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Past glacial and interglacial conditions in the Arctic Ocean and marginal seas – a review

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Abstract

Past changes in the Arctic Ocean and its marginal seas have been profound, even during the last 10,000 years. Understanding these changes, such as those occurring during the transition from glacial to interglacial climates, are important for research on modern processes, because this knowledge provides a framework and unique perspective in which to view the modern physical and biological processes. This paper discusses our current understanding of past environmental change and processes relative to those currently in progress. Special emphasis is placed on the most recent transition from a glacial state to the modern interglacial conditions.

Keywords: Arctic Ocean; Paleoclimate; Paleo-environment

1. Introduction

The Arctic Ocean is a complex natural system characterized by several sets of climatic, hydrographic, sedimentary, and biological features that make it unique among the Earth's oceans. The most distinctive features of the Arctic Ocean system are the perennial ice cover over most of the ocean, the relative importance of the continental shelves and shelf processes, and the complex interaction of water masses of various origins including the Atlantic, Pacific, and riverine sources. All of these features varied profoundly during the Quaternary times, thus incurring dramatic changes within and far beyond the Arctic Ocean. In order to assess the environmental changes in the Arctic over the last several decades, an understanding of the long-term changes is critical, not just for an historical perspective, but to understand these changes fully.

Repeated formation of large ice sheets in the Arctic and associated sea-level fluctuations immensely affected the Arctic Ocean during the Quaternary. This includes the exposure/inundation of shallow shelves, dramatic changes in water-exchange and circulation systems, and direct effects of ice sheets on sedimentary environments.

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The sedimentary records studied in the Arctic encompass the deep basins of the Arctic Ocean that have not been directly affected by sea-level changes and glacial erosion and are therefore most suitable for the study of the long-term history of Quaternary climates. Continental shelves and slopes, on the other hand, have generally higher sedimentation rates and thus provide more detailed sedimentary archives for the time period since the Last Glacial Maximum (LGM). In this paper we review the most revealing features of sedimentary records from both the deep basins and continental shelves/slopes that help to elucidate the past changes in the Arctic Ocean system. We focus our discussion on the dramatic shifts between glacial and interglacial conditions and the significant variations that occurred during the last interglacial (Holocene).

2. Quaternary glaciations and sea-level changes in the Arctic

There is an extensive body of evidence for the existence of large ice sheets at the periphery of the Arctic Ocean during Pleistocene glaciations, although their geometry and chronology are yet to be determined, except for the youngest glacial events (Fig. 1) (Dyke and Evans, 2003; Svendsen et al., 2004a; Spielhagen et al., 2004; and references therein). Thus, it is well documented that the Laurentide and Innuitian ice sheets coalesced into a huge ice-sheet complex that occupied most of northern North America and extended to the Arctic continental shelf during the Last Glacial Maximum (Dyke et al., 2002). Ice sheets of comparable dimensions occupied northern Eurasian, including the continental shelves of the Barents and Kara seas in the Middle Pleistocene; smaller, but still formidable ice sheets formed in that region during younger glaciations (Siegert and Dowdeswell, 2003; Astakhov, 2004; Svendsen et al., 2004a,b). Altogether, ice sheets during some glacial maxima covered more than 2/3 of the perimeter of the Arctic Ocean sparing the shelves of northeastern Siberia and Alaska that were largely subaerially exposed at lower glacial sea levels (Fig. 1). Due to the exceptionally high proportion of continental shelves in the Arctic Ocean (Jakobsson, 2002), the combined effect of glaciation and sea-level fall reduced the area of this ocean by as much as 50%, and had a profound effect on hydrographic, sedimentary, and biologic processes.

Vast extents of circum-Arctic glaciations inevitably resulted in the discharge of very large volumes of ice into the central basin of the Arctic Ocean. Recent findings show that ridges and plateaus in the ocean interior were affected by grounded ice at water depths reaching as deep as 1000 m (Vogt et al., 1994; Jakobsson, 1999; Polyak et al., 2001; Kristoffersen et al., 2004; Jakobsson et al., 2005). For example, the Lomonosov Ridge in

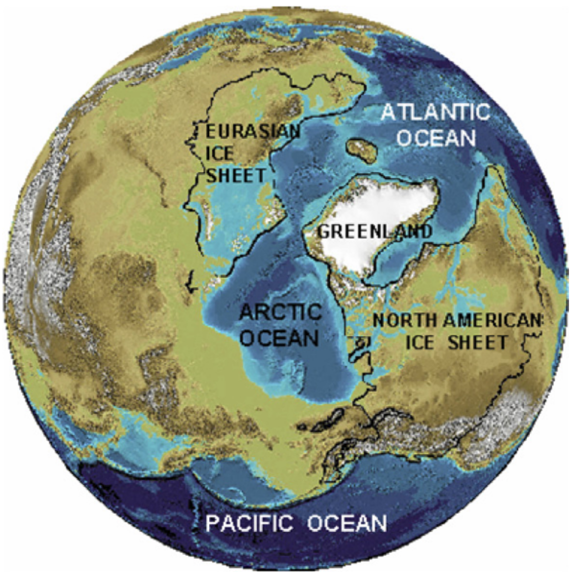

Fig. 1. Paleogeography of the Arctic Ocean during the Last Glacial Maximum. Base map – IBCAO (Jakobsson et al., 2000a). Limits of major ice sheet are from Dyke et al. (2002) and Svendsen et al. (2004a,b). During earlier glaciations the Eurasian Ice Sheet was more extensive on its Siberian side.

the center of the Arctic Ocean was eroded by an ice shelf and/or armadas of huge icebergs emanating from the Barents-Kara continental shelf (Jakobsson, 1999; Polyak et al., 2001; Kristoffersen et al., 2004); whereas, the Chukchi Borderland north of Alaska was repeatedly covered by grounded ice originating from the Laurentide Ice Sheet (Polyak et al., 2001; Jakobsson et al., 2005).

