CAPE 2000

Circumpolar Arctic PaleoEnvironments

ICAPP 2000

Ice-core Circum-Arctic Paleoclimate Programme

Sea Ice in the Climate System
The Record of the North Atlantic Arctic

June 2-6, 2000
Kirkjubæjarklaustur, Iceland

Sponsored by:

RANNIS (Iceland Research Council)
IGBP-PAGES Core Project Office
PARCS (Paleoenvironmental Arctic Sