PALEOCEANOGRAPHY, VOL. 13, NO. 2, PAGES193-204, APRIL 1998

Central Arctic surface ocean environment during the past 80,000 years

Niels Nørgaard-Pedersen, Robert F. Spielhagen, Jörn Thiede,[1] and Heidemarie Kassens

Research Center for Marine Geosciences, GEOMAR, Kiel University, Kiel, Germany

Abstract. Stable oxygen and carbon isotope and sedimentological-paleontological investigations supported by accelerator mass spectrometry ^{14}C datings were carried out on cores from north of 85°N in the eastern central Arctic Ocean. Significant changes in accumulation rates, provenance of ice-rafted debris (IRD), and planktic productivity over the past 80,000 years are documented. During peak glacials, i.e., oxygen isotope stages 4 and 2, the Arctic Ocean was covered by sea ice with decreased seasonal variation, limiting planktic productivity and bulk sedimentation rates. In early stage 3 and during Termination I, major deglaciations of the circum-Arctic regions caused lowered salinities and poor oxygenation of central Arctic surface waters. A meltwater spike and an associated IRD peak dated to ~14-12 ^{14}C ka can be traced over the southern Eurasian Basin of the Arctic Ocean. This event was associated with the early and rapid deglaciation of the marine-based Barents Sea Ice Sheet. A separate Termination Ib meltwater event is most conspicuous in the central Arctic and is associated with characteristic dolomitic carbonate IRD. This lithology suggests an origin of glacial ice from northern Canada and northern Greenland where lower Paleozoic platform carbonates crop extensively out.

1. Introduction

The intention of the present work is to document temporal and spatial changes in the hemipelagic sediment flux over the central Arctic Ocean during the past 80 kyr (i.e., late oxygen isotope stage (OIS) 5-1). The prerequisite is stratigraphic and quantitative sedimentologic work on high-quality box cores to obtain proxy data for environmental parameters such as sea ice distribution, sediment ice rafting, meltwater influx, surface ocean stratification, and plankton productivity. In addition, we attempt to link the Arctic Ocean data to ocean and terrestrial climate records from the circum-Arctic and the North Atlantic region and to discuss the importance of the Arctic Ocean system under different climatic conditions.

During the last decade the discovery of recurrent short-lived (few millenia) warming-cooling events in Greenland ice cores and North Atlantic marine records, covering the late Quaternary, has challenged our view of glacial-interglacial environmental conditions and the dynamics of global climate [cf. *Dansgaard et al.*, 1993; *Bond et al.*, 1993]. Though changes in freshwater outflow from the Arctic Ocean may be considered an important trigger for changes in the thermohaline circulation of the North Atlantic, the Arctic Ocean climate record has in this context received only limited attention. Difficult access, enigmatic and discontinous oxygen isotope records and low hemipelagic sedimentation rates have hampered major progress.

A few studies have been able to document the effects of the last deglaciation in the eastern and central Arctic Ocean on the basis of oxygen and carbon isotope records, accelerator mass spectrometry (AMS) ^{14}C datings, and basic sedimentologic-micropaleontologic parameters [e.g., *Zahn et al.*, 1985; *Markussen*, 1986; *Mienert et al.*, 1990; *Köhler*, 1992; *Stein et al.*, 1994a, b; *Nørgaard-Pedersen*, 1996]. They, in general, confirm very low hemipelagic sedimentation rates (few mm kyr^{-1}) for the last glacial maximum. For the last deglacial period and the Holocene, sedimentation rates increasing to about 1 cm kyr^{-1} and increasing abundances of planktic foraminifera have been documented. Comparable results were obtained by *Darby et al.* [1998] from new radiocarbon-dated box cores from the Amerasian Basin (western Arctic Ocean). For eastern Arctic Ocean sediment cores the combined use of nannoplankton stratigraphy, magnetostratigraphy and ^{230}Th- and ^{10}Be-stratigraphy have been able to document OIS 5 and last interglacial sediments [*Gard*, 1993; *Nowaczyk et al.*, 1992, 1994; *Eisenhauer et al.*, 1994]. In the western Arctic Ocean lithostratigraphy and magnetostratigraphy have formed the basis for a subdivision of the Brunhes magnetic chronozone (the last 780,000 years) into 100 kyr glacial-interglacial cycles [e.g., *Boyd et al.*, 1984; *Poore et al.*, 1993; *Phillips and Grantz*, 1997]. From a Lomonosov Ridge core in the central Arctic Ocean, 100 kyr cycles within the Brunhes were found in ^{10}Be isotope records and faunal-sedimentological data [*Spielhagen et al.*, 1997]. The above studies, however, have focused little on Arctic Ocean environmental conditions during the last glacial cycle where the best global climate reference data are available.

2. Materials and Methods

Data from five large-volume box cores from ridges and turbidite-protected sites in the Arctic Ocean north of 85°N are presented (Figure 1 and Table 1). The cores were obtained from RV *Polarstern* during the ARCTIC'91 expedition [*Fütterer*, 1992]. The cores were selected on the basis of their undisturbed stratigraphic sections, continuous $\delta^{18}O$ and $\delta^{13}C$ records, available AMS ^{14}C datings, and regional representative character [cf. *Nørgaard-Pedersen*, 1996]. All cores consist of brownish to olive gray silty and sandy clays. Detailed core descriptions are given by *Fütterer* [1992].

The box cores were subcored and sampled in 1 cm slices (50 cm^3). Sediments were freeze-dried, weighed, and washed in deionized water through a 63 µm mesh. After drying, the coarse fraction was sieved in separate grain size fractions. In the fractions 125-250 µm and 250-500 µm, representative

[1]Now at Alfred-Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.

Paper number 97PA03409.
0883-8305/98/97PA-3409$12.00

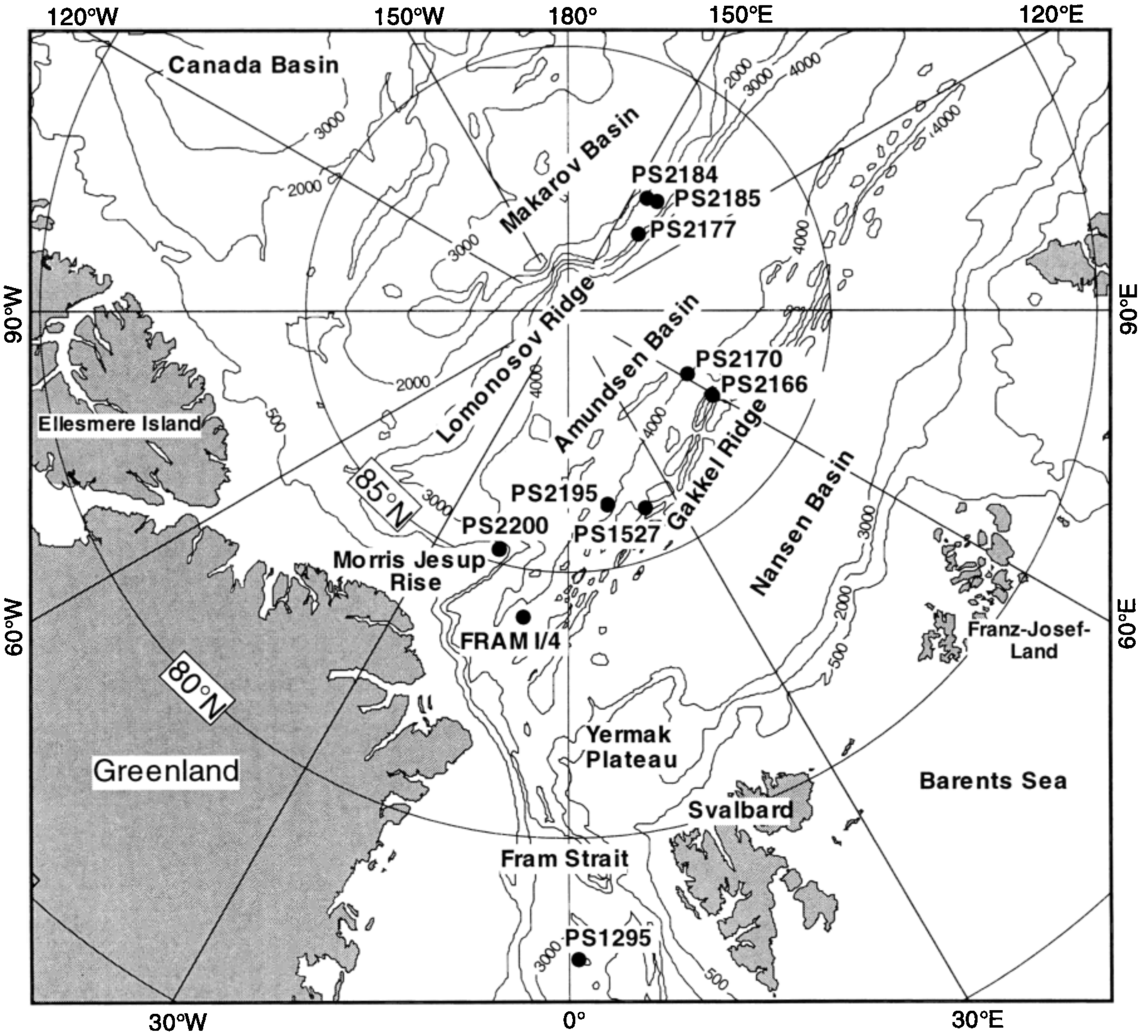

Figure 1. Locations of cores used in this study. The Lomonosov Ridge in the central Arctic separates the eastern (Eurasian) basin (Nansen Basin, Gakkel Ridge, and Amundsen Basin) from the western (Amerasian) basin (Makarov Basin and Canada Basin).

sample splits of ~400 grains were used to determine absolute and relative contents of planktic foraminifera, benthic foraminifera, and lithic grains. The fraction 500-1000 µm was used to determine the abundance and lithologic composition of coarse ice-rafted debris (IRD). Because of the generally sparse IRD content, usually all grains were counted. Sample splits of ~400-600 grains were used in IRD rich samples. A LECO CS-125™ carbon/sulphur infrared analyzer was used for determination of calcium carbonate content expressed as weight percent of the bulk sediment. Oxygen and carbon isotope measurements were carried out on equally shaped four-chambered planktic foraminifera *Neogloboquadrina pachyderma* (sin.) from the 125-250 µm fraction (~25 individuals on average). All measurements were performed on Finnigan MAT 251™ mass spectrometers (Kiel University and Alfred-Wegener-Institute, Bremerhaven). Results are expressed in the δ-notation (permille versus Vienna Pee Dee Belemnite (PDB)), which is defined in terms of National Bureau of Standards (NBS) 19 calcite [*Coplen*, 1996]. The external reproducibility is 0.08‰ for $\delta^{18}O$ and 0.04‰ for

Table 1. Coring Sites, Water Depths, and Core Lengths

Core	Area	Latitude	Longitude	Water Depth, m	Core Length, cm
PS2166-2	Gakkel Ridge	86°51.6' N	59°45.9' E	3636	40
PS2177-1	Lomonosov Ridge	88°02.2' N	134°55.1' E	1388	45
PS2184-1	Lomonosov Ridge	87°36.7' N	148°08.4' E	1640	30
PS2185-3	Lomonosov Ridge	87°31.9' N	144°22.9' E	1051	38
PS2195-4	Amundsen Basin	86°13.7' N	9°35.6' E	3873	45
PS2200-2	Morris Jesup Rise	85°19.6' N	14°00.0' W	1074	35

Table 2. Results of Accelerator Mass Spectrometry (AMS) ^{14}C datings on Planktic Foraminifera

Core	Depth, cm	Corrected Age,* ^{14}C years	Error, ±years	Calendar Age,# years BP	Laboratory
PS2166-2	0	2395	65	2395	AAR-1729
PS2166-2	8.5	7130	80	8000	AAR-1730
PS2166-2	13.5	13610	130	16040	AAR-1731
PS2166-2	15.5	12490	140	14650	AAR-1732
PS2166-2	19.5	33800	1500	38490	AAR-1733
PS2166-2	22.5	38400	760	42940	AAR-1734
PS2166-2	25.5	>42000	-	-	AAR-1735
PS2177-1	0	2070	110	2070	AAR-2415
PS2177-1	4.5	5660	60	6180	ETH-10901
PS2177-1	9.5	6630	65	7380	ETH-10902
PS2177-1	14.5	12890	90	15140	ETH-10903
PS2177-1	16.5	19910	230	23850	AAR-2093
PS2177-1	19.5	17070	130	20330	ETH-11209
PS2177-1	21.5	34700	820	39380	AAR-2094
PS2177-1	23.5	>39000	-	-	AAR-2095
PS2185-3	0	2680	65	2680	ETH-9868
PS2185-3	1.5	3105	65	3010	ETH-9869
PS2185-3	2.5	4555	60	4810	ETH-10576
PS2185-3	4 5	5290	60	5720	ETH-10313
PS2185-3	6.5	6740	75	7520	ETH-10574
PS2185-3	7.5	7975	75	9050	ETH-10573
PS2185-3	8.5	8370	85	9540	ETH-9870
PS2185-3	9.5	10310	85	11940	ETH-10575
PS2185-3	10.5	16730	150	19910	ETH-9871
PS2185-3	10.5	16130	140	19160	AAR-1717
PS2185-3	11.5	13950	160	16460	ETH-10314
PS2185-3	11.5	13250	210	15590	ARR-1718
PS2185-3	12.5	15560	110	18450	AAR-1719
PS2185-3	13.5	18110	190	21620	AAR-1720
PS2185-3	14.5	23250	230	27350	AAR-1721
PS2185-3	15.5	25500	250	29830	AAR-1722
PS2185-3	16.5	30380	530	35020	ETH-9873
PS2185-3	19.5	33670	550	38360	ETH-10315
PS2185-3	20.5	(?>)39950	1450	-	ETH-9874
PS2185-3	22.5	(?>)37350	690	-	ETH-10577
PS2195-4	0	2790	80	2790	AAR-1723
PS2195-4	6.5	11350	100	13230	AAR-1724
PS2195-4	9.5	23050	440	27120	AAR-1725
PS2195-4	11.5	28100	490	32630	AAR-1726
PS2195-4	15.5	>37000	-	-	AAR-1727
PS2200-2	0	5215	60	5440	ETH-11212
PS2200-2	3.5	11050	85	12680	ETH-11213
PS2200-2	6.5	19720	150	23150	ETH-11214
PS2200-2	8.5	26620	280	30890	ETH-11215
PS2200-2	10.5	32060	460	36590	ETH-11216
PS2200-2	14.5	>34870	-	-	ETH-11217

*A 400 year reservoir correction [*Bard*, 1988] was applied to all ages. Corresponding calendar age estimates are shown for finite dating results.

#Calendar ages were calculated using a linear apporximation of *Bard* [1992] for the period <18 ^{14}C ka: Calendar age = 1.24 (^{14}C age) - 840, and an extended second order fit for the interval 18-40 ^{14}C ka: Calendar age = -5.85 10^{-6} (^{14}C age)^2 + 1.39 (^{14}C age) - 1807 [*Bard et al.*, 1992].

$\delta^{13}C$. Planktic foraminifera were used also for AMS ^{14}C dating at suitable levels (Table 2). The ^{14}C dates provided by the laboratories (Eidgenossische Technische Schule (ETH), Zürich and Aarhus University, Denmark) were corrected for a reservoir effect of 400 years [*Bard*, 1988]. Calendar ages were calculated using a linear approximation of *Bard et al.* [1992, 1993] for ages <18 ^{14}C ka and an extended second-order fit [*Bard et al.*, 1992, 1993] for the period 18-40 ^{14}C ka. When not specified as ^{14}C ages, given ages are calendar ages.

Beyond the range of ^{14}C datings, correlation to high-resolution oxygen and carbon isotope records from the Norwegian-Greenland Sea [e.g., *Vogelsang*, 1990; *Weinelt*, 1993; *Stein et al.*, 1996] and the Fram Strait [*Köhler and Spielhagen*, 1990; *Dokken and Hald*, 1996; *Vogt*, 1997] is attempted. Isotopic events and the corresponding astronomical ages are identified according to *Martinson et al.* [1987].

In addition to the $\delta^{18}O$ down-core pattern, strong $\delta^{13}C$ transitions associated with oxygen isotope stage (OIS) boundaries (e.g. OIS 4 and 5) serve as correlation points [cf. *Jansen*, 1989]. Moreover, major meltwater events (e.g. substage event 3.31) typically can be identified by low $\delta^{13}C$ values accompanying low $\delta^{18}O$ values [cf. *Duplessy et al.*, 1988; *Weinelt*, 1993; *Stein et al.*, 1994a, b; *Nørgaard-Pedersen*, 1996]. Analyses of coccolith assemblages have been performed by *Gard* [1993] in smear slides from the box cores included in the present study and associated longer gravity and piston cores. As a marked difference in species composition of Holocene sediments (dominated by *Emiliania huxley* and *Coccolithus pelagicus*) compared to OIS 5 sediments (dominated by *Gephyrocapsa* species) has been documented in high-latitude records, a rough stratigraphic subdivision is possible [*Gard*,

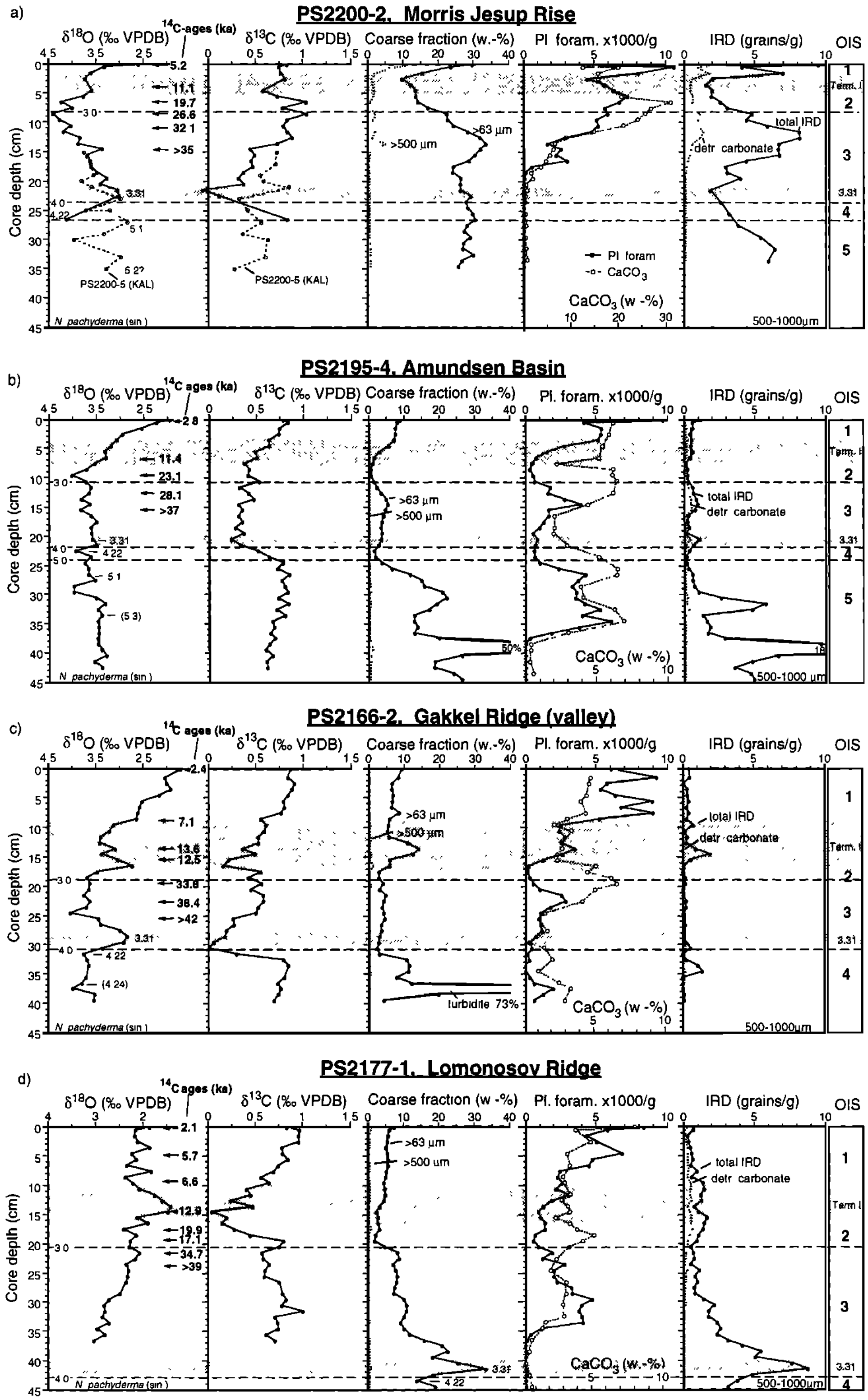

Figure 2. *Neogloboquadrina pachyderma* (sin.) records of $\delta^{18}O$ and $\delta^{13}C$, coarse fraction wt. % (>63µm and >500µm), planktic foraminifera tests g^{-1}, wt % $CaCO_3$, and ice-rafted debris (IRD) grains g^{-1} (500-1000µm: total number g^{-1} and number of detrital carbonate grains g^{-1}). Accelerator mass spectrometry (AMS) ^{14}C ages (^{14}C ka) are shown next to the $\delta^{18}O$ records. Also indicated are oxygen isotope stage boundaries and specific isotopic events (3.0, 3.31(shaded area), 4.0, 4.22, 5.0, and 5.1) and Termination Ia and Ib (shaded area): (a) PS2200-2, Morris Jesup Rise, (b) PS2195-4, Amundsen Basin, (c) PS2166-2, Gakkel Ridge (valley); (d) PS2177-1, Lomonosov Ridge; and (e) PS2185-3, Lomonosov Ridge.

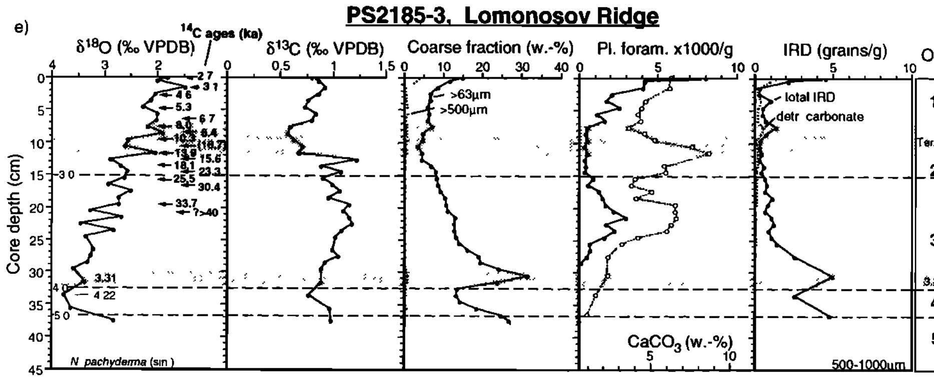

Figure 2. (continued)

1986, 1993]. The coccolith stratigraphy is used to confirm our stable isotope chronology. Moreover, lithostratigraphic correlation of the cores from the Lomonosov Ridge is used to apply the oxygen isotope stage division established on cores PS2185-3 and PS2184-1 into the foraminifera-barren lower part of core PS2177-1.

Age models for the five cores are developed in order to get a more detailed picture of flux rates of specific sediment components. The age fix points used are based on radiocarbon datings (in calendar ages) for the timescale <40 ka and on isotopic events 3.31 (55.5 ka), 4.0 (OIS 4/3 transition: 59.0 ka), 4.22 (64.1 ka), 5.0 (OIS 5/4 transition: 73.9 ka), and 5.1 (79.3 ka). Two cases of radiocarbon age reversals in cores PS2166-2 and PS2177-1 are dealt with by assigning an average age to the level between the radiocarbon-dated samples, using this age, instead of the radiocarbon-dated levels as an age fix point. The anomalous radiocarbon age in core PS2185-3 at 10.5 cm is rejected by the age model construction. Linear interpolation is applied between age fix points. Bulk accumulation rates (g cm^{-2} kyr^{-1}) are calculated from linear sedimentation rates (cm kyr^{-1}) and dry bulk density data (g cm^{-3}). The flux of planktic foraminifera and IRD are calculated on the basis of split count data and bulk sediment accumulation rates. The data presented in Figure 2 and Table 2 are available at the World Data Center-A for Paleoclimatology, 325 Broadway, Boulder, CO; http://www.ngdc.noaa.gov/paleo/paleo.html; e-mail: paleo@ngdc.noaa.gov.

3. Stratigraphy and Oxygen and Carbon Isotope Records

Our stable isotope records from the central Arctic Ocean cover late OIS 5 to the Holocene (Figures 2 and 3). Their different character may be explained by variable stratigraphic resolution and by regional differences in $\delta^{18}O$ values of surface waters (related to freshwater influx). The last glacial-interglacial transition is evident in our cores by a 1‰-2‰ decrease of $\delta^{18}O$ values. In general, the last deglaciation (Termination I) is well defined by one or two characteristic low-$\delta^{18}O$ spikes marking Termination Ia and a general $\delta^{18}O$ decrease during Termination Ib to Holocene levels. Prominent $\delta^{13}C$ minima parallel the low-$\delta^{18}O$ excursions. The last glacial maximum (LGM) can be defined by relatively high $\delta^{18}O$ values preceding Termination Ia. The LGM signals, however, are probably smoothed by limited stratigraphic resolution since very low accumulation rates (few mm kyr^{-1}) characterize the OIS 2 interval. Beyond the range of ^{14}C datings a characteristic low-$\delta^{18}O$ spike associated with a $\delta^{13}C$ minimum reaching 0‰ can be observed (Figure 2). These signals are interpreted to reflect a meltwater event correlating to isotope event 3.31 (55.5 ka), in accordance with very similar features in Norwegian-Greenland Sea records [cf. *Duplessy et al.*, 1988; *Vogelsang*, 1990; *Weinelt*, 1993; *Dokken*, 1995; *Stein et al.*, 1996]. This correlation is supported by nannoplankton data from sites PS2195 and PS2166, where *Gard* [1993, personal communication, 1995] reported a typical substage 5a *Gephyrocapsa* spp. dominated assemblage below the section characterized by a prominent $\delta^{13}C$ decrease (typical for the OIS 5/4 transition).

4. Sediment Composition

The hemipelagic muds show about 5%-30% coarse fraction (>63µm) composed mainly of planktic foraminifera and lithic ice-rafted grains (Figure 2). Specific sections dominated by planktic foraminifera reaching ~4,000-7,000 tests g^{-1} bulk sediment are noticed in sediments of the Holocene, the middle part of OIS 3, and late OIS 5 (core PS2195-4). The state of preservation of the planktic foraminifera is mostly good, and we interpret the major variations in planktic foraminiferal abundances to be a function primarily of productivity rather than of changes in dissolution. Only in the foraminifera-barren lower part of the cores from the Morris Jesup Rise and the Lomonosov Ridge, assigned to late OIS 5 to early OIS 3, can signs of strong carbonate dissolution of planktic and benthic foraminifera be observed. Calcium carbonate contents, at most sites showing values in the range of 0.5%-7%, mostly parallel the abundance curves of planktic foraminifera. However, as noted by *Darby et al.* [1989], most of the calcium carbonate in Arctic Ocean sediments is found in the silt fraction. Maximum $CaCO_3$ values found at the OIS 2 level in our cores are associated with a minimum in planktic foraminiferal abundance and appear, at least in cores PS2200-2, PS2166-2, and PS2177-1, to be associated with abundant authigenic calcium carbonate precipitates. The whitish amorphous precipitates in core PS2200 have been determined by X-ray diffraction to a high-Mg calcite [*Nørgaard-Pedersen*, 1996; *Vogt*, 1997]. The fragile condition as well as findings of *N. pachyderma* sin. and detrital grains as inclusions in the precipitates support an authigenic origin. In cores PS2166-2 and PS2177-1, several authigenic calcium carbonate morphotypes are found. Here rod-, hemisphere- and sphere-shaped crystal bundles of aragonite are common [*Nørgaard-*

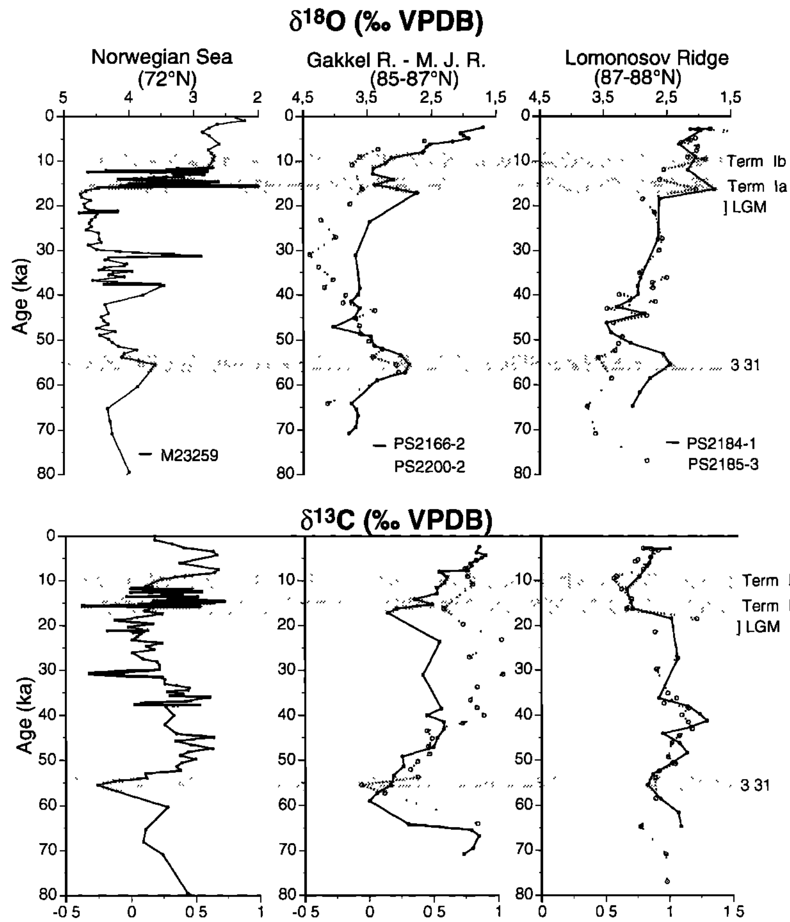

Figure 3. Comparison of a high resolution stable isotope record (*N pachyderma* sin.) from the Norwegian Sea with records from the central Arctic Ocean covering the past 80 kyr (calendar ages). Major deglacial events (isotopic event 3.31 and Termination Ia and Ib) can be traced in all records. Data for core M23259 (Bear Island Fan) are from *Weinelt* [1993]; the records of PS2166-2, PS2200-2, PS2185-3, and PS2184-1 are from *Nørgaard-Pedersen* [1996] and this study.

Pedersen, 1996; *Vogt*, 1997]. Similar calcium carbonate precipitates have been described by *Buczynski and Chafetz* [1991].

Abundance peaks of IRD in the size range 500-1000 μm are found in middle(?) OIS 5, early and middle OIS 3, and Termination I to the early Holocene. Considerable regional variability in amount and composition of the IRD material is evident. The IRD grains mainly are composed of five lithotypes: quartz, metamorphites, igneous rocks, siliciclastic sediment, and detrital carbonate rocks. At the Morris Jesup Rise, the western Amundsen Basin, and the Lomonosov Ridge sites, a large content of detrital carbonate IRD is noticed in the younger part of the records. The detrital carbonate fragments are light brownish or light greyish, show a microcrystalline texture, and are only rarely fossiliferous. X-ray diffraction measurements of the detrital carbonate grains show dolomite contents in the range 85%-95% [*Vogt*, 1997; *Nørgaard-Pedersen*, 1996]. At site PS2166-2 (Gakkel Ridge) a high content of siliciclastic material characterises the peak of IRD dated to ~14-12 ^{14}C ka. A more comprehensive presentation of the IRD composition is given by *Nørgaard-Pedersen* [1996].

5. Accumulation Rates and Flux of Sediment Components

The calculated bulk sediment accumulation rates for the last 80 kyr are in the range 0.2-1.0 g cm^{-2} kyr^{-1} (Figure 4). Maximum rates were attained in early OIS 3 (55-35 ka) as well as during Termination I to the middle Holocene (17-5 ka). Minimum accumulation rates apparently characterized the peak glacial periods of OIS 4 (74-59 ka) and the late OIS 3-OIS 2 interval (35-17 ka). The calculated flux of planktic foraminifera is in the range 0-10,000 tests cm^{-2} kyr^{-1} (Figure 5a). Flux maxima are obtained for the middle Holocene, the middle part of OIS 3 (50-35 ka), and substage 5a (one core). In the peak glacial intervals, the calculated flux of planktic foraminifera reach only a few hundred tests cm^{-2} kyr^{-1}. In cores PS2166-2 and PS2177-1, which show the best time resolution of the last deglacial period, a two-step increase in foraminiferal flux is noticed. During Termination Ia a rapid increase to ~2,000-3,000 tests cm^{-2} kyr^{-1} took place. This was followed by a stagnation. During the early Holocene a further increase took place, reaching a peak level of about

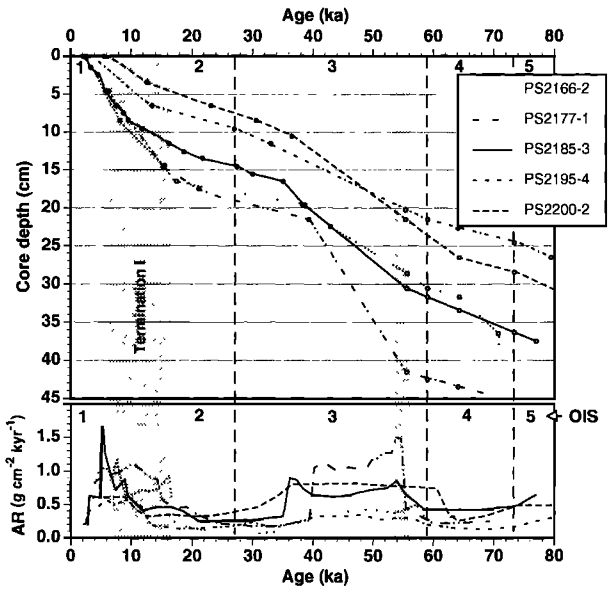

Figure 4. Calendar age versus depth models for the cores investigated. Solid dots represent ^{14}C age based fix points. Open dots represent fix points based on the oxygen and carbon isotope records. The corresponding accumulation rate (AR) values are shown below.

4,000-7,000 tests cm^{-2} kyr^{-1} at ~7-6 ka. Surface sediments representing late Holocene conditions show a flux of ~2,000-4,000 tests cm^{-2} kyr^{-1}. The IRD records (Figure 5b) document highest fluxes during early OIS 3 (especially at the Lomonosov Ridge sites), in the middle part of OIS 3 (~40-45 ka on the Morris Jesup Rise), and during Termination I. At Gakkel Ridge site PS2166-2, peak IRD fluxes are related to the Termination Ia event (14-12 ^{14}C ka). Siliciclastics (grey mudstones and sandstones) dominate the IRD assemblage here. The other core sites, however, show peak IRD flux values related to Termination Ib. High fluxes of detrital carbonate IRD are determined for the periods 45-40 ka and the Termination Ib-early Holocene (Figure 5b).

6. Discussion

Our proxy data (flux records and isotopic records) can be related to changes of paleoenvironmental parameters like ice cover concentration, surface ocean salinity and stratification, planktic productivity, and influx of terrigenous ice-rafted material. Figure 6 summarizes three end-member states envisaged for the central Arctic Ocean environment: (a) full glacial periods (e.g., OIS 4 and 2), (b) major deglacial intervals (e.g., early OIS 3 and Termination Ia and Ib), and (c) interglacials or interstadial periods of longer duration (e.g., late OIS 5, middle OIS 3, and the Holocene).

OIS 4 and 2 were characterized by extremely low sedimentation rates (few mm kyr^{-1}), very low planktic productivity, and very low IRD flux. These periods coincide with minima of summer insolation [*Berger and Loutre*, 1991], maxima of terrestrial ice sheet extension, and lowered sea levels [*Chappel and Shackleton*, 1986]. The limiting effect of perennial sea-ice coverage on the flux of planktic foraminifera has been documented by *Carstens and Wefer* [1992] along a transect across the Eurasian Basin. Accordingly, we interpret the very low flux of planktic foraminifera and the low sediment accumulation rates as indicative of a closely packed sea-ice cover in the central Arctic Ocean throughout the peak glacials. *Darby et al.* [1998] also present evidence for a thick ice cover which was established at ~40 ^{14}C ka and lasted to ~11 ^{14}C ka

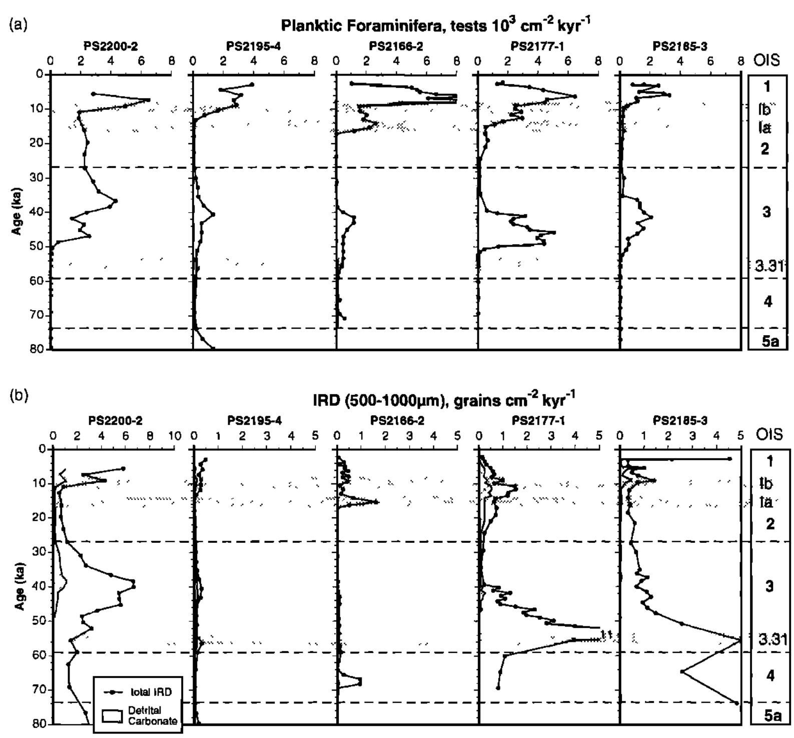

Figure 5. Flux records versus calendar age: (a) planktic foraminifera (tests 10^3 cm^{-2} kyr^{-1}) for the five cores investigated, and (b) total IRD flux and detrital carbonate IRD flux, 500-1000µm (grains cm^{-2} kyr^{-1}); note the different scale at site PS2200

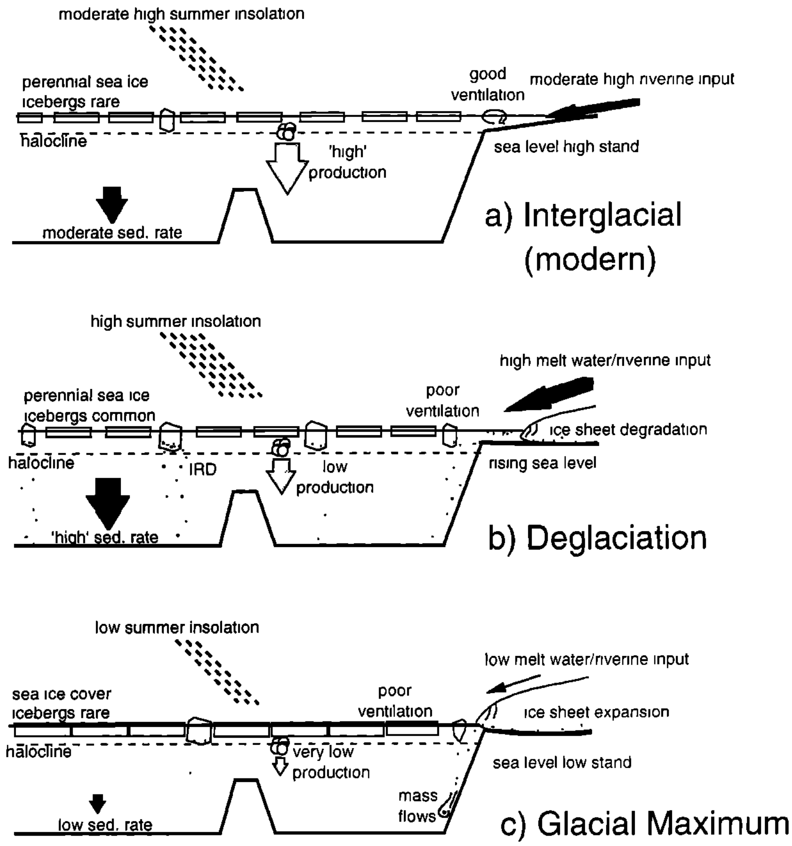

Figure 6. Models of late Quaternary Arctic surface ocean conditions and sedimentation patterns for three end-member climate situations: (a) interglacial or warm interstadial; (b) deglacial period, and (c) glacial maximum

over the western Arctic Ocean. Lowered sea levels (especially during OIS 2), causing subaereal exposure of wide parts of the Siberian and North American shelf areas, probably reduced potential entrainment of sediment into sea ice [*Pfirman et al.*, 1990] and ice rafting of coarse terrigenous material. The low flux of coarse IRD may imply that icebergs capable of transporting such material were not very common (or were not melting) in the central and eastern Arctic Ocean during peak glacials. Evidence from the poorly investigated continental margins of Northern Canada and Northern Greenland, for ice sheet expansion beyond the present coastline, is sparse [*Andrews*, 1987; *Funder and Hansen*, 1996]. *Dyke and Prest* [1987], however, proposed for the LGM marine-based ice shelves reaching out onto the narrow Beaufort Sea Shelf through the deep (>400m) M'Clure Strait and Amundsen Gulf bordering Banks Island. Moreover, *Bischof and Darby* [1997], *Darby et al.* [1998], and *Phillips and Grantz* [1997] document deglacial episodes of detrital carbonate IRD deposition in the Amerasian Basin. This implies that certain sectors of the Laurentide Ice Sheet reached the Arctic shelf margin during the last glacial. The Barents Sea Ice Sheet expanded to the northern shelf margin during both OIS 4 and 2 [*Mangerud and Svendsen*, 1992; *Forman et al.*, 1995]. During OIS 4 and 2, the eastern Fram Strait was, periodically, characterized by relatively high accumulation rates and an increased flux of IRD and planktic foraminifera (including subpolar forms) suggesting partly open waters with abundant drifting icebergs [*Hebbeln et al.*, 1994; *Dokken and Hald*, 1996]. The low bulk sediment/foraminifera fluxes in our cores, however, suggest that these warming episodes, associated with a "modern" Atlantic Water advection to high northern latitudes, did not influence the central Arctic Ocean environment.

The major deglacial events following OIS 4 and 2 were accompanied by a drastic increase in bulk accumulation rates. In our central Arctic records, an early OIS 3 low-δ^{18}O/low-δ^{13}C meltwater spike with amplitudes ≥1‰, not less than Termination I meltwater events, apparently correlates to isotope event 3.31 (Figure 3). Characteristics for event 3.31 are extremely low δ^{13}C values and minimum calcium carbonate contents. This event may reflect a voluminous meltwater discharge subsequent to the large glaciation occurring around 60 ka both on Svalbard [*Mangerud and Svendsen*, 1992] and Fennoscandia [*Mangerud*, 1991; *Baumann et al.*, 1995]. It seems possible that mid-Weichselian (mid-Wisconsin) ice sheets in northern Greenland and northern Canada [cf. *Andrews*, 1987] also experienced degradation and contributed to the early OIS 3 meltwater episode. Thus *Darby et al.* [1998] report a >40 ka (possibly mid-Wisconsin) major deglacial IRD event in western Arctic Ocean box cores.

Stable isotope records of cores from the Fram Strait [*Jones and Keigwin*, 1988; *Dokken*, 1995] to the central Arctic Ocean [*Markussen*, 1986; *Köhler*, 1992; *Stein et al.*, 1994b; *Nørgaard-Pedersen*, 1996] documenting the OIS 2/1 transition reveal a rapid decrease of δ^{18}O and δ^{13}C values at about 15-13.5 ^{14}C ka. This suggests a major influx of meltwater and the establishment of a poorly ventilated surface water layer with reduced salinities. Two peak deglacial meltwater episodes culminating at ~14-12 ^{14}C ka (mwp Ia) and ~10-8 ^{14}C ka (mwp Ib) are evident from our central Arctic records (Figure 7). In

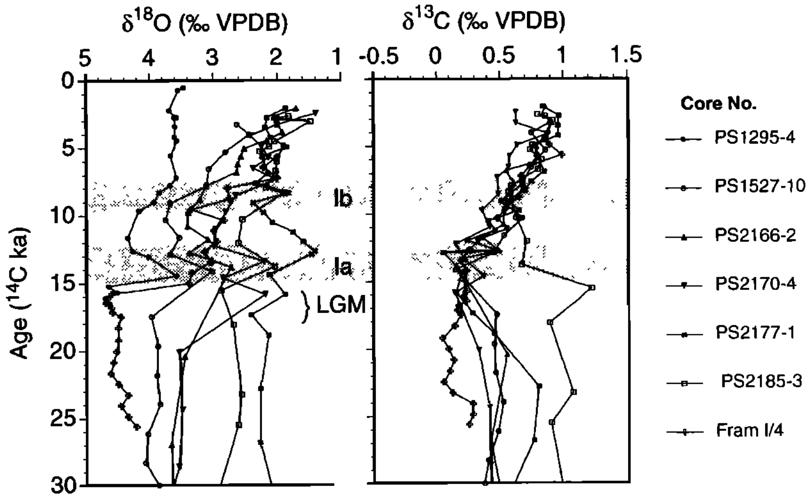

Figure 7. Radiocarbon-dated records of $\delta^{18}O$ and $\delta^{13}C$ from the Fram Strait to the central Arctic Ocean The record of core PS1295-4 is from *Jones and Keigwin* [1988], PS1527-10 is from *Köhler* [1992], PS2170 is from *Stein et al* [1994b], Fram I/4 is from *Markussen* [1986], and PS2166-2, PS2177-1, and PS2185-3 are from this study. A standard reservoir correction of 400 years was subtracted from all AMS ^{14}C datings used.

core PS2166-2 (Gakkel Ridge), a low-$\delta^{18}O$ spike dated to ~14 ^{14}C ka, preceding a characteristic peak of IRD (with abundant siliciclastic material), possibly reflects the early and rapid deglaciation of the marine-based Barents Sea Ice Sheet [cf. *Jones and Keigwin*, 1988; *Polyak and Solheim*, 1994; *Elverhøi et al.*, 1995; *Lubinski et al.*, 1996]. On the basis of a single AMS ^{14}C dating from site PS2170 close to site PS2166-2, *Stein et al.* [1994a] suggested that a major influx of meltwater to the Arctic Ocean commenced as early as 15.7 ^{14}C ka. However, by comparing all available AMS ^{14}C dated records from the Eurasian Basin and the central Arctic Ocean [e.g., *Markussen*, 1986; *Köhler*, 1992; *Stein et al.*, 1994b; this study], the cluster of low-$\delta^{18}O$ and low-$\delta^{13}C$ spikes at 15-13.5 ^{14}C ka suggests a slightly younger age of the first extensive deglacial meltwater event in the Arctic Ocean (Figure 7).

A separate Termination Ib meltwater event is most conspicuous in central Arctic Ocean stable isotope records. In contrast to the event at 14-12 ^{14}C ka, it is associated with a peak flux of detrital carbonate IRD, showing increasing values toward the Morris Jesup Rise and the Makarov Basin [*Nørgaard-Pedersen*, 1996]. This supports the assumption of an origin of melting icebergs from northern Canada and/or northern Greenland where lower Paleozoic platform carbonates crop extensively out [*Dawes*, 1976; *Okulitch*, 1991; *Higgins et al.*, 1991a, b; *Henriksen*, 1992]. The northwestern sector of the Laurentide Ice Sheet is thought to have disappeared during Termination Ia [*Dyke and Prest*, 1987; *Hodgson*, 1994; *Peltier*, 1994] and probably contributed to the Termination Ia meltwater episode recorded in central Arctic Ocean cores. For the northeastern sector of the Laurentide Ice Sheet, the Innuitian Ice Sheet on Ellesmere Island, and the northern part of the Greenland Ice Sheet, there is considerable terrestrial evidence that main ice sheet retreat occurred later at ~10-8 ^{14}C ka [*Andrews*, 1987; *Hodgson*, 1989; *Funder*, 1989]. Episodic surging or readvances of ice streams and ice shelves during this period may have delivered icebergs to the Amerasian Basin and the northern Greenland shelf break. Maximum summer insolation values and a global rapid sea level rise at ~10-9 ^{14}C ka [*Berger and Loutre*, 1991; *Fairbanks*, 1989; *Bard et al.*, 1996] probably also accelerated the final decay or retreat of ice sheets.

The middle OIS 3 and middle to late Holocene periods have left lithologically similar hemipelagic sediment records with relatively high accumulation rates of brownish silty clay rich in planktic foraminifera. By analogy with the modern interglacial environment we interpret these data as the result of a high open water (lead) proportion during summers and extensive sea ice rafting of finely grained terrigenous sediments (high seasonal ablation rates). For substage 5a a high foraminifera flux is suggested too by the record of core PS2195-4 and other studies of the Eurasian Basin record [*Köhler*, 1992; *Pagels*, 1992; *Nørgaard-Pedersen*, 1996]. The influence of carbonate dissolution on the Lomonosov Ridge and Morris Jesup Rise OIS 5 records, however, limits the interpretations that can be done for the central Arctic environment.

Global climate changes as observed in marine and terrestrial records from lower latitudes are indeed reflected in deep Arctic Ocean sediments. Apparently, the gross environmental changes occur more or less parallel to the oscillations in northern hemisphere insolation (Figure 8) which, partly indirectly, have controlled the growth and decay of major ice sheets, the fall and rise of sea level, and the influx of freshwater to the Arctic Ocean. Millenia-scale climatic changes as documented by the high-resolution GISP 2 ice core record (Figure 8) can be documented only for the last deglacial central Arctic records. The abrupt excursions of the stable isotope and sediment flux records suggests a rapid change of the surface ocean environment at ~15-13.5 ^{14}C ka. For the last glacial period, correlation of single interstadial events is prevented by the low sedimentation rates and limited age fix points of the Arctic Ocean records. It is doubtful also to what extent the unstable nature of the last glacial climate documented in lower latitude ice core and marine records [*Dansgaard et al.*, 1993; *Bond et al.*, 1993] influenced the central Arctic region. The circum-Arctic cold-based ice sheets (except the Barents Sea?) in low-precipitation regions were probably far less vulnerable to surging and to rapid ocean-atmosphere temperature shifts than the middle latitude, southwestern sector of the Laurentide Ice Sheet [*Bond et al.*, 1993] or the Scandinavian Ice Sheet [*Baumann et al.*, 1995; *Fronval et al.*, 1995].

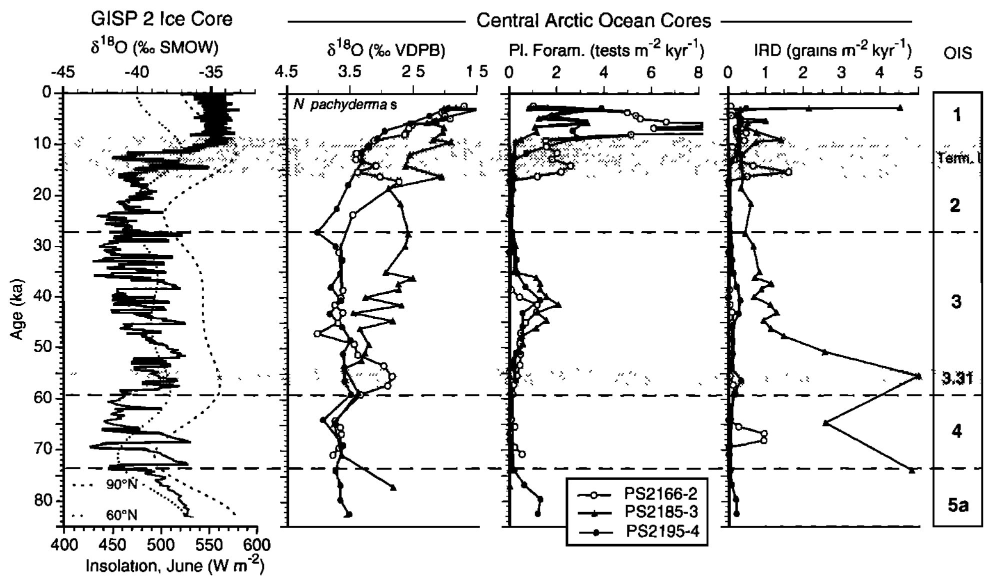

Figure 8. Proxy climate data for the last 80 kyr recorded in sediment cores from the Gakkel Ridge (PS2166-2), the Amundsen Basin (PS2195-4), and the Lomonosov Ridge (PS2185-3) compared with the $\delta^{18}O$ record in the GISP 2 ice core, central Greenland [*Grootes et al.*, 1993; *Stuiver et al.*, 1995; *Meese et al.*, 1994; and *Sowers et al.*, 1993] and the summer insolation variation at 60°N and 90°N [*Berger and Loutre*, 1991].

7. Conclusions

During the last 80 kyr the central Arctic Ocean repeatedly experienced changes in its environmental state from peak glacial over deglacial to interglacial-like states. The most important factors that influenced the hemipelagic deep sea record were probably terrigenous sediment influx, sea-ice concentrations, and seasonal ablation rates. The extremely low flux of terrigenous material and planktic foraminifera in the central Arctic Ocean during OIS 4 and 2 was probably caused by a dense cover of sea ice in combination with generally low biologic productivity and reduced summer insolation.

Abrupt meltwater incursions from major deglaciations of various continental ice sheets can be traced in the central Arctic surface layer by the stable isotope signature of planktic foraminifera *N. pachyderma* (sin.). A deglacial event during early OIS 3 had a strong influence on the Arctic surface ocean environment and caused locally high IRD fluxes. This event, possibly reflecting a major circum-Arctic deglaciation of lower to middle Weichselian ice sheets, may correspond to isotopic event 3.31 (~55 ka) which is also the most conspicuous OIS 3 deglacial event in Norwegian-Greenland Sea records.

The diachronic character of the last deglaciation of the Barents Sea Ice Sheet and the northern sectors of the Laurentide-Greenland Ice Sheet is reflected in the sediments of the Arctic Ocean. The rapid deglaciation of the marine-based Barents Sea Ice Sheet, associated with Termination Ia, can be traced by $\delta^{18}O$ meltwater spikes and associated IRD peaks in eastern Arctic Ocean sediment cores. A second major meltwater event associated with Termination Ib is most conspicuous in isotope records from the central Arctic Ocean. Its association with detrital carbonate IRD suggests an origin of icebergs and meltwater from the northeastern Laurentide, Innuitian, and Greenland Ice Sheets.

The Holocene after 8 ^{14}C ka, an interstadial in middle OIS 3 (~50-35 ka), and late OIS 5 were characterized by a high open water (lead) proportion during summers, extensive sea ice rafting, and deposition of finely grained sediments incorporated on the wide shallow shelf seas.