The disintegration of these huge, marine based ice sheets and ice shelves involved dramatic events related to pulses of iceberg and meltwater discharge (e.g., Knies et al., 2001; Darby et al., 2002; Knies and Vogt, 2003). During the last deglaciation large amounts of icebergs entered the Arctic Ocean in several pulses between ca. 18,000 and 12,000 calendar (cal.) years ago (Polyak et al., 1997; Knies et al., 2001; Knies et al., 2003; Darby et al., 2002; Andrews and Dunhill, 2003). These events were accompanied by the meltwater floods into the Arctic Ocean from North American proglacial lakes via the Mackenzie River drainage (Lemmen et al., 1994; Teller et al., 2002) and outbursts from glacially-dammed Eurasian rivers that occurred during earlier deglaciations and possibly during the last deglaciation as well (Polyak et al., 2002; Stein et al., 2002; Mangerud et al., 2004). Such sudden influxes of large quantities of freshwater must have had a profound effect on the hydrology and productivity in the surface waters of the central Arctic Basin and on the Arctic shelves since they re-submerged, ca. 10,000 years ago (ka).

3. Paleoceanographic environments in the Arctic Ocean during the glacial–interglacial cycles

Formation and disintegration of ice sheets at the Arctic margins, combined with ice shelves and iceberg armadas in the central basin, profoundly affected oceanic and atmospheric circulation, hydrological balance, biology, and sedimentation in the Arctic Ocean. Sediment cores recovered from across the central Arctic Ocean generally display a cyclic sequence of gray or gray-brown, nearly abiotic layers, and brown, faunal-rich beds. These cycles are interpreted to represent a succession of Pleistocene glaciations and interglacial/interstadial periods, respectively (Fig. 2) (e.g., Poore et al., 1994; Darby et al., 1997; Jakobsson et al., 2000b; Polyak et al., 2004). Brown beds, including the surficial Holocene interval, contain low to moderate amounts of ice-rafted debris (IRD, usually defined as coarser than 63 μm) and elevated concentrations of faunal remnants and chemical species indicative of an oxidizing environment, primarily Mn oxides. Gray beds corresponding to glacial periods are almost unfossiliferous and largely fine-grained, but some contain prominent IRD layers

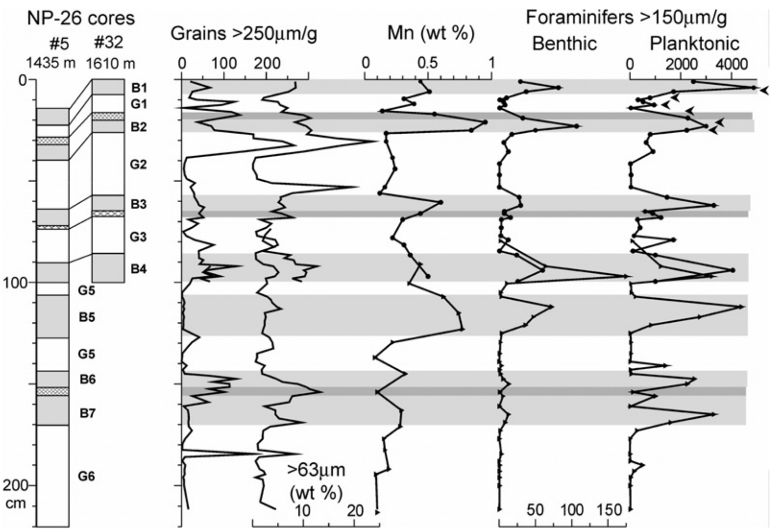

Fig. 2. Example of the stratigraphy of bottom sediments from the Mendeleev Ridge, western Arctic Ocean (from Polyak et al., 2004). Indices to the right of the lithologic columns show lithologic units (B – brown, G – grey). Brown (interglacial) beds are shaded; a criss-cross pattern or darker shading shows pink-white detrital-carbonate layers used as stratigraphic markers. Arrows next to the planktonic foraminiferal curve show position of ^{14}C ages. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of the Polyak article.)

near the top and/or bottom of gray units that may extend into the adjacent brown interglacial unit (Fig. 2). Overall, glacial intervals have very low sedimentation rates and may contain hiatuses (Darby et al., 1997; Nørgaard-Pedersen et al., 1998; Stein et al., 1994b; Stein et al., 2003; Polyak et al., 2004). Higher resolution records such as in the Fram Strait indicate episodes within the glacial intervals when significant amounts of icebergs passed through the Arctic Ocean (Darby et al., 2002).

3.1. Lithology

The distinct alternation of brown and gray lithological units provides a preliminary correlation tool for sediment cores in the Arctic Ocean and reflects variation in the degree of sediment oxidation resulting from changes in ventilation of bottom waters, although the exact mechanisms for these changes are still speculative (Jakobsson et al., 2000b; Polyak et al., 2004). One likely process is the down slope sinking of dense bottom waters into the Arctic basins from adjacent shelves, a process related to sea-ice formation and cooling of advected Atlantic waters. During glacial intervals, continental shelves were largely exposed and others like the Barents and Kara Seas were wholly or partially occupied by ice sheets (Fig. 1), which dramatically reduced the sites for deep-water formation. We note that sediment oxidation is also a function of the rates of sediment burial below the redox boundary, so that on the continental slopes and adjacent areas where turbidity flows and drift deposits result in higher sedimentation rates, even well ventilated environments are characterized by grayish sediment coloration (e.g., Darby et al., 2001).

IRD in Arctic deep-sea cores can be derived from icebergs and/or sea ice and occurs throughout glacial and interglacial intervals, but its amount and composition vary significantly. Glacial (iceberg rafted), coarse (usually measured as >250 μm) IRD is often concentrated in spikes related to iceberg discharge events, where its concentration may exceed 30% of the total dry-sediment weight (Fig. 2) (e.g., Knies et al., 2001; Darby et al., 2002; Spielhagen et al., 2004). During interglacials, IRD is dominated by sea-ice rafting and its amount is generally less than 1–2% in the central Arctic Ocean, but can increase to >10% on some occasions. Thus, while IRD texture gives an approximate indication of the type of sedimentation regime, it can be misleading and needs to be supplemented by the determination of sediment sources and details of the IRD size distribution. Considering both texture and sediment provenance provide a much sounder interpretation of sea ice versus iceberg rafting. For example, fine sand-sized IRD from unglaciated shelves are clearly sea ice-rafted. There are few provenance indicators that can provide accurate source identification, such as unique mineral or lithic grains or a geochemical signature. Lithic fragments are commonly used to identify the source of iceberg-derived IRD (Bischof et al., 1996; Phillips and Grantz, 2001), but they are less helpful for sea-ice material that is dominated by fine sand-sized grains, mostly quartz. A basis for identification of the sources of both glacial and sea-ice debris can be provided by the geochemistry of individual detrital Fe minerals, a technique that has been successfully used in several Arctic studies (Darby et al., 2002; Darby, 2003; Darby and Bischof, 2004). One important result of these studies is that sea-ice IRD is ubiquitous and commonly occurs not only in the interglacials, but also during glacial times. Thus some sea ice forms along the outer margins of the largely exposed Arctic shelves during lower sea levels of glacial intervals.

3.2. Deposition rates

While the deposition rates in the Arctic Ocean over the entire Pleistocene are still debatable (Backman et al., 2004), the last glacial and Holocene are well documented by radiocarbon chronology (e.g., Darby et al., 1997; Nørgaard-Pedersen et al., 2003; Stein et al., 2003; Polyak et al., 2004). These results suggest average Holocene rates in the central Arctic of about 1 cm^{-ka}, increasing near the continental margins to a few cm^{-ka} and in some locations along the continental slopes where possible drift deposits have been found, rates can exceed 1.5 m^{-ka} in the Holocene. During glacial periods, exemplified by the last glaciation, deposition rates display a much larger variability, reaching tens of cm^{-ka} during episodes of massive iceberg discharge, but decreasing to very low values or even forming a hiatus of up to several thousand years during the glacial maximum in the Amerasian Basin (Fig. 3). This drop in the deposition rates is coupled with the absence of faunal remnants and indicates that a very thick and solid packice or even an ice shelf that suppressed both biological productivity and lithic deposition capped the water column in this region.

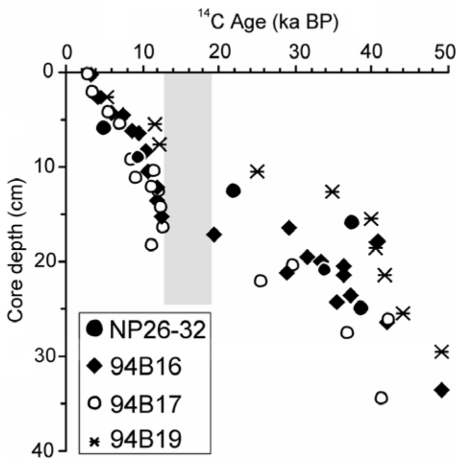

Fig. 3. Age-depth distribution in sediments from the Mendeleev Ridge area (Polyak et al., 2004). Reservoir correction applied is 440 yr (Mangerud and Gulliksen, 1975); however, actual reservoir time could be larger in the Arctic Ocean, especially during glacial periods. Shading highlights a possible hiatus between 13 and 19 ka.

3.3. Fossil record

Biological proxies most commonly found and investigated in the Arctic Ocean sediments are foraminiferal tests (e.g., Scott et al., 1989; Poore et al., 1994; Polyak et al., 2004). Other paleontological specimens are either limited to episodic high-productivity interglacial environments (dinocysts, coccoliths), or are profoundly affected by dissolution except in drift deposits (diatoms, radiolarians). The temporal distribution of foraminifers, corroborated by data available for other biological proxies, fluctuated dramatically, peaking during the interglacial/interstadial periods and strongly decreasing during glacial times, which is presumably associated with drastic reduction in organic productivity (e.g., Poore et al., 1994; Phillips and Grantz, 1997; Darby et al., 1997; Spielhagen et al., 2004). This pattern is especially evident in the Western Arctic, where glacial foraminiferal numbers decrease to nearly zero (Fig. 2). In contrast, detailed studies of sediment cores from the Eurasian Basin indicate relatively high-productive episodes within glacial periods, presumably related to the advection of North Atlantic waters and adiabatic winds flowing off the Barents Ice Sheet to create polynyas (Knies et al., 1999; Spielhagen et al., 2004). In cores with elevated sedimentation rates, variations in the amounts and composition of foraminifers and other biological proxies are also recorded for interglacials including the Holocene (Darby et al., 2001; Wollenburg et al., 2004).

While planktonic foraminifers in the Arctic are represented largely by one species, *Neogloboquadrina pachyderma* (left-coiling), benthic foraminiferal fauna is characterized by a well-pronounced diversity. Although the controls on the habitats of benthic foraminifers in the Arctic Ocean are not completely understood, we recognize distinct patterns in the modern distribution of foraminiferal assemblages reflecting a bathymetric zonation, changes in water masses and/or sea-ice conditions (Lagoe, 1977; Polyak, 1990; Scott and Vilks, 1991; Ishman and Foley, 1996; Wollenburg and Mackensen, 1998). Variations in foraminifera abundance and distribution form an actualistic basis for a comprehensive reconstruction of paleoenvironments in the Arctic Ocean during the Late Cenozoic.

