.886	10.4	
535.5	7183	8076	0.846	12.5	
540.5	7291	8204	0.857	11.9	
545.5	7399	8332	0.884	11.6	
550.5	7507	8461	0.846	13.0	
555.5	7615	8589	0.832	12.4	
560.5	7723	8717	0.869	12.0	
565.5	7830	8846	0.855	12.1	
570.5	7938	8974	0.850	12.6	
575.5	8046	9102	0.874	12.0	
580.5	8154	9231	0.881	12.2	
585.5	8262	9359	0.848	12.1	
590.5	8370	9487	0.867	11.7	
595.5	8477	9615	0.858	12.4	
602.5	8628	9795	0.866	12.0	
605.5	8693	9872	0.881	11.4	
610.5	8801	10000	0.894	12.2	
615.5	8909	10128	0.885	11.9	
620.5	9017	10256	0.889	12.3	
625.5	9124	10385	0.862	12.5	
630.5	9232	10513	0.889	11.9	
635.5	9340	10641	0.894	10.0	
640.5	9448	10770	0.876	11.0	
645.5	9556	10898	0.888	10.7	
650.5	9663	11026	0.884	12.0	
655.5	9771	11155	0.875	11.4	

[a] Shown is MD95-2011 depth (cm), ^{14}C age (years BP, reservoir-corrected), calendar age (years BP = 1950), communality values obtained from the factor analysis, and summer sea surface temperature (°C); nonanalog samples (NA) are marked by an asterisk.

masking of siliceous tests by glaciomarine sediments. We believe that the almost absence of siliceous microfossils during glacial periods most likely is a result of low biogenic production. If the conditions then were as described by *Rahmstorf* [2001] and *Sarnthein et al.* [2001], with a reduced amount of warm North Atlantic Drift into the

Table 4. Datum Points for MD95-2011 and HM79-4 With References and Error Estimate[a]

Depth, cm	^{14}C Age, yrs. BP	^{14}C Age, yrs. BP −400	Error, ±	Age Determination Method	Reference	Calendar Age, yrs. BP	Reference
				MD95-2011			
10.5	980	580	60	AMS ^{14}C	*Dreger* [1999]	548	Calib 4.3
30.5	1040	640	40	AMS ^{14}C	N. Koç (personal communication, 1999)	622	Calib 4.3
47.5	1160	760	30	AMS ^{14}C	N. Koç (personal communication, 1999)	685	Calib 4.3
70.5	1460	1060	50	AMS ^{14}C	*Dreger* [1999]	981	Calib 4.3
89.5	1590	1190	30	AMS ^{14}C	N. Koç (personal communication, 1999)	1152	Calib 4.3
154.0	2335	1935	25	AMS ^{14}C	N. Koç (personal communication, 1999)	1937	Calib 4.3
170.5	2620	2220	60	AMS ^{14}C	*Dreger* [1999]	2306	Calib 4.3
269.5	3820	3420	35	AMS ^{14}C	N. Koç (personal communication, 1999)	3755	Calib 4.3
320.5	4330	3930	50	AMS ^{14}C	*Dreger* [1999]	4429	Calib 4.3
520.5	7260	6860	60	AMS ^{14}C	*Dreger* [1999]	7691	Calib 4.3
655.5				*R. boreale* peak	*Dolven and Bjørklund* [2001]	11155	Calib 4.3
750.5	12220	11820	90	AMS ^{14}C	*Dreger* [1999]	13805	Calib 4.3
				HM79-4			
55.5	10280	9880	55	*R. boreale* peak	*Dolven and Bjørklund* [2001]	11155	Calib 4.3
90.0	10310	10310	50	Vedde Ash	*Birks et al.* [1996]	11980	*Birks et al.* [1996]
110.0	11595	11195	160	AMS ^{14}C	*Koç Karpuz and Jansen* [1992]	13131	Calib 4.3
145.0	12725	12325	195	AMS ^{14}C	*Koç Karpuz and Jansen* [1992]	14144	Calib 4.3
175.0	12780	12380	105	AMS ^{14}C	*Koç Karpuz and Jansen* [1992]	14280	Calib 4.3
230.0	13565	13165	130	AMS ^{14}C	*Koç Karpuz and Jansen* [1992]	15702	Calib 4.3
270.0	14500	14100	155	AMS ^{14}C	*Koç Karpuz and Jansen* [1992]	16784	Calib 4.3

[a] The calendar years BP ages are calculated by the Calib 4.3 program [*Stuiver et al.*, 1998].
See also program of Stuiver and Reimer (available at http://depts.washington.edu/qil/dloadcalib/).

