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Past Climate Variability and Change in the Arctic and at High Latitudes

Chapter 8. History of Sea Ice in the Arctic

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ABSTRACT

Dramatic ongoing reduction in the Arctic sea ice necessitates a thorough understanding of its history in the geologic past. Clues to this history can be provided by sedimentary proxy records from the Arctic Ocean floor as well as from the surrounding coasts. Although sketchy, existing data provide an outline of the development of Arctic sea ice during the last several million years. Some data indicate that a consistent sea-ice cover over at least part of the Arctic Ocean existed no less than 13-14 million years, with the most severe ice conditions during the last approximately two million years in relationship with overall cooler Earth's climate. Nevertheless, episodes with considerably reduced ice cover or even seasonally ice free Arctic Ocean probably punctuated even this latter period. These episodes of ice diminishing occurred during the warmer climate events associated with changes in the Earth orbital parameters on the time scale of tens of thousands of years. The current ice reduction in the Arctic started since the late 19th century and accelerated during the last several decades. This process resulted in the largest ice reduction for at least the last few thousand years with a very fast rate that appears to have no analogs in the past. Because these changes occur so fast, it is essential to develop a comprehensive investigation of warming events in the Arctic in the past. Data obtained from this investigation will provide a critical information for assessing the magnitude and rate of the approaching ice loss and for understanding the conditions in the low-ice or seasonally ice free Arctic.

8.1 Introduction

The most defining feature of the surface of the Arctic Ocean and adjacent seas is its sea ice cover, which waxes and wanes with the seasons, but also changes in extent and thickness on interannual and longer time scales. These changes are both controlled by climate, notably temperature (e.g., Smith et al., 2003), and affect atmospheric and hydrographic conditions in high latitudes (Kinnard et al., 2008; Steele et al., 2008). Observations over the past several decades document significant retreat and thinning of the Arctic sea ice cover, a trend that is accelerating and is expected to continue with a possibility that the Arctic Ocean may become seasonally ice free as early as 2030 (Holland et al., 2006a; Comiso et al., 2008; Stroeve et al., 2008). A reduction in sea ice will enhance Arctic warming through the ice-albedo feedback mechanism and will thus influence weather systems in the northern high and perhaps middle latitudes. Changes in ice cover and freshwater flux out of the Arctic Ocean will also affect oceanic circulation of the North Atlantic, which has profound influence on European and North American climate (Seager et al., 2002; Holland et al., 2006b). Furthermore, continued retreat of sea ice will accelerate coastal erosion due to increased wave action. Ice loss will change the Arctic Ocean food web and wildlife, such as polar bears and seals that depend on the ice cover. These changes, in turn, would affect indigenous human populations that harvest such species. All of these possibilities necessitate scientific prediction of the rates and consequences of Arctic ice reduction, a task that requires thorough understanding of the natural variability of ice cover in the recent and longer-term past.

8.2 Background on Arctic sea ice cover

8.2.1 Ice Extent, Thickness, Drift and Duration

Arctic sea ice cover grows to its maximum extent by the end of winter and shrinks to a minimum in September. Over the period of reliable satellite observations (1979-2007), extremes in northern hemisphere ice extent are 16.44×10^6 km^2 for March 1979 and 4.28×10^6 km^2 for September 2007. Ice extent is defined as the region of the ocean with an ice concentration (fractional ice cover) of a least 15%. The ice cover can be broadly divided into a perennial ice zone where ice is present throughout the year, and a seasonal ice zone where ice is present only on a seasonal basis. A considerable fraction of the Arctic sea ice is perennial, which differs strongly from Antarctic sea ice which is nearly all seasonal in nature. Ice concentrations in the perennial ice zone typically exceed 97% in winter, falling to 85-95% in summer. Sea ice concentrations in the seasonal ice zone are highly variable, and in general (but by no means always) they decrease toward the southern sea ice margin.

Sea ice thickness exhibits high spatial and temporal variability that can be described by a probability distribution. While the peak of this distribution is typically cited at about 3 m, there is growing evidence (discussed below) that downward trends in ice extent over recent decades have been accompanied by significant thinning. Although many different types of sea ice can be defined, there are two basic categories, **first-year ice**, which represents a single-year's growth, and **multiyear ice**, which has survived one or more melt seasons. While in general, multiyear ice is thicker, ridging processes can result locally in very thick first-year ice (up to 20-30 m).

Under the influence of winds and ocean currents, the Arctic sea ice cover is in near constant motion. The large–scale circulation principally consists of the Beaufort Gyre, a mean annual clockwise motion in the western Arctic Ocean with a drift speed of 1-3 cm s^{-1}, and the Transpolar Drift, a motion of ice from the coast of Siberia, across the pole and into the North Atlantic via Fram Strait, which lies between northern Greenland and Svalbard. Ice velocities in the Transpolar Drift increase toward Fram Strait, where the mean drift speed is 5-20 cm s^{-1} (**Figure 8.1**) (Thorndike, 1986; Gow and Tucker, 1987). About 20% of the total ice area of the Arctic Ocean is discharged through Fram Strait on an annual basis, the majority being multiyear ice. This ice subsequently melts in the northern North Atlantic, and since the ice is relatively fresh compared to sea water, this melting results in a freshwater flux to the ocean in those regions.

8.2.2 Influences on the Climate System

Seasonal changes in the **net surface heat flux** associated with sea ice processes modulate atmospheric energy transports and exchange. The albedo (reflectivity) of the ice cover ranges from 80% when freshly snow covered to around 50% during the summer melt season (but lower in areas of **ponded ice**). This high reflectivity is in stark contrast to the dark ocean surface which has an albedo of less then 10%. The high ice albedo over a large surface area, coupled with energy used to melt ice and to increase the sensible heat content of the ocean, keeps the Arctic atmosphere cool during summer. From atmospheric heat budget requirements, this cooler polar atmosphere helps to maintain a robust poleward transport of atmospheric energy into the Arctic from lower latitudes. During autumn and winter, energy derived from incoming solar radiation is small or nonexistent. However, heat loss from the surface adds heat to the atmosphere, reducing the requirements for poleward atmospheric energy transports into the Arctic (Serreze et al., 2007a).

A growing number of model experiments have addressed potential changes in regional and large-scale aspects of the atmospheric circulation associated with loss of sea ice, often using projected ice conditions through the 21st century (see following section). Magnusdottir et al. (2004) found that altered winter sea ice conditions in the North Atlantic sector affects modeled circulation similar to the **North Atlantic Oscillation** (NAO); declining ice promotes a negative NAO response, with a weaker, southward-shifted storm track. There is ample observational evidence for the effects of sea ice in this region on mid- and high-latitude cyclone development because of the strong horizontal temperature gradients along the ice margin (e.g., Tsukernik et al., 2007). Singarayer (2006) forced a model with observed sea ice from 1980-2000 and projected sea ice reductions until 2100. In one simulation, mid-latitude storm tracks were intensified, increasing precipitation over western and southern Europe in winter. Sewall and Sloan (2004) found impacts of reduced ice cover on precipitation patterns leading to less rainfall in the American west. In summary, while these and other simulations point to the importance of sea ice on climate outside of the Arctic, results from different simulations vary widely. A coordinated set of experiments with a suite of models is needed to help to reduce uncertainty.

Climate models also indicate that changes in the melting and export of sea ice to the North Atlantic can modify the large-scale ocean circulation (e.g. Delworth et al., 1997; Mauritzen and Hakkinen, 1997; Holland et al., 2001). In particular, increased freshwater export from the Arctic may alter the Atlantic **meridional overturning circulation** (MOC) by increasing upper-ocean stability and suppressing North Atlantic deepwater formation. This suppression could have far reaching climate consequences. Observations suggest that the considerable freshening in the North Atlantic since the 1960s has an Arctic source (Peterson et al., 2006). Total Arctic freshwater output to the North Atlantic is projected to increase through the 21st century, with decreases in sea ice export more than compensated by the liquid freshwater export (associated with Arctic ice melt and increased net precipitation). However, reductions in local ice melt in the Greenland-Iceland-Norwegian seas due to a smaller Fram Strait ice transport may more directly impact the deep water formation regions and counteract increased ocean stability due to the warming climate (a warmer upper ocean is more stable) (Holland et al., 2006b). Additionally, as discussed by Levermann et al. (2007) sea ice retreat may help directly stabilize the Atlantic meridional overturning circulation through the removal of the insulating ice cover which limits ocean heat loss. These sea ice influences could help to maintain deepwater formation in the Greenland-Iceland-Norwegian seas.

8.2.3 Recent Changes and Projections for the Future

Based on satellite records from the National Snow and Ice Data Center (NSIDC, http:/nsidc.org/data/seaice_index/) that combine information from the Nimbus-7 Scanning Multichannel Microwave Radiometer (October 1978-1987) and the Defense Meteorological Satellite Program Special Sensor Microwave/Imager (1987-present), ice extent has diminished in every month, most obviously in September for which the trend over the period 1979-2007 is 10% per decade (**Figure 8.2**). Conditions in 2007 serve as an exclamation point on this ice loss (Comiso et al., 2008; Stroeve et al., 2008). The average September ice extent for 2007 of 4.28

million square km was the least ever recorded, and 23% lower than the previous September record of 5.56 million square km set in 2005. This difference corresponds to an area roughly the size of Texas and California combined. Based on an extended sea ice record using the Hadley Centre sea ice and sea surface temperature data set (HadlSST) (Rayner et al., 2003), it appears that ice extent in September 2007 represents a 50% reduction compared to conditions in the 1950s – 1970s.

Many factors may have contributed to this ice loss (as reviewed by Serreze et al. 2007b), such as general Arctic warming (Rothrock and Zhang, 2005), extended summer melt (Stroeve et al., 2006), effects of the changing phase of the **Northern Annular Mode, North Atlantic Oscillation** and other atmospheric patterns that have flushed some of the older, thicker ice out of the Arctic, leaving thinner ice that is more easily melted out in summer (e.g., Rigor and Wallace, 2004; Rothrock and Zhang, 2005; Maslanik et al., 2007a), changes in ocean heat transport (Polyakov et al., 2005; Shimada et al. 2006) and recent increases in spring cloud cover that augment the longwave radiation flux to the surface (Francis and Hunter, 2006). Strong evidence for a thinning ice cover comes from an ice tracking algorithm applied to satellite and buoy data, which suggests that the area of the Arctic Ocean covered by predominantly older (hence generally thicker) ice types (ice 5 years old or older) decreased by 56% between 1982 and 2007. Within the central Arctic Ocean, the coverage of old ice has declined by 88%, and ice that is at least 9 years old (ice that tends to be sequestered in the Beaufort Gyre) has essentially disappeared. Examination of the ice thickness distribution suggests that this loss of older ice translates to a decrease in mean thickness over the Arctic from 2.6 m in March 1987 to 2.0 m in 2007 (Maslanik et al., 2007b).

The role of greenhouse gas forcing on the observed ice loss finds strong support from the study of Zhang and Walsh (2006) who show that over the period 1979-1999, the multi-model mean trend from models discussed in the Intergovernmental Panel of Climate Change Fourth Assessment Report (IPCC-AR4) is downward, as are trends from most individual models. However, Stroeve et al. (2007) find that few or none (depending on the time period of analysis) of the September trends from the IPCC-AR4 runs are as large as observed. If the multi-model mean trend is assumed to be a reasonable representation of forced change by greenhouse gas loading, then 33-38% of the observed September trend from 1953 to 2006 is externally forced, growing to 47-57% from 1979 to 2006, when both the model mean and observed trend are larger. Although this trend argues that natural variability has strongly contributed to the observed trend, Stroeve et al. (2006) concluded that as a group, the models underestimate the sensitivity of the sea ice cover to greenhouse gas forcing. Overly thick ice in many of the models appears to provide at least a partial explanation.

The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) models driven with the SRES A1B emissions scenario (in which CO_2 reaches 720 ppm by the year 2100), point to nearly complete or complete loss (less than $1x10^6$ km^2) of September sea ice anywhere from 2040 to well beyond the year 2100, depending on the model and particular run for that model (ensemble member). Even by the late 21st century, most models project a thin ice cover in March (Serreze et al., 2007b). However, given the findings just discussed, the models as a group may be too conservative regarding when an ice-free summer Arctic Ocean will be realized.

A wild card in future Arctic ice conditions regards the possibility of abrupt change. Simulations based on the Community Climate System Model, version 3 (Holland et al., 2006a) indicate that the end-of-summer ice extent is sensitive to ice thickness in spring. If the ice thins to a more vulnerable state, a "kick" associated with natural climate variability can result in rapid summer ice loss due to the ice-albedo feedback. In the Community Climate System Model, version 3 events, anomalous ocean heat transport acts as this trigger. In one ensemble member, September ice extent decreases from about $6x10^6$ km^2 to $2x10^6$ km^2 in ten years, resulting in essentially ice-free September conditions by 2040. This is not just an artifact of Community Climate System Model, version 3:, a number of other climate models show similar rapid ice loss events.

These recent reductions in the extent and thickness of ice cover and the projections for its further shrinkage necessitate a comprehensive investigation of the longer-term history of Arctic sea ice to enable the understanding of its natural variability. A special emphasis should be placed on the times of change such as the initiation of seasonal and then perennial ice and the periods of its later reductions.