3.4. Stable isotopes

Similar to glacial–interglacial fluctuations in foraminiferal numbers, stable-isotope compositions in foraminiferal tests, especially in planktonic foraminifers, show strong variability that increases towards the western Arctic Ocean (Fig. 4). As planktonic foraminifers in the Arctic live within a wide range of several tens of meters below the surface, with most calcification occurring below the mixed surface layer, oxygen and carbon stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) in foraminiferal tests are used for evaluating the subsurface hydrography

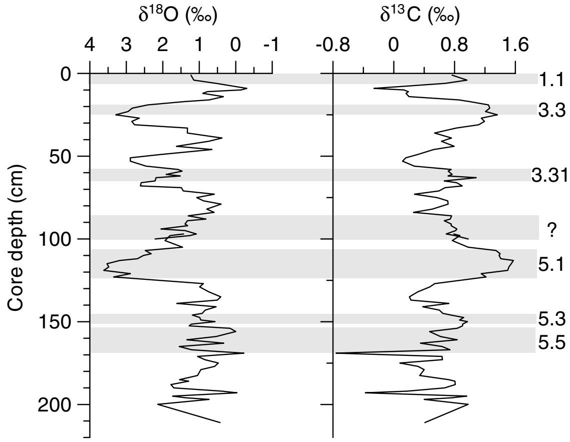

Fig. 4. Stable-isotopic records from the Mendeleev Ridge, western Arctic, showing glacial–interglacial contrasts (Polyak et al., 2004). Interglacial/ interstadial intervals are shaded and tentatively correlated with standard Marine Isotope Stages (on the right) via correlation with stratigraphies in the eastern Arctic Ocean (Jakobsson et al., 2000b; Jakobsson et al., 2001; Backman et al., 2004).

(Bauch et al., 1997; Volkmann, 2000; Volkmann and Mensch, 2001; Hilliare-Marcel et al., 2004). Mixing of isotopically light fluvial runoff and marine, Atlantic-derived water primarily controls the water $\delta^{18}O$ composition in the Arctic Ocean (Schlosser et al., 2000). Accordingly, both the lateral and vertical distribution of $\delta^{18}O$ in the Arctic Ocean correlates strongly with salinity. The equilibrium calcite $\delta^{18}O$ is additionally affected by temperature that is linked with the advection of Atlantic water. This results in a lowering of $\delta^{18}O$ equilibrium calcite in the subsurface water by almost 1‰ in the Eurasian Basin (Bauch et al., 1997; Lubinski et al., 2001), but in the Amerasian Basin, where the Atlantic influence is weaker, this lowering is much smaller.

The modern distribution of planktonic foraminiferal $\delta^{18}O$ in the Arctic Ocean, except for the area near the Fram Strait that is affected by warm Atlantic water, suggests that down-core $\delta^{18}O$ variations will primarily reflect the history of the freshwater budget rather than temperature changes. Indeed, $\delta^{18}O$ fluctuations in sediment cores from the central and, especially, western Arctic Ocean are generally characterized by heavier values in interglacial/interstadial intervals and light peaks associated with glacial beds (Fig. 4; Polyak et al., 2004; Spielhagen et al., 2004), in contrast to the global open ocean $\delta^{18}O$ stratigraphy that extends into the Greenland Sea and adjacent area of the Eurasian Basin (Nørgaard-Pedersen et al., 2003). The youngest $\delta^{18}O$ minima in records from the central and western Arctic Ocean represent meltwater events corresponding to the last deglaciation of the adjacent Arctic margins (Stein et al., 1994a; Nørgaard-Pedersen et al., 1998; Poore et al., 1999; Polyak et al., 2004; Spielhagen et al., 2004). We infer that older $\delta^{18}O$ minima in Arctic Ocean cores also reflect deglacial events. Some interglacials and/or interstadial intervals in the western Arctic Ocean have maxima (heavy spikes) of planktonic $\delta^{18}O$ that are heavier than modern values by as much as 2‰. Because water could not have been much colder than modern temperatures that are just slightly above the freezing point, these heavy $\delta^{18}O$ spikes reflect anomalous reductions in the amount of fresh water in the Arctic Ocean. The causes of these events of increased salinity are not well understood and require further investigation.

The modern values of $\delta^{13}C$ in planktonic foraminifera in surficial sediments increase from the Fram Strait towards the Amerasian Basin despite an increase in ice coverage (Spielhagen and Erlenkeuser, 1994). This pattern may be explained by a shift in habitats of subsurface plankton to surface/halocline waters, because the shelf-born halocline water is better ventilated than the Atlantic-derived water (e.g., Anderson et al., 1999). The high interglacial/interstadial planktonic $\delta^{13}C$ values observed in cores from the Arctic Ocean (Fig. 4) (Poore et al., 1999; Polyak et al., 2004), therefore, reflect the import of surface and halocline water from well-ventilated shelves, such as occurs today (cf. Bauch et al., 2000). In contrast, during glacial periods with low sea levels and ice-sheet growth, fluxes of water from the shelves to the Arctic Ocean interior were greatly reduced, which resulted in low $\delta^{13}C$ values. This lowering was possibly enhanced by a more solid ice cover that reduced air-sea exchange of CO_2.

The general co-variation of down-core changes in planktonic $\delta^{13}C$ and $\delta^{18}O$ in the Arctic Ocean records indicates the possibility of a common control. This control could be the restriction or slowing of circulation during glacial periods and the resulting pooling of surface water, especially in the western Arctic Ocean (Poore et al., 1999; Nørgaard-Pedersen et al., 2003). Such pooling would maintain low $\delta^{18}O$ values by a build-up of runoff and/or meltwater and low $\delta^{13}C$ due to reduced ventilation.

4. Paleoceanographic environments of the last deglaciation and the Holocene – shelf records

Circum-arctic continental shelves have considerably higher sedimentation rates than the central basins, especially in areas with high inputs of riverine suspended load (Kara and Laptev seas) and in ice marginal zones (e.g., Barents Sea). Sedimentary records from these shelves therefore contain a wealth of information on paleoenvironments since the LGM and the associated low sea-level stand.