Nordic Seas and ice free conditions only during summers, the low production in the water masses would be a result of very cold water temperatures, and presence of sea ice and/or a meltwater lid (the latter not favorable for marine organisms living in the upper part of the water column). A similar situation is found in the Arctic ocean today: radiolarians are living and reproducing in these cold and seasonally ice free water masses, but the number of species and specimens is highly reduced compared to the Nordic Seas [*Bjørklund and Kruglikova*, 2002].

4.2. Radiolarian SSST Data

[17] The radiolarian data show that the SSST in the Norwegian Sea about 13,400 ^{14}C years ago was very similar to that of today. The asymmetrical temperature curve (from ~13,200 ^{14}C years until the Younger Dryas/Preboreal transition), showing a gradual cooling and an abrupt warming, reveals the same trends as seen in $\delta^{18}O$ records in Greenland ice cores [*Broecker*, 1992].

[18] *Mangerud et al.* [1974] defined the Younger Dryas chronozone as a cold event lasting from 11,000 to 10,000 ^{14}C years BP. It has since been reported in many different sediment [e.g., *Kellogg*, 1976; *Koç Karpuz and Jansen*, 1992; *Sarnthein et al.*, 1994, 2001] and ice core [e.g., *Johnsen et al.*, 1992; *Alley et al.*, 1997] records several places around the world. What triggered this event is not yet completely understood, but many different hypotheses have been suggested. Among these are a reorganization of the ocean-atmosphere system, an ice sheet collapse, a large-scale release of meltwater, and a "switch off" of the Atlantic thermohaline circulation.

[19] While the glacial climate is known for its large-scale temperature variations, the Holocene climate is commonly thought to be relatively stable. More recent evidence from deep sea sediment and ice core records reveals otherwise. The Holocene climate is characterized by many abrupt climatic shifts and some records show a cyclicity close to 1470 ± 500 years [*Bond et al.*, 1997, 2001]. *Bond et al.* [2001] suggest that the so-called "1500 years" cycles are mainly a result of solar variability which influences the sea ice fluxes into the Nordic Seas and thereby also the North Atlantic thermohaline overturning.

[20] Several of the Holocene oscillations in the radiolarian SSST record show a temperature drop of up to 2°C. The first occurs in the Preboreal chronozone at about 9340 ^{14}C years BP (~10,640 calendar years BP). We suggest this to be the same as the "10,300 calendar years event" reported from the GRIP and the GISP2 ice cores [*Dansgaard et al.*, 1993; *Stuiver et al.*, 1995; *Björck et al.*, 2001], ice-rafted debris data [*Bond et al.*, 1997] and diatom SSST data [*Birks and Koç*, 2002]. The cause of this temperature change is yet not known. It might have something to do with the large meltwater pulse that took place at 9500 ^{14}C years BP, depicted in coral reefs drilled offshore Barbados [*Fairbanks*, 1989]. The author suggests that the meltwater pulses are a result of rapid disintegration of the Northern Hemisphere ice sheets and correlates the meltwater peak with two distinct $\delta^{18}O$ minima in the Camp Century and Dye 3 ice cores (the latter minimum dated at ~9320 ^{14}C years BP). He believes that these minima may be a result of source-water variability as well as temperature. *Björck et al.* [2001] infer that a decreased ocean ventilation caused by a large freshwater forcing, could not have been the only triggering mechanism for this cold event. They suggest that a decreased solar forcing may also have played an important role.

