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History of Atlantic Water Advection to the Arctic Ocean: A Review of 20 Years of Progress Since the “Oden”–“Polarstern” Expedition ARCTIC 91*

by Robert F. Spielhagen

Abstract: The variability of Atlantic Water advection to the Arctic Ocean is described for the last about 50 million years based on available published sources. Until the opening of the Fram Strait as a deep-water passage at about 17 million years before present the inflow of Atlantic Water may have occurred through gaps in morphologic barriers, but results from microfossil findings are in part contradictory and difficult to interpret. After the opening, brownish deep-sea Arctic sediments reflect well-oxygenated deep-sea conditions and an improved exchange with the North Atlantic. The build-up of first ice sheets on northern Eurasian continental and shelf areas in the Late Tertiary may have resulted in intensive brine formation at the ice sheet margins and a significantly weaker influence of Atlantic Water on the Arctic intermediate waters. The history of Quarternary glacial-interglacial variability in the central Arctic is not well understood for most of the last 2 million years due to the lack of carbonate microfossils. For the last 200,000 years, however, short intervals of intensive Atlantic Water advection during interglacials and interstadials can be clearly identified in a number of sediment cores. Seasonally open water conditions (i.e., reduced sea ice) during these periods and even during maximum glaciation at Arctic continental margins probably made additional moisture available for the (re)growth of adjacent ice sheets. After the last deglaciation, Atlantic Water quickly returned to the Arctic and established conditions close to the modern ones. High-resolution records from the Fram Strait, however, indicate a rapid temperature rise of the Atlantic Water layer during the last 100 years, which most probably reflects on-going global warming and the so-called “Arctic Amplification“.

Zusammenfassung: In diesem Artikel wird die Veränderlichkeit des Einstroms von Atlantikwasser in die Arktis für die letzten ca. 50 Millionen Jahre beschrieben, basierend auf publizierten Quellen. Bis zur Öffnung der Framstraße vor ca. 17 Millionen Jahren konnte Atlantikwasser höchstens durch Lücken in morphologischen Barrieren in den Arktischen Ozean einströmen, doch sind die Ergebnisse von Mikrofossilfunden in dieser Hinsicht z. T. widersprüchlich und nicht eindeutig interpretierbar. Bräunliche arktische Tiefseesedimente sind ein deutlicher Hinweis auf gut durchlüftete Wassermassen in der Tiefsee in der Zeit nach der Öffnung und auf einen verbesserten Austausch mit dem Nordatlantik. Der Aufbau erster Eisschilde auf den Land- und Schelfgebieten im nördlichen Eurasien im Spätquartär (letzte 200.000 Jahre) hatte womöglich eine intensive Bildung dichter, salzreicher Wassermassen an der Eiskante zur Folge, was in einem schwächeren Einfluss des Atlantikwassers auf das arktische Zwischenwasser resultierte. Über die Geschichte quartärer Eiszeit-Warmzeit-Zyklen ist wegen des weitgehenden Fehlens kalkiger Mikrofossilien in entsprechenden Ablagerungen bisher wenig bekannt. In Warmzeiten und Interstadialen im Spätquartär erfolgte jedoch jeweils ein vergleichsweise starker Einstrom von Atlantikwasser. Im Sommer auftretende offene Wasserflächen trugen vermutlich über verstärkte Verdunstung und entsprechende Niederschläge zum Aufbau zirkumarktischer Eisschilde bei. Nach dem Ende der letzten Eiszeit drang das Atlantikwasser rasch wieder in den Arktischen Ozean vor, verbunden mit Umweltbedingungen ähnlich den heutigen Verhältnissen. Zeitlich hochauflösende Datenserien aus der Framstraße haben jedoch gezeigt, dass es in den letzten 100 Jahren im Atlantikwasser einen besonders raschen Temperaturanstieg gab der vermutlich mit der „Arktischen Verstärkung“ der globalen Erwärmung zusammenhängt.

INTRODUCTION

On September 7, 1991, the Swedish icebreaker “Oden“ and the German research icebreaker “Polarstern” together reached the geographic North Pole as the first non-nuclear powered ships, after several weeks of struggle through the Arctic sea ice. The data and samples collected on this ARCTIC 91 expedition helped to greatly expand our knowledge about past and present processes and developments in the Arctic Ocean. On the occasion of the 20th anniversary of that magic day when both ships had reached the northernmost point on earth, crew members and scientists from 1991 gathered in Kiel for a symposium to commemorate the epic voyage and to discuss the progress in science that has been made since. This manuscript, which is based on a presentation given at the symposium, is intended to summarize our knowledge of the history of the advection of Atlantic Water to the Arctic Ocean.

The Arctic and North Atlantic ocean basins are connected via three gateways (Fig. 1). The Fram Strait (~500 km wide) is the only deep-water passage with a sill depth of >2500 m while the NW Barents Sea is a shallow seaway (50-500 m). Various narrow straits through the Canadian Arctic archipelago serve mainly as pathways for the export of sea ice and Arctic surface waters. Waters of the ice-covered, 50-200 m thick low-salinity surface water layer in the Arctic Ocean (S <34) contain large amounts of freshwater, which are supplied by the large rivers entering the ocean in Siberia and North America, and to a lesser extent to the influx of low-salinity Pacific waters and the melting of sea ice. Atlantic Water is advected to the Arctic Ocean today both through the Fram Strait and across the Barents Sea. In these gateways it is characterized by relatively high temperatures (maxima of 6–8 °C in summer) and salinities of >35 (SCHAUER et al. 2002). As a result of heat loss and mixing, values are lower in the Arctic interior but remain >0 °C and >34.7 throughout the entire Arctic basin. Thus, Atlantic Water is the main source of salt and heat for waters in the deep-sea Arctic Ocean. The influence of the Atlantic Water is seen in the occurrence of typical Atlantic faunas along its pathway in the Arctic Ocean (CARMACK & WASSMANN 2006). This pathway can be traced eastward along the Siberian continental margin (WOODGATE et al. 2001) and into the interior Arctic basins (MCLAUGHLIN et al. 2004).

Advection of Atlantic Water to and into and within the Arctic Ocean is part of the Atlantic meridional overturning circulation (AMOC, KUHLBRODT et al. 2007). The strong temperature and salinity contrasts between the Arctic and Atlantic oceans are an important boundary condition for the thermohaline convection in the North Atlantic, which is a major driver

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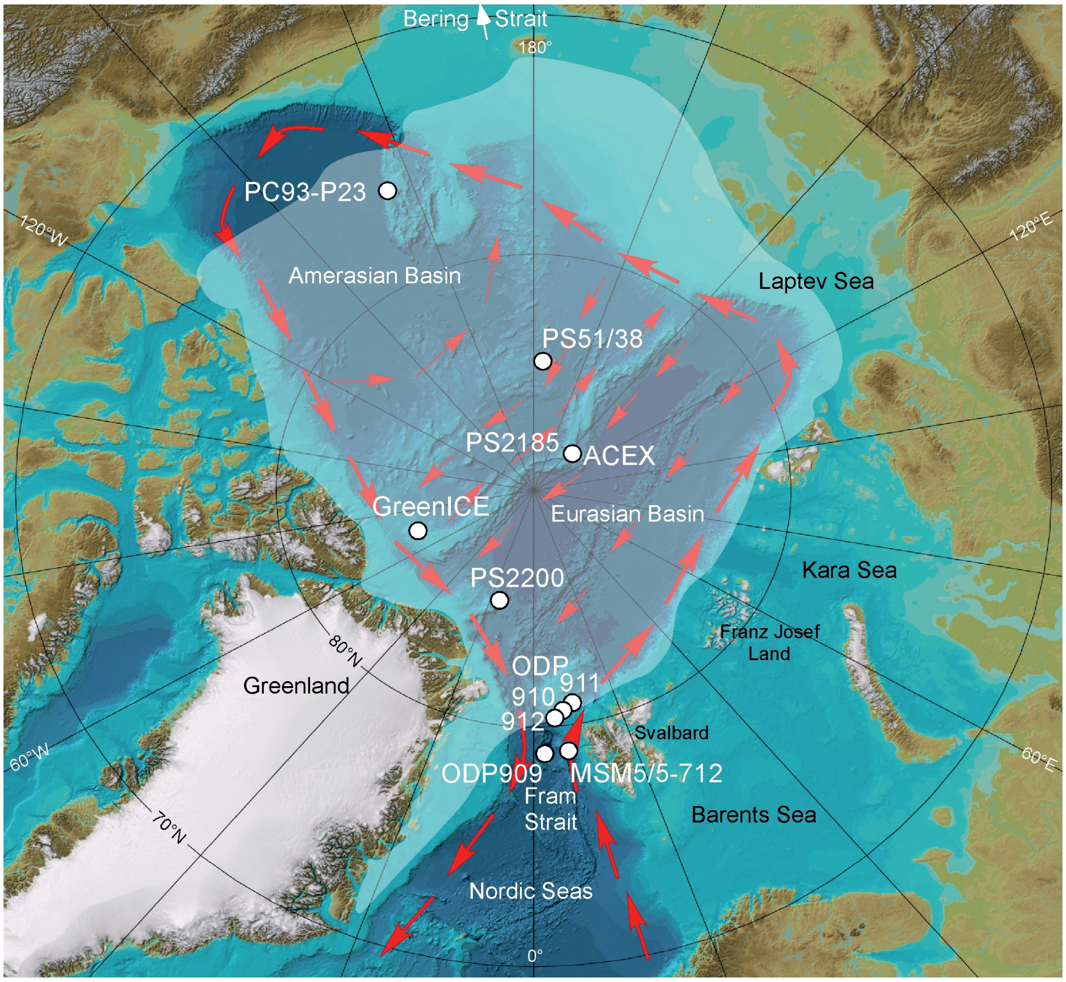


Fig.1: Bathymetric map of the Arctic Ocean (www.ibcao.org); average summer ice coverage (light shading); circulation of Atlantic Water (red arrows, after Rudels et al. 1994), and core sites mentioned in the text (white dots).

Abb. 1: Bathymetrische Karte (www.ibcao.org) des Arktischen Ozeans, durchschnittliche sommerliche Eisbedeckung (helle Schattierung), Zirkulation des Atlantikwassers (nach Rudels et al. 1994) und im Text erwähnte Lokationen von Sedimentkernen (weiße Kreise).

of the AMOC. Geological data and modelling experiments have shown that the AMOC is sensitive to freshwater perturbbations (Bond et al. 1993, Rahmstorf 1995) and was significantly weakened at times in the Late Quaternary, with profound consequences for global climate (e.g., Clark et al. 2002). Until about three decades ago, the history of Atlantic Water in the Arctic could be reconstructed only indirectly, based on marine sediment cores from the Nordic Seas. Several thin (3 cm) sediment cores obtained from ice islands in the Amerasian part of the Arctic Ocean in the 1960s and 1970s were studied intensively (e.g., Clark et al. 1980, Herman & Hopkins 1980, Clark 1982). However, the age models established for these cores indicated extremely low sedimentation rates (mm per 1000 years, mm ky-1) for the western Arctic, which rendered the detection of short-term events difficult. Much later it could be shown that sedimentation rates were indeed higher than previously assumed (Darby et al. 1997, Jakobsson et al. 2000, Backman et al. 2004) and that the older stratigraphic models had to be revised. In the meantime, newly developed ice-going research vessels and icebreakers with capabilities to deploy heavy research equipment including large-volume sediment corers had performed several geoscientific expeditions to the major Arctic Ocean basins. In 2004, the first successful deep-sea drilling effort in the central Arctic Ocean during Integrated Ocean Drilling Program Leg 302 recovered a 425 m long sedimentary sequence, which helped to unveil the Arctic Ocean history since the Paleocene (Backman et al. 2005, Moran et al. 2006) and closed a gap in our knowledge of earth history.

This manuscript reviews the history of the oceanic connection between the northern North Atlantic and the Arctic Ocean, from its initiation in the Tertiary to its variability in historical times. Ages for the youngest part of the Cenozoic are given as calibrated years before present (1950 CE). The oceanic history is reconstructed from various sediment cores obtained in the Arctic Ocean in the last 20 years – the first decades of modern central Arctic geoscientific exploration.

TERTIARY ONSET OF DEEP-WATER EXCHANGE

A few of the sediment cores taken from ice island T-3 in the deep-sea of the Western Arctic Ocean in the 1960s and 1970s contained Late Cretaceous and Early Tertiary sediments, but no continuous sequences (Clark 1974). The recovered black muds were rich in siliceous microfossils and dinocysts, indicating warm surface water temperatures (Clark et al. 1986, Clark 1988). On the other hand, it became clear that at these times the deep Arctic Ocean basins were poorly ventilated, a fact that precludes an extensive exchange with the deep North Atlantic at the time of formation and points to an Arctic estuary-type environment where deep-water ventilation may have occurred by seasonal convection (Jakobsson et al. 2007). No sedimentary records were found to document the transition to the modern, ice-covered and well-ventilated Arctic Ocean. Only in 2004, during the Arctic Coring Expedition (ACEX, IODP Leg 302), was the first continuous sedimentary profile from the interior Arctic recovered from the top of the Lomonosov Ridge (Fig. 1). The lower half of the 415 m sequence was grey or dark grey with mostly 1.5 % of organic carbon (Fig. 2), but at 193 m core depth a remarkable change to brownish muds with ~0.5 % organic carbon was

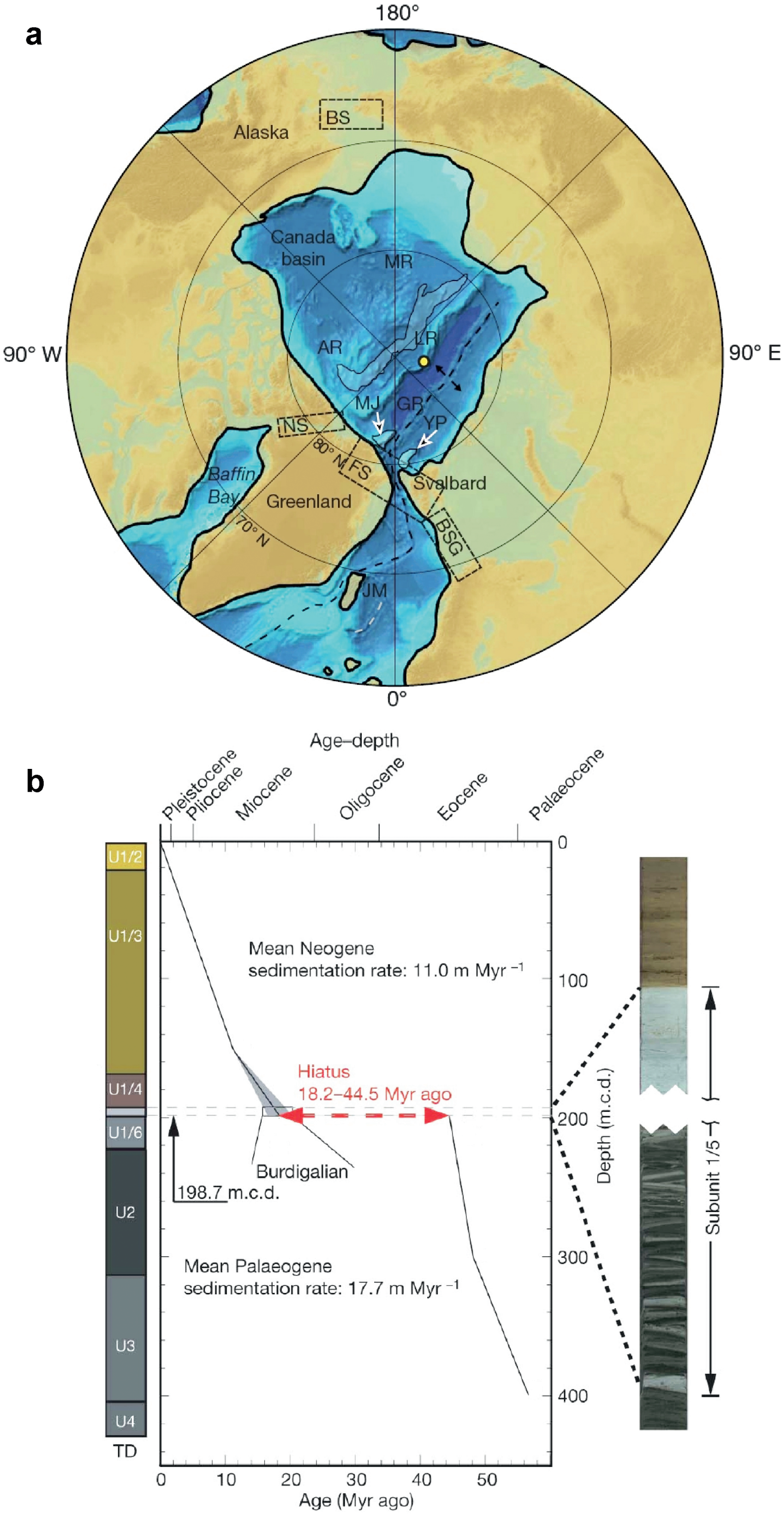


Fig. 2: (a) Paleogeographic map of the Arctic in the Miocene (from JAKOBSSON et al. 2007), AR = Alpha Ridge, BS = Bering Strait, BSG = Barents Sea Gateway, FS = Fram Strait, GR = Gakkel Ridge, JM = Jan Mayen, MJ = Morris Jesup Plateau, MR = Mendeleyev Ridge, NS = Nares Strait, LR = Lomonosov Ridge, YP = Yermak Plateau. (b) Generalized sediment types and age-depth profile from the ACEX drill site on the Lomonosov Ridge (yellow dot in (a)). Details of sedimentary subunit 1/5 are displayed on the right. From JAKOBSSON et al. (2007).

Abb. 2: (a) Paläogeographische Karte des Arktischen Ozeans im Miozän (aus JAKOBSSON et al. 2007), AR = Alpharücken, BS = Beringstraße, BSG = Barentssee-Meeresverbindung, FS = Framstraße, GR = Gakkelrücken, JM = Jan Mayen, MJ = Morris-Jesup-Plateau, MR = Mendelejewrücken, NS = Naresstraße, LR = Lomonosowrücken, YP = Yermak-Plateau. (b) Vereinfachtes Diagramm der Sedimenttypen und Alters-Tiefen-Profil für die ACEX-Bohrung auf dem Lomonosowrücken (gelber Punkt in (a)). Details der Untereinheit 1/5 sind rechts dargestellt. Aus JAKOBSSON et al. (2007).

found (MORAN et al. 2006). Age determinations for the very uppermost greyish sediments just below this colour change reveal an apparent gap in the sediment ages whose nature and extent are still under debate. It may represent either a hiatus from about 44.5 to 18.2 million years before present (Ma) (BACKMAN et al. 2006, JAKOBSSON et al. 2007) or an interval of extremely slow deposition (POIRIER & HILLAIRE-MARCEL 2009, 2011). Depending on the age model used, the prominent colour change of the sediments dates to ~17.5 Ma (Jakobsson et al., 2007) or 36 Ma (POIRIER & HILLAIRE-MARCEL 2011). Unequivocally, however, it is correlated to the opening of the Fram Strait as a deep-water passage, which allowed the intrusion of saline Atlantic Water into the Arctic and, through the establishment of stronger salinity contrasts, the ventilation of deep-water in the Arctic basins (JAKOBSSON et al. 2007). The transition from the "Arctic Estuary" stage to the "Ocean" stage may have taken 0.7-2 million years (My) and resulted in a ventilated Arctic Ocean although it is difficult to estimate the volume flux of Atlantic Water in the early phase of Fram Strait opening (JAKOBSSON et al. 2007).

The Neogene development of Atlantic Water in the Arctic Ocean still remains poorly known in detail. There is evidence from probably ice-rafted heavy minerals, clay minerals, and detrital iron oxide grains that a sea-ice cover developed ~13–14 Ma (DARBY 2008, KRYLOV et al. 2008). The low temperatures required to maintain such an ice cover rule out warm Atlantic Water near the surface. Results about any Atlantic Water contribution to the Arctic intermediate water (i.e., the water at the paleodepth of the ACEX drill site) which today consists almost entirely of Atlantic Water, appear controversial. HALEY et al. (2008) analyzed the Neodymium isotope composition (εNd ~^{143}Nd/^{144}Nd) of authigenic coatings on minerals grains from ACEX sediments of the last 15 My, which are assumed to form at the ocean-seafloor interface and store the εNd value of the bottom water. High ("radiogenic") εNd values are typical for water masses that attained their Nd signature from erosion of magmatic rocks while low ("non-radiogenic") εNd values are typical for waters from sedimentary rock sources. The results (Fig. 3) reveal a dominant radiogenic εNd signature until ~2 Ma. The most likely source rocks for such high values are found in the Siberian Putorana Plateau, which consists of trap basalts and is drained to the North by major Siberian rivers. It is the only major complex of magmatic rocks on the circum-Arctic continents. However, to explain the high εNd values in the intermediate water at the ACEX site, a vigorous mechanism is needed to transport high -εNd waters from surface to depth. HALEY et al. (2008) proposed brine formation as the responsible process, i.e., the rejection of salt during freezing of sea-water and formation of sea ice. This process is especially effective where katabatic winds flowing down large ice sheets can permanently cool the adjacent ocean surface and at the same time induce an offshore drift of the newly formed ice (GILL 1973, MARSLAND et al. 2004). Accordingly, large-scale North Siberian glaciations in the Late Tertiary were proposed and a strong influence of North Atlantic-derived waters on Arctic intermediate water was largely excluded (HALEY et al. 2008). A Late Miocene onset

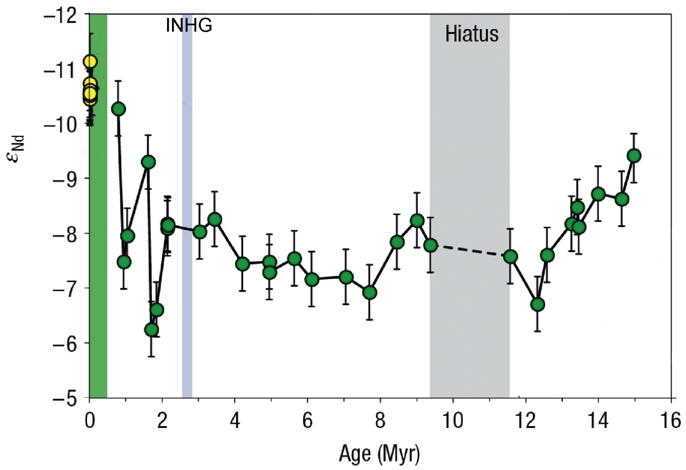


Fig. 3: Neodymium isotope (εNd) record (HALEY et al. 2008) of the last 15 My at the ACEX drill site (cf. Figs. 1, 2). Green circles = Record from sediment leaches (incl. 2s error); yellow circles = Data from deep-sea Arctic core-top samples; green box = The range of data from site PS2185 close to ACEX, covering the last ~400 ky. INHG = Intensification of Northern Hemisphere Glaciation.

Abb. 3: Neodymisotopen-Datensatz (εNd) für Sedimente der letzten 15 Mio. Jahre (HALEY et al. 2008) aus der ACEX-Bohrung (vgl. Abb. 1, 2). Grüne Kreise = Werte aus Laugungslösungen (inkl. 2s-Fehlerbereich); gelbe Kreise = Daten aus arktischen Sedimentoberflächenproben; grünes Rechteck = Wertebereich von Sedimentkern PS2185 (nahe ACEX entnommen) für die letzten 400.000 Jahre. INHG = Intensivierung der Nordhemisphären-Vereisung.

of glaciations on the northern Eurasian shelf (Barents Sea) was also suggested by KNIES & GAINA (2008) based on IRD, organic carbon and clay mineral data from ODP Leg 909 in the central Fram Strait. However, the authors also proposed the coeval northward intrusion of Atlantic waters into the Arctic.

Benthic foraminiferal associations in Neogene sediments from the ACEX site apparently tell a different story than the Neodymium isotopes. Deep-water agglutinated foraminifers found in the lowermost brownish layers clearly have Atlantic/Norwegian Sea affinities and point to an Atlantic source of the intermediate water on the Lomonosov Ridge (KAMINSKI et al. 2009). This finding is in line with the conclusion of JAKOBSSON et al. (2007) about the onset of deep-water ventilation in the Arctic. On the other hand, KAMINSKI et al. (2009) pointed out that Early Miocene sediments from ODP Site 909 in the central Fram Strait (Fig. 1) contain deep-water agglutinated foraminifers of presumably Atlantic origin. Furthermore, similar "Atlantic" associations were found in Oligocene deposits obtained from exploration wells in the northern Canadian Beaufort-Mackenzie Basin (MCNEIL 1996, 1997). Based on these data, KAMINSKI et al. (2009) speculate on a faunal exchange of deep-water species already in the Oligocene. They conclude that "these faunal connections were certainly in place by the Early Miocene".

At first sight, the results of KAMINSKI et al. (2009) are difficult to reconcile with those of HALEY et al. (2008) and with a Fram Strait opening in the late Early Miocene (JAKOBSSON et al. 2007). Recent geophysical results, however, suggest that sediments found today on the Yermak Plateau were deposited in the last 33–35 My and that the present-day barrier to deep-water flow was a gateway in the Oligocene (GEISSLER et al. 2011). Due to the hiatus in the ACEX core, this interval is not recorded on the Lomonosov Ridge (BACKMAN et al. 2006). Successive filling of the gateway in the present-day Yermak Plateau (GEISSLER et al. 2011) may have cut off the Arctic Ocean from the Atlantic and weakened deep-water ventilation in the Arctic. Only when the separation of Greenland and Svalbard allowed a penetration of Atlantic-derived deep-water to the Fram Strait (in the Early(?) Miocene) and a true deep-water connection with the Arctic (in the early Late Miocene), deep-water agglutinated foraminifers could be exchanged between both basins. The proposed onset of large-scale glaciations on northern Siberia and associated deep-water renewal from brine formation around 15 Ma (HALEY et al. 2008) are largely coeval with a decline in the preservation of deep-water agglutinated foraminifers at the seafloor on the Lomonosov Ridge (cf. KAMINSKI et al. 2009). According to HEMLEBEN & KAMINSKI (1990), the preservation potential largely depends on the availability of silica, which replaces the organic cement in deep-water agglutinated foraminifers after death. Present deep-water environments off the Weddell Sea in the Antarctic, which may serve as a possible modern analog for the Late Tertiary ice sheet scenario of HALEY et al. (2007), are both brine-enriched and rich in silica (BAUCH & BAUCH 2001, RUTGERS VAN DER LOEFF & VAN BENNEKOM 1989). Transfer

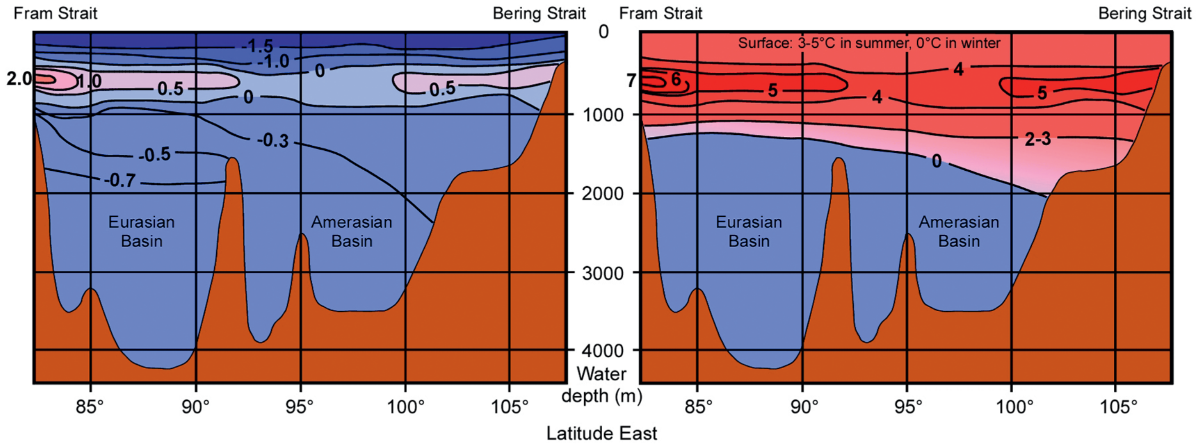


Fig. 4: Modern water temperature profile across the Arctic Ocean (left) and reconstruction of Pliocene conditions (redrawn from CRONIN et al. 1993).

Abb. 4: Heutige Wassertemperaturen im Arktischen Ozean (links) und Rekonstruktion für das Pliozän (umgezeichnet nach CRONIN et al. 1993).

of this analog certainly depends on the availability of silica in the Late Tertiary deep Arctic Ocean – a factor unknown so far. Thus, further research is necessary to understand how an Atlantic-type deep-water fauna could survive when deep-waters in the Arctic Ocean were mainly renewed within the Arctic Ocean and not by massive advection of Atlantic Water from the south. On the other hand, further research on the Neodymium transfer to deeper waters in the Arctic may find an alternative explanation for the radiogenic εNd signal in Miocene and Pliocene sediments at the ACEX site. This alternative explanation must permit to reconcile these data with the paleontological evidence for warmer temperatures than today in the Late Tertiary Arctic Ocean, especially in the Pliocene, as elaborated below.

PLIOCENE AND EARLY QUATERNARY VARIABILITY

From the central Arctic Ocean drill site ACEX there is little micropaleontological information on the variability of Atlantic Water advection to the Arctic during the Pliocene and the transition to the Pleistocene (~5.3–1.8 Ma). What were thought to be Pliocene deposits in a large number of sediment cores from the western and central Arctic Ocean (e.g., Clark et al. 1980, Herman & Hopkins 1980, Clark 1982, 1996, Scott et al. 1989, Spielhagen et al. 1997) must now be regarded as Quaternary sediments, according to the revised model of Backman et al. (2004) for sedimentation rates in the Arctic Ocean. On the Northwind Ridge in the Western Arctic Ocean, Mullen & McNeil (1995) found a distinct Early Pliocene assemblage of benthic foraminifers at the base of piston core 93-P23. They noted that although paleogeographic affinities of the bulk of the assemblage are indicative of connections to the Atlantic, the occurrence of some Arctic endemic species suggests environmental differences or a partial isolation of the western Arctic Ocean.

A series of Pliocene paleoclimatic data from terrestrial and onshore marine deposits in northernmost North America and Greenland consistently suggests a climate with mean annual air temperatures up to 15–20 °C warmer than today. Evidence comes from, e.g., beetle findings (Elias & Matthews 2002, Elias et al. 2006), plant remains (e.g., Bennike et al. 2002, Ballantyne et al. 2006, 2010), macro- and microfossils (e.g., Funder et al. 1984, 2001), aminoacid (Kaufman & Brigham-Grette 1993) and isotopic data (Csank et al. 2011) and can only be explained by strong northward heat transport from the Atlantic. A conceptual model approach to estimate Late Pliocene to Early Quaternary (3.5–2.0 Ma) water temperatures in the Arctic Ocean was put forward by Cronin et al. (1993). They compared Pliocene marine ostracod assemblages from 13 sites in NW Europe, the American Arctic, and the NW Pacific with a database of assemblages from more than 800 sediment surface samples, which are thought to reflect modern environmental conditions. Although the age control for some of the Late Pliocene sites holds uncertainties of several hundred thousand years and limits the possibilities to present a chronological order of paleoenvironmental changes, the results suggest a relatively strong influx of warm waters from the Atlantic, at least during interglacials. The conceptual model of water temperatures in the Late Pliocene to Early Quaternary Arctic Ocean, as presented by Cronin et al. (1993), shows a similar structure as today, but significantly higher temperatures (up to 6 °C), at least in the upper ca. 1200 m (Fig. 4). Surface water temperatures were estimated to be 3–5 °C in summer and around 0 °C in winter, which is largely incompatible with a perennial sea ice cover. The authors conclude on an increased heat supply from a strong North Atlantic Drift reaching the Arctic Ocean as the most likely mechanism to facilitate a temperature regime well above the present-day level.

Recently, improved stratigraphic models and partly new IRD, clay mineral, and seismic data from the ODP drill sites on the Yermak Plateau and in the Fram Strait have revealed new details of the onset of glaciation in the Barents Sea-Svalbard region (Knies et al. 2009, Laberg et al. 2010). According to this reconstruction, ice accumulation in the northernmost Barents Sea started in the Late Pliocene (~3.5 Ma), contributing to the increasing northern hemisphere glaciation (cf. Raymo 1994). It intensified in two steps at ~2.4 and 1.0 Ma, eventually merging with the Scandinavian ice sheet. It is important to note, however, that there were large variations within all three glaciation phases. Knies et al. (2009) surmise that the glaciers were waxing and waning between their maximum size and an almost complete absence. Evidence for warmer intervals comes from microfossil findings in sediments from ODP sites 910–912 on the Yermak Plateau. Variable planktic foraminifer associations point to several short warm-temperate to subtropical surface-water ingressions (Spiegler 1996). Unusually high abundances of the dinoflagellate cyst *Operculodinum centrocarpum* (Fig. 5), which is considered as an indicator of enhanced advection of warm surface water from the Atlantic, were found in ODP Hole 911A (Knies et al. 2002). According to the revised stratigraphic model (Knies et al. 2009), the most prominent warm interval was largely coeval with the Pliocene Climate Optimum at ~3 Ma (Matthiessen et al. 2009). Sea surface temperature (SST) estimates from Mg/Ca measurements on planktic foraminifers and alkenone ($U^{k'}37$) data from lipids from ODP sites 909 (Fram Strait) and 911 gave values of up to 19 °C (Robinson 2009) which is about 10 °C higher than present day temperatures. Although these values likely represent peak temperatures during summer and are possibly biased by uncertainties regarding preservation effects and SST calibration, they are in support of Pliocene intervals in the Arctic with temperatures significantly higher than today.

As a whole, there is compelling evidence both for a build-up of ice sheets on the Barents Sea and for a relatively strong Atlantic Water advection to the Arctic in the (Late) Pliocene and Early Quaternary. The results – though contradictory at first sight – suggest that climatic variability similar to the Middle and Late Quaternary glacial/interglacial cycles had developed already in the Pliocene. Stratigraphic and sampling resolution often limits possibilities to unambiguously determine the length of warm and cool periods. Possibly, these periods of strong Atlantic Water advection to the Arctic lasted much longer in the "41 ky world" (Raymo et al. 2006) than the relatively short interglacial periods of the last 0.7–1.0 My.

QUATERNARY GLACIAL-INTERGLACIAL CYCLES

High-resolution records documenting Early Quaternary (~1.8–0.8 Ma) Milankovitch-type climatic variability in the Arctic are still rare and restricted mostly to sequences from

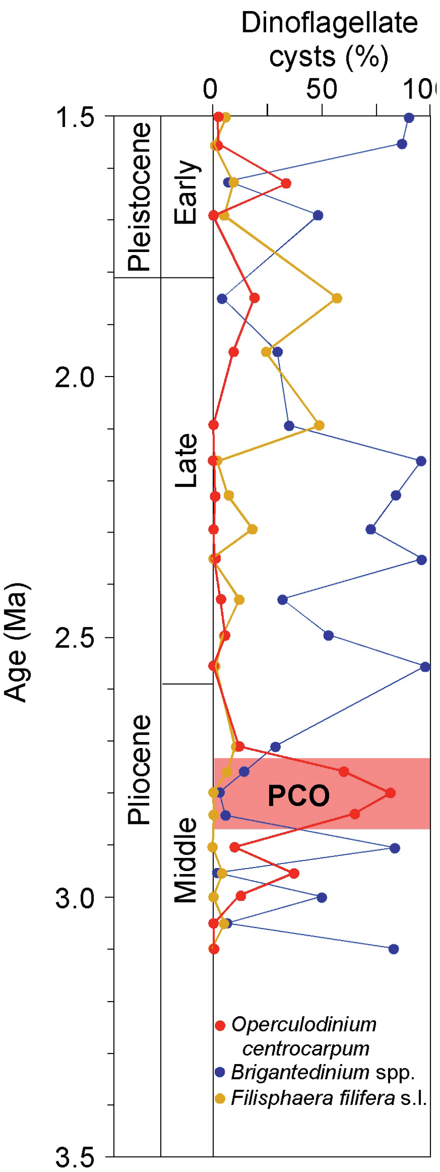


Fig. 5: Dinocyst distribution in sediments from ODP site 911A (redrawn from Matthiessen et al. 2009). Note the relative abundance of species *Operculodinum centrocarpum*, which is considered to be indicative of warm water masses of Atlantic origin especially in the Pliocene climate optimum (PCO).

Abb. 5: Dinozystenverteilung in Sedimenten von ODP-Site 911A (umgezeichnet nach Matthiessen et al. 2009). Auffällig ist der hohe relative An–teil der Art *Operculodinum centrocarpum* besonders in Sedimenten aus dem pliozänen Klimaoptimum (PCO); diese Art gilt als Anzeiger für relativ warme Wassermassen atlantischen Ursprungs.

ODP/ IODP drillholes. Knies et al. (2007, 2009) compiled a quasi-contin-uous planktic oxygen isotope record from ODP Hole 910A (Yermak Plateau), which exhibits a distinct variability interpreted by the authors as glacial-interglacial cycles. Maxima in the δ^{18}O record are increasing from 1.3 to 0.95 Ma (a hiatus covers 0.95-0.79 Ma), eventually reaching values of 4.0 ‰. Modern (interglacial) values are 2.9–3.4 ‰ in this area (Spielhagen & Erlenkeuser 1994) while glacial maximum values from marine isotope (sub) stages (MIS) 2 and 6.2 are 4.5–4.9 ‰ (Spielhagen et al. 2004). Both ranges are thought to reflect mostly Atlantic Water (Nørgaard-Pedersen et al. 2003, Spielhagen et al. 2004). According to Liesicki & Raymo (2004), the global ice volume increase between glacial maxima in the 1.5–1.0 Ma interval and in MIS 2 and 6.2 was equivalent to ~0.8 ‰. When subtracting this 0.8 ‰, the Early Quaternary planktic δ^{18}O values on the Yermak Plateau (Knies et al. 2007, 2009) come out comparable to MIS 2 and 6.2 values. This may indicate that Atlantic Water was present in the Arctic Gateway not only during interglacials but also during Early Quaternary glacial maxima.

Cronin et al. (2008) analyzed the foraminiferal fauna in the uppermost 18 m of sediments from ACEX Hole 4C which were deposited in the last 1.5 My (O'Regan et al. 2008). Only the upper few meters contain layers with abundant planktic and calcareous benthic foraminifers – a feature seen also in other central Arctic Ocean cores (Aksu 1985, Poore et al. 1994, Ishman et al. 1996, Spielhagen et al. 1997, 2004, Polyak et al. 2004, Nørgaard-Pedersen et al. 2007). Below, agglutinated benthic foraminifers are strongly dominating the foraminiferal fauna, but show a high variability in abundance (Fig. 6). According to the latest ACEX age model for the Pleistocene sequence (O'Regan et al. 2008), abundance peaks result from interglacials. Cronin et al. (2008) speculate that the almost equal numbers of interglacials and agglutinated benthic foraminifer peaks may suggest a downcore extrapolation of this pattern to the MIS 64/65 boundary (~1.8 Ma). The dark brownish colour of the interglacial and interstadial layers in the ACEX Quaternary sediment sequence and other sediment cores from the Lomonosov Ridge had previously been attributed to the enhanced manganese oxide contents measured in the respective layers (Jakobsson et al. 2000, Polyak et al. 2004, O'Regan et al. 2008). Diminished deep-water ventilation from decreased Atlantic Water advection had been discussed earlier as a possible cause of low MnO in glacial sediments (Jakobsson et al. 2000). A combination of geochemical results published by O'Regan et al. (2010), however, suggest that the variable MnO content is most likely a primary sedimentary signal, resulting from variable Mn input to the Arctic Ocean. Nevertheless, the finding of low (Atlantic Water type) εNd values in dark brownish interstadial and interglacial sediments of the last 350 ky on the Lomonosov Ridge (Haley et al. 2008), taken together with the foraminifer findings (Cronin et al. 2008), may suggest that Atlantic Water advection and enhanced intermediate/deep-water ventilation were characteristic features of the warmer intervals in the entire Quaternary.

The foraminiferal faunas in the ACEX core indicate two intervals with significant changes in the Quaternary Arctic Ocean climate system (Cronin et al. 2008). Sediments from the mid-Pleistocene transition (~1.2–0.9 Ma) contain several intervals, which hold very few or no agglutinated foraminifers (Fig. 6) and are thought to represent severe glacial events with perennial sea ice (Cronin et al. 2008). Although better knowledge of their ecology may be necessary for detailed paleoenvironmental reconstructions, the lack of foraminifers may also indicate that there was no (or weak) Atlantic Water advection at depth during these glacials. The second important change occurred at the εNd of the so-called "mid-Brunhes event" (~0.6–0.2 Ma), which represents a period of unusually strong carbonate dissolution in the world ocean, related to changes in the carbon cycle (cf. Barker et al. 2006). The transition to conditions resembling the modern Arctic Ocean may have occurred at ~300,000–250,000 before present (~300–250 ka), as shown by changes in benthic foraminiferal faunas in the Amerasian Basin indicating a stronger Atlantic Water inflow (Ishman et al. 1996). Deposits from the last ~200,000 years (~200 ky) in sediment cores from Arctic submarine highs (Lomonosov Ridge, Alpha Ridge, Morris Jesup Rise) contain several layers with abundant planktic foraminifers (Spielhagen et al. 2004, Cronin et al. 2008). This indicates a significant amelioration of the carbonate preservation potential in Arctic intermediate waters, which are today fed mostly

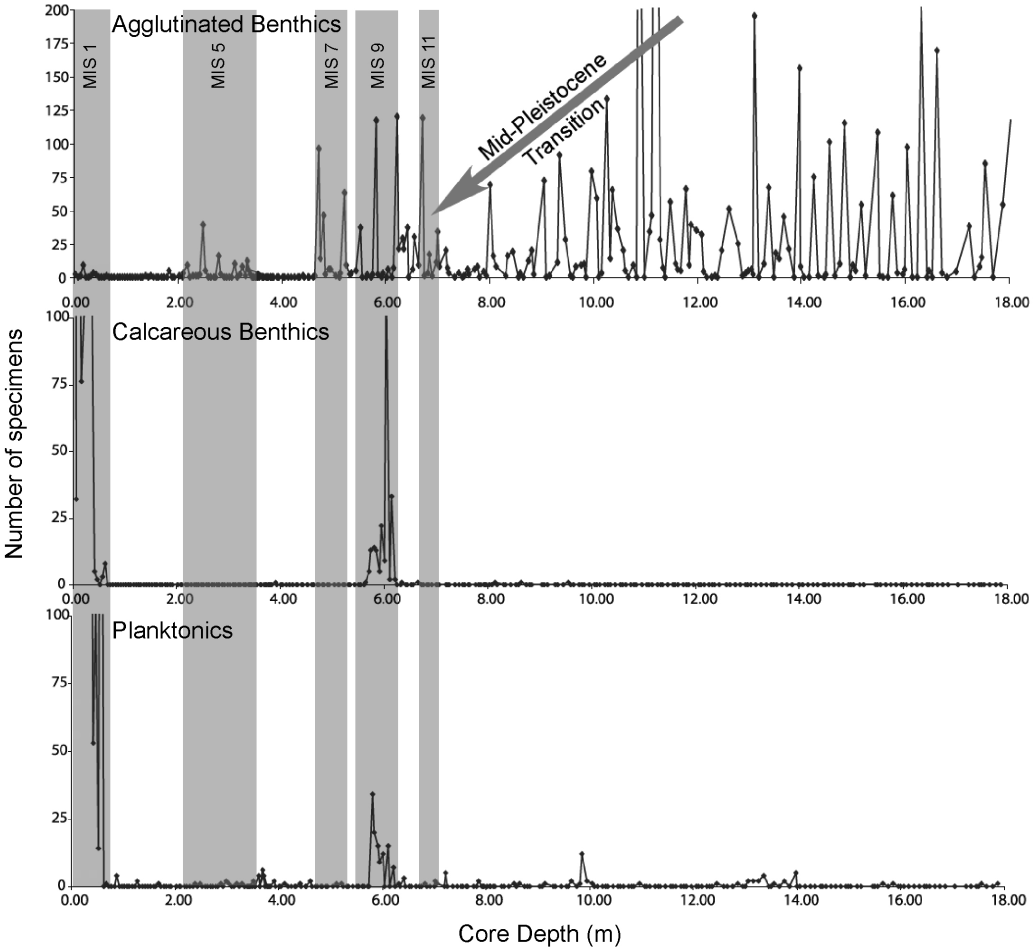


Fig. 6: Distribution of foraminifers of Quaternary ACEX drill site sediments (modified from CRONIN et al. 2008). The mid-Pleistocene transition is reflected in a decrease of agglutinated benthic specimens between 12 and 7 m core depth. Sections from interglacials of marine isotope stages (MIS) 1-11 are indicated according to age model of O'REGAN et al. (2010).

Abb. 6: Verteilung der Foraminiferen im Quartär der ACEX-Bohrung (verändert aus CRONIN et al. 2008). Die mittelpleistozäne Übergangszone ist durch einen Rückgang agglutinierender benthischer Foraminiferen zwischen 12 und 7 m Kernteufe charakterisiert. Grau markiert = interglaziale Kernintervalle der marinen Isotopenstadien (MIS) 1-11 (Alter nach O'REGAN et al. 2010).

by Atlantic Water advection. In summary, it must be stated that there is only indirect evidence of Atlantic Water advection for most of the Quaternary, owing to the lack of undoubtedly indicative microfossil contents. On the other hand, the changes towards more negative (non-radiogenic) Nd isotope values after 2 Ma (Fig. 3) and the variability seen in the benthic foraminiferal record make a relatively strong Atlantic Water inflow during interglacials more likely than the opposite.

VARIABILITY AND INTERACTIONS OF ATLANTIC WATER INFLOW AND EURASIAN ICE SHEETS IN THE LAST 200 KY

Arctic Ocean deposits from the last two glacial interglacial cycles show a much higher variability in a number of important parameters than those from the older part of the Quaternary. Typically, sediments from MIS 6 are almost barren of calcareous microfossils and have a high coarse fraction content interpreted as the result of intensive iceberg rafting (JAKOBSSON et al. 2000, SPIELHAGEN et al. 2004, O'REGAN et al. 2010). Very similar IRD-rich layers also appear further up in the sequence and were shown to be deposited in MIS 5b (~90–80 ka), in late MIS 5a (~75 ka), and at the MIS 3/4 boundary (~65–50 ka)(SPIELHAGEN et al. 2004). The source area of the IRD can be traced to the area of the Barents-Kara Sea shelf by the unusually high smectite contents in the IRD-rich layers (VOGT et al. 2001, SPIELHAGEN et al. 2004) and by coal particles found in the oldest and the youngest of these layers (BISCHOF et al. 1990). Relatively high (radiogenic) εNd values (Fig. 7) determined for authigenic precipitates on sediment grains from the IRD-rich layers on the Lomonosov Ridge largely exclude a strong inflow of Atlantic Water during the periods of extensive glaciations on northern Eurasia between 200 and 50 ka (HALEY et al. 2008).

In contrast to the IRD-rich deposits, the intercalated sediments from interglacials and interstadials, as well as those from the last 50 ky (all ages <50 ka are given in calendar years before present), hold evidence for a relatively strong inflow of Atlantic Water to the Arctic Ocean. The εNd values of precipitates on the Lomonosov Ridge are relatively low (non-radiogenic) and in the range of typical Atlantic Water (HALEY et al. 2008). Furthermore, the sediments hold unusually high amounts of calcareous microfossils (Fig. 7). Both coccoliths and planktic foraminifers show peak abundances especially in MIS 7a, 5e (last interglacial, "Eemian"), 5c, 5a, and in the Holocene (Gard 1993, Baumann 1990, Jakobsson et al. 2000, Backman et al. 2004, Spielhagen et al. 2004, Nørgaard-Pedersen et al. 2007). These abundance peaks can be traced southward to the Fram Strait (e.g., Gard 1987, Hebbeln & Wefer 1997, Spielhagen et al. 2004). Being remains of photoautotrophic algae, the coccoliths are indicative of at least seasonally open ice cover. The same accounts for the heterotrophic planktic foraminifers which feed on phototrophic phytoplankton. Organic geochemical components and findings of dinoflagellate cysts in interglacial and interstadial deposits of the last 150 ky in sediment cores from the northern Eurasian continental margin also indicate a direct relationship of strong Atlantic Water inflow and seasonally open waters in the Arctic Ocean (Knies et al. 2000, Matthiessen & Knies 2001, Matthiessen et al. 2001). Relatively high amounts of subpolar planktic foraminifers (up to 50 % of all foraminifers in the >63 μm fraction) were found in Eemian and MIS 5a deposits in the GreenICE sediment cores from 85° N off Ellesmere Island and northern Greenland (Fig. 1). Although such high abundances in Arctic sediments are usually interpreted as strong evidence of Atlantic Water, Nørgaard-Pedersen et al. (2007) relate them more cautiously to a reduced ice cover in an area which today is densely ice-covered around the year even in times of a generally shrinking Arctic sea-ice cover. In summary, several different and independent proxies in Arctic sediment cores unequivocally point to a significant inflow of Atlantic Water to the Arctic Ocean and its spread throughout the basin during at least six periods of the last 200 ky. The length of these periods probably varied between 5 and 10 ky, except for the last 50 ky which apparently had continuous Atlantic Water inflow and will be discussed later. From the available data it seems difficult to draw quantitative conclusions on the volumes and temperatures of Atlantic Water inflow. Detailed oceanographic measurements in the Fram Strait in the last few decades showed these parameters to be positively correlated (Rudels et al. 1994, Karcher et al. 2003, Dmitrenko et al. 2010). However, the peaks in microfossil abundances in sediments from MIS 5a and 5e (Baumann 1990, Jakobsson et al., 2000, Matthiessen et al. 2001, Backman et al. 2004, Spielhagen et al. 2004, Nørgaard-Pedersen et al. 2007) may indicate that open water conditions in summer occurred more frequently in these intervals than at other times.

The abundance of microfossils (especially planktic foraminifers) in sediments from ~50–30 ka (Fig. 7) appears somewhat unusual and its interpretation in terms of Atlantic Water inflow may be ambiguous. An abundance peak building up already in the uppermost sediments of the youngest IRD-rich layer from the 60–50 ka glaciation in northern Eurasia indicates an Atlantic Water inflow and warming event possibly related to the Dansgaard-Oeschger events 17–14 in Greenland ice cores which mark a time of climatic amelioration in the northern hemisphere in the first half of MIS 3. Firm stratigraphic constraints are difficult to establish for this interval in central Arctic sediment cores (Nørgaard-Pedersen et al. 1998, Spielhagen et al. 2004, Hanslick et al. 2010). Since higher-resolution cores from the Atlantic Water inflow path in the eastern Fram Strait and Yermak Plateau hold only a thin foraminifer-rich layer at ~52 ka and are almost barren for the 50–35 ka interval (Hebbeln & Wefer 1997, Spielhagen et

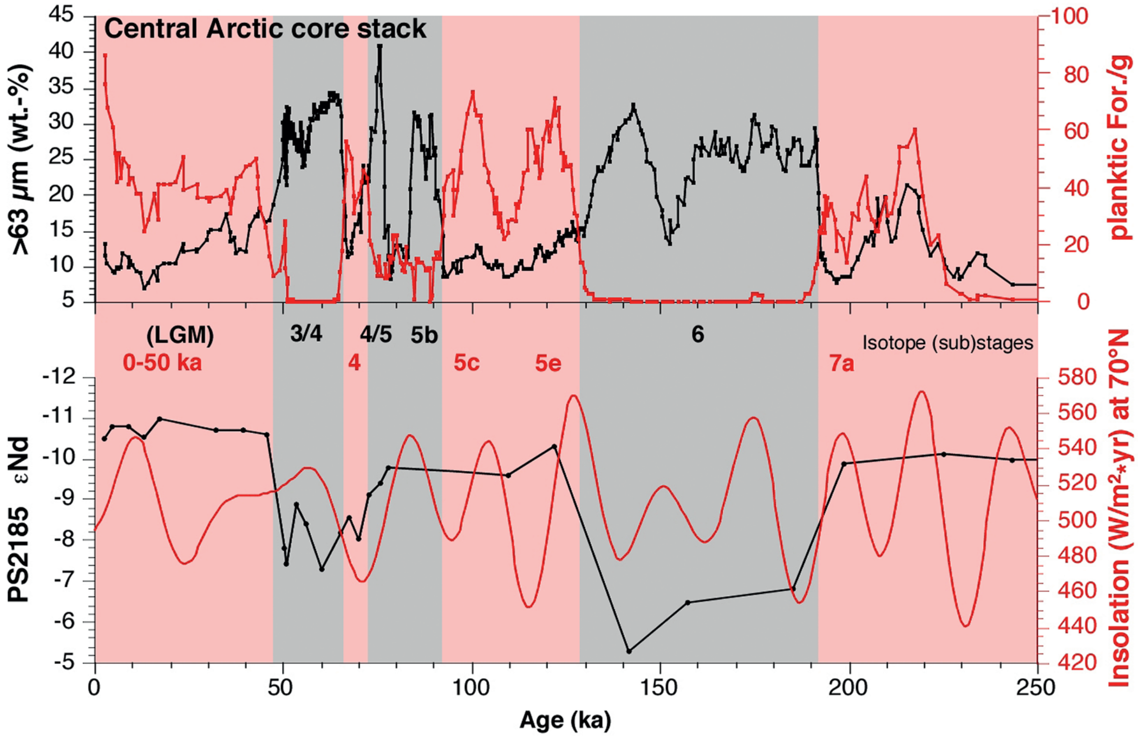


Fig. 7: Stacked coarse fraction and planktic foraminifer abundance records from cores PS2185, PS2200, and PS51/038 (data from Spielhagen et al. 2004); εNd record from PS2185 (Haley et al. 2008), and summer peak insolation (June 21st) at 70° N (from Laskar et al. 2004) for the last 200 ky.

Abb. 7: Zusammengesetzte Häufigkeitsverteilungen von Grobfraktion und planktischen Foraminiferen der Sedimentkern PS2185, PS2200 und PS51/038 (nach Spielhagen et al. 2004); εNd-Daten von PS2185 (aus Haley et al. 2008) und max. Insolation (für 21. Juni) bei 70° N (aus Laskar et al. 2004) für die letzten 200.000 Jahre.

al. 2004), the apparent continuous distribution of foraminifers in central Arctic MIS 3 sediments may in fact result from very low sedimentation rates and bioturbation. This could mean that a strong inflow was in fact restricted to short events just before 50 ka and after ~35 ka. On the other hand, very homogeneous and non-radiogenic εNd values from the Lomonosov Ridge suggest a continuous influence of Atlantic Water on Arctic Ocean intermediate waters after 50 ka (HALEY et al. 2008). At first sight, it seems difficult to reconcile this finding with the low sedimentation rates from MIS 3 in the central Arctic. Particularly low sedimentation rates in Arctic environments are usually associated with a dense sea-ice coverage (HEBBELN & WEFER 1991) but not with strong Atlantic Water advection. Recent faunal and geochemical data from ostracods, however, point to an Atlantic Water layer significantly warmer than at present during or just before millenial scale Heinrich events in MIS 3 (POIRIER et al. 2012, CRONIN et al. 2012). During these intervals, decreased freshwater run-off from the continents may have resulted in a thickening of the Arctic halocline layer which caused the warm Atlantic Water layer to reach deeper than today. The observed low sedimentation rates and lack of planktic foraminifers in MIS 3 sequences may then be explained by a dense and thick sea-ice cover and salinities which were too low for foraminifers to dwell.

Considering the interlayering of foraminifer-rich and IRD-poor intervals with foraminifer-poor and IRD-rich central Arctic deposits from the last 200 ky, the role of Atlantic Water advection to the Arctic in the build-up of ice sheets needs special attention. A first detailed analysis of sediment cores with high temporal resolution from the eastern Fram Strait (HEBBELN et al. 1994, ELVERHØI et al. 1995) revealed a complex relationship between both processes during the growth and decay of the Svalbard-Barents Sea ice sheet around and in the last glacial maximum (LGM). The ice sheet grew when seasonally open waters, identified by high contents of planktic foraminifers in the sediments, served as a moisture source for oceanic evaporation and subsequent terrestrial precipitation (Fig. 8). When the ice sheet had reached the shelf break, it supplied icebergs with IRD and freshwater to the Fram Strait and the Atlantic Water advection ceased. The Fram Strait data suggest that this pre-LGM cycle was repeated, as a second step of ice sheet growth, around 20 ka during the LGM proper. Organic geochemical and IRD data from the northern Eurasian continental margin suggest a similar linkage of Atlantic Water inflow, seasonally open waters, and ice-sheet build-up also for earlier glaciations in the last 150 ky (KNIES et al. 1999, 2000, 2001), possibly in a polynya-like situation. For the large northern Eurasian ice sheet KNIES et al. (2001) point out the importance of advection of moisture-laden air from more southerly sources in the North Atlantic.

Close inspection of the central Arctic deposits shows that foraminifer-rich layers occur both directly below and directly above the IRD-rich deposits (Fig. 7). Although bioturbation may have played a role in mixing of both sediment components at the interfaces of the layers, it becomes clear that there was apparently only a very short time offset in deposition of both facies. Concerning the coarse layers, it is important to note that the basin-scale IRD deposition, as indicated by the very similar IRD content pattern in sediment cores several hundred kilometres apart from each other (Fig. 1), could occur only when the large northern Arctic ice sheets had reached the coastline. Several critical factors determine the growth of ice sheets on land, and model results suggest that a time span of several thousand years was necessary for the ice sheet to reach the northern shelf break (SIEGERT & DOWDESWELL 2004) as a long ice sheet front from where icebergs could be discharged to the Arctic Ocean. This implies that seasonally open water conditions were still present also in the central Arctic when ice sheet growth had already started in the hinterland. This situation most likely was facilitated by relatively strong but decreasing insolation in the northern high latitudes (Fig. 7) and a relatively strong advection of Atlantic Water to the Arctic (Fig. 9) and may have persisted for several thousand years during interglacials and interstadials, assuming that average sedimentation rates of ~1 cm ky^{-1} can be applied. In essence, seasonally open waters in a large part of the Arctic Ocean, reaching well into the Amerasian Basin, were available as a moisture source for precipitation on the nearby Arctic continents when ice sheet growth was initiated there. Apparently, Atlantic Water advection ceased when the ice sheet had reached sea level and discharged icebergs and freshwater. Alternatively, the Atlantic Water layer may have dived below a thickened freshwater-rich surface layer. No data are available, though, to support the latter scenario for the time intervals before 50 ka when ice sheets on the Eurasian continent reached a significantly larger size than thereafter.

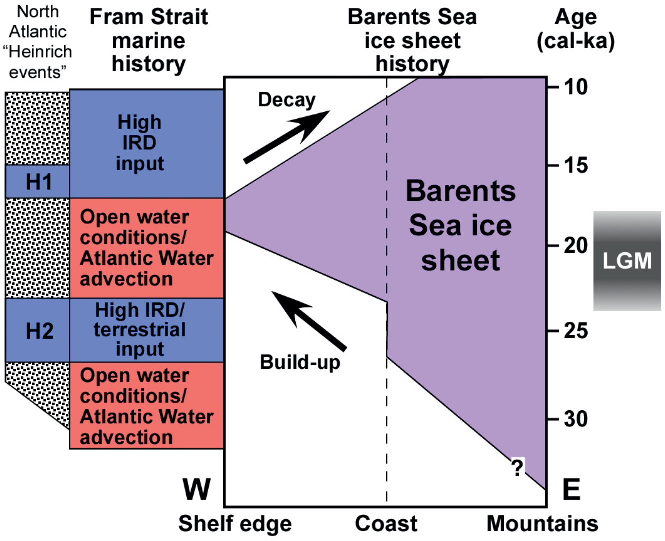


Fig. 8: Correlation of Atlantic Water advection and growth of the Barents Sea ice sheet near the western Svalbard continental margin during the last glaciation (modified from HEBBELN et al. 1994).

Abb. 8: Korrelation der Advektion von Atlantkwasser und Wachstum des Barentssee-Eisschildes nahe dem westlichen Kontinentalrand von Svalbard während der letzten Eiszeit (umgezeichnet nach HEBBELN et al. 1994).

The foraminifer-rich layers directly overlying the IRD deposits suggest that seasonally open waters and Atlantic Water returned quickly to the central Arctic after and probably already during the major deglaciations. However, increasing insolation in the northern high latitudes (Fig. 7) and rising global sea level were now in support of a rapid decay of the northern Eurasian ice sheet. All these factors, in addition to atmospheric heat transport by westerly winds from the North Atlantic, led to the deglaciations and to the establishment of interglacial or interstadial conditions with almost no or only minor remnants of ice sheets on land.