4.1. Siberian shelves: the transition from dry land to shelf environment, the influence of runoff

Due to intensive recent investigations of sediments along the north Siberian margin, notably in the Kara and Laptev seas, this region is now probably the most comprehensively studied seafloor along the Arctic margins (Bauch et al., 1999; Stein et al., 2004 and references therein). Radiocarbon dated sediment cores from various water depths across the shelf and slope provide insight into the history of vast Siberian shelves since the last glaciation. Whereas most of the shelf areas east of Taymyr Peninsula were subaerially exposed during the LGM, the postglacial sea level rise transformed them from a periglacial permafrost landscape into a modern shallow shelf (Bauch et al., 1999; Bauch et al., 2001b). Micropaleontological, sedimentological, and geochemical studies of sediment cores allow reconstruction of not only the postglacial inundation history, but also of concomitant paleoceanography and climate-driven environmental change (Bauch et al., 2001a; Fig. 5).

The hydrography of the Kara and Laptev seas is profoundly influenced by large amounts of Siberian river runoff discharged during summer. Tracer studies show that river water, delivered to the Arctic Ocean mainly by the large Siberian rivers, constitutes a significant portion of the ~50-m thick, low-salinity surface water layer and overlying sea-ice cover. Since a substantial part of the Arctic sea ice, which drifts through Fram Strait within a few years, is also produced on the broad Siberian shelves, these areas are especially important for our understanding of marine environmental changes in the northern high latitudes. A critical issue that requires further study is the temporal variability of runoff and ice formation in the marginal arctic seas. Based on shelf-sediment-core studies, large temporal changes in hydrographic conditions are observed in the postglacial sedimentary records. For example, stable isotope ratios in water and consequently in calcareous fossils on Siberian shelves are primarily affected by riverine discharge, thus enabling the interpretation of past variations in runoff and its interaction with marine waters (Bauch et al., 2003; Polyak et al., 2003; Simstich et al., 2004). Notably, an important step in addressing the issue of interannual runoff variability is achieved by the study of annual growth layers of bivalve shells (Mueller-Lupp et al., 2003; Mueller-Lupp and Bauch, 2005; Fig. 5).

In addition to water discharge, the Siberian rivers also deliver large amounts of suspended particulate material including organic carbon. Characteristics of the organic carbon in marine sediments such as the $\delta^{13}C$, C/N ratio, Rock-Eval pyrolysis data for organic matter, and biomarkers allow determination of the terrestrial or marine provenance of the organic fractions (Stein et al., 1999; Fahl and Stein, 1999; Fahl et al., 2003). Thus, the composition of the arctic shelf sediments helps to trace land-to-ocean pathways of organic matter and to identify temporal depositional changes. Landward shifts over thousands of years (time-transgressive) in accumulation rates of total organic matter and sediment, coupled with a significant increase in the content of terrestrial organic fractions, reflect the continuously rising postglacial sea level and the resulting southward retreat of the coastline and, thus, main sediment depocenters on the shelf (Mueller-Lupp et al., 2000; Stein and Fahl, 2000, 2003; Stein et al., 2004). After reaching its Holocene maximum at about 6–5 ka, the sea level stabilized, eventually leading to the establishment of modern depositional environments characterized by ice-free conditions and enhanced bioproductivity during the short summer season (Bauch et al., 2001a, 2004; Stein et al., 2004).

To interpret in more detail the major environmental changes that occurred on the shelves during and after the postglacial sea-level rise, paleontological tools offer a wealth of possibilities (Fig. 5). Based on modern