8.3 Types of Paleoclimate Archives and Proxies for the Sea-Ice Record

Records of past sea ice distribution are found in sediments preserved on the sea floor as well as in deposits along many Arctic coasts. Indirect information on sea-ice extent can be also derived from cores drilled in glaciers and ice sheets such as that on Greenland that provide a record of atmospheric precipitation, which is linked with air-sea exchanges in surrounding oceanic areas.

These types of paleoclimatic information provide a context within which the patterns and effects of the current and future ice-reduced state of the Arctic can be evaluated.

8.3.1 Marine sedimentary records

The most complete and spatially extensive records of past sea ice are provided by seafloor sediments from areas that are or have been covered by floating ice. Deposition of such sediments is directly or indirectly affected by ice through various physical, chemical, and biological processes. These processes and, thus, ice characteristics can be reconstructed from a number of sediment proxies outlined below.

Sediment cores that represent the long-term history of sea ice embracing several million years are most likely to be found in the deep, central part of the Arctic Ocean where the seafloor was not affected by erosion during periods of sea-level fall and ice-sheet growth. On the other hand, rates of sediment deposition in the central Arctic Ocean are generally low, on the order of centimeters or even millimeters per thousand years (Backman et al., 2004; Darby et al., 2006), so that sedimentary records from these areas may not capture short-term variations in paleo-environments. In contrast, cores from Arctic continental margins usually represent a much shorter time interval, less than 20 ka since the last glacial maximum, but they sometimes provide high-resolution records that capture events on century or even decadal time scales. Therefore, a combination of sediment cores from the central basin and continental margins of the Arctic Ocean is needed for a comprehensive characterization of sea-ice history and its relation to climate change.

Until recently, most cores relevant to the history of sea ice cover were collected from the low-Arctic marginal seas, such as the Barents Sea, and the Norwegian-Greenland Sea. There modern ice conditions allow for easier ship operation, whereas sampling in the central Arctic Ocean requires the use of heavy icebreakers. Recent advances in tapping the Arctic paleoceanographic archives, notably the first deep-sea drilling in the central Arctic Ocean (Backman et al., 2006) and the 2005 Trans-Arctic Expedition (HOTRAX: Darby et al., 2005), provide new, high-quality material from the Arctic Ocean proper with which to characterize variations in ice cover during the late Cenozoic (the last few million years).

A number of sediment proxies have been used to predict the presence or absence of sea ice in down-core studies. The most direct proxies are derived from sediment that melts out or drops off from ice due to the succession of following processes: 1) sediment is entrained in sea-ice, 2) this ice is transported by wind and surface currents to the sites of interest, and 3) sediment is released and deposited. The size of sediment grains is often used to identify ice-rafted debris, however, much of the coarse ice-rafted debris (sand and coarser grains) originates from floating icebergs rather than regular sea ice (Dowdeswell et al., 1994; Andrews, 2000). The entrainment of sediments on and in sea ice occurring mostly on the shallow continental margins during periods of ice freeze-up, is largely restricted to silt and clay-size sediments and rarely contains grains larger than 0.1 millimeters (Lisitzin, 2002; Darby, 2003). Coarse grains can also be shed onto land-fast ice from steep coastal cliffs, but the sediment volumes associated with this process are small. A more detailed investigation of ice-rafted debris than just measuring its content is needed for linking the sediment with sea ice: for example, examination of shapes and surface textures of quartz grains that aids in distinguishing between sea-ice and iceberg rafted material

(Helland and Holmes, 1997; Dunhill et al., 1998). Detailed grain size distributions also provide insights in ice conditions; for example, massive accumulation of silt-size grains (mostly larger than 0.01 millimeters) may indicate the position of an ice marginal zone where sedimentation is predominated by ice melting processes (Hebbeln, 2000).

Sediment **provenance** indicators provide valuable information on the sources of sediment, which can also aid the tracking of ice drift. Especially telling is sediment carrying some diagnostic signature that is "foreign" to the site of deposition and can be explained only by ice transport. For example, a useful proxy is the composition of iron-oxide sand grains that can be matched to an extensive data base of source areas from around the Arctic Ocean (Darby, 2003). Bulk sediment analyzed by quantitative methods such as X-ray diffraction can also be used in those instances where mineral that are "exotic" relative to the composition of the nearest terrestrial sources are deposited. One example is quartz in Iceland marine cores (Moros et al., 2006; Andrews and Eberl, 2007) and another is dolomite, (limestone rich in magnesium), in sediments deposited along eastern Baffin Island and Labrador (Andrews et al., 2006).

Micropaleontological objects such as skeletal-bearing microscopic organisms (for example foraminifers, diatoms, and dinocysts) found in sediment cores are widely used for deciphering past environments in which these organisms lived. Some marine **planktonic organisms** live in or on sea ice, or are somehow associated with ice. The presence of skeletons of such organisms in bottom sediments indicates the condition of ice cover over the study site. On the other hand, organisms indicative of open water are critical for identification of ice reduction events. Remnants of ice-related algae such as diatoms and dinocysts have been used to infer changes in the length of the ice cover season (Koç and Jansen, 1994; de Vernal and Hillaire-Marcel, 2000;

Mudie et al., 2006; Solignac et al., 2006). To quantify the relationship between paleontological objects and paleoenvironment, three major research steps are required. The first is the development of a database of the percent compositions in a certain group of organisms from water-column and/or surface seafloor samples that span a wide environmental range. Secondly, various statistical methods must be used to express the relationship (usually called "transfer functions") between these compositions and key environmental parameters, such as sea-ice duration and summer surface temperatures. Finally, sediment cores are analyzed and the transfer functions that are developed on the modern data sets are then applied to the temporal (i.e. down-core) data. The veracity of the transfer functions, however, depends upon the accuracy of the environmental data, which is often quite limited in Arctic areas.

Bottom dwelling (benthic) organisms in polar seas are also affected by ice cover because it effectively controls availability of food that reaches sea floor. Variations in composition of such organisms in sediments can aid in distinguishing ice-covered sites. Changes from heavily ice-covered conditions to ice-marginal conditions can be very pronounced because the latter are characterized by high seasonal productivity, in contrast to environments within the pack ice that have very low productivity. Accordingly, species of bottom-dwelling organisms that prefer high fluxes of fresh organic matter can be used on the Arctic shelves as ice-margin indicators (Polyak et al., 2002; Jennings et al., 2004). In the central Arctic Ocean benthic foraminifers and ostracodes also offer a good potential for identifying variability in ice conditions (Cronin et al., 1995; Wollenburg and Kuhnt, 2000; Polyak et al., 2004).

The composition of organic matter in sediment, including specific organic compounds (biomarkers), can also be used for reconstructing environments in which it was formed. A recent advance has been the recognition that a specific **biomarker**, IP25, can be associated with diatoms living in sea ice (Belt et al., 2007). The method has been tested by the analysis of seafloor samples from the Canadian Arctic and is being further applied to down-core samples for characterization of the past ice conditions.

It is important to understand that although all of the above proxies have a potential for identifying the former presence or even seasonal duration of sea-ice cover, each of them has limitations that complicate interpretations based on a single proxy. A case in point is the estimation in a dinocyst transfer function from East Greenland that the sea-ice duration is ~2–3 months (Solignac et al., 2006) when in reality it is closer to 9 months (Hastings, 1960). Multi-proxy records are required for a confident and detailed documentation of variations in sea-ice conditions. The success in development and refining of sea-ice proxies in sedimentary records from strategically selected sites across the Arctic Ocean and its continental margins is a key to a thorough understanding of sea-ice history.

8.3.2 Coastal records

In many places along the Arctic and subarctic coasts, evidence of past sea ice extent is recorded in coastal plain sediments, marine terraces, ancient barrier island sequences, and on beaches. All of these formerly marine deposits are now emerged due to relative changes in sea level caused by **eustatic, glacioisostatic, or tectonic** factors. Although the evidence from these types of coastal archives is inherently limited in geographic distribution and temporal scale, these deposits provide critical information for comparison with marine sediment records. The primary difference between coastal and seafloor records is in the type of fossils recovered. Notably, the spacious extent of coastal exposures in comparison with sediment cores enables findings of large paleontological objects such as plant remains, driftwood, whalebone, and relatively large mollusks. These proxies contribute valuable information on sea-surface and air temperatures, the northward expansions of subarctic and more temperate species, and the seasonality of sea ice cover in the past. For example, fossils preserved in these sequences document the dispersals of coastal marine biota between the Pacific, Arctic and North Atlantic regions, and often carry a telling evidence of ice conditions. Plant remains in their turn provide a much-needed link to documented information about past changes in the vegetation cover on land across the arctic and subarctic regions. The location of the northern treeline that is presently controlled by the July 7^{o}C mean isotherm is a critical paleobotanic indicator for understanding ice conditions in the Arctic. Nowhere in the Arctic do trees exist nearshore where there is perennial sea ice, but only in southerly reaches of regions with seasonal ice. The combination of spatial relationships between marine and terrestrial data allows a comprehensive reconstruction of the past climate.

8.3.3 Coastal plains and raised marine sequences

A number of coastal plains around the Arctic are blanketed by marine sediment sequences laid down during high sea level events. Although these sequences are located inland from coastlines that today experience perennial to seasonal sea ice, they commonly contain packages of fossil-rich sediments that provide an exceptional record of earlier warm periods. The most well-documented sections are those preserved along the eastern and northern coasts of Greenland (Funder et al., 1985, 2001), the eastern Canadian Arctic (Miller et al., 1985), Ellesmere Island (Fyles et al., 1998), Meighen Island (Matthews, 1987; Matthews and Overden, 1990; Fyles et al., 1991), Banks Island (Vincent, 1990; Fyles et al., 1994), the North Slope of Alaska (Carter et al., 1986; Brigham-Grette and Carter, 1992); the Bering Strait (Kaufman and Brigham-Grette, 1993; Brigham-Grette and Hopkins, 1995), and in the western Eurasian Arctic (Funder et al., 2002) (**Figure 8.3**). In nearly all cases the primary evidence used for estimating the extent of past sea ice is the *in situ* molluscan and microfossil assemblages. These types of data from a host of sites, coupled with evidence for the northward expansion of treeline during interglacials (e.g., Funder et al, 1985; Repenning et al., 1987; Bennike and Bocher, 1990; CAPE, 2006) provides an essential view of past sea ice conditions with direct implications for sea surface temperatures, sea ice extent, and seasonality.

8.3.4 Driftwood

One of the most discussed lines of evidence for the presence or absence of sea ice is the distribution of tree logs, mostly spruce and larch found in raised beaches along the coasts of Arctic Canada (Dyke et al., 1997), Greenland (Bennike, 2004), Svalbard (Haggblom, 1982), and Iceland (Eggertsson, 1993). Highest numbers of driftwood on the coasts are probably associated with the proximity of ice margin, while both too much ice and too open water conditions are unfavorable for driftwood delivery. Most of the logs found are attributed to a northern Russian source although some can be traced to northwest Canada and Alaska. Studies indicate that logs can only drift for about 1 yr before they become waterlogged and sink (Haggblom, 1982). The logs are probably derived from the spring snowmelt-derived floods that bring sediments and trees onto the **landfast ice** around the margin of the Arctic Basin. In areas other than Iceland, the **glacial isostatic uplift** of the land has led to a staircase of raised beaches and variations in the numbers of logs with time has resulted in an extensive data base of variations in the beaching of logs during the present interglacial (Holocene). These variations have been associated with the growth and disappearance of landfast sea-ice (which restricts the beaching of driftwood) and changes in atmospheric circulation with resulting changes in ocean surface circulation (Dyke et al., 1997).

8.3.5 Whalebone

Reconstructions of sea-ice conditions in the Canadian Arctic Archipelago have to date been derived mainly from the spatial and temporal distributions of marine mammal bones in raised marine deposits (Dyke et al., 1996, 1999; Fisher et al., 2006). Several large marine mammals have strong affinities for sea ice, such as polar bear, several species of seal, walrus, narwhal, beluga (white) whale, and bowhead (Greenland right) whale. Of these, the bowhead has left the most abundant, hence most useful, fossil record, followed by the walrus and the narwhal. Radiocarbon dating of these remains has yielded a large set of results, largely available through Harington (2003) and Kaufman et al. (2004).

The basic premise for reconstructing former sea-ice conditions from bowhead whale remains is based on the fact that the seasonal migrations of the whale are dictated by the oscillations of the sea-ice pack. The species is thought to have developed a strong preference for ice-edge environments since the Pliocene [2.6 – 5.3 million years (**Ma**) ago], perhaps because that environment allows it to escape from its only natural predator, the killer whale. Thus, the Pacific population of bowheads spends winter and early spring along the ice edge in the Bering Sea and advances northward with summer ice recession to the Canadian Beaufort Sea region along the western edge of the Canadian Arctic Archipelago. Similarly, the Atlantic population spends winter and early spring in the northern Labrador Sea between southwest Greenland and northern Labrador and advances northward in summer into the eastern channels of the Canadian Arctic Archipelago. In normal summers, the Pacific and Atlantic bowheads are prevented from meeting by a large persistent sea-ice plug that occupies the central region of the Canadian Arctic Archipelago; i.e., the central part of the Northwest Passage (**Figure 8.4**). Both populations retreat southward upon autumn freeze-up.

However, the preferred ice-edge environment is a hazardous one, especially during freeze-up, when individuals or pods may become entrapped, as has been observed to happen today. Detailed fossil skull measurements allow a reconstruction of the lengths of bowheads that have ended up in the raised marine deposits (Dyke et al., 1996; Savelle et al., 2000). These compare very closely with the length (a proxy of age) distribution of the modern Beaufort Sea bowhead population (**Figure 8.5**), indicating that the cause of death of many bowheads in the past was a catastrophic process that affected all age classes indiscriminately. This process can be best interpreted as ice entrapment.

8.3.6 Ice cores

Among paleoenvironmental archives, ice cores from glaciers and ice sheets have a particular strength as a rather direct recorder of atmospheric composition, especially in the polar regions, at a fine time resolution. The main issue is whether ice cores contain any information about past sea ice extent. Of course, such information may be inferred indirectly: for example one can imagine that warmer temperatures recorded in an ice core are associated with reduced sea ice. However, the real goal is to find a chemical indicator whose concentration is mainly controlled by past sea ice extent (or by a combination of ice extent and other climate parameters that can be deduced independently). Any such indicators must be transported over relatively long distances from the sea ice or the ocean beyond. Such an indicator would offer the advantage that ice cores might give an integrated view over a region over some time average , but the disadvantage that atmospheric transport can start to play a dominant role in determining what is delivered to the ice.

The ice-core proxy that has most commonly been considered as a possible sea ice indicator is sea salt, estimated by measuring one of the major ions in sea salt, such as sodium (Na). Over most of the world, atmospheric sea salt aerosol derives from bubble bursting at the ocean surface, and is related to wind speed at the ocean surface (Guelle *et al.*, 2001). Expanding sea ice moves the source region further from ice core sites, so that a first assumption is that a more extensive sea ice cover should lead to less sea salt in an ice core.

A statistically significant inverse relationship between annual average sea salt in the Penny Ice Cap ice core (Baffin Island) and the spring sea ice coverage in Baffin Bay (Grumet *et al.*, 2001) was found for the 20th century and it has been suggested that the extended record could be used to assess past sea ice extent in this region. However, the correlation coefficient in this study was low, indicating that only about 7% of the variability in the sea salt was directly linked to sea ice variability. The inverse relationship between sea salt and sea ice cover in Baffin Bay was also reported for a short core from Devon Island (Kinnard et al 2006). However, more geographically extensive work is needed to show whether these records can reliably reconstruct past sea ice extent.

For Greenland, the use of sea salt in this way seems even more problematic. Sea salt in aerosol and snow over the Greenland plateau tends to peak in concentration in the winter months (Mosher et al., 1993; Whitlow et al., 1992), when sea ice extent is largest, which already suggests that other factors are more important than the proximity of open ocean. Most authors carrying out statistical analyses on sea salt in Greenland ice cores in recent years have found relationships with aspects of atmospheric circulation patterns, rather than with sea ice extent (Fischer, 2001; Fischer and Mieding, 2005; Hutterli *et al.*, 2007). Sea salt records from Greenland ice cores have therefore been used as general indicators of storminess (inducing production of sea salt aerosol) and transport strength (Mayewski et al., 1994; O'Brien et al., 1995), rather than as direct sea ice proxies.

An alternative possible interpretation has arisen from study of Antarctic aerosol and ice cores, where it has been shown (Rankin *et al.*, 2002) that the sea ice surface itself can be a source of significant amounts of sea salt aerosol in coastal Antarctica. The obvious question arises as to whether this relationship between sea salt and sea ice might also be applicable at some sites in the Arctic (Rankin *et al.*, 2005). The current ideas about the sea ice source relate it to the production of new, thin ice. In the regions around Greenland and the nearby islands, much of the sea ice is old ice that has been advected, rather than new ice. It therefore seems unlikely that the method can easily be applied under present conditions (Fischer et al., 2007). The complicated geometry of the oceans around Greenland compared to the radial symmetry of Antarctica also poses problems in any interpretation. It is possible that under the colder conditions of the last glacial period, new ice production around Greenland may have led to a more dominant sea ice source, opening up the possibility that there may be a sea ice record available within this period. However, there is no published basis on which to rely at the moment and the balance of importance between salt production and transport in the Arctic needs to be investigated through fieldwork and modeling.

One other chemical (methanesulfonic acid, MSA) has been used as a sea ice proxy in the Antarctic (e.g Curran et al 2003). However studies of MSA in the Arctic do not yet support any simple statistical relationship with sea ice there (Isaksson et al 2005).

In summary, ice cores hold an attractive potential to add a well-resolved and regionally integrated picture of past sea ice extent to the point information that can be obtained from marine records. However, although there is weak statistical evidence for a relationship between sea ice extent and sea salt at one site, the complexities caused by the combination of aerosol production and transport effects that control the likely proxies mean that there is not yet any solid basis for using ice core sea ice proxies in the Arctic. Further investigation is warranted to establish whether such proxies might be usable: what is required is better understanding of their sources in the Arctic region, further statistical study of the modern controls on their distribution, and modeling studies to assess their sensitivity to major changes in sea ice extent.

8.3.7 Historical records

One way of gaining insights into recent paleoclimatic processes is through information from historical records of factors such as weather and ice conditions. The longest historical records of ice cover going back beyond the 20th century exist from ice-marginal areas that are more accessible for shipping than areas covered by heavy ice. Systematic records of the position of sea-ice margin around the Arctic Ocean have been compiled for the period since 1870 (Walsh, 1978; Walsh and Chapman, 2001). These sources vary in quality and availability over time. More reliable observational data on ice concentrations for the entire Arctic are available since 1953, and the most accurate data from satellite imagery is available since 1972 (Cavalieri et al., 2003).

Seas around Iceland provide a rare opportunity to investigate the ice record in a more distant past because Iceland has a 1200-year history of observations of drift ice (i.e. sea-ice and icebergs) following the settlement of the island in approximately 870 CE (Koch, 1945; Bergthorsson, 1969; Ogilvie, 1984; Ogilvie et al., 2000). This long record has facilitated efforts to quantify the changes in the extent and duration of drift ice around the Iceland coasts over the last 1200 years (Koch, 1945; Bergthorsson, 1969). During times of extreme drift-ice incursions, the ice wraps around Iceland in a clockwise motion. The most common occurrence of ice is off the northwest and north coasts with only occasional excursions of ice into southwest Iceland waters (Ogilvie, 1996). Historical sources have been used to construct a sea-ice index that compares well with springtime temperatures at a climate station in northwest Iceland (**Figure 8.6**).

8.4 History of Arctic Sea Ice Extent and Circulation Patterns

8.4.1 Pre-Quaternary History (prior to ~2.6 Ma ago)

The shrinkage of the perennial ice cover in the Arctic and predictions that it may completely disappear within the next 50 years or even faster (Holland et al., 2006a; Stroeve et al., 2008) are especially disturbing in light of recent discoveries that sea ice in the Arctic has been a persistent entity for the past two million years and may have originated several million years earlier (Darby, 2008; Krylov et al., 2008). Until recently, evidence of long-term (million-year scale) climatic history of the north Polar areas was limited to fragmentary records from the Arctic periphery. The ACEX deep-sea drilling borehole in the central Arctic Ocean (Backman et al., 2006) provides a new insight into its Cenozoic history for comparison with circum-Arctic records. Drilling results confirmed that at ~50 Ma, during the **Eocene Optimum** (**Figure 8.7**) the Arctic Ocean was significantly warmer than it is today, up to 24ºC at least in the summers, with fresh-water subtropical aquatic ferns growing in abundance (Moran et al., 2006). This environment is consistent with forests of enormous metasequoia that stood at the same time at the Arctic Ocean shores such as on Ellesmere Island across lowlying delta floodplains riddled with lakes and swamps (Francis, 1988; McKenna, 1980) Coarse grains occurring in ACEX sediment as old as ~46 Ma indicate a possibility of the onset of drifting ice and possibly even some glaciers in the Arctic with a cooling that followed the thermal optimum (Moran et al., 2006; St. John, 2008). This cooling compares in timing with a large-scale reorganization of the continents, notably the oceanic separation of Antarctica, and occurs at the same time as a dramatic, >1000 ppm decrease in atmospheric CO_2 concentrations (Pearson and Palmer, 2000; Lowenstein and Demicco, 2006; also see **Figure 4.2**). It should be noted, however, that in the Eocene the ACEX site was at the margin rather than in the center of the Arctic Ocean (O'Regan et al. in press) and therefore coarse grains may have been delivered to this site by agents other than drifting ice, for example by riverine inputs. The circum-Arctic coasts at this time were still occupied by rich, high-biomass forests of redwood with wetlands characteristic of temperate conditions (LePage et al., 2005; Williams et al, 2003). A continued cooling, with an abrupt temperature decrease at the Eocene/Oligocene boundary ~34 Ma that triggered the massive Antarctic glaciation may theoretically have also lead to the increase in winter Arctic ice coverage; this inference cannot yet be verified in the central Arctic Ocean as no sediment between ~44 to 18 Ma has been recovered in the ACEX record. Mean annual temperatures at the Eocene/Oligocene transition [~33.9 Ma] dropped from nearly 11°C to 4^{o} C in southern Alaska (Wolfe, 1980, 1997) at this time, while fossil assemblages and isotopic data in marine sediments along the coasts of the Beaufort Sea suggest waters with a seasonal range between 1^{o}C and 9^{o}C (Oleinik et al., 2007). The first glaciers possibly started to develop in Greenland at about the same time, based on the finding of coarse grains interpreted as iceberg rafted debris in the North Atlantic (Eldrett et al., 2007). Sustained, relatively warm conditions lingered during the early Miocene (between ~23 to 16 Ma) when cool-temperate metasequoia dominated the forests of northeast Alaska and the Yukon (White and Ager, 1994; White et al., 1997), while the central Canadian Arctic Islands were covered in mixed conifer-hardwood forests similar to those of southern Maritime Canada and New England today. Such forests and associated wildlife would have easily tolerated seasonal sea ice, but would not have survived the harshness of perennial ice cover of the adjacent ocean (Whitlock and Dawson, 1990).

A large unconformity (gap) in the ACEX record prevents us from characterizing sea-ice conditions between ~44 to 18 Ma (Backman et al., 2008). Sediments immediately above this unconformity contain only low numbers of ice-rafted debris indicative of low sea ice volume in the Arctic Ocean at that time (St. John, 2008). Dramatic changes in Arctic climatic conditions occurred in the middle Miocene concurrent with the global cooling and the onset of Antarctic reglaciation (**Figure 8.7**). These changes were also possibly enhanced by the development of the modern circulation system in the Arctic Ocean after the opening of the Fram Strait between Eurasian and Greenland margins at ~17 Ma (Jakobsson et al., 2007). The resultant cooling led to a change from pine–redwood to larch–spruce dominated floodplains and swamps at the Arctic periphery at ~16 Ma as recorded for example on Banks Island by extensive peats with stumps in growth position (Fyles et al 1994; Williams, 2006). A combination of cooling and increased moisture supply from the North Atlantic caused the growth of ice masses on and around Svalbard and the discharge of icebergs into the eastern Arctic Ocean and the Greenland Sea at ~15 Ma (Knies and Gaina, 2008). A succeeding change of sediment **provenance** in the central Arctic Ocean between 13-14 Ma indicates the likelihood of the formation of perennial sea ice (Krylov et al., 2008), although its geographic distribution and persistence is not yet understood. Another **provenance** study infers that evidence of perennial ice influence can be found in sediments even older than this transition, starting from at least 14 Ma (Darby, 2008). Several succeeding pulses of elevated ice-rafted debris fluxes in the late Miocene ACEX record indicate further ice growth (St. John, 2008), consistent with the spread of pine-dominated forests in northern Alaska indicative of the deterioration of climatic conditions (White et al., 1997). Nevertheless, paleobotanical evidence suggests that throughout the late Miocene and most of the Pliocene there were at least some periods when perennial ice was severely restricted,or absent. Thus, extensive braided river deposits of the Beaufort Formation (early-mid Pliocene, ~5.3 to 3 Ma) covering much of the western Canadian Arctic Islands enclose abundant logs and other woody detritus representing over 100 vascular plants including pine (2 and 5 needles) and birch, and dominated at some locations by spruce and larch (Fyles, 1990; Devaney, 1991). Although these floral remains indicate overall boreal conditions cooler than in the Miocene, extensive perennial sea ice is not likely to have existed in the adjacent Beaufort Sea during this time. This inference is consistent with the presence of the bivalve Icelandic Cyprine (*Arctica islandica)* in marine sediments capping the Beaufort Formation on Meighen Island at 80^{o}N and dated to the peak of Pliocene warming, ~3.2 Ma (Fyles et al. 1991). Foraminifers in Pliocene deposits in the Beaufort-Mackenzie area are also characteristic of boreal, but not yet high-arctic waters (McNeil, 1990), whereas the only known pre-Quaternary foraminiferal evidence from the central Arctic Ocean indicates seasonally ice free conditions in the early Pliocene ~700 km north of the Alaskan coast (Mullen and McNeil, 1995).

Cooling in the late Pliocene caused a profound reorganization of the Arctic system including the retreat of tree line away from the Arctic coasts (White et al. 1997; Matthews and Telka, 1997), the formation of permafrost (Sher et al, 1979; Brigham-Grette and Carter, 1992), and the growth of continental ice masses around the Arctic Ocean such as the advance of the Svalbard ice sheet on the outer shelf (Knies et al., 2002) and the initiation of ice sheets in North America between 2.9 to 2.6 Ma (Duk-Rodkin et al., 2004). The ACEX record demonstrates especially high ice-rafted debris fluxes in the Arctic Ocean around 2 Ma (St. John, 2008). Despite the overall cooling, evidence of extensive warming periods during the late Pliocene and the initial stages of the Quaternary (between ~2.4 to 3 Ma) is repeatedly documented at the Arctic periphery from northwest Alaska to northeastern Greenland (Feyling-Hanssen et al., 1983; Funder et al., 1985, 2001; Carter et al., 1986; Bennike and Böcher, 1990; Kaufman, 1991; Brigham-Grette and Carter, 1993). For example, beetle and plant macrofossils in the nearshore high energy sediments of the upper Kap København Formation on northeast Greenland, dated to ~2.4 Ma, emulate paleoenvironmental conditions similar to those of southern Labrador today (Funder et al., 1985, 2001; Bennike and Böcher, 1990). At the same time, marine conditions were distinctly Arctic, but an analogy with present faunas along the Russian coast shows that there must have been a period with open water of 2-3 months in the summer. These results imply that summer sea ice in the entire Arctic Ocean was probably much reduced.

Complete documentation of the history of perennial vs. seasonal sea ice and ice-free intervals over the past several million years requires more sedimentary records, geographically distributed across the Arctic Ocean, and a synthesis of the sediment and paleobiological evidence from both the land and the sea. Learning this history will provide new clues as to the stability of the Arctic sea ice as well as the sensitivity of the Arctic Ocean to changing temperatures and other climatic features such as snow and vegetation cover.

8.4.2 Quaternary variations (the past ~2.6 Ma)

The Quaternary period of Earth's history over the past ~2.6 Ma is characterized by overall low temperatures and especially large swings in climate regime (**Figure 8.8**). These swings are related to changes in insolation (incoming solar radiation) modulated by Earth's orbital parameters with periodicities of tens to hundreds of thousand years. During the cold periods such as the Quaternary when large ice masses are formed, these variations are amplified by powerful feedbacks due to changes in the albedo (reflectivity) of the Earth's surface and concentration of greenhouse gases in the atmosphere. Quaternary climate history is comprised of cold intervals (glacials) when very large ice sheets formed in northern Eurasia and North America, intersperspersed with warm intervals (interglacials), such as the present one, referred to as the Holocene (last ~11.5 thousand years [henceforward indicated as **ka**]). Temperatures at the Earth's surface during some interglacials were similar or even somewhat warmer than those of today; therefore, climatic conditions during those times can be used as approximate analogs for the conditions predicted by climate models for the 21st century (Otto-Bliesner et al., 2006; Goosse et al., 2007). One of the biggest questions in this respect is how strongly reduced sea-ice cover was in the Arctic during those warm intervals. It must be said that this issue is insufficiently understood because of fragmentary exposures of interglacial deposits at the Arctic margins (CAPE, 2006) and generally low resolution of sedimentary records from the Arctic Ocean. Even the age assignment of sediments that appear to be interglacial is often problematic because of the poor preservation of fossils and various stratigraphic complications (e.g., Backman et al., 2004). A better understanding starts to emerge based on recent collections of sediment cores from strategically selected sites in the Arctic Ocean such as the ACEX drilling (Backman et al., 2006) and HOTRAX collection (Darby et al., 2005). The severity of ice conditions during glacial stages is indicated by a practically complete absence of biological remains in respective sediment layers and possible non-deposition intervals due to especially solid ice (Polyak et al., 2004; Darby et al., 2006; Cronin et al., 2008). In contrast, interglacials are characterized by higher marine productivity and, thus indicate reduced ice cover. In particular, it has been demonstrated that planktonic foraminifers indicative of subpolar, seasonally open-water conditions lived in the area north of Greenland during the last interglacial, Marine Isotope Stage 5e, 120-130 ka ago (**Figure 8.9**, Nørgaard-Pedersen et al., 2007a,b). Given that this area is presently characterized by especially high ice conditions, this finding indicates the possibility that the entire Arctic Ocean may have been free of summer ice cover 120–130 ka. This inference necessitates careful examination of correlative sediments across the Arctic Ocean to test whether the observed low-ice to possibly ice-free conditions was a local or basin-wide phenomenon. Some intervals in sediment cores from various sites in the central Arctic have been reported to contain subpolar microfauna (e.g., Herman, 1974; Clark et al., 1990), but their age was not well constrained. New sediment core studies are needed to place these intervals in the coherent stratigraphic context and to reconstruct corresponding paleo-ice conditions. This task is especially significant as only records from the central Arctic Ocean can provide a direct evidence for ocean-wide ice-free water.

Some coastal exposures of interglacial deposits such as MIS 11 (~400 ka ago) and 5e (~120–130 ka ago) also indicate water temperatures warmer than present and reduced ice influence. For example, deposits of the last interglacial on the Alaskan coast of the Chukchi Sea (so-called Pelukian transgression) contain some fossils of species that are limited today to the northwest Pacific, whereas the findings of inter-tidal snails near Nome, just slightly south of the Bering Strait, suggest that the coast here may have been annually ice free (Brigham-Grette and Hopkins, 1995; Brigham-Grette et al., 2001). On the Russian side of the Bering Strait, formaniniferal assemblages suggest that coastal waters were fairly warm, like those in the Sea of Okhotsk and Sea of Japan (Brigham-Grette et al., 2001). Deposits of the same age along the Northern Arctic coastal Plain show that at least eight mollusk species extended their distribution ranges well into the Beaufort Sea (Brigham-Grette and Hopkins, 1995). Deposits near Barrow include at least one mollusk and several ostracode species only known from the North Atlantic. Taken together, these findings suggest that during the peak of the last interglacial, ~120–130 ka, the winter sea ice limit did not extend south of the Bering Strait and was located perhaps 800 kilometers north of historical limits, while summer sea surface temperatures were warmer than present through the Strait and into the Beaufort Sea.

8.4.3 The Holocene (the most recent 11.5 ka)

The present interglacial that has lasted for approximately the past 11.5 ka is characterized by much more paleoceanographic data than earlier warm periods because of the typically ubiquitous presence of Holocene deposits on continental shelves and in many coastal records. Due to relatively high sedimentation rates at the continental margins, some records allow reconstruction of ice drift patterns on sub-millennial scales. Thus, the periodic influx of large numbers of iron oxide grains from specific sources such as the Siberian margin to seafloor area north of Alaska has been linked to a certain mode of the atmospheric circulation pattern (Darby and Bischof, 2004). If this linkage is proven, it will signify the existence of longer-term atmospheric cyclicity in the Arctic than the decadal **Arctic Oscillation** observed during the last century (Thompson and Wallace, 1998).

Many proxy records indicate that the early Holocene experienced temperatures warmer than today temperatures and reduced ice conditions in the Arctic. This is consistent with higher levels of insolation peaking at ~11 ka ago due to Earth's orbital variations. This picture is notably apparent in records from the high Arctic in places such as Svalbard and northern Greeland, northwestern North America, and east Siberia (Kaufman et al., 2004; Blake, 2006; Fisher et al., 2006; Funder and Kjær, 2007). Decreased sea-ice cover in the western Arctic during the early Holocene has also been inferred from high sodium concentrations in the Penny Ice Cap of Baffin Island (Fisher et al., 1998) and the Greenland Ice Sheet (Mayewski et al., 1994), although the significance of this proxy yet needs to be defined. Areas that were affected by the extended melting of the Laurentide ice sheet, especially the northeastern sites in North America and the adjacent North Atlantic, show more complex temperature and ice distribution patterns (Kaufman et al., 2004).

An extensive record has been compiled from bowhead whale findings along the coasts of the Canadian Arctic Archipelago straits (Dyke et al., 1996, 1999; Fisher et al., 2006). Understanding the dynamics of ice conditions in this region is especially important for modern-day considerations because ice-free, navigable straits through the Canadian Arctic Archipelago will provide new opportunities for shipping lanes. The current set of radiocarbon dates on bowheads from the Canadian Arctic Archipelago coasts is grouped into three regions: western, central, and eastern (**Figure 8.10**). The central region today is the area of normally persistent summer sea ice; the western region is within the summer range of the Pacific bowhead; the eastern region is within the summer range of the Atlantic bowhead. These three graphs allow us to draw the following conclusions:

1. The maximum frequency of bowhead findings in all three regions occurred during the early Holocene (10 to 8 ka ago). At that time Pacific and Atlantic bowheads were commonly able to intermingle freely along the length of the Northwest Passage indicating at least periodically ice free summer conditions.
2. Following an interval (8-5 ka ago) of lessened occurrences, there was a strong recurrence of bowhead findings in the eastern channels during the middle Holocene (5-3 ka ago). At times, the Atlantic bowheads penetrated into the central region, particularly 4.5-4.2 ka ago. The Pacific bowhead apparently did not extend its range at this time.
3. A final peak of bowhead occurred about 1.5-0.75 ka ago in all three regions, suggesting an open Northwest Passage during at least some summers. It was notably within this interval that the bowhead-hunting Thule Inuit (Eskimo) expanded eastward out of the Bering Sea region, ultimately spreading to Greenland and Labrador.
4. The decline of bowhead abundances during the last few centuries, evident in all three graphs, coincides with the abandonment of High Arctic regions of Canada and Greenland by Thule bowhead hunters during the Little Ice Age, and an increased focus on alternate resources by Thule living in more southern Arctic regions.

The summer temperature conditions that accompanied the early Holocene bowhead maximum are estimated at about 3°C above mid-twentieth century conditions based on the summer ice melt record of the Agassiz Ice Cap (Fisher et al., 2006). Unless other processes, such as a different ocean circulation pattern, were also forcing greater summer sea-ice clearance at that time, the value of 3°C is an upper bound on the amount of warming necessary to clear the Northwest Passage region of summer sea ice. Clearly there were times during the middle and late

Holocene (especially 4.5-4.2 ka ago) when the threshold condition was approached and, at least briefly, met. The actual threshold condition for clearance of ice from the Northwest Passage was actually crossed in summer 2007. Whether this will be a regular event and what the consequences might be for Pacific-Atlantic exchanges of biota remains to be seen.

The bowhead record can be compared to data on the distribution of driftwood that has been collected and dated on raised marine beaches, notably around the margins of Baffin Bay (Blake, 1975), and has been used to infer changes in the transport of sea-ice from the Arctic Basin (Dyke et al., 1997) (**Figure 8.11**). The driftwood ratio of larch (mainly derived from Russia) versus spruce (northwest Canada) shows a significant and rapid decline about 7 ka before present. This abrupt shift might have been caused by the intensity of ice drift from the Arctic Ocean and/or changes in its trajectories (Tremblay et al., 1997), or it might also be modified by changes in forest composition and extent. It appears from this data that the delivery of driftwood, which probably came via the East Greenland Current, peaked during the early Holocene, possibly in relationship with lower ice cover in the Arctic Ocean at that time.

Levac et al. (2001) estimated the duration of sea-ice cover during the Holocene in northern Baffin Bay (southern reach of Nares Strait between Ellesmere Island and NW Greenland) based on transfer functions of dinocyst assemblages. The present-day duration of the ice cover in this area is ~8 months, whereas the predicted duration over the Holocene varied between 7 and 10-12 months at the extreme. An interval of minimal sea-ice cover occurred between ca. 8.5 to 4.5 ka, whereas afterwards the sea-ice cover was considerably more extensive (**Figure 8.12**).

Along the North Greenland coasts, isostatically raised “staircases” of wave-generated beach ridges (**Figure 8.13**) show that these areas once saw seasonally open water (Funder and Kjær, 2007). In addition to beach ridges, large amounts of striated boulders in and on the marine sediments also indicate that the ocean was open enough for icebergs to drift along the shore and drop their loads. Presently the North Greenland coastline is permanently surrounded by pack ice, and rare icebergs are locked up in the sea ice. Radiocarbon-dated mollusk shells from beach ridges show that the beach ridges were formed in the early Holocene, within the interval from ~8.5– 6 ka, and progressively shorter from south to north. The occurrence of these wave-generated shores and abundant iceberg-deposited boulders indicates the possibility that the adjacent Arctic Ocean was free of sea ice in summer at this time.

A somewhat different Holocene history of ice extent emerges from the northern North Atlantic and Nordic seas, exemplified by the Iceland margin. A 12,000 year record of quartz content, which is used in this area as a proxy for the presence of drift ice (Eiriksson et al., 2000), has been produced for a core MD99-2269 from the northern Iceland shelf at a 30-yr/sample resolution (Moros et al., 2006); these results are consistent with data obtained further from 16 cores across the northwestern Iceland shelf (Andrews, 2007). These data show that the minimum in quartz and, thus, ice cover occurred at the end of deglaciation, while in the early Holocene amount of ice increased and then reached another minimum around ca. 6 ka, after which the content of quartz has steadily risen (**Figure 8.14**). The lagged Holocene optimum in the North Atlantic in comparison with high-Arctic records can be explained by the specifics of oceanic controls on ice distribution. In particular, the discharge of glacial meltwater from the remains of the Laurentide ice sheet dampened the warming in the North Atlantic region in the early Holocene (Kaufman et al., 2004). Additionally, a seesaw pattern in oceanic circulation between the eastern and western regions of the Nordic seas existed throughout much of the Holocene. For example, in the Norwegian Sea the Holocene ice-rafting maximum occurs in the mid-Holocene, 6.5 to 3.7 ka (Risebrobakken et al., 2003), along with orbitally forced decreasing summer temperatures and decreased seasonality (Moros et al., 2004). By contrast, the middle Holocene is a relatively warm period off East Greenland, with strong Atlantic Water inflow as a subsurface current between 6.5 and 4 ka, while ice-rafted debris was low (Jennings et al., 2002). These patterns are expected from modern observations of the marine and atmospheric temperatures (seesaw effect of van Loon & Rogers, 1978).