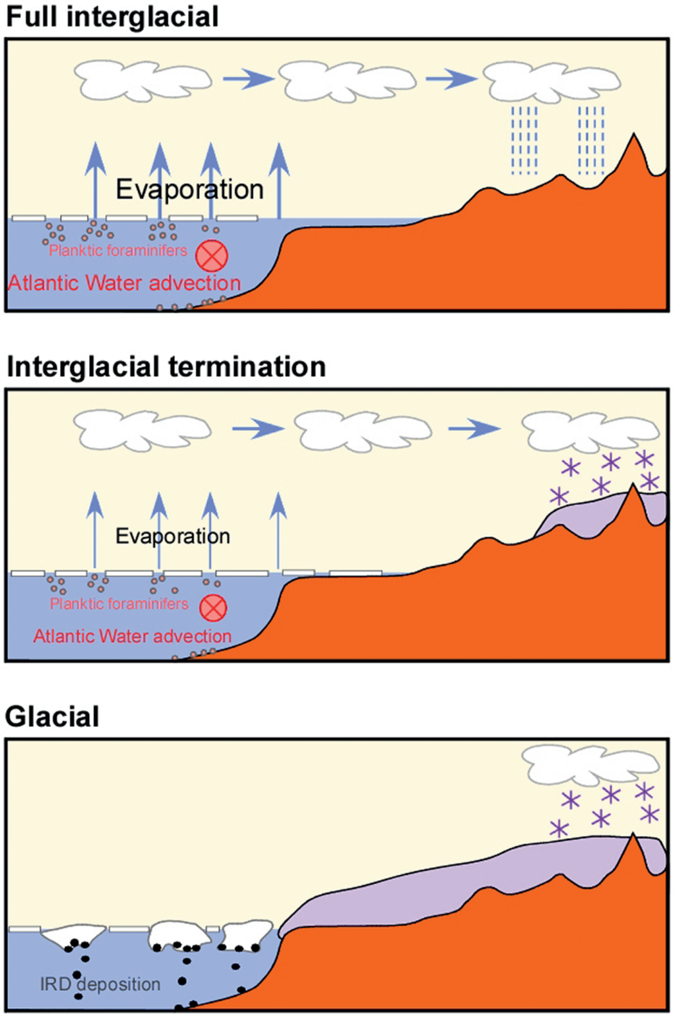


Fig. 9: Conceptual model displaying the role of Atlantic Water for ice sheet build-up on the northern Eurasian continental shelves and hinterland. It is proposed that evaporation from partly ice-free waters in summer supported the growth of ice sheets until the ice eventually reached the shelf break/coastline as a continuous ice sheet front from where icebergs and ice-rafted detritus were discharged to the deep-sea. See text for further explanation and discussion.

Abb. 9: Konzeptuelle Darstellung für die Rolle des Atlantikwassereinstroms beim Aufbau der Eisschilde auf dem eurasischen Schelf und im Hinterland. Danach verstärkte die im sommerlich offenen Meerwasser verdunstete Feuchtigkeit die Niederschläge an Land und das Wachstum der Eisschild bis eine kontinuierliche Gletscherfront die Schelfkante erreicht hat und Eisberge mit dem in ihnen enthaltene Gesteinsmaterial in den Ozean freigesetzt wurden. Siehe Text für weitere Details und Diskussion.

ATLANTIC WATER ADVECTION DURING THE LAST GLACIAL MAXIMUM (LGM)

The role of Atlantic Water advection to the Arctic is known particularly well for the last glacial maximum (LGM, ~21.5–18 ka) because LGM deposits are usually contained in the large number of analysed short sediment cores (multicores and box cores) from the Arctic and because these can be dated precisely by radiocarbon accelerator mass spectrometry (^{14}C-AMS). When the first (conventional) radiocarbon dates of Arctic Ocean deep-sea cores were performed, it became clear that LGM sedimentation rates in the central Arctic had been extremely low (Olson & Broecker 1961, Hunkins & Kutschale 1965, Ku & Broecker 1967). AMS radiocarbon datings from Alpha Ridge sediments (Clark et al. 1986), Gakkel Ridge cores obtained during the 1987 expedition of RV "Polarstern" (Mienert et al. 1990, Köhler 1992) and short cores obtained on a transect acoss the Eurasian Basin during the "Oden"-"Polarstern" expedition in 1991 (Stein et al. 1994a, b) supported this conclusion. On the other hand, cores from inside and north of the Fram Strait were known to hold several centimetres of LGM sediments (Markussen et al. 1985, Zahn et al. 1985, Marquard & Clark 1987, Jones & Keigwin 1988, Köhler & Spielhagen 1990). In a synoptic study of 52 sediment cores from the Greenland Sea to the Lomonosov Ridge, Nørgaard-Pedersen et al. (2003) could locate an abrupt transition at 84–85° N in the Eurasian Basin (Fig. 10). In the north, LGM sediments were hardly detectable by ^{14}C-AMS datings of sediment cores (e.g., Stein et al. 1994a,b, Darby et al. 1997, Spielhagen et al. 1997, Nørgaard-Pedersen et al. 1998, Adler et al. 2009, Hanslik et al. 2010). Either an age jump from ~27–30 to ~14 ka was found within 1–2 centimetres or the LGM interval was masked by apparent age reversals. South of 84–85° N, sediment cores revealed a regular sequence of radiocarbon dates and sedimentation rates of 1–3 cm ky^{-1} in the LGM (Fig. 11), increasing towards the Barents Sea continental margin. Two other features were different in both regions. Cores from the north had a minimum in coarse fraction and planktic foraminifer contents in sediments from the tentatively located LGM interval, and the few foraminifers had relatively low oxygen isotope values (Fig. 11). In contrast, cores from south of 84–85° N had a (local) maximum in planktic foraminifer abundances in LGM sediments, and these foraminifers had relatively heavy oxygen isotope values. Values of 4.5–4.7 ‰, with only very little regional variation (Fig. 10), were found to be typical of Atlantic Water, which had spread all over the Nordic Seas in the LGM (Sarnthein et al. 1995). The results from Nørgaard-Pedersen et al. (2003) allow expansion of earlier, more regional environmental reconstructions (Hebbeln et al. 1994, Elverhøi et al. 1995, Knies & Stein 1998, Knies et al. 1999, 2000, 2001). The current picture, complemented by more recent work on cores from the Svalbard continental margin (Rasmussen et al. 2007, Jessen et al. 2010) is as follows: During the LGM Atlantic Water reached the eastern Fram Strait and flowed around Svalbard eastward along the northern Barent Sea continental margin. It can be traced without doubt to ~30° E (e.g., Knies & Stein 1998, Matthiessen et al. 2001) and probably to ~45° E (Knies et al. 1999, 2000), but cores further to the east do not hold clear evidence (Matthiessen et al. 2001). North of Fram Strait, Atlantic Water spread as a subsurface water mass to 84–85° N from where it may have turned westward and then southward to eventually exit through the western Fram Strait. The boundary to the north is surprisingly narrow. Within ~100 km calculated LGM sedimentation rates in the analysed cores drop almost by an order of magnitude and the peak in planktic foraminifer abundances disappears. Recent results from ostracod geochemistry and faunal distributions (Poirier et al. 2012, Cronin et al. 2012) suggest an alternative explanation for the changes observed in the transition zone. Similar to earlier periods with Atlantic Water advection to the Arctic in MIS 3, the warm, saline water may penetrated farther into the Arctic Basin than anticipated by Nørgaard-Pedersen et al. (2003), thereby diving below a thickened halocline at 84-85° N. In this case, the typical isotopic signature of Atlantic Water may not have been recorded in the geochemistry of planktic foraminifers because their habitat was too shallow. Whether

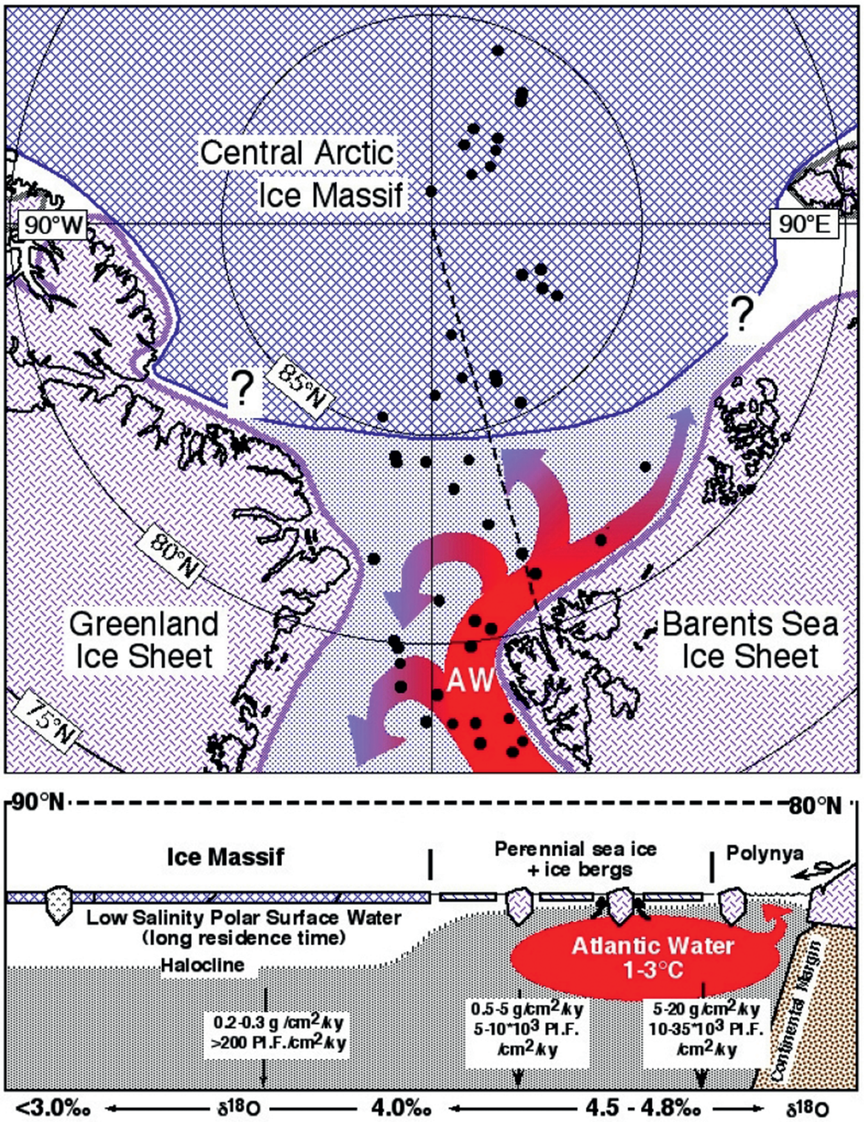


Fig. 10: Spread of Atlantic Water (AW) and distribution of environmental provinces and planktic oxygen isotope values in the last glacial maximum in the Fram Strait and the Arctic Ocean displayed in a map and along a transect from northern Svalbard to the North Pole (modified from NØRGAARD-PEDERSEN et al. 2003). Fluxes of bulk sediment and planktic foraminifers (Pl.F.) are indicated in the white boxes.

Abb. 10: Ausbreitungt des Atlantikwassers (AW) und Verteilung von Umweltmilieus und planktischen Isotopenwerten zum letzten glazialen Maximum in der Framstraße und im Arktischen Ozean in Kartendarstellung und entlang eines Schnitts von Nord-Svalbard bis zum Nordpol (nach NØRGAARD-PEDERSEN et al. 2003). Stofffflüsse von Gesamtsediment und planktischen Foraminiferen (Pl.F.) sind in den weißen Rechtecken aufgeführt.

or not there really is a hiatus present for the LGM period (i.e., non-deposition, cf. POLYAK et al. 2009, ADLER et al. 2009) or rather extremely slow sedimentation in the range of 1-2 mm ky^{-1}, later mixed by bioturbation with pre- and post-LGM sediments, seems almost impossible to determine.

VARIABLE ATLANTIC WATER ADVECTION DURING THE LAST DEGLACIATION

According to published results, the last deglaciation was highly complex in the Arctic Ocean. This holds true especially for the marginal areas which were influenced by interfering factors like Atlantic Water advection, continental ice break-up, meltwater discharge, isostatic rebound of previously glaciated shelves, and global sea level rise. Not necessarily these developments occurred synchronously around the Arctic Ocean. In this paper, only the available evidence for Atlantic Water advection will be discussed.

Until the decay of the large Barents Sea ice sheet into several local ice caps at ~15 ka (WINSBORROW et al. 2010), Atlantic Water could enter the Arctic Ocean only through the Fram Strait. Based on a multi-proxy study of sediment cores from the southwestern Svalbard continental slope and shelf (76° N), RASMUSSEN et al. (2007) demonstrated that Atlantic Water has been continuously present in this area since at least 20 ka. Relatively high abundances of subpolar planktic foraminifers in LGM sediments indicate Atlantic Water temperatures only slightly lower than today, but decreasing numbers and percentages of the total planktic foraminifer fauna, as well as increasing planktic oxygen isotope values reveal a cooling trend towards the deglaciation (RASMUSSEN et al. 2007). This suggests that the strength of the northward flow had ceased in the late LGM, possibly due to early deglacial effects and meltwater discharge further upstream. Rather abrupt changes in sedimentological and faunal parameters (e.g., planktic and benthic foraminifers) in a variety of cores obtained from the western and northern Svalbard margins and shelves are interpreted as evidence of a rapid return of (subsurface) Atlantic Water around 15 ka (KOÇ et al. 2002, ŚLUBOWSKA et al. 2005, RASMUSSEN et al. 2007, ŚLUBOWSKA-WOLDENGEN et al. 2007, 2008). It must have spread quickly along the northern Eurasian margin and may have reached the Laptev Sea continental margin already before 15.4 ka (TALDENKOVA et al. 2010). Apparently contradictory age differences may in part be related to variable reservoir ages of the water masses.