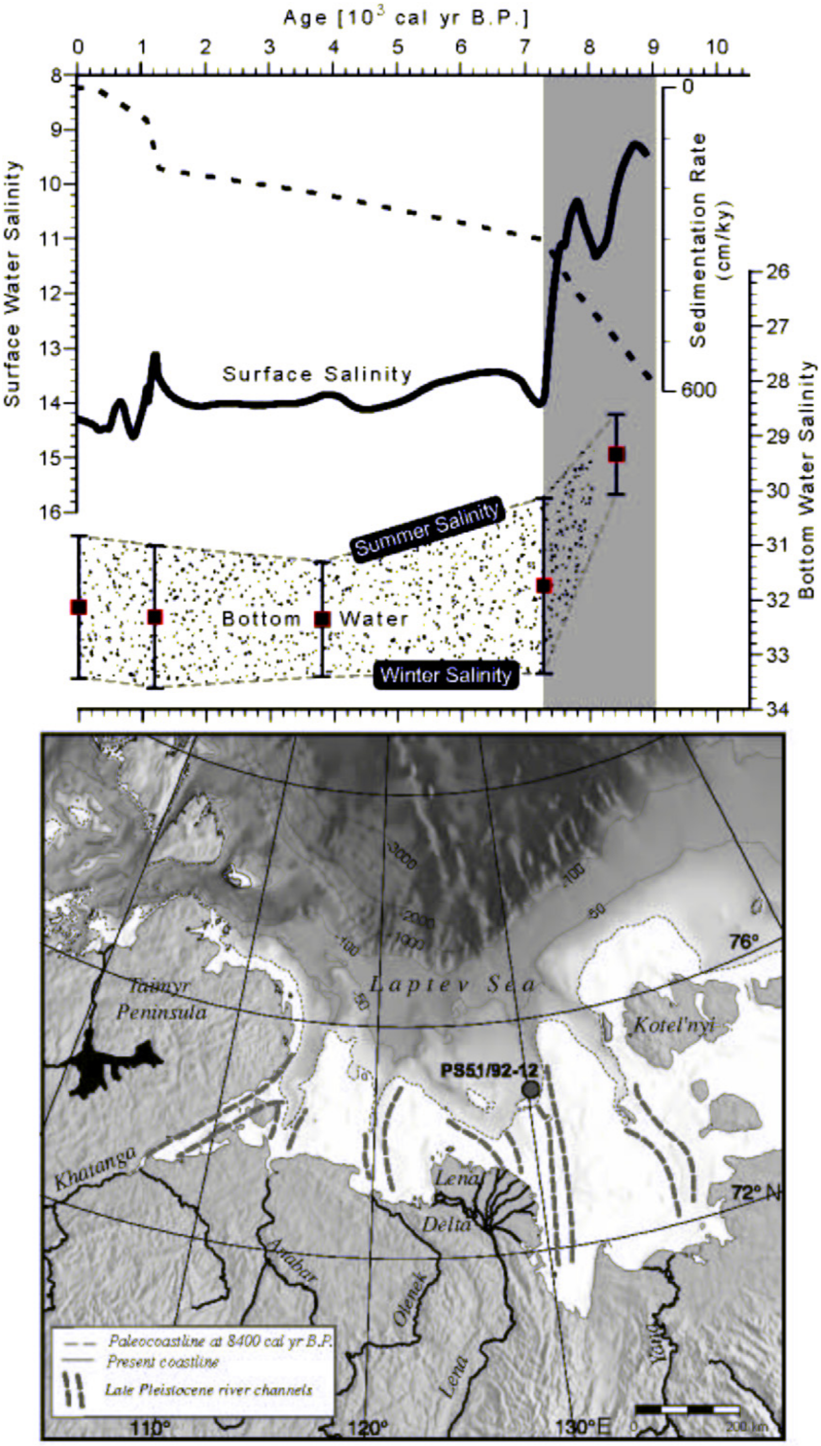

Fig. 5. Exemplified paleoenvironmental changes on the Laptev Sea mid-shelf (core PS51/92-12) during and after the Holocene global sea level rise. The transgressing sea after the last glaciation led to a drastic depositional increase in sediments on the shallow shelf due to reworking and erosion of the formerly subaerially exposed glacial landscape. During this time, the north-to-south moving coastline with its river mouths as main freshwater source caused a gradual change in surface and bottom water salinities (after Bauch et al., 2001b; Bauch and Polyakova, 2003; Mueller-Lupp et al., 2004).

analogues, which are applied to evaluate major ecological preferences, various fossil groups such as diatoms, dinocysts, aquatic and terrestrial palynomorphs, ostracods, foraminifers, and bivalves all provide ample evidence of the profound transformation from fluvial to marine environments (Kunz-Pirrung, 1999; Naidina and Bauch, 2001; de Vernal et al., 2001; Bauch and Polyakova, 2003; Stepanova et al., 2003; Polyakova and Stein, 2004). In addition, ecological characteristics of both planktonic and benthic fossil communities allow the interpretation of past water depths, depositional settings, and influence of paleo-river discharge on the shelf hydrography (Taldenkova et al., 2005).

Overall, the postglacial paleoenvironmental change on the shallow Siberian shelf can be subdivided into three major phases: (1) an early fluvial period characterized by high deposition of terrigenous material and dominance of freshwater biota, mainly from terrestrial sources due to riverine discharge and coastal erosion; (2) a brackish-marine, transitional phase marked by increasing appearance of marine biota and decreasing sediment input from land; (3) a shallow marine environment with relatively low sedimentation rates and modern-like distribution of aquatic biota on the shelf. Smaller, yet considerable changes in hydrographic conditions during the later phase were driven by variations in river discharge (e.g., Bauch and Polyakova, 2000; Stein et al., 2004; Fig. 5). Investigating recent runoff fluctuations, on interannual to decadal time scales, is especially important for the evaluation of future changes in the Arctic hydrography.

4.2. Marginal Ice Zone

Unlike the runoff dominated Siberian shelf exemplified by the Kara and Laptev seas, hydrologic and biological processes in the Barents and Chukchi seas are most profoundly affected by interaction of Arctic and subarctic (Atlantic and Pacific, respectively) waters and processes in the Marginal Ice Zone (MIZ). While the history of MIZ in the Chukchi Sea is in the initial phase of investigation (Darby et al., 2001; Lundeen et al., 2004; de Vernal et al., 2005), more is known about the postglagial development of the Barents Sea (e.g., Polyak et al., 1996; Hald et al., 1999; Lubinski et al., 2001; Voronina et al., 2001; Sarnthein et al., 2003). The Barents Sea continental margin was entirely covered by a grounded ice sheet during the LGM and largely deglaciated by ca. 13 ^{14}C ka ago (Fig. 1) (Svendsen et al., 2004b and references therein). The relatively high sea level at this time, combined with generally large water depths and additional glacioisostatic depth increase, resulted in a negligible effect of sea-level change on post-glacial development of the Barents Sea. Meanwhile, the hydrographic system, characterized by an intense interaction of Atlantic and polar waters, and the MIZ position underwent considerable variations that were likely controlled by both climatic and dynamical oceanographic factors. Following the complete deglaciation of the Barents Sea, the early Holocene conditions were characterized by seasonally ice-free water and possibly elevated productivity throughout a large portion of the Barents Sea, consistent with warm summer temperatures in the region (Salvigsen et al., 1992; Polyak et al., 1996; Lubinski et al., 2001; Sarnthein et al., 2003). However, the strongest influence of advected Atlantic waters in the eastern Barents Sea and farther east along the Eurasian margin occurred later on, between $\sim$8 and 6 cal. ka ago (Polyak et al., 1996; Duplessy et al., 2001; Lubinski et al., 2001; Voronina et al., 2001). We hypothesize that this Atlantic maximum was primarily controlled by dynamic factors, possibly associated with changes in the North Atlantic circulation after the complete deglaciation of the Canadian Arctic (Williams et al., 1995). The subsequent development of the Barents Sea system featured generally more restricted Atlantic influence and a more southerly position of the MIZ, but with considerable fluctuations and possibly a return to mid-Holocene influx levels of Atlantic waters to the Barents Sea by 4.7 cal. ka (Duplessy et al., 2005; Lubinski et al., 2001; Voronina et al., 2001). The latter were probably related to North Atlantic Oscillation-type processes, especially pronounced in winter, as indicated by paleo-environments in the Norwegian Sea (Risebrobakken et al., 2003; Moros et al., 2004). More investigations of postglacial changes in MIZ on the arctic shelves are needed to understand the Holocene history of climate and ocean dynamics in the Arctic.