The Neoglacial cooling (last few thousand years) is considered overall to be related to decreasing summer solar insolation (Koç and Jansen, 1994); however, high resolution climate records reveal greater complexity in the system involving changes in seasonality and links with low latitude and southern high latitude conditions (e.g. Moros et al., 2004). Flux variations in the ice-rafted debris records indicate multiple cooling and warming intervals during the Neoglaciation, similar to the so-called ‘Little Ice Age’ and ‘Medieval Warm Period’ type cycles of greater and lesser sea ice extent (Jennings and Weiner, 1996; Jennings et al., 2002; Moros et al., 2006; Bond et al., 1997). Polar Water excursions have been reconstructed as multi-century to decadal-scale variations superimposed on the Neoglacial cooling at several sites in the subarctic North Atlantic (Andersen et al., 2004; Giraudeau et al., 2004; Jennings et al., 2002). In contrast, a decrease in drift ice during the Neoglacial is documented for areas influenced by the North Atlantic Current, possibly indicating a warming in the eastern Nordic Seas (Moros et al., 2006). A seesaw climate pattern has been evident between seas adjacent to West Greenland and Europe so that well-known European warmings such as the Roman and the Medieval Warm Period have been documented as cold periods on West Greenland resulting from low entrainment of warm

Atlantic Water into the West Greenland Current, while the Dark Ages experienced increased meltwater runoff suggesting warming (Seidenkrantz et al., 2007).

Bond et al (1997, 2001) suggested that cool periods manifested as past expansions of drift ice and ice-rafted debris (most notably, hematite stained quartz grains) in the North Atlantic punctuated deglacial and Holocene records at intervals of about 1500 years and that these drift ice events were a result of climate cyclicity independent from glacial influence. Bond et al., (2001) concluded that Holocene drift ice peaks resulting from southward expansions of polar waters were correlated with times of reduced solar output. This conclusion suggested a causative association between the sun's output and centennial to millennial scale variations in Holocene climate that may have been transmitted/amplified through effects on production of North Atlantic Deep Water. However, continued investigation of the drift ice signal indicates that although the variations reported by Bond et al. may record a solar influence on climate, they likely do not pertain to a simple index of drift ice (Andrews et al., 2006). In addition, those cooling events prior to the Neoglacial interval may stem from deglacial meltwater forcing rather than from southward drift of Arctic ice (Giraudeau et al., 2004; Jennings et al., 2002). In an effort to test the idea of solar forcing of 1500 year cycles in Holocene climate change, Turney et al. (2005) compared Irish tree-ring derived chronologies and radiocarbon activity, a proxy for solar activity, with the Holocene drift ice sequence of Bond et al. (2001). They found a dominant 800-year cyclicity in moisture, reflecting atmospheric circulation changes during the Holocene, but no coherency with solar activity was supported by their data.

Despite multiple records from the Arctic margins indicating considerably reduced ice conditions in the early Holocene, no evidence of the decline of perennial ice cover has been found in sediment cores from the central Arctic Ocean. The reason for this inference is that the investigated sediments contain some ice-rafted debris interpreted to arrive from distant shelves requiring more than one year of ice drift (Darby and Bischof, 2004). One possible explanation is that the true record of low-ice conditions has not yet been found in the Arctic Ocean interior because of low sedimentation rates and stratigraphic uncertainties. Additional investigation employing multi-proxy approach to cores with highest possible resolution is needed to verify the distribution of ice in the Arctic during the warmest phase of the current interglacial.

8.4.4 Historical period

A compilation of Arctic paleoclimate records from various proxies such as lake and marine sediments, trees, and ice cores indicates that from the mid-19th to late 20th century the Arctic warmed to the highest temperatures in at least four centuries (Overpeck et al., 1997). A recent study of subglacial material exposed by retreating glaciers in the Canadian Arctic indicates that modern temperatures are warmer than any time in at least the past 1600 years (Anderson et al 2008). Paleoclimatic proxy records of the last two centuries agree well with hemispheric and global data including instrumental measurements (Mann et al., 1999; Jones et al., 2001). The composite record of ice conditions for Arctic ice margins since 1870 shows a steady retreat of seasonal ice from the beginning of the 20th century and then the accelerating retreat of both seasonal and annual ice for the last 50 years (**Figure 8.15**; Kinnard et al., 2008). The latter observations are the most reliable for the entire data set and are based on satellite imagery since 1972. Patterns of ice-margin retreat vary between different periods and regions of the Arctic, but the overall trend unmistakably attests to the dramatic current decline of the Arctic sea-ice cover that overwhelms decadal-scale climatic and hydrographic periodicities (e.g., Polyakov et al., 2005; Steele et al., 2008). This remarkable warming and associated ice shrinkage is especially anomalous because orbitally driven insolation has been decreasing steadily since it maximum 11 ka ago, and is now near its minimum of the 21 ka precession cycle (e.g., Berger and Loutre, 2004) which should be leading to climatic cooling.

8.5 Synopsis

Geological data indicate that the history of Arctic sea ice is closely linked with temperature changes. Sea ice in the Arctic Ocean may have appeared as early as 46 Ma after the onset of a long-term climatic cooling related to a reorganization of the continents and subsequent formation of large ice sheets in polar areas. Year-round ice in the Arctic possibly developed as early as 13-14 Ma, in relation to a further overall climatic deterioration and the establishment of the modern-type hydrographic circulation in the Arctic Ocean. Nevertheless, extended seasonally ice-free periods were likely until the onset of large-scale Quaternary glaciations in the Northern hemisphere approximately 2.5 Ma, which was likely to have been accompanied by a fundamental increase in the extent and duration of sea ice. Some data suggest that ice reductions marked Quaternary interglacials, and the Arctic Ocean may have even been seasonally ice free during the warmest events due to insolation changes modulated by orbital variations operating on time scales of tens to hundred thousand years. Low-ice conditions are inferred for example for the last interglacial and the onset of the current interglacial, ~130 and 10 ka ago. These low-ice periods can be used as ancient analogs for future conditions expected from the dramatic ongoing loss of Arctic ice cover. On medium-term time scales, of thousands and hundreds of years, there are some signs of variability in ice circulation; this feature is not yet well understood, but in any case significant periodic reductions in ice cover on these time scales are unlikely. In the most recent times, historical observations suggest that ice cover has been consistently shrinking since the late 19th century, with an accelerating decline during the last several decades that already resulted in the largest ice reduction for at least the last few thousand years. This ice loss appears to be unrelated to natural climatic and hydrographic variability on decadal time scales and longer-term orbital insolation changes. These conclusions underscore the immense magnitude and unprecedented nature of the current ice loss and dictate the urgent need for a comprehensive investigation of involved linkages and a development of accurate predictive models for the future state of the Arctic. The latter task in its turn requires realistic boundary conditions verified by paleoclimatic data.

FIGURE CAPTIONS

Figure 8.1. "Ocean currents and sea ice extent." UNEP/GRID-Arendal Maps and Graphics Library. Dec 97. UNEP/GRID-Arendal. 19 Feb 2008. Philippe Rekacewicz, UNEP/GRID-Arendal) <http://maps.grida.no/go/graphic/ocean_currents_and_sea_ice_extent>.

Figure 8.2. Time series of Arctic sea ice extent for September over the period 1979-2007. The linear trend (trend line shown in blue) including 2007 shows a decline of 10% per decade (courtesy National Snow and Ice Data Center, Boulder, Colorado).

Figure 8.3. Index map of key marine sedimentary sequences exposed at the coasts of Arctic North America and Greenland.

Figure 8.4. Satellite image showing typical late 20^{th} century summer ice conditions in the Canadian Arctic Archipelago.

Figure 8.5. The reconstructed lengths of Holocene bowhead whales based on skull measurements (485 animals) and mandible measurements (an additional 4 animals) (Savelle, et al., 2000). This distribution is very similar to the lengths of living Pacific bowheads, indicating that past strandings affected all age classes.

Figure 8.6. The sea-ice index on the Iceland shelf shows a good correlation with spring-time air temperatures in NW Iceland that are affected by the distribution of ice in this region (from Ogilvie, 1996).

Figure 8.7. Global climate change over the last 65 Ma based on a world-wide compilation of oxygen isotope measurements ($\delta^{18}O$) on benthic foraminifera (Zachos et al., 2001, adapted by Rohde, 2007a) which reflect a combination of local bottom-water temperatures and changes in

the isotopic composition of sea water associated with the growth and melting of continental ice sheets during the last ~35 Ma. For the most recent period, benthic $\delta^{18}O$ data are tightly correlated with temperature changes measured in the Vostok ice core, Antarctica (see Figure 8.8 for detail); modern temperature (as of 1950) is taken as 0º C (dotted line in the lower right, blue section of this graph). Abbreviations Pal, Eo, Ol, Mio, Pli, and Plt stand for Paleocene, Eocene, Oligocene, Miocene, Pliocene, and Pleistocene.

Figure 8.8. Globally integrated climate record for the last 5 Ma (Lisiecki and Raymo, 2005 and associated website, adapted by Rohde, 2007). Right scale bar refers to changes in ocean bottom waters (as in Figure 8.7); left scale bar refers to deviations from modern temperatures over East Antarctica as measured in the Vostok ice core (Petit et al., 1999). Green bars show predominant cyclicity in insolation (orbital parameters). Note very large temperature swings during the Quaternary, last ~2.0 Ma, with overall low temperatures and several events with temperatures higher than today.

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Figure 8.10. The distributions of radiocarbon ages (in thousands of years) of bowhead whales in three regions of the Canadian Arctic Archipelago (data from Dyke et al., 1996; Savelle et al., 2000).

Figure 8.11. Distribution of Holocene driftwood on the shores of Baffin Bay (from Dyke et al., 1997).

Figure 8.12. Reconstruction of the duration of ice cover (months per year) in northern Baffin Bay during the Holocene based on dinocyst assemblages (from Levac et al., 2001).

Figure 8.13. Aerial photo (left) of wave-generated beach ridges (BR) at Kap Ole Chiewitz, 83°25'N, northeast Greenland. D1-D4 are raised deltas. The oldest, D1, is dated to ~10 ka while D4 is the modern delta. Only D3 is associated with wave activity. The period of beach ridge formation is dated to ca. 8.5–6 ka. The photo on the right shows the upper beach ridge.

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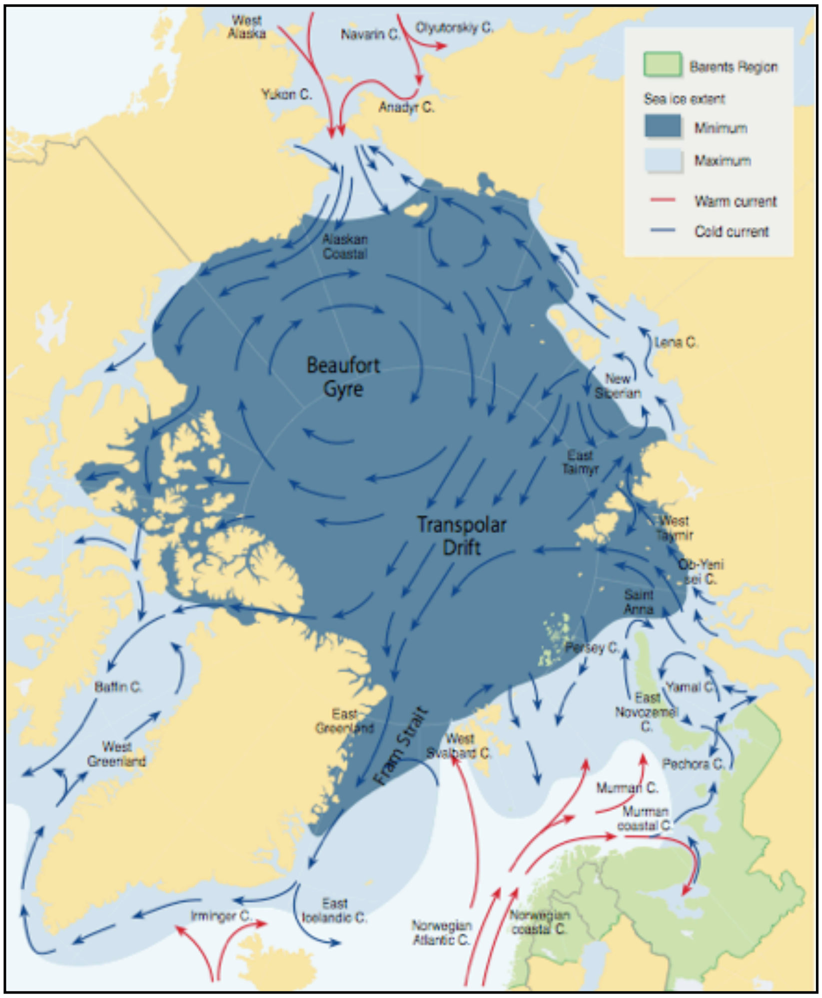


Figure 8.1. "Ocean currents and sea ice extent." UNEP/GRID-Arendal Maps and Graphics Library. Dec 97. UNEP/GRID-Arendal. 19 Feb 2008. Philippe Rekacewicz, UNEP/GRID-Arendal) <http://maps.grida.no/go/graphic/ocean_currents_and_sea_ice_extent>.