Acknowledgments. We thank the captain, crew, and chief scientist of RV *Polarstern* and the Alfred-Wegener Institute for Polar and Marine Research (AWI) for their support during cruise ARCTIC'91 For technical assistance in sample preparation many thanks go to S. O. Bude, R. Freitag, S. Marczinek, D. Rau, and S. Steinke. We are grateful to H Erlenkeuser and the staff of the ^{14}C laboratory, Kiel University, for performing the stable isotope measurements. For preparation of samples for AMS ^{14}C datings we acknowledge G. Bonani and B. Kromer, Heidelberg Academy of Sciences, and J. Heinemeier, AMS Laboratory at Aarhus University. ^{14}C datings were performed at the Swiss Federal Institute of Technology (ETH) AMS-facility, Zürich, and at the AMS laboratory at Aarhus University, Denmark. We acknowledge R. Stein, C. Vogt, and C. Schubert from AWI for discussions and supply of unpublished data. We thank the three reviewers, D. L. Clark, D. A. Darby, and R. L Phillips for offering many useful suggestions to improve the paper. The English was corrected by C. Bradley. This work was funded by the German Federal Ministery for Education, Research, and Technology (FKZ03F0131A and FKZ03G0507A) and by the Office of Naval Research.

References

Andrews, J. T., The late Wisconsian glaciation and deglaciation of the Laurentide Ice Sheet, in *The Geology of North America*, vol. K3, *North America and Adjacent Oceans During the Last Deglaciation*, edited by W. F. Ruddiman and H. E. Wright, Jr, pp. 13-38, Geol. Soc. of Am., Boulder, Co., 1987.

Bard, E., Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: Paleoceanographic implications, *Paleoceanography, 3*, 635-645, 1988.

Bard, E., M. Arnold, and B. Hamelin, Present status of the radiocarbon calibration of the late Pleistocene, 4th Internat. Conf. on Paleoceanography, abstract, Rep. 15, pp. 52-53, Res. Center for Marine Geosci., GEOMAR, Kiel, Germany, 1992.

Bard, E., M. Arnold, R. G. Fairbanks, and B. Hamelin, ^{230}Th-^{234}U and ^{14}C ages obtained by mass spectrometry on corals, *Radiocarbon, 35*, 191-199, 1993.

Bard, E., B. Hamelin, M. Arnold, L. Montaggioni, G. Cabioch, G. Faure, and F.

Rougerie, Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge, *Nature, 382*, 241-244, 1996.

Bauch, D., The distribution of $\delta^{18}O$ in the Arctic Ocean: Implications for the freshwater balance of the halocline and the sources of deep and bottom waters, *Ber. Polarforsch., 159*, 144 pp., Alfred-Wegener Inst. for Polar and Marine Res., Bremerhaven, Germany, 1995.

Baumann, K.-H., K. S. Lackschewitz, J. Mangerud, R. Spielhagen, T. C. W. Wolf-Welling, R. Henrich, and H. Kassens, Reflection of Scandinavian Ice Sheet fluctuations in Norwegian Sea sediments during the past 150,000 years, *Quat. Res., 43*, 185-197, 1995.

Bischof, J. F., and D. A. Darby, Mid- to late Pleistocene ice drift in the western Arctic Ocean: Evidence for a different circulation in the past, *Science, 277*, 74-78, 1997.

Berger, A., and M. F. Loutre, Insolation values for the climate of the past 10 million years, *Quat. Sci. Rev., 10*, 297-317, 1991.

Bond, G., W. Broecker, S. Johnsen, J McManus, L. J. Labeyrie, J. Jouzel, and G Bonani, Correlation between climate records from North Atlantic sediments and Greenland ice, *Nature, 365*, 143-147, 1993.

Boyd, R. F., D. L. Clark, G. Jones, W. F. Ruddiman, A. McIntyre, and N. G. Pisias, Central Arctic Ocean response to Pleistocene Earth-orbital variations, *Quat. Res., 22*, 121-128, 1984.

Buczynski, C., and H. S. Chafetz, Habit of bacterially induced precipitates of calcium carbonate and the influence of medium viscosity on mineralogy, *J. Sediment. Petrol., 61*, 226-233, 1991.

Carstens, J., and G. Wefer, Recent distribution of planktonic foraminifera in the Nansen Basin, Arctic Ocean, *Deep-Sea Res., 39*, 507-524, 1992.

Chappel, J., and N. J. Shackleton, Oxygen isotopes and sea level, *Nature, 324*, 137-140, 1986.

Coplen, T. B., Editorial: More uncertainty than necessary, *Paleoceanography 11*, 369-370, 1996.

Dansgaard, W. et al., Evidence for general instability of past climate from a 250-kyr ice-core record, *Nature, 364*, 218-220, 1993.

Darby, D. A., A. S. Naidu, T. C. Mowatt, and G. Jones, Sediment composition and sedimentary processes in the Arctic Ocean, In *The Arctic Seas: Climatology, oceaography, geology, and biology*, edited by Y. Herman, pp. 657-720, Van Nostrand Reinold, New York, 1989.

Darby, D. A., J. F. Bischof, and G. A. Jones, Radiocarbon chronology of depositional regimes in the western Arctic Ocean, *Deep-Sea Res.*, in press,. 1998.

Dawes, P. R., Precambrian to Tertiary of northern Greenland, in *Geology of Greenland*, edited by A. Escher and W. S. Watt, pp. 249-303, Geol. Survey of Greenland, Copenhagen, Denmark, 1976.

Dokken, T., Last interglacial/glacial cycle on the Svalbard/Barents Sea margin,. Ph. D. thesis, Univ. of Tromsø, Tromsø, Norway, 1995.

Dokken, T. M., and M. Hald, Rapid climatic shifts during isotope stages 2-4 in the polar North Atlantic, *Geology, 27*, 599-602, 1996.

Duplessy, J.-C., N. J. Shackleton, R. G. Fairbanks, L. D. Labeyrie, D. Oppo, and N. Kallel, Deepwater source variations during the last climatic cycle and their impact on the global deepwater cirkulation, *Paleoceanography, 3*, 343-360, 1988.

Dyke, A. S., and V. K. Prest, Late Wisconsian and Holocene record of the Laurentide Ice Sheet, *Géogr. Phys. et Quat., 41*, 237-263, 1987.

Eisenhauer, A., R. F. Spielhagen, M. Frank, G. Hentzschel, A. Mangini, P. W. Kubik, B. Dietrich-Hannen, and T. Billen, ^{10}Be records of sediment cores from high northern latitudes: Implications for environmental and climatic changes, *Earth Planet. Sci. Lett., 124*, 171-184, 1994.

Elverhøi, A., E. S. Andersen, T. Dokken, D. Hebbeln, R. F. Spielhagen, J. I. Svendsen, M. Sørflaten, A. Rørnes, M. Hald., M., and C. F. Forsberg, The growth and decay of the late Weichselian ice sheets in western Svalbard and adjacent areas based on provenance studies of marine sediments, *Quat. Res., 44*, 303-316, 1995.

Fairbanks, R. G., A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation, *Nature, 342*, 637-642, 1989.

Forman, S. L., D. J. Lubinski, G. H. Miller, G. Matishov, J. Snyder, and S. Korsun, Post-glacial emergence and distribution of Late Weichselian Ice Sheet loads in the Northern Barents and Kara Seas, Russia, *Geology, 23*, 113-116, 1995.

Fronval, T., E. Jansen, J. Bloemendal, and S. Johnsen, Oceanic evidence for coherent fluctuations in Fennoscandian and Laurentide ice sheets on millenium timescales, *Nature, 374*, 443-446, 1995.

Funder, S., Quaternary geology of the ice-free areas and adjacent shelves of Greenland, in *The Geology of North America*, vol. K1, *Quaternary Geology of Canada and Greenland*, edited by R. J. Fulton, pp. 743-792, Geol. Soc. of Am., Boulder, Co., 1989.

Funder, S., and L. Hansen, The Greenland ice sheet - A model for its culmination and decay during and after the last glacial maximum, *Bull. Geol. Soc. Denmark, 42*, 137-152, 1996.

Fütterer, D., ARCTIC'91: The expedition ARK-VIII/3 with RV 'Polarstern' 1991, *Ber. Polarforschung, 107*, 267 pp., Alfred-Wegener Inst.. for Polar and Mar. Res., Bremerhaven, Germany, 1992.

Gard, G., Calcareous nannofossil biostratigraphy of Late Quaternary Arctic sediments, *Boreas, 15*, 217-229, 1986.

Gard, G., Late Quaternary coccoliths at the North Pole: Evidence of ice-free conditions and rapid sedimentation in the central Arctic Ocean, *Geology, 21*, 227-230, 1993.

Grootes, P.M., M. Stuiver, J. W. C. White, S. Johnsen, and J. Jouzel, Comparison of oxygen isotope records from the GISP 2 and GRIP Greenland ice cores, *Nature, 366*, 552-554, 1993.

Hebbeln, D., T. Dokken, E. S. Andersen, M. Hald, and A. Elverhøi, Moisture supply for northern ice-sheet growth during the last glacial maximum, *Nature, 370*, 357-360, 1994.

Henriksen, N., Geological map of Greenland, Nyeboe land (sheet 7), Peary Land (sheet 8), scale 1:500,000, Geol. Surv. of Greenland, Copenhagen, Denmark, 1992.

Higgins, A. K., J. R. Ineson, J. S. Peel, F. Surlyk, and M. Sønderholm, Lower Paleozoic Franklinian Basin of North Greenland, *Bull. Grønlands Geol. Undersøgelse, 160*, 71-139, 1991a.