5. Shelf–ocean interaction

The dispersal and fate of arctic runoff and sea ice are the basic elements for understanding past and future climate change in the Arctic and beyond the polar regions. A critical issue is not only the temporal variability of runoff and ice formation in the marginal Arctic seas, but also the extended freshwater propagation into the

Arctic Ocean and the adjacent Nordic seas. Because sedimentation rates in the Arctic Ocean basins are overall considerably lower than at the margins, it may not be possible to trace all fluctuations of runoff and sea-ice inputs in the deep-sea sedimentary records. An important task therefore is to identify sites with increased temporal resolution and to develop a correlation of paleoceanographic events throughout the Arctic Ocean and into the Nordic seas on a sub-millennial time scale. The most telling types of data that allow tracing the paleo-dispersal of ice and freshwater in the Arctic Ocean are stable-isotopic and IRD compositions in sedimentary records.

5.1. Stable-isotopic indications of meltwater events

Periods of disintegration of ice sheets at the Arctic periphery resulted in dramatic pulses of freshwater discharge that need to be distinguished from runoff fluctuations. These events are identified based mainly on planktonic stable-isotope composition and IRD distribution in sediment cores from the central and marginal parts of the Arctic Ocean. Despite some uncertainties regarding the residence time of the surface water mass, the initial freshwater pulse of the last deglaciation can be traced in the eastern Arctic Ocean by a prominent $\delta^{18}O$ minimum as early as 15–14 ^{14}C ka (Stein et al., 1994a; Nørgaard-Pedersen et al., 1998). A similar timing for an early deglacial meltwater release has also been recognized farther south in Fram Strait and the neighboring Nordic seas (Jones and Keigwin, 1988; Weinelt et al., 1991; Bauch et al., 2001b), supporting the idea of an early response of the high northern latitudes to climate change at the beginning of the last glacial–interglacial transition. The marine-based Barents/Kara Ice Sheet is the most obvious source of this early meltwater event (Polyak et al., 1995; Svendsen et al., 2004b), but there were also large contributions from the North American ice sheets (Darby et al., 2002). The $\delta^{18}O$ minimum in the western Arctic Ocean is centered at a somewhat later time of ka. 12 ^{14}C ka (Poore et al., 1999; Polyak et al., 2004). Data on concomitant barium content (Hall and Chan, 2004) and indications that icebergs from the Laurentide Ice Sheet peaked at about this time (Darby et al., 2002) suggest that this meltwater event was primarily associated with deglaciation at the North American side of the basin. At the Laptev Sea continental margin, a pronounced freshwater spike is recognized in planktonic foraminiferal $\delta^{18}O$ at ca. 11.5 ^{14}C ka (Spielhagen et al., 2005). It remains to be investigated how these events are related between each other and with changes in deep water convection in the Nordic seas, which possibly caused the widespread climate cooling known as the Younger Dryas (Bauch et al., 2001b; Tarasov and Peltier, 2005). More detailed studies of Arctic meltwater events are needed to understand the connection of environmental changes in the Arctic Ocean and its marginal seas with regions outside the Arctic.

The available Holocene records from the Arctic Ocean have smaller amplitudes of stable-isotopic curves (Nørgaard-Pedersen et al., 1998; Poore et al., 1999; Hilliare-Marcel et al., 2004), generally consistent with smaller variability of interglacial freshwater inputs in comparison with deglacial events. The comprehensive interpretation of these records is hampered by insufficient spatial resolution and by uncertainties about life and calcification patterns in Arctic planktonic foraminifera. These uncertainties, for example, do not allow unequivocal interpretation of moderate $\delta^{18}O$ variability as resulting primarily from temperature or salinity changes (Poore et al., 1999; Hilliare-Marcel et al., 2004).

5.2. Sources of IRD from icebergs – indications of ice sheets and their rapid decay

Instabilities and collapses of ice sheets surrounding the Arctic Ocean during glacial periods are reflected in IRD events in sedimentary records. When tracked across the basin, these events provide valuable information on the conditions of the ice sheets and the concomitant Arctic circulation. Provenance studies of the IRD and enclosing sediment indicate that icebergs in the eastern Arctic have mostly originated from the Eurasian ice sheets (Knies et al., 2001; Knies and Vogt, 2003; Spielhagen et al., 2004). Over the last ~150 ka, these inputs were especially large during earlier glaciations, but more modest during the LGM. Iceberg-rafted deposits in the western Arctic show a more complex picture with prevailing contributions from the North American sources including several events during the last deglaciation (Bischof and Darby, 1997; Phillips and Grantz, 2001; Darby et al., 2002).

There are two dominant sources for the IRD deposited from the icebergs that calved from North American ice sheets. One is the Banks and Victoria Island area, the loci of ice flow out of the northern Laurentide Ice Sheet into the Arctic Ocean. The other is the Queen Elizabeth Islands of northern Canada. Evidence for both of these is two-fold: studies of the glacial morphologies preserved on land (Clark and Stokes, 2001; Stokes and Clark, 2001; Dyke et al., 2002) and IRD studies in cores from the Arctic Ocean and Fram Strait (Bischof and Darby, 1997; Phillips and Grantz, 2001; Darby et al., 2002). These ice sheets depressed the adjacent shelves by tens of meters during the glacial maximum, only to have them rebound soon after the ice melted. There are several sharp peaks of IRD from specific ice sheet sources, suggesting that the volume of calving icebergs was not constant but marked by short-lived purges. This is consonant with rapid disintegration of parts of ice sheets (Clark and Stokes, 2001; Stokes and Clark, 2001; Darby et al., 2002; Stokes et al., 2005). One of these peaks near 18 calendar ka ago in the Fram Strait is well dated and suggests duration of about a few centuries. Thus large amounts of icebergs calved into the western Arctic Ocean from northern Canada and drifted out of the Arctic through Fram Strait and the timing of these iceberg armadas corresponds closely to or precedes Heinrich Events in the North Atlantic, which are due to the collapse of the eastern Laurentide Ice Sheet through Hudson Strait.