[21] The second, and most marked, Holocene cooling event in the radiolarian record occurred at ~7100 ^{14}C years BP (~8000 calendar years BP). The temperature drops by 2.1°C in about one hundred years. This event is also found in the isotope ($\delta^{18}O$) data from MD95-2011 (data not shown

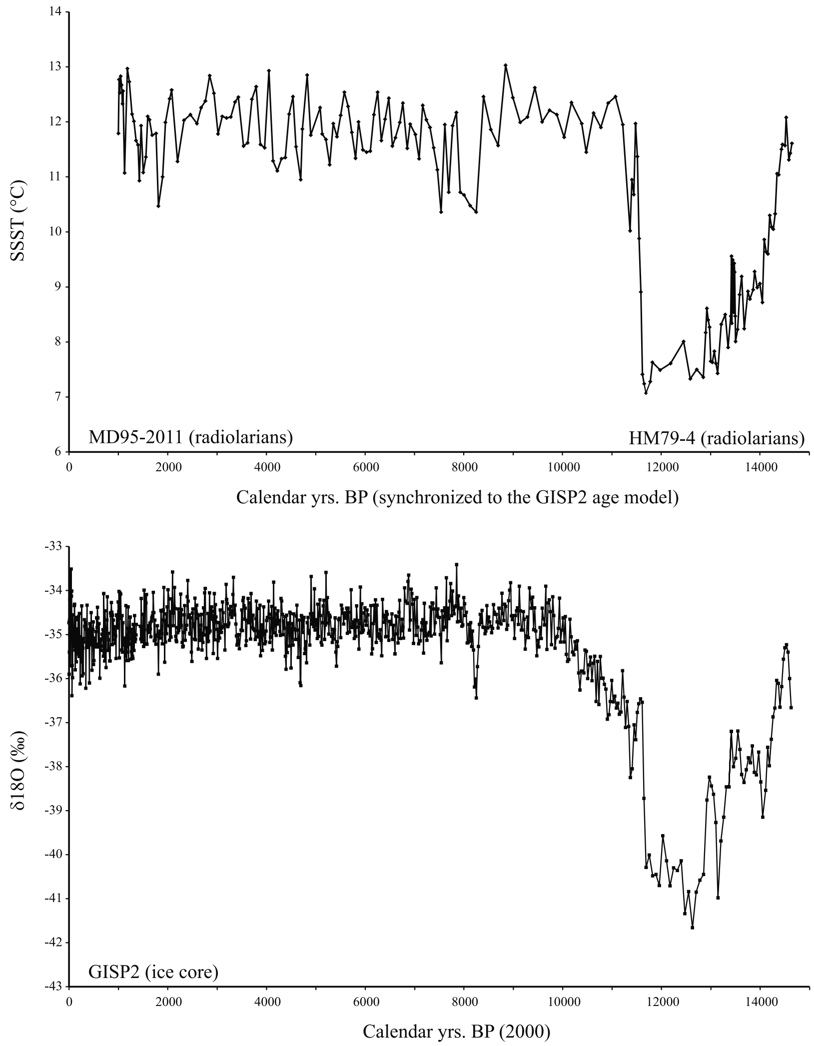

Figure 4. Upper panel: radiolarian SSST record from 1000 to 14,600 calendar years BP (age model has been GISP2 corrected, see main text for details). Lower panel: isotopic ($\delta^{18}O$) record of the GISP2 ice core from 0 to 14,600 calendar years. BP [*Stuiver et al.*, 1995].

here), and has previously been documented at ~8400 to 8000 calendar years BP in several records ($\delta^{18}O$, temperature, snow accumulation, chloride, calcium and methane) from GISP2 [*Alley et al.*, 1997] and $\delta^{18}O$ records from GRIP [*Johnsen et al.*, 1992], Dye3 and Camp Century [*Dansgaard*, 1987], all ice cores collected in Greenland. It is often referred to as the "8200 years event". Based on the records of wind-blown sea salt, continental dust and trapped gas (in the GISP2 ice core), *Alley et al.* [1997] suggest that it is a global event that can be correlated with cold, dry and/or windy conditions recorded simultaneously other places in the world (e.g., Sweden, Canada, Africa, Tibet and NW India). The event has also been recognized in radiolarian SSST records from the Southern Ocean [*Cortese and Abelmann*, 2002]. *Broecker et al.* [1990] and *Alley et al.* [1997] suggest that the event is a result of an increased freshwater supply to the North Atlantic, causing a decreased North Atlantic thermohaline circulation, but no such increased freshwater flux has yet been identified. *Bond et al.* [1997] recognized, by studying lithic grains, volcanic glass and hematite-stained grains in two cores from the North Atlantic, an ice rafted debris (IRD) event at 8100 years BP. They concluded that this event is part of the recurring series of Holocene climatic shifts ("1500 year cycles"), which are probably induced by a solar forcing mechanism [*Bond et al.*, 2001] and amplified by reductions in the North Atlantic thermohaline circulation.