While Atlantic Water was present in the troughs northwest and northeast of Franz Josef Land and at the Laptev Sea margin only intermittently until ~12 ka (LUBINSKI et al. 2001, TALDENKOVA et al. 2010), faunal records from the western and northern Svalbard margins suggest a continuous presence as a subsurface water mass below cool and fresh surficial waters after ~15 ka, with a possibly weakened advection around 13.4 ka (RASMUSSEN et al. 2007, ŚLUBOWSKA-WOLDENGEN et al. 2007, 2008). This is corroborated by organic-geochemical data from sediment cores obtained in the Fram Strait and on Yermak Plateau which indicate seasonally open water conditions and enhanced biologic productivity, especially pronounced in the Bølling interstadial (BIRGEL & STEIN 2003, BIRGEL & HASS 2004). For the Younger Dryas stadial (~12.6–11.5 ka), faunal changes in cores from

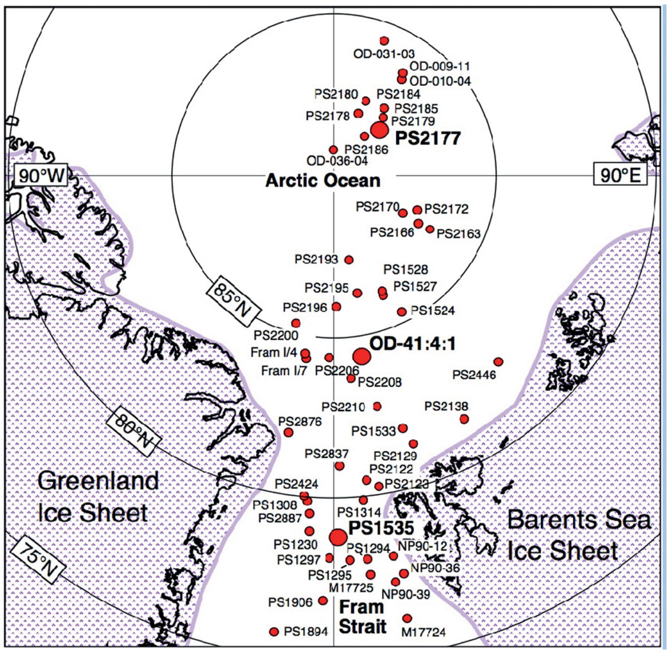
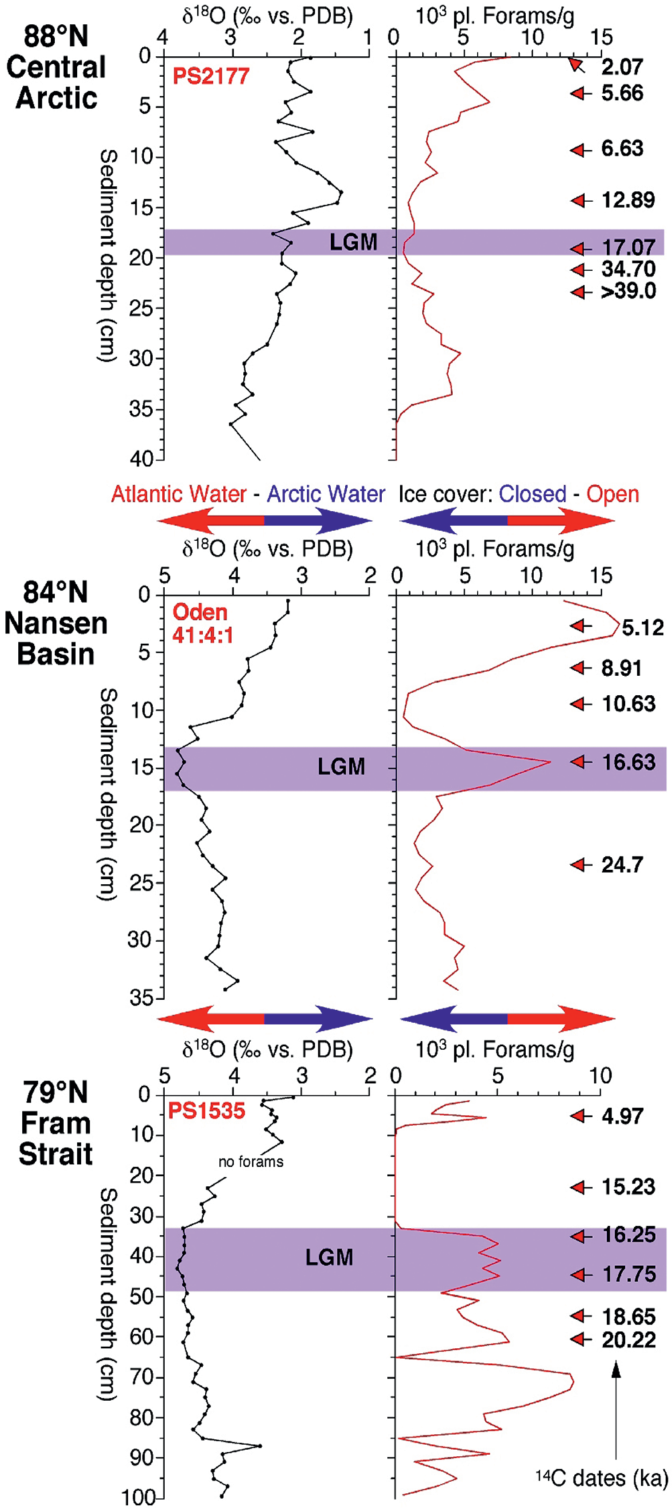


Fig. 11: Oxyen isotope records of *Neogloboquadrina pachyderma* (sin.) and abundance of planktic foraminifers in three representative sediment cores (large red dots in map) from the Fram Strait and the Arctic Ocean (data from Nørgaard-Pedersen et al. 2003). LGM marks the last glacial maximum. Also shown are sites of other cores used in the LGM reconstruction (see Fig. 10).

Abb. 11: Sauerstoff Isotopenwerte von *Neogloboquadrina pachyderma* (sin.) und Häufigkeit planktischer Foraminiferen in drei repräsentativen Sedimentkernen (große rote Kreise) aus der Framstraße und dem Arktischen Ozean (Daten aus Nørgaard-Pedersen et al. 2003). Das letzte glaziale Maximum (LGM) ist markiert. Ebenfalls eingezeichnet sind die Positionen weiterer für die LGM-Rekonstruktion (siehe Abb. 10) genutzter Sedimentkerne.



the Svalbard margins provide clear evidence for cooler and fresher conditions, probably with diminished Atlantic Water inflow (Rasmussen et al. 2007, Ślubowska-Woldengen et al. 2007, 2008). This scenario is not easily reconciled with open water conditions and relatively high bioproductivity, as suggested by organic-geochemical data from the Yermak Plateau (Birgel & Hass 2004). More high-resolution multiproxy data sets are needed from the deeper waters around Svalbard to get a broader picture of environmental conditions in this area during the Younger Dryas.

ATLANTIC WATER ADVECTION FROM THE EARLY HOLOCENE THERMAL MAXIMUM TO PRESENT

By a correlation of foraminiferal, isotope, and $U^{k'}37$ data series from sediment cores obtained along a transect from the North Sea to the western Svalbard continental margin and the Barents Sea, Hald et al. (2007) and Risebrobakken et al. (2011) revealed an enhanced flow Atlantic Water which rapidly advanced northwards after the Younger Dryas. A series of studies (Ebbesen et al. 2007, Hald et al. 2007, Rasmussen et al. 2007, Ślubowska-Woldengen et al. 2007, 2008) showed that in the middle Preboreal (~11 ka) it had reached the eastern Fram Strait and remained the dominant near-surface water mass until shortly after 9 ka when a rapid change from subpolar to polar planktic foraminifers in the sediments indicates a return of colder surface waters to the area. This interval, termed the (Early) Holocene Thermal Maximum (HTM; Kaufman et al. 2004), is generally attributed to the summer insolation maximum in the northern high latitudes peaking between 9 and 11 ka (Berger & Loutre 1991).

Microfossil data from a number of cores obtained on Arctic Ocean continental margins and nearby slopes and shelves show that the Atlantic Water reached far into the basin (Fig. 12), probably following its present-day path eastward from the northern Barents Sea margin. Isostatic depression of

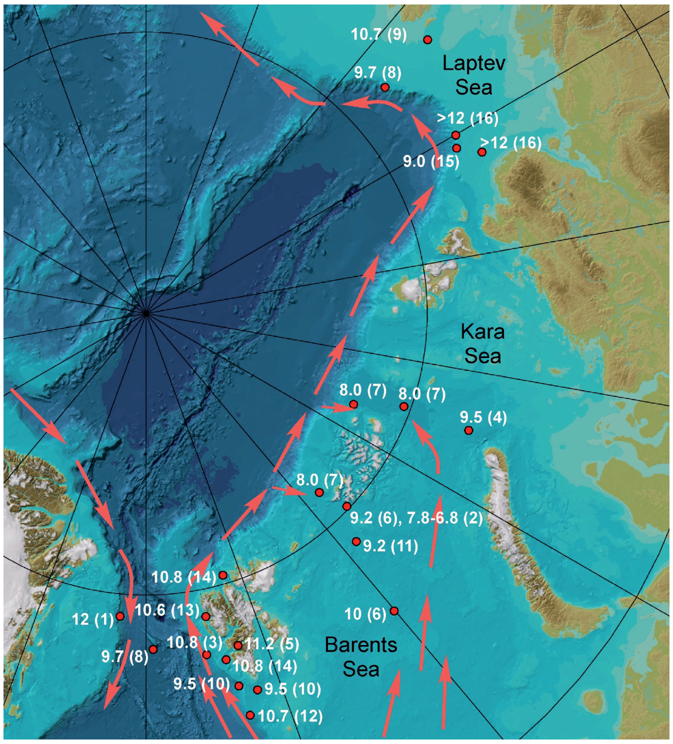


Fig. 12: Variable timing for the onset of strong Early Holocene Atlantic Water advection to sites in the Fram Strait and at the northern Eurasian continental margin. Data were obtained from various types of records, most of which are microfossil distributions. The relatively wide range of data displays the problem to clearly define this onset.
Data sources are given in parantheses: (1) = Bauch et al. (2001), (2) = Duplessy et al. (2001, 2005), (3) = Ebbesen et al. (2007), (4) = Hald et al. (1999), (5) = Hald et al. (2004), (6) = Ivanova et al. (2002), (7) = Lubinski et al. (2001), (8) = Matthiessen et al. (2001), (9) = Polyakova et al. (2005), (10) = Rasmussen et al. (2007), (11) = Risebrobakken et al. (2011), (12) = Sarnthein et al. (2003), (13) = Skirbekk et al. (2010), (14) = Ślubowska-Woldengen et al. (2007), (15) = Stein & Fahl (2000), (16) = Taldenkova et al. (2008, 2010).

Abb. 12: Darstellung des uneinheitlichen Beginns der starken frühholozänen Advektion von Atlantikwasser an verschiedenen Kernstationen in der Framstraße und am eurasischen Kontinentalrand. Die Daten entstammen unterschiedlichen Datensätzen (meist Mikrofossilien); die Datenquellen sind in Klammern genannt: (1) = Bauch et al. (2001), (2) = Duplessy et al. (2001, 2005), (3) = Ebbesen et al. (2007), (4) = Hald et al. (1999), (5) = Hald et al. (2004), (6) = Ivanova et al. (2002), (7) = Lubinski et al. (2001), 8) = Matthiessen et al. (2001), (9) = Polyakova et al. (2005), (10) = Rasmussen et al. (2007), (11) = Risebrobakken et al. (2011), (12) = Sarnthein et al. (2003), (13) = Skirbekk et al. (2010), (14) = Ślubowska-Woldengen et al. (2007), (15) = Stein & Fahl (2000), (16) = Taldenkova et al. (2008, 2010).

the Barents Sea, which was by then ice-free, was probably supportive of an enhanced Atlantic Water inflow to the Arctic Ocean (Lubinski et al. 2001). At least in areas where this water was at the surface (e.g. at 75° N on the western Barents Sea margin) it may have been warmer than today (Sarnthein et al. 2003). On its cyclonic path around the Arctic it was recorded by occurrences of subpolar microfossils, indicative benthic foraminifer species, unique isotopic compositions, and organic sediment parameters around Franz Josef Land (e.g., Lubinski et al. 1996, 2001, Hald et al. 1999, Duplessy et al. 2001, 2005, Ivanova et al. 2002, Risebrobakken et al. 2011), at the Laptev Sea continental margin (e.g., Boucsein et al. 2000, Matthiessen et al. 2001, Stein & Fahl 2000, Polyakova et al. 2005, Taldenkova et al. 2008, 2010) and on the upper slope off northern Alaska (Andrews & Dunhill 2004). The timing of the HTM apparently varied spatially; some records reveal maximum warmth as late as 7.8–6.8 ka southwest of Franz-Josef Land (Duplessy et al. 2001). Sites from the shelf and upper slope of western and northern Svalbard generally show a noticable but more limited influence of Atlantic Water (Ślubowska et al. 2005, Ślubowska-Woldengen et al. 2007), which is probably due to the influence of colder and less saline surface waters originating from the remaining ice caps over Svalbard.