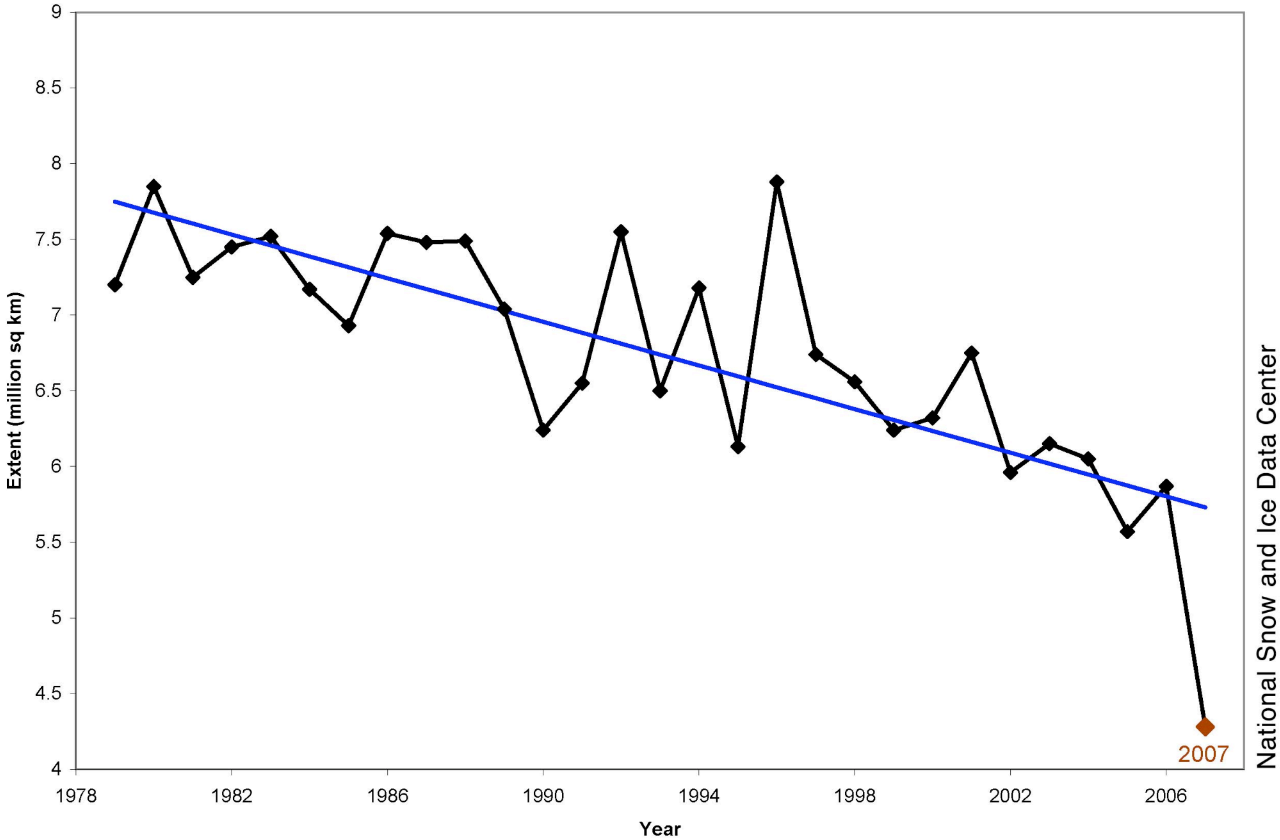


Figure 8.2. Time series of Arctic sea ice extent for September over the period 1979-2007. The linear trend (trend line shown in blue) including 2007 shows a decline of 10% per decade (courtesy National Snow and Ice Data Center, Boulder, Colorado).

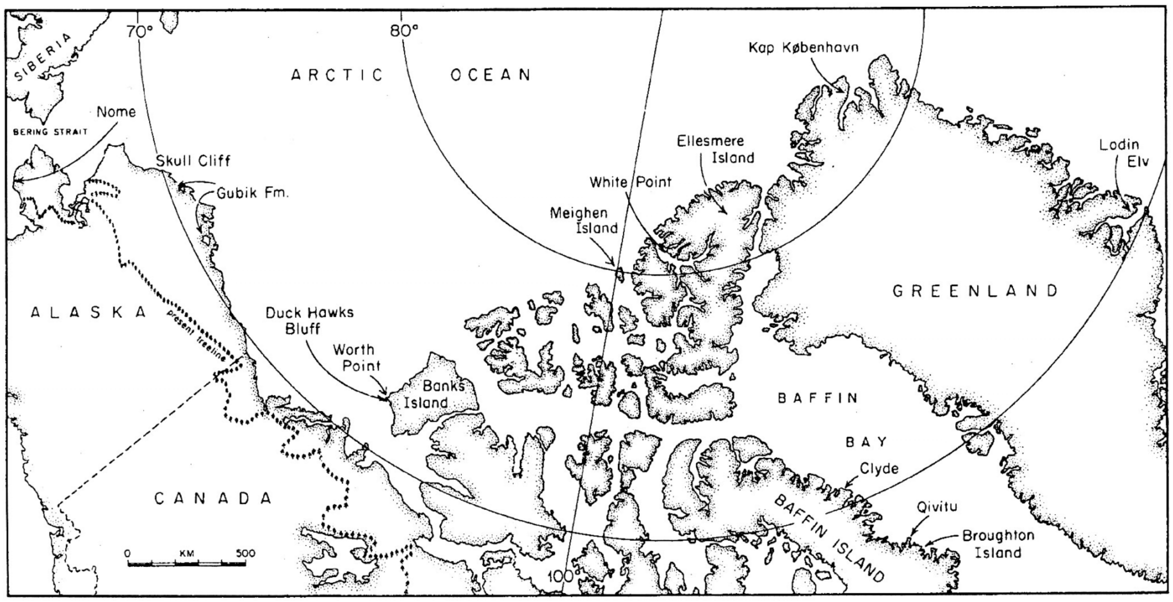


Figure 8.3. Index map of key marine sedimentary sequences exposed at the coasts of Arctic North America and Greenland.

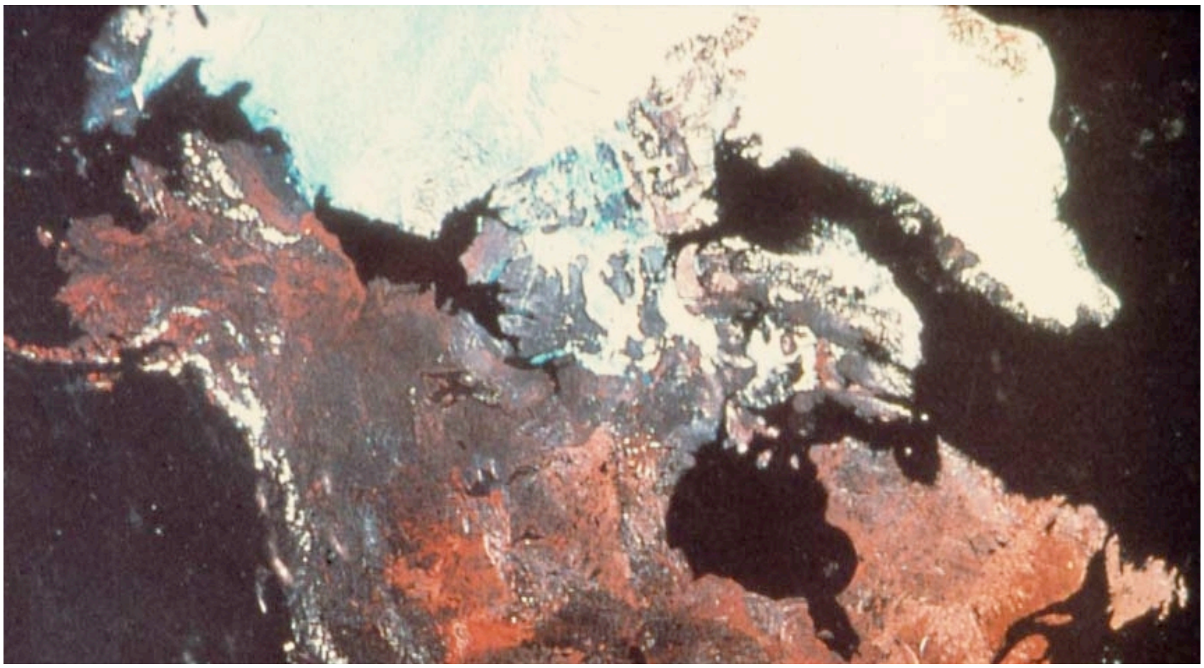


Figure 8.4. Satellite image showing typical late 20th century summer ice conditions in the Canadian Arctic Archipelago.

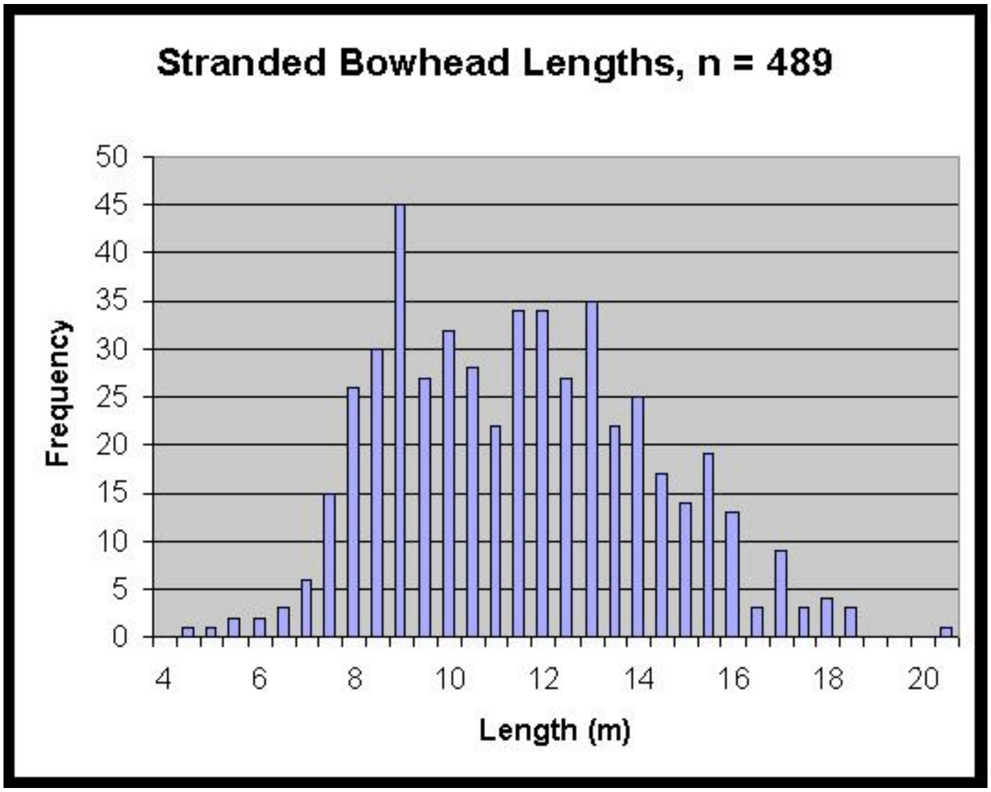
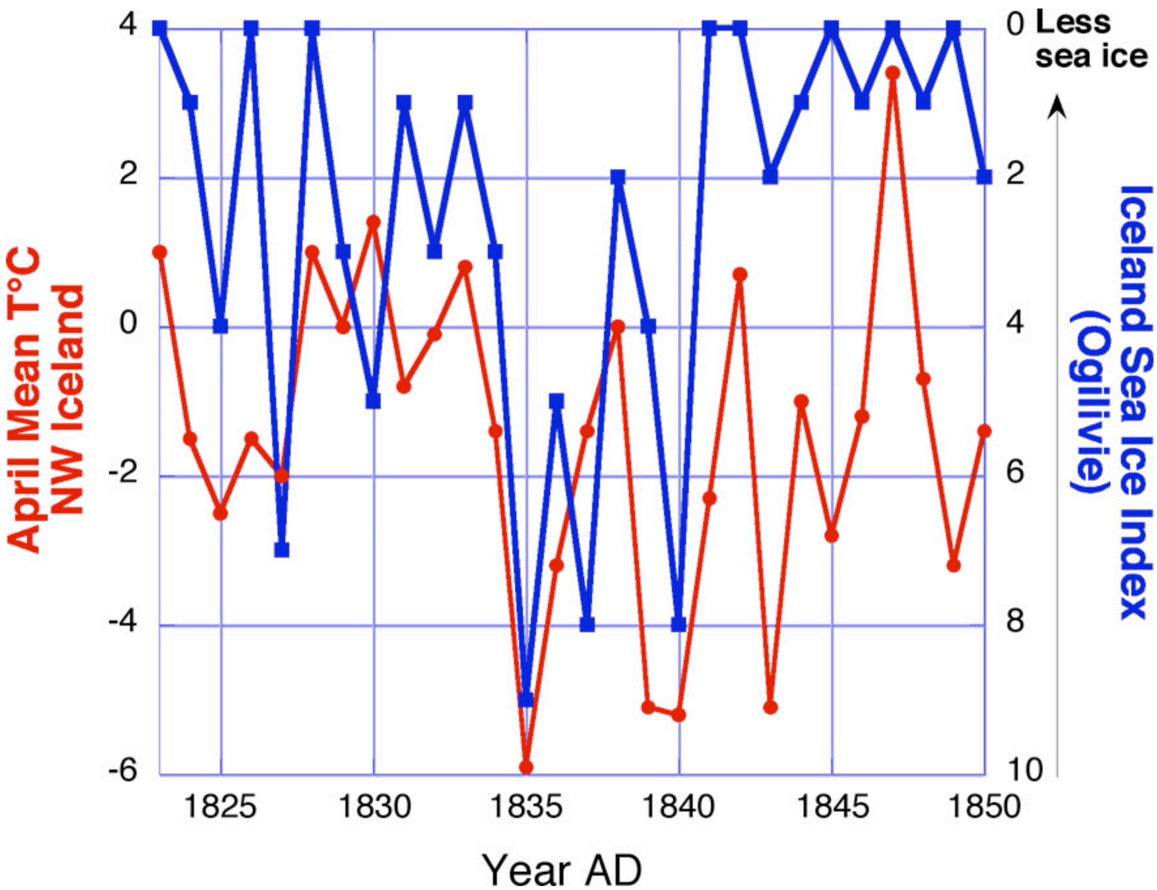


Figure 8.5. The reconstructed lengths of Holocene bowhead whales based on skull measurements (485 animals) and mandible measurements (an additional 4 animals) (Savelle, et al., 2000). This distribution is very similar to the lengths of living Pacific bowheads, indicating that past strandings affected all age classes.