[22] The next cooling episode recorded in the radiolarian data took place at ~6400 ^{14}C years BP (~7200 calendar years BP). This may be the same event as depicted in *Acropora* reefs from the Caribbean-Atlantic region [*Blanchon and Shaw*, 1995]. The *Acropora* reefs were drowned during an abrupt sea level rise starting ~7600 (±0,1 ka) calendar years BP (lasting 140 ± 50 years). *Blanchon and Shaw* [1995] relate this to the Antarctic ice sheet instability dated ~7–8000 calendar years ago.

[23] The last main cooling event depicted in the radiolarian record (Figure 3) is dated 1650 ^{14}C years BP (1640 calendar years BP). This cold spike has, to our knowledge, not been observed in other sediment cores from the Norwe-

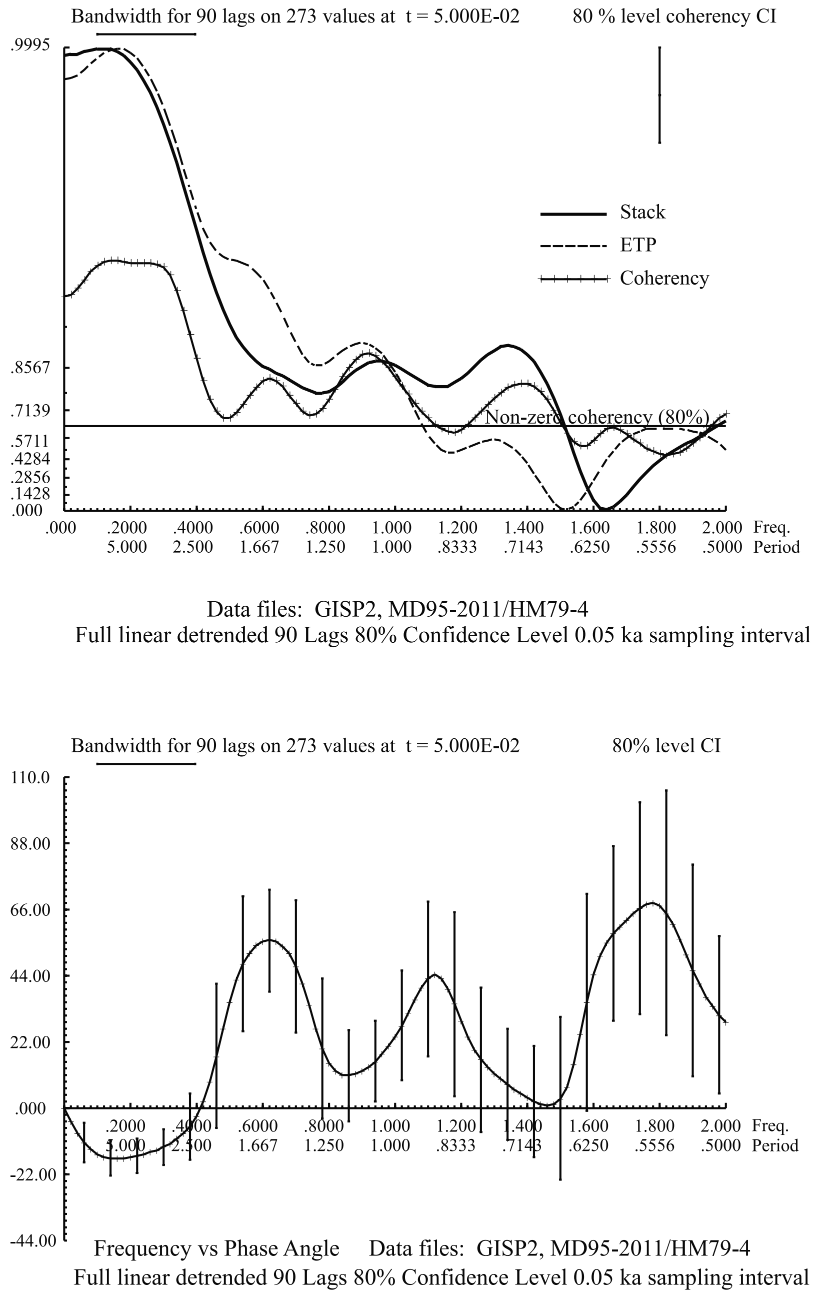

Figure 5. Upper panel: autospectra of the two series (stack = GISP2; ETP = radiolarian SSSTs) and coherency as a function of frequency/period. Lower panel: phase between the two series as a function of frequency/period.

gian Sea, nor is there an evident spike in the $\delta^{18}O$ data from the Greenland GISP2 ice core (Figure 4). However, supporting data of a similar cold period (at ~400 AD) is found in isotopic $\delta^{18}O$ and $\delta^{13}C$ data from a stalagmite (SG95) collected in the Søylegrotta in Rana, Northern Norway [*Linge et al.*, 2001].

4.3. Radiolarian SSST Data Versus the GISP2 $\delta^{18}O$ Record

[24] The resemblance between the MD95-2011 plus HM79-4 SSST oceanic core records and the isotopic record from the GISP2 ice core is striking (Figure 4). Both records depict many of the same events (e.g., the Younger Dryas and "8200 calendar years BP" cooling events). Cross-spectral analysis (Figure 5) reveals that these two records are coherent, at the 80% level of confidence, for frequencies of 0.90 and 1.35 cycles/kyr (corresponding to periods of 1.11 and 0.74 kyr, respectively). The phase relationship, for periods shorter than 2.5 kyr, always indicates a slight lead (with a maximum of 256 years) by the GISP2 record compared to the marine record.

[25] This strong coupling between the two records indicates that the same factor that influences SSST in the Norwegian Sea plays an equally important role in control-