High abundances of subpolar planktic foraminifers in a sediment core from the Greenland slope in the Fram Strait (79° N) indicate the presence of Atlantic Water between ~12 and ~8.5 ka (Bauch et al. 2001). However, these specimens were probably not transported loopwise through the entire Arctic. Most likely they originate from a westward expansion of Atlantic Water in the Early Holocene and a shallower halocline in the Fram Strait which allowed subpolar planktic foraminifers to dwell in an area which after 8 ka was populated only by polar foraminifers. Although apparently not fully time-equvalent, the Atlantic Water advection to the western Fram Strait and the related heat transfer may have played a major role in the establishment of reduced sea ice conditions at Northeast Greenland coasts at ~8.5–6.0 ka (Funder et al. 2011).

Cores from the deep Arctic basins and contained bathymetrical highs usually do not resolve the deglacial and Early Holocene interval in such detail as cores from the Arctic margins do. Nevertheless, Early Holocene Arctic deep-sea sediments are often characterized by higher microfossil and carbonate contents than younger deposits (e.g., Baumann 1990, Gard 1993, Stein et al. 1994, Spielhagen et al. 1997, 2004, Nørgaard-Pedersen et al. 1998, 2003, Poore et al. 1999, Polyak et al. 2004, Hanslik et al. 2010). In other cases – especially when very low sedimentation rates are noted – the carbonate and microfossil contents increase more or less gradually from LGM towards Holocene sediments, probably caused by bioturbation and mixing of fossil-poor (de) glacial and relatively fossil-rich Holocene deposits. A study by Bauch (1999) showed that subpolar species are absent in Holocene sediments on the Lomonosov Ridge at 87.5° N, except for <5 % Neogloboquadrina pachyderma (dex.) which may, however, represent aberrant forms of the sinistral coiling species (cf. Bauch et al. 2003). In summary, the elevated microfossil abundances in Early Holocene Arctic Ocean sediments all over the basin suggest an extraordinarily vigorous inflow from the south during the HTM, probably both through the Fram Strait and across the Barents Sea.

Arctic deep-sea sediments younger than the HTM usually contain lower amounts of microfossils (e.g., Spielhagen et al. 1997, 2004, Nørgaard-Pedersen et al. 1998, 2003, Bauch 1999, Polyak et al. 2004, Hanslik et al. 2010), although some cores may show a maximum at the surface. The latter feature may again result from bioturbation and/or a better preservation of carbonate in oxygenated near-surface sediments. A trend towards lower near-surface or subsurface water temperatures is seen in almost all Holocene sediment records from the circum-Arctic continental margins and shelves for the times after the HTM (e.g., Hald et al. 1999, 2007, Stein & Fahl 2000, Duplessy et al. 2001, 2005, Lubinski et al. 2001, Matthiessen et al. 2001, Ivanova et al. 2002, Andrews & Dunhill 2004, Polyakova et al. 2005, Taldenkova et al.

2010, Risebrobakken et al. 2011). The overall picture shows the establishment of conditions close to modern around 5 ka, followed by some minor variability.

Measurements of Atlantic Water temperatures and flux (i.e., volume per time) in the last few decades have revealed a close positive correlation between both parameters (Karcher et al. 2003, Schauer et al. 2004). Recent sediment core data from the upper continental margin north of Alaska (160° W) show that several centennial-scale periods within the last 8,000 years were characterized by unusually warm Atlantic Water and reduced ice cover (Farmer et al. 2011). Most likely, these were intervals with a stronger Atlantic inflow to the Arctic. Further upstream, high-resolution sediment records from core MSM5/5-712 in the eastern Fram Strait (Fig. 1) revealed a multi-centennial temperature variability of Atlantic Water on its way to the Arctic Ocean which thus most probably was concurrent with a stronger advection of warm and saline waters (Spielhagen et al. 2011, Werner et al. 2011). Temperature reconstructions were based on transfer functions utilizing planktic foraminifer associations and on Mg/Ca measurements of planktic foraminifers. Both methods gave very similar results (Fig. 13). It could be shown that Atlantic Water temperatures in the last two millennia (average ~3.5 °C at 50 m water depth) were elevated by ~0.5–1 °C during warmest intervals of the Medieval Climate Anomaly (~800–1400 CE) and lower than average during the Dark Ages Cold Period (~500–800 CE) and the Little Ice Age (~1400–1900 CE). The last ~100 years, however, showed an unprecedented temperature rise by >2 °C, eventually resulting in modern values of ~6 °C. Most likely, this temperature increase is one of the various aspects of a rapid response of the Arctic to Global Warming. Both atmospheric data series (Kaufman et al. 2009) and the record of oceanic heat advection by Atlantic Water through Fram Strait (Spielhagen et al. 2011) show that warming in the Industrial Period has reversed a cooling trend in the Arctic which has lasted (with internal variations) for at least 2000 years and probably for several thousand years more. Model-based scenarios, e.g., in the IPCC Report (2007), predict a progressive sea-ice loss in the Arctic caused mainly by atmospheric warming over the Arctic. The recent results from the Fram Strait, however, suggest that warmer and intensified Atlantic Water advection to the Arctic and the increased temperature difference between the Atlantic Water layer and the surface may also contribute to a development, which may eventually lead to an ice-free Arctic.

ATLANTIC WATER, ARCTIC OCEAN CIRCULATION TYPES, AND THE ROLE OF THE ARCTIC IN PAST CLIMATE CHANGES

Geoscientific research in the last 20 years has revealed that Atlantic Water advection to the Arctic was quite variable in the 50 million years. Until the opening of the Fram Strait as a passage for intermediate and deep water exchange which occurred either at 17.5 Ma (Jakobsson et al. 2007) or at 36 Ma (Poirier & Hillaire-Marcel 2011), bathymetry of the gateway, erosion of nearby land areas and filling of morphologic gaps as well as eustatic sea-level changes were probably the major factors controlling the exchange with the North Atlantic. Thereafter, a free exchange was physically possible but climate-related developments on the surrounding continents apparently controlled the inflow and outflow. In times of extended glaciations water masses in the upper half of the water column did not show signs of intensive Atlantic Water advection and an estuarine circulation type may have developed. This type of circulation was characterized by a dominating export of surface, subsurface and intermediate waters which contained variable, but significant contributions of brines that had formed at the northern ice sheet margin and can be traced by relatively high εNd values (Haley et al. 2008). Such scenarios apparently developed both in the Miocene-Pliocene and in the Late Quaternary. On the other hand, in intervals with significantly reduced glaciation (e.g., in parts of the Pliocene and in various interglacials and interstadials of the Late Quaternary, including the Holocene), an anti-estuarine circulation type persisted, with a strong inflow from the Atlantic which filled the Arctic Basin below a halocline separating cold, low saline riverwater-fed outflowing surface waters from underlying warmer, saline Atlantic Water. The change from one circulation type to the other may often have been somewhat “chaotic”: Freshwater contributions from melting ice on the continents and icebergs in the ocean, as well as from previously ice-dammed lakes probably induced a “super-estuarine” circulation type which then, during a deglacial interval of climatic amelioration, switched to the anti-estuarine type. Details of these changes are still poorly understood and need further research and modelling.

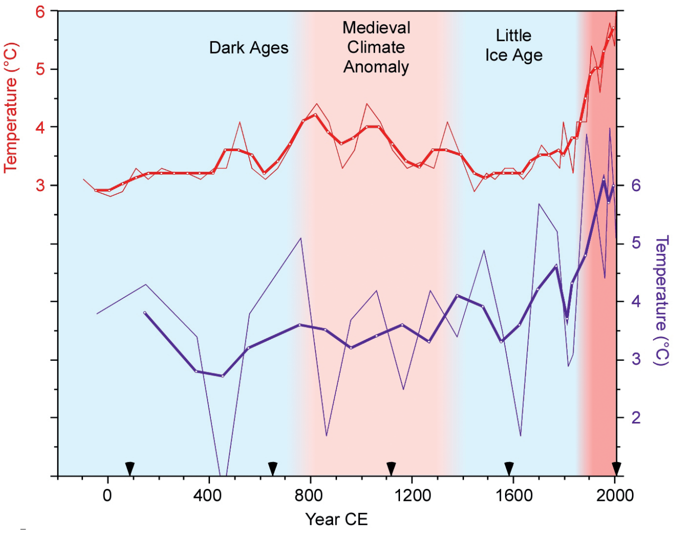


Fig. 13: Temperature reconstructions of the Atlantic Water layer at ca. 50 m water depth in the eastern Fram Strait at 79° N based on planktic foraminifer species distributions (red) and Mg/Ca ratios (blue) in core MSM5/5-712-1 for the last ca. 2,000 years (data from Spielhagen et al. 2011). Thick lines are 3-point running means, black triangles mark radiocarbon dates (converted to calendar years).

Abb. 13: Temperaturrekonstruktion für die Atlantikwasserschicht in 50 m Wassertiefe in der östlichen Framstraße (79° N) in den letzten ca. 2000 Jahren, basierend auf der Artenverteilung (rot) und Mg/Ca-Verhältnissen (blau) planktischer Foraminiferen in Sedimentkern MSM5/5-712-1 (Daten aus Spielhagen et al. 2011). Fette Linien zeigen Dreijahresmittelwerte; schwarze Dreiecke markieren mittels Radiokarbonmethode gemessene Alter in Kalenderjahren (CE).

While the prominent role of the Arctic Ocean in the present-day ocean circulation system seems undoubted, there is significantly less knowledge about an active role in climate changes of the past. The opening of the Fram Strait in the Tertiary may have seen the initiation of such a role. It induced the transition from a freshwater-dominated environment with presumably relatively little exchange with the world ocean to a ventilated subbasin of the North Atlantic and possibly the establishment of stronger E-W contrasts there. However, little is known in detail about this transition and even its timing is uncertain. Somewhat better understood is the role of Atlantic Water inflow in interglacial-to-glacial changes (and vice versa) in the Late Quaternary. The rapid change from foraminifer-bearing to IRD-bearing sediments reveals a persisting Atlantic Water inflow to the Arctic Ocean while ice sheets were already growing on the circum-Arctic continents. The inflow may have supported seasonally open water conditions along the continental margins from where evaporation could foster ice sheet growth. In sediments from glacial-interglacial transitions, microfossil-based evidence for Atlantic Water inflow shows up when the IRD content is still relatively high. At these times, heat advection by Atlantic Water may have helped to raise atmospheric temperatures and enforce ice sheet melt. Thus, ice sheet history and Atlantic Water development seem closely tied, at least in the Late Quaternary. A third stage for an active role of the Arctic in climate change was apparently opened when large amounts of freshwater entered the Arctic Ocean during the collapse of ice sheets and release of freshwater from ice-dammed lakes, e.g. at the MIS 6/5 and MIS 4/3 transitions. The contemporaneous breakdown of deep-water ventilation in the North Atlantic (e.g., CHAPMAN et al. 2000) may suggest that freshwater export from the Arctic disturbed vertical convection in the Nordic Seas and the North Atlantic and thereby stopped the advection of Atlantic Water to the Arctic for a few thousand years and cooled northwestern Europe.

The above examples show that Atlantic Water advection to the Arctic was both active and passive during climate change of the past. While the term of "Arctic Amplification" of global warming suggests a passive role of the Arctic, the ongoing changes in the Arctic related to the temperature increase may relatively soon allocate a more active role to this area when increased freshwater fluxes and a disappearing ice cover will potentially interact strongly with global oceanic and atmospheric circulation. Further geoscientific research on the geological history of the Arctic will certainly help to improve our understanding of past, present, and future changes in this highly vulnerable part of our planet.

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