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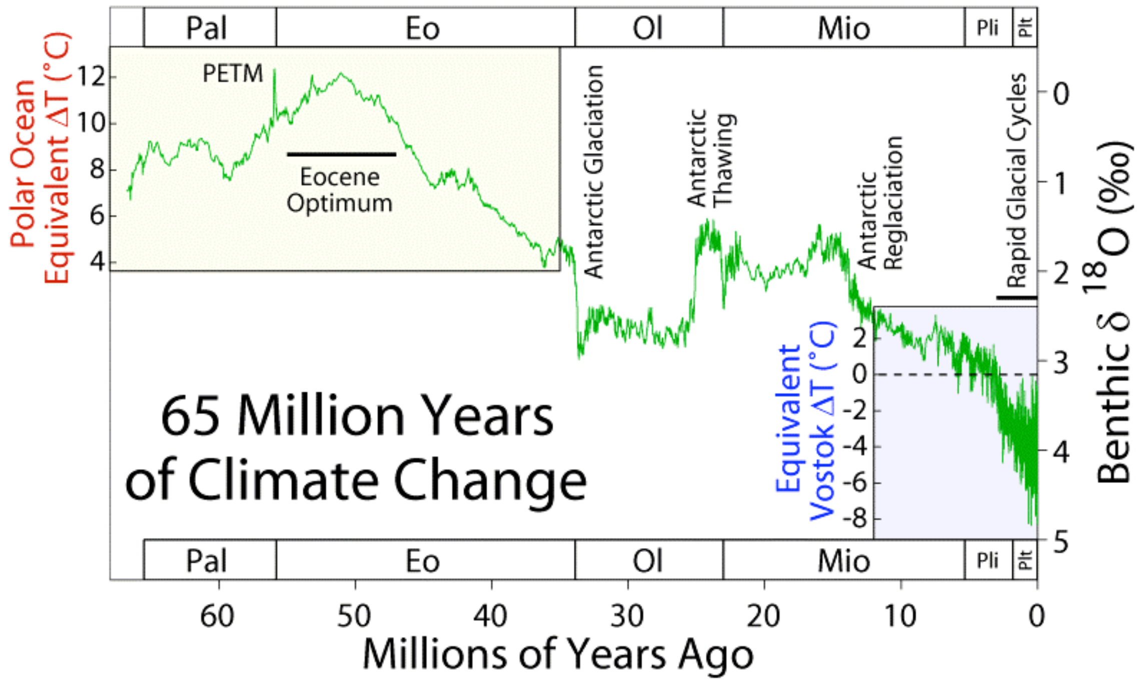

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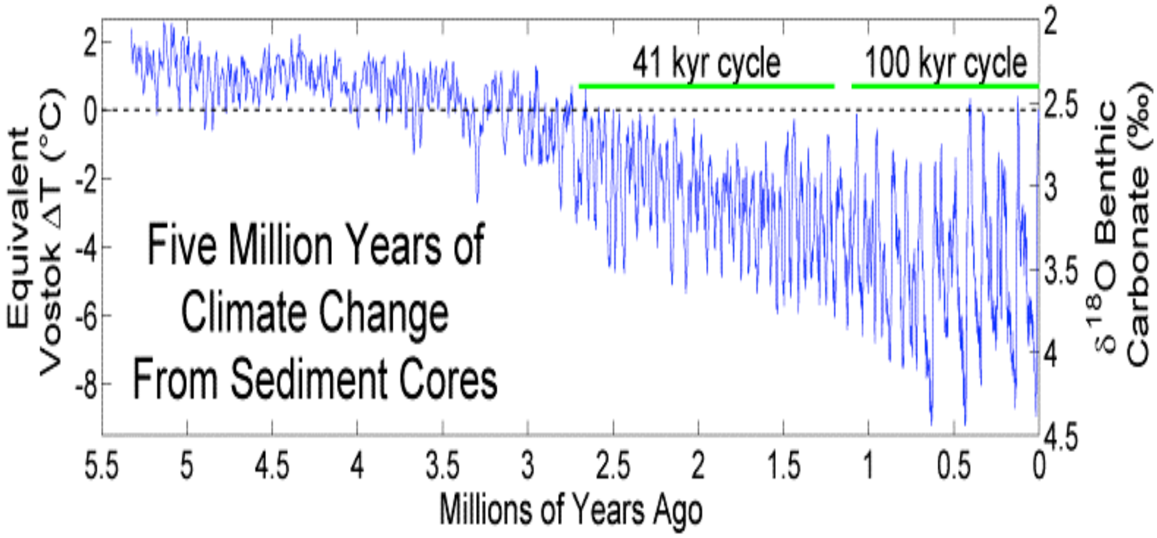

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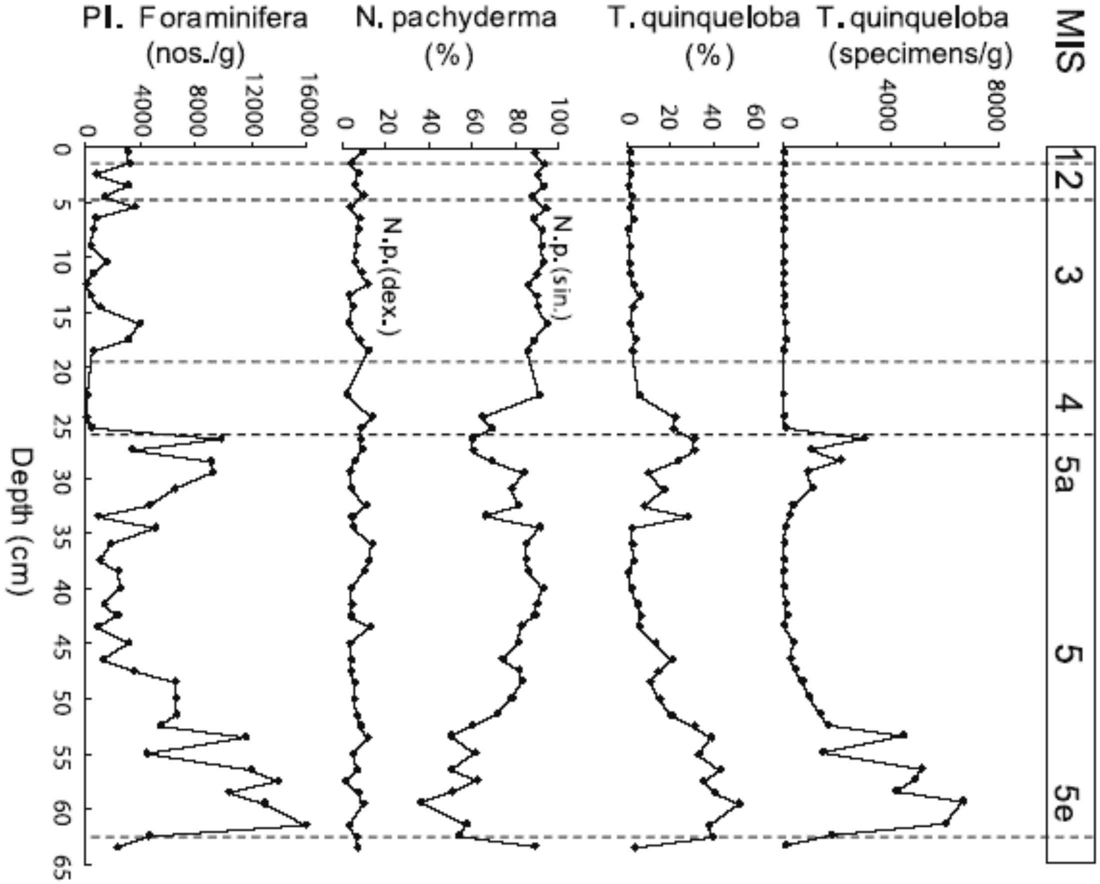

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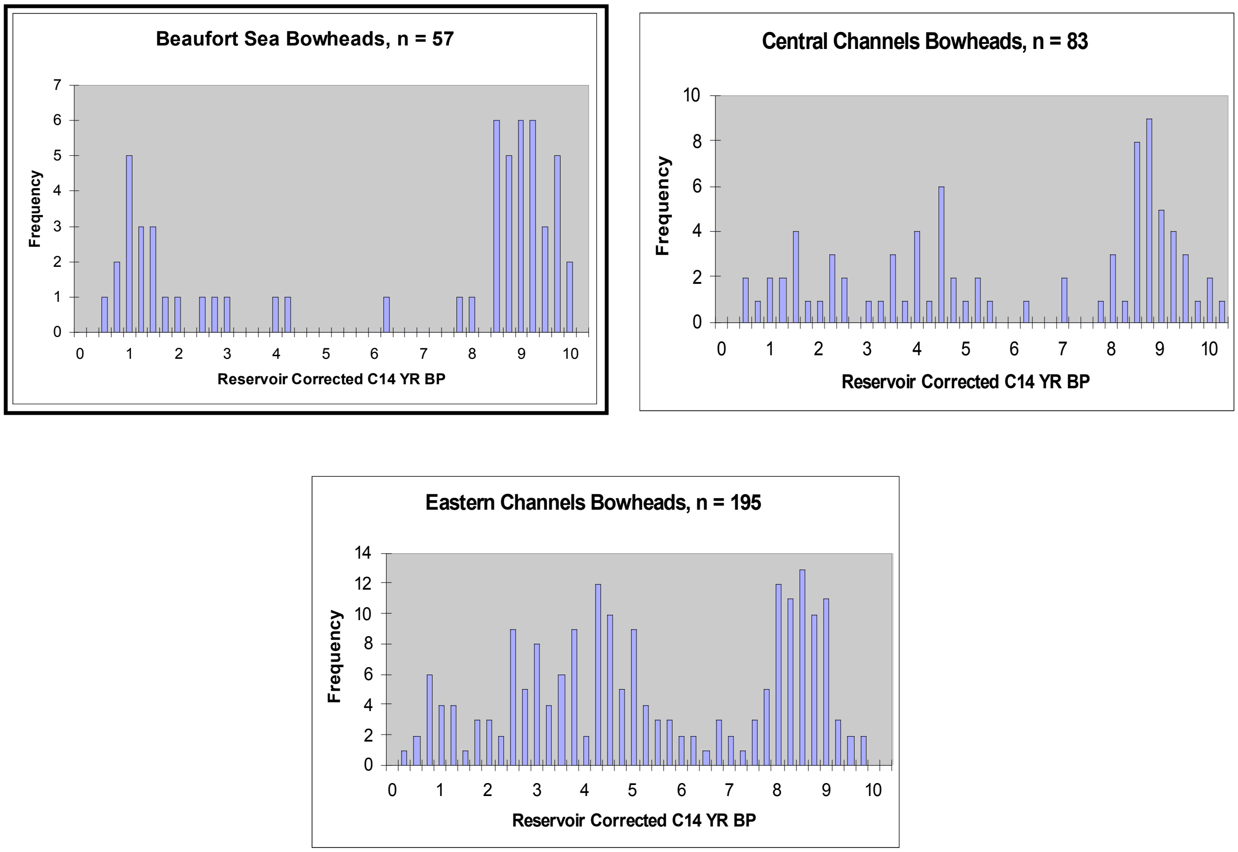