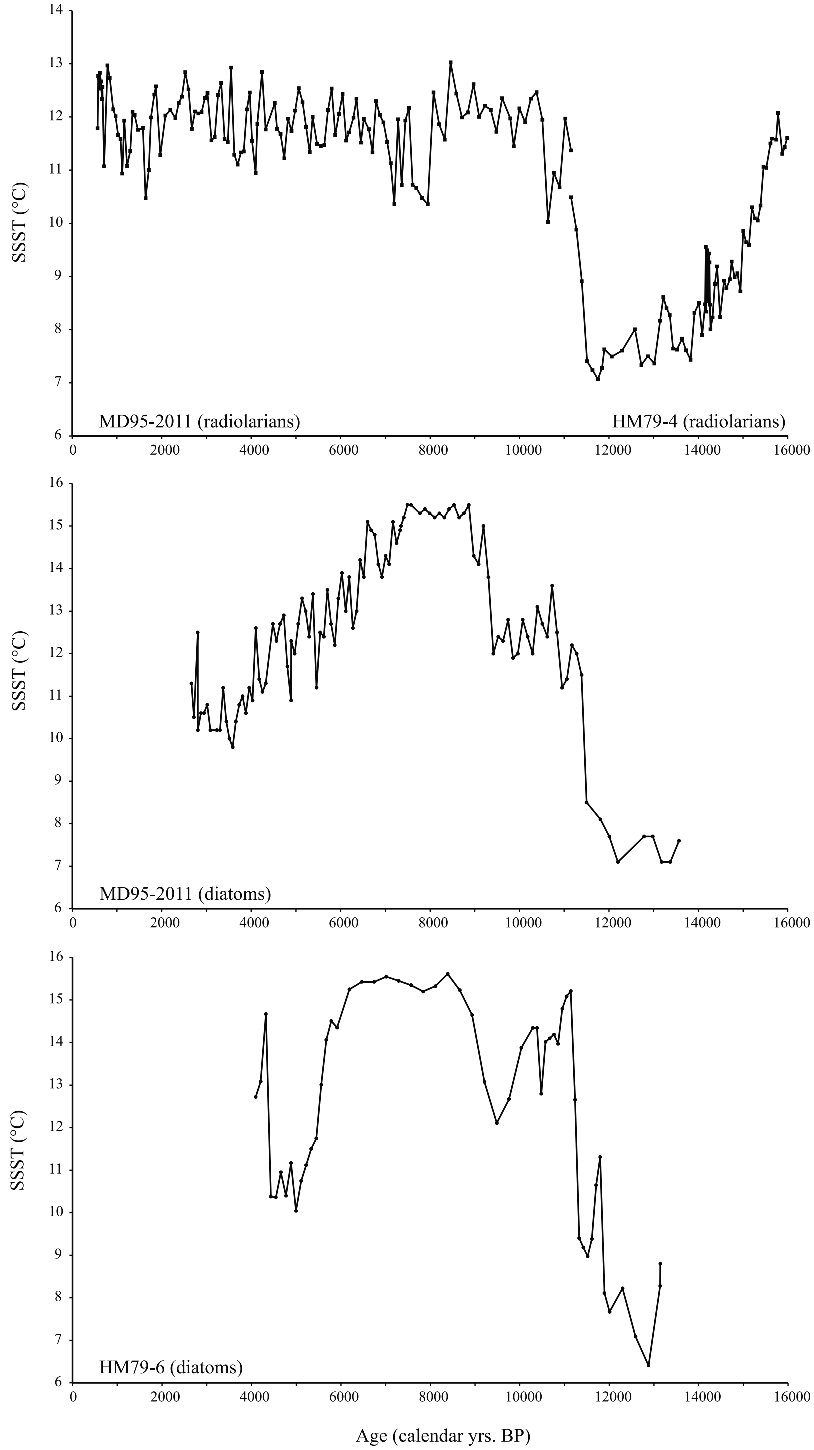

Figure 6. Radiolarian summer SSST record in MD95-2011/HM79-4 (upper panel) compared to diatom SSSTs in MD95-2011 (middle panel) and HM79-6 (lower panel) [*Birks and Koç*, 2002].

ling the isotopic signal recorded in the precipitation over Greenland. The causal linkages can be as follows: a change in the influx of North Atlantic surface water (heat) into the Nordic Seas will change the temperature and amount of moisture in the low atmospheric layers in this area, and thereby directly affect the amount of "lighter" $\delta^{18}O$ precipitated as snow on the Greenland ice cap, as reflected in the isotopic record of GISP2. This signal would then be transmitted to the ocean with a time lag spanning from a few tens to a few hundred years (as demonstrated by the phase relationship between the records at periods shorter than 2.5 kyr, Figure 5).

[26] As for the significant climatic signatures recognized in the record of the MD95-2011/HM79-4 cores, we suggest

Table 5. The Pointers Used to Synchronize the MD95-2011/HM79-4 Ages to the GISP2 Ages [*Meese et al.*, 1994, 1997] by Peak to Peak Correlation at These Values and Linear Interpolation in Between

MD95-2011/HM79-4, calendar yrs. BP	GISP2, calendar yrs. BP
600	1030
711	1127
1639	1811
4099	4693
7202	7541
7948	8252
10641	11370
11753	11689
13016	12853
13826	13144
14939	14050
15783	14531

that, within the error margin of the cross-spectral method, the spectral peak having a period of ca. 1.1 kyr could be equivalent to the "1500 year" cycle recently recognized in oceanic records from the North Atlantic [*Bond et al.*, 2001].

4.4. Radiolarian Versus Diatom SSST Record

[27] Radiolarian SSST data reveal some similarities (Figure 6) with paleotemperature data based on diatoms [*Birks and Koç*, 2002]. Both the radiolarian and diatom records clearly depict the Younger Dryas cold period, the rapid temperature increase at the Younger Dryas/Preboreal transition, as well as the "10,300 calendar years" event mentioned earlier. The diatom records, however, do not display the "8200 years event" found in the radiolarian record. Instead they show a Holocene climatic warm optimum not seen in the radiolarian record. The diatoms also reveal a slightly larger temperature range between maximum and minimum values (SSSTs between 6 and 16°C) compared to the radiolarians (SSSTs between 7 and 13°C). The differences in temperature ranges may be explained by occupancy of different niches and depths in the water column. While diatoms are most frequently found in the upper 10 m of the water column, where the temperature is highly variable, radiolarians live deeper down (~50 m), where temperature fluctuations are less marked. This might not be very important or evident during warm interglacial time periods, when the water column is well mixed and the temperature more uniformly distributed with depth (e.g., at present). But it can, however, become an important factor when the water column gets strongly stratified, with a surface lid of cooler meltwaters, and/or when a stronger temperature gradient exists with depth (e.g., the last deglaciation).