5.3. Sea ice surface drift patterns in the Holocene

The drift of sea ice in the Arctic today is a direct response to surface atmospheric pressure gradients (Thompson and Wallace, 1998; Rigor et al., 2002). Any change in these pressure gradients, such as the Arctic Oscillation, has a profound effect on the both the pattern and velocity of ice motion in the Arctic Ocean (Fig. 6). Thus the appearance of iron grains from Siberian sources in modern floes in the Beaufort Sea is direct

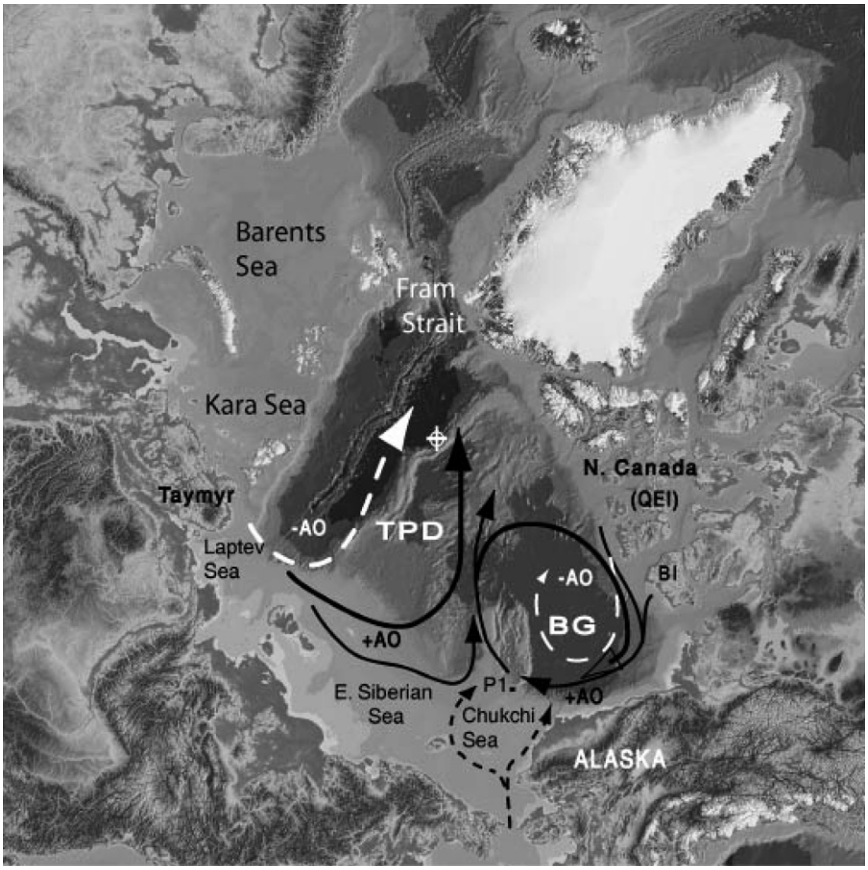

Fig. 6. Modern Arctic surface circulation dominated by the Trans-Polar Drift (TPD) and the weaker Beaufort Gyre (BG) is shown as drift patterns for a positive Arctic Oscillation (+AO) scenario (solid black) and a-AO (dashed white). Northward drift from the Bering Strait is shown by dashed black. Important source areas during-AO and a stronger BG include the shelf off Banks Island (BI) and the Mackenzie River (Darby and Bischof, 2004).

evidence of the net effect of the Trans Polar Drift shifting towards Alaska and the capture of floes that originated in the Laptev Sea by the Beaufort Gyre (Darby, 2003; Darby and Bischof, 2004). The fact that this source of Fe grains in cores from the Chukchi margin routinely alternates in relative abundance with North-American sources with a century-scale quasi-periodicity in the Holocene suggests that the atmospheric pressure system responsible also has a similar history of change. Thus the Arctic Oscillation and its close cousin the North Atlantic Oscillation have a long history of fluctuation that influences sea ice drift and potentially ice export into the Nordic Seas stretching back thousands of years. The appearance of sand-size Fe grains from the Russian shelves such as the Laptev Sea, during the last several glacial cycles suggests that a similar drift pattern existed during the Pleistocene for both the interglacial and at least portions of glacial intervals (Polyak et al., 2004; D. A. Darby, unpublished data).

6. Summary

The Quaternary history of the Arctic Ocean is marked by dramatic changes in paleoceanographic and climatic regimes related to glaciations of the Arctic periphery and sea-level fluctuations. These changes affected all aspects of the Arctic Ocean system, including hydrography, sedimentation, and biota. The last major revolution of arctic environments occurred during the last glacial to Holocene transition circa 10 ka ago. Besides the disappearance of large ice sheets in many parts of the circum-Arctic, the associated climatic warming, the rising sea level, and atmospheric changes affected environmental conditions dramatically in the central Arctic Ocean and its marginal regions. During this transition, the shallow continental shelf became widely flooded, which precipitated a profound reorganization of the circum-Arctic environment, from a dominantly terrestrial-fluvial to a marine environment with a strong fluvial influence over the vast width of the Siberian shelves. Time-transgressive changes in sedimentation together with geochemical and micropaleontological proxy data give clear evidence of the southwardly transgressing sea on the shallow shelves until about 5–6 ka. After that time, the modern sea-ice regime and hydrological patterns were fully developed in the Arctic, including enhanced water-mass exchange with the adjacent sub-polar seas through Fram Strait, Bering Strait, the Canadian Archipelago, and across the Barents Sea.

Centennial- to millennial-scale climate changes are also documented in the Arctic during the Holocene, primarily in sedimentary records from continental margins that have higher sedimentation rates and thus provide better time resolution. These changes include fluctuations in the pattern of ice rafting, the position of the Marginal Ice Zone, and temperature and salinity in both surface and subsurface water masses. Interpretation and causes of these changes are still under investigation, but there is little doubt that these Holocene climatic variations are at least as significant as recent warming.

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