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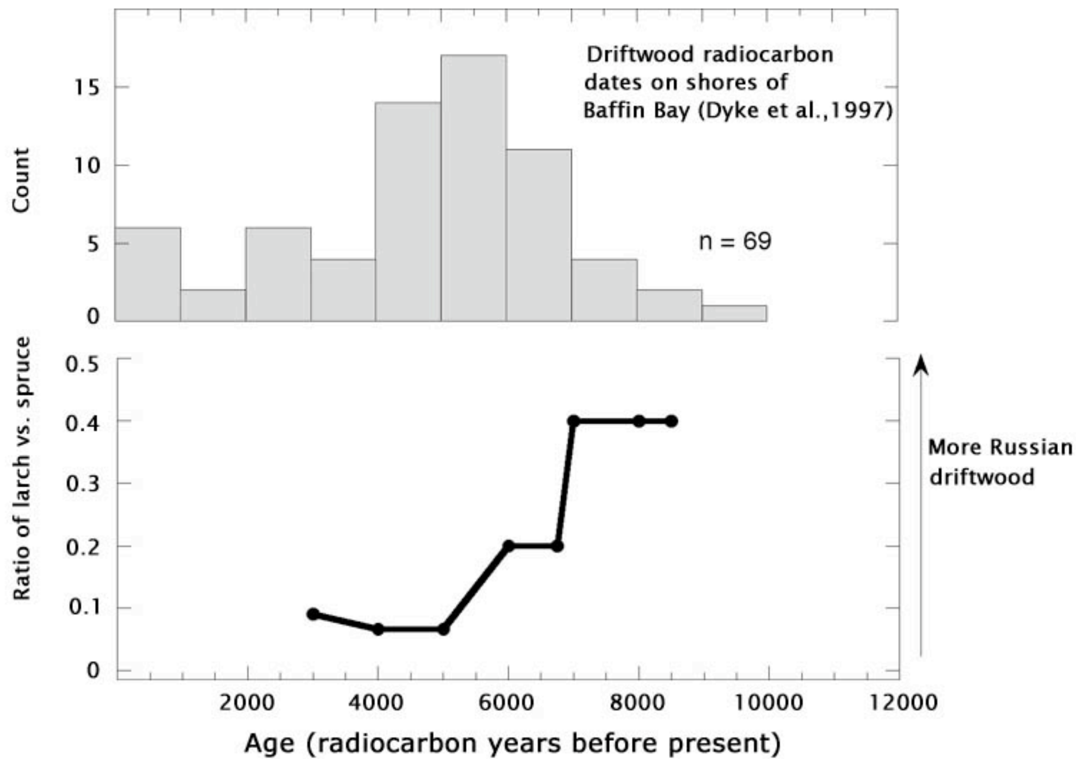

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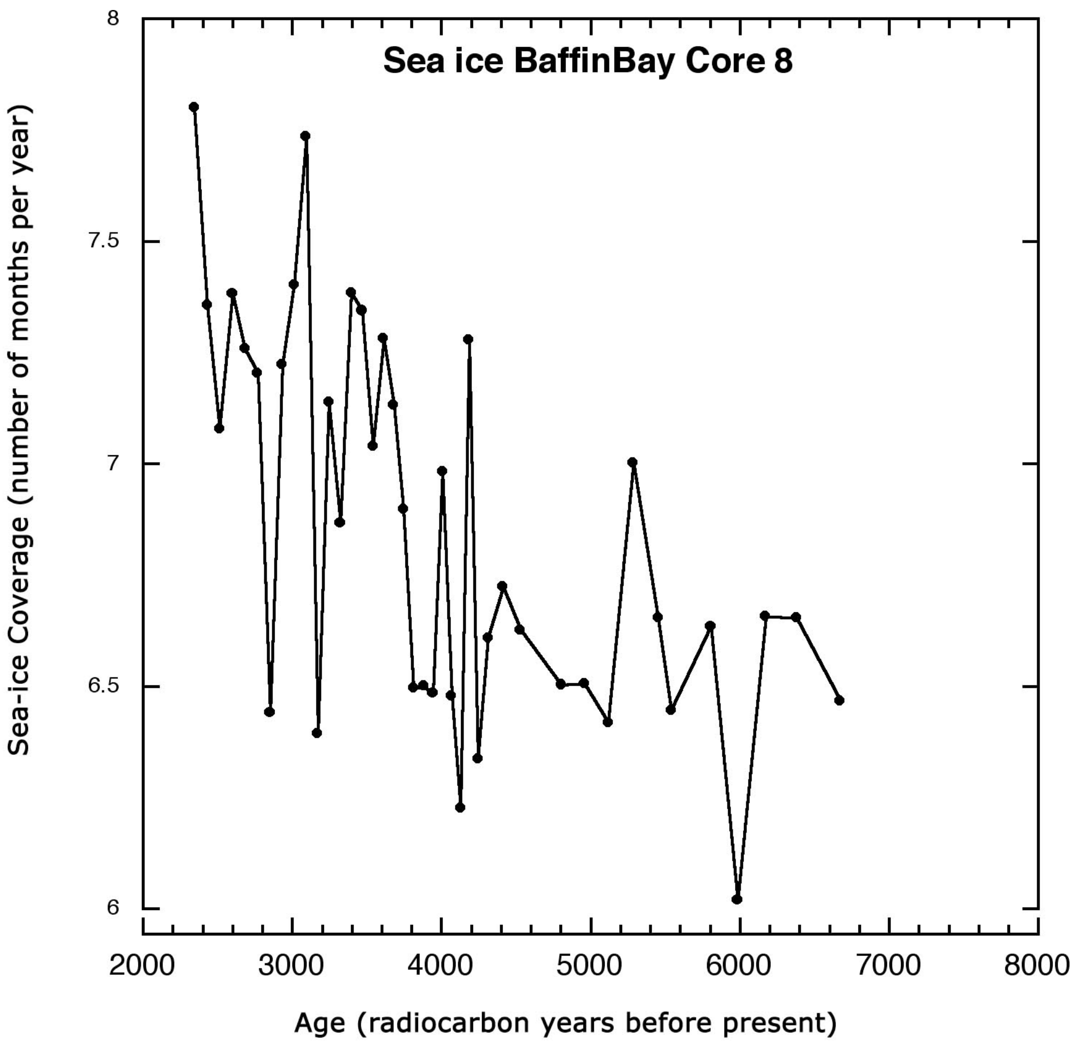

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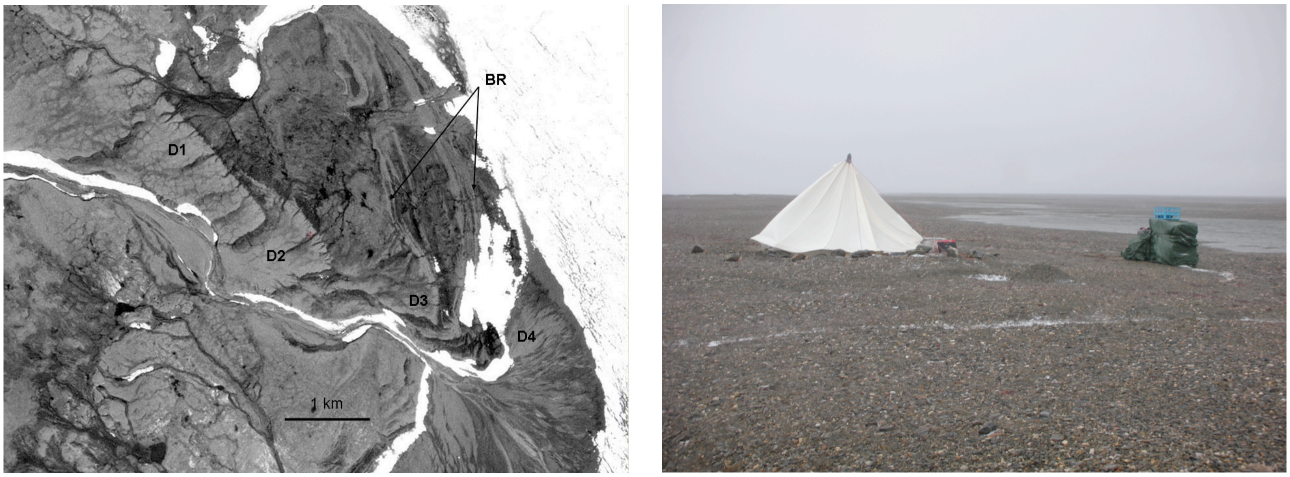

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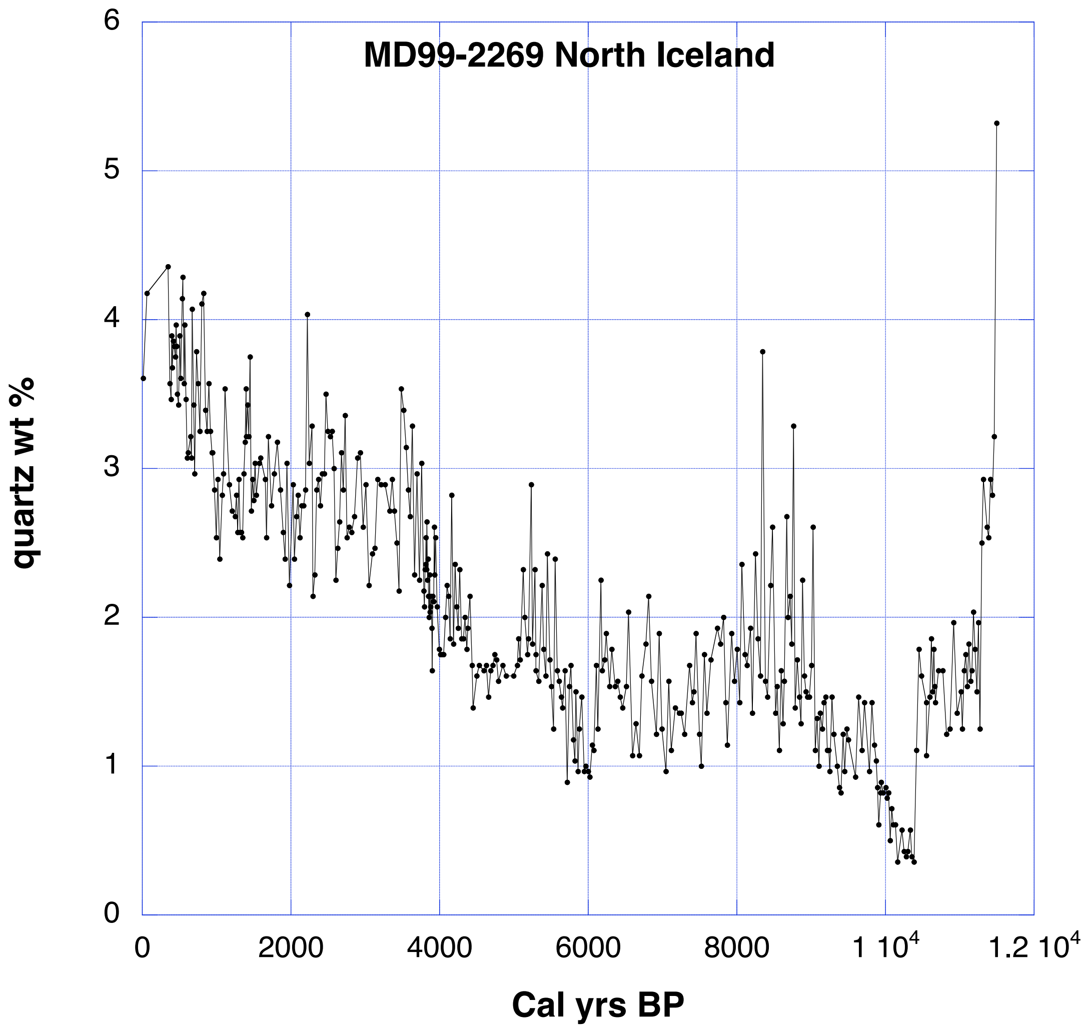

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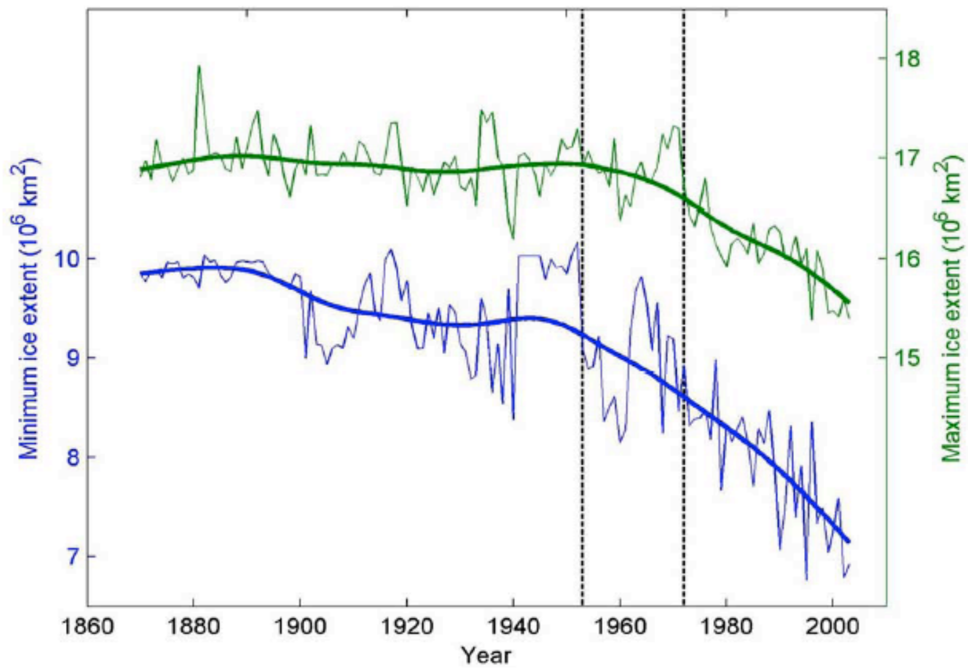

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