Higgins, A. K., J. R. Ineson, J. S. Peel, F. Surlyk, and M. Sønderholm, Cambrian to Silurian basin development and sedimentation, North Greenland, in *The Geology of North America*, vol. E., *Geology of the Innutian Orogen and Arctic Platform of Canada and Greenland*, edited by H. P. Trettin, pp. 109-161, Geol. Surv. of Canada, Calgary, Alberta, 1991b.

Hodgson, D. A., Quaternary geology of the Queen Elizabeth Islands, in *The Geology of North America, vol. K-1, Quaternary Geology of Canada and Greenland*, edited by R. J. Fulton, pp. 443-477, Geol. Soc. of Am., Boulder, Co., 1989.

Hodgson, D. A., Episodic ice streams and ice shelves during retreat of the northwesternmost sector of the late Wisconsian Laurentide Ice Sheet over the central Canadian arctic archipelago, *Boreas, 23*, 14-28, 1994.

Jansen, E., The use of stable oxygen and carbon isotope stratigraphy as a dating tool, *Quat. Int., 1*, 151-166, 1989.

Jones, G. A., and L. D. Keigwin, Evidence from Fram Strait (78°N) for early deglaciation, *Nature, 336*, 56-59, 1988.

Köhler, S. E. I., Spätquartäre paläoozeanographische Entwicklung des Nordpolar-meeres und Europäischen Nordmeeres anhand von Sauerstoff- und Kohlenstoff-isotopenverhältnissen der planktischen Foraminifere *Neogloboquadrina pachyderma* (sin.), *GEOMAR Rep., 13*, 103 pp., Res. Center for Marine Geosci., Kiel, Germany, 1992.

Köhler, S. E. I., and R. F. Spielhagen, The enigma of oxygen isotope stage 5 in the central Fram Strait, in *Geological History of the Polar Oceans: Arctic versus Antarctic*, edited by U. Bleil, and J. Thiede, pp. 489-498, *NATO ASI Ser., vol. C 308*, Kluwer Academic Publishers, Norwell, Mass., 1990.

Lubinski, D. J., S. Korsun, L. Polyak, S. L. Forman, S. J. Lehman, F. A. Herlihy, and G. H. Miller, The last deglaciation of the Franz Victoria Through, northern Barents Sea, *Boreas, 25*, 89-100, 1996.

Mangerud, J., The Scandinavian Ice Sheet through the last interglacial/glacial cycle, in *Klimageschichtliche Probleme der letzten 30,000 Jahre*, edited by B. Frenzel, pp. 307-330, G. Fischer, New York, 1991.

Mangerud, J., and J. I. Svendsen, The last interglacial-glacial period on Spitsbergen, Svalbard, *Quat. Sci. Rev., 11*, 633-644, 1992.

Markussen, B., Late Quarternary sedimentation and paleoceanography in the eastern Arctic Ocean, Ph. D. thesis, 174 pp., Univ. of Oslo, Oslo, Norway, 1986.

Martinson, D. G., N. G. Pisias, N. D. Hays, J. Imbrie, T. C. Moore, and N. J. Shackleton, Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000 year chronostratigraphy, *Quat. Res., 27*, 1-29, 1987.

Meese, D., R. Alley, T. Gow, P. M. Grootes, P. Mayewski, M. Ram, K. Taylor, E. Waddington, and G. Zielinski, Preliminary depth-age scale of the GISP 2 ice core, *Cold Regions Res. and Eng. Lab. Spec. Rep., 94-1*, Hanover, N. M., 1994.

Mienert, J., L. Mayer, G. A. Jones, and J. W. King, Physical and acoustic properties of Arctic Ocean deep-sea sediments: Paleoenvironmental implications, in *Geological History of the Polar Oceans: Arctic Versus Antarctic*, NATO ASI Ser., vol. C 308, edited by U. Bleil and J. Thiede, pp. 455-473, , Kluwer Acad., Norwell, Mass., 1990.

Nørgaard-Pedersen, N., Late Quaternary Arctic Ocean sediment records: Surface ocean conditions and provenance of ice-rafted debris, Ph. D. thesis, 115 pp., Univ. of Kiel, Kiel, Germany, 1996.

Nowaczyk, N. R. and M. Baumann, Combined high-resolution magnetostratigraphy and nannofossil biostratigraphy for late Quaternary Arctic Ocean sediments, *Deep-Sea Res.*, *39*, suppl. 2, 567-601, 1992.

Nowaczyk, N.R., T. W. Frederichs, A. Eisenhauer, and G. Gard, Magnetostratigraphic data from late Quaternary sediments from the Yermak Plateau, Arctic Ocean: Evidence for four geomagnetic polarity events within the last 170 ka of the Brunhes Chron, *Geophys. J. Int.*, *117*, 453-471, 1994.

Okulitch, A. V., Geology of the Innutian Orogen and Arctic Platform of Canada and Greenland, in *The Geology of North America,* vol. E., *Geology of the Innutian Orogen and Arctic Platform of Canada and Greenland*, edited by H. P. Trettin, map sheet, scale 1: 200,000, no 3., Geol. Surv. of Canada, Calgary, Alberta, 1991.

Pagels, U., Sedimentologische Untersuchtungen und Bestimmung der Karbonatlösung in spätquartären Sedimenten des östlichen Arktischen Ozeans, *GEOMAR Rep.*, *10*, 106 pp, Res. Center for Marine Geosci., Kiel, Germany, 1992.

Peltier, W. R., Ice age paleotopography, *Science*, *265*, 195-201, 1994.

Pfirman, S., M. A. Lange, I. Wollenburg, and P. Schlosser, Sea ice characteristics and the role of sediment inclusions in deep-sea deposition: Arctic-Antarctic comparison, in *Geological history of the Polar Oceans: Arctic versus Antarctic*, NATO ASI Ser., vol. C 308, edited by U. Bleil and J. Thiede, pp. 187-211, Kluwer Acad., Norwell, Mass., 1990.

Phillips, R. L., and A. Grantz, Quaternary history of sea ice and paleoclimate in the Amerasia Basin, Arctic Ocean, as recorded in the cyclical strata of Northwind Ridge, *Geol. Soc. Am. Bull.*, *109*, 1101-1115, 1997.

Polyak, L., and A. Solheim, Late- and postglacial environments in the northern Barents Sea west of Franz Josef Land, *Polar Res.*, *13*, 197-207, 1994.

Poore, R.Z., R. L. Phillips, and H. J. Rieck, Paleoclimate record for Northwind Ridge, western Arctic Ocean, *Paleoceanography*, *8*, 149-159, 1993.

Sowers, T., M. Bender, L. Labeyrie, D. Martinson, J. Jouzel, D. Raynaud, J. J. Pichon, and Y. Korotkevich, 135,000 year Vostok-SPECMAP common temporal framework, *Paleoceanography*, *8*, 737-766, 1993.

Spielhagen, R. F. et al., Arctic Ocean evidence for late Quaternary initiation of northern Eurasian ice sheets, *Geology*, *25*, 769-864, 1997.

Stein, R., S. I. Nam, C. Schubert, C. Vogt, D. Fütterer, and J. Heinemeier, The last deglaciation event in the eastern central Arctic Ocean, *Science*, *264*, 692-696, 1994a.

Stein, R., C. Schubert, C. Vogt, and D. Fütterer, Stable isotope stratigraphy, sedimentation rates and paleosalinity in the latest Pleistocene to Holocene Central Arctic Ocean, *Mar. Geol.*, *119*, 333-355, 1994b.

Stein, R., S. I. Nam, H. Grobe, and H. Hubberten, Late Quaternary glacial history and short-term ice-rafted debris fluctuations along the East Greenland continental margin, in *Late Quaternary paleoceanography of the North Atlantic Margins*, edited by J. T. Andrews et al., *Geol. Soc. Spec. Publ.*, *111*, 135-151, 1996.

Stuiver, M., P. M. Grootes, and T. Braziunas, The GISP2 $\delta^{18}O$ climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes, *Quaternary Research*, *44*, 341-354, 1995.

Vogelsang, E., Paläo-Ozeanographie des Europäischen Nordmeeres an Hand stabiler Kohlenstoff- und Sauerstoffisotope, *Ber. Sonderforschungsbereich 313*, *vol. 23*, 136 pp., Univ. of Kiel, Kiel, Germany, 1990.

Vogt, C., Zeitliche und räumliche Verteilung von Mineralvergesellschaftungen in spätquartären Sedimenten des Arktischen Ozeans und ihre Nützlichkeit als Klimaindikatoren während der Glazial/Interglazial-Wechsel, *Ber. Polarforsch.*, *251*, 309 pp., Alfred-Wegener Inst. for Polar and Marine Res., Bremerhaven, Germany, 1997.

Weinelt., M., Veränderungen der Oberflächenzirkulation im Europäischen Nordmeer während der letzten 60,000 Jahre - Hinweise aus stabilen Isotopen, Ph. D. thesis, 105 pp., Univ. of Kiel, Kiel, Germany, 1993.

Zahn, R., B. Markussen, and J. Thiede, Stable isotope data and depositional environments in the late Quaternary Arctic Ocean, *Nature*, *314*, 433-435, 1985.

H. Kassens, N. Nørgaard-Pedersen, R. F. Spielhagen, and J. Thiede, Research Center for Marine Geosciences, GEOMAR, Wischhofstrasse 1-4, D24148 Kiel, Germany. (e-mail: nnoergaa@geomar.de)

(Received August 11, 1997; revised November 18, 1997; accepted November 26, 1997.)