[28] At high southern latitudes, diatom-based SSST estimates in the northern sub-Antarctic zone and in the southern Antarctic zone are affected by assemblage dominance, and artificial enrichment in the sediment, of the dissolution-resistant species *Fragilariopsis kerguelensis* [*Zielinski and Gersonde*, 1997]. The same situation arises for their Boreal counterparts from the Nordic Seas, with a dominance of the assemblages by few species (distorting the relative abundance of the remaining species) and/or an important differential dissolution bias in the diatom floral composition. Indeed, the floral counts in the Nordic Seas are usually carried out on a *Chaetoceros*-free basis [*Koç et al.*, 1993], implying that this taxon dominates the assemblages.

[29] This can drastically affect both the range and the absolute values of diatom-derived SSSTs. In fact, previous diatom works carried out in this area [*Koç Karpuz and Jansen*, 1992] with the same method (factor analysis), but with a different calibration equation, produced other SSST values and ranges than those shown in Figure 6. Previously published values were: minimum and maximum SSSTs (1.1–14.6°C), Holocene (8.1–14.6°C, average 12.8°C), Younger Dryas (1.1–3.0°C, average 1.5°C), Allerød and down (2.8–8.0°C, average 6.0°C).

[30] This problem becomes apparent when looking at Figure 6: When compared to radiolarian-based estimates, the diatom SSSTs display both a trend toward cooler values during the Holocene (16 to 10.5°C) in core MD95-2011, and a cooling event at around 5.5 ka (by ca. 5°C) in core HM79-6. A cooling trend during the Holocene has recently been reported for the northeast Atlantic [*Marchal et al.*, 2002], with a magnitude trend (from a minimum of 1.2 to a maximum of 2.9°C), i.e., about half of the shift in diatom-SSST shown in core MD95-2011 (Figure 6). Moreover, alkenon-based paleotemperature estimates carried out on the same core [*Marchal et al.*, 2002, Figure 9] display an Holocene cooling of less than 2°C, hardly reconcilable with the 6°C shift shown in the diatoms SSST record. This could mean that the signal provided by diatom transfer functions in the Nordic Seas, at least during some periods (e.g., parts of the Holocene), is strongly altered and distorted.

5. Conclusion

1. Radiolarian data from core MD95-2011 and core HM79-4 provide a high-resolution SSST record for the last 600–13,400 ^{14}C years BP. The records are unique in a micropaleontological context due to their high time resolution (average of 73 and 55 years, respectively).

2. The SSST in the SE Norwegian Sea at 13,400 ^{14}C years BP was about the same as today.

3. Several cooling events are depicted in the record. The most important are the Younger Dryas cold period and the "8200 years event" in the early Holocene.

4. There are close similarities between our radiolarian record and the stable oxygen isotope record of the GISP2 ice core. Cross-spectral analysis reveals that these two records are coherent, at the 80% level of confidence, for frequencies of 0.90 and 1.35 cycles/kyr (corresponding to periods of 1.11 and 0.74 kyr, respectively). The phase relationship, for periods shorter than 2.5 kyr, always indicates a slight lead (with a maximum of 256 years) by the GISP2 record compared to the marine record. This stresses the importance of the Norwegian Sea as a mediator of heat/precipitation exchange and transport between the North Atlantic, the atmosphere, and the Greenland ice sheet.

5. There are some similarities between the radiolarian- and diatom-based paleotemperature records. The Younger Dryas cold period, the rapid temperature change at the Younger Dryas/Preboreal transition, as well as the "10,300 calendar years" event are found in both proxy data. The

main differences are that the "8200 years cold event" is only recorded in the radiolarian data, while the Holocene climatic warm optimum is only found in the diatom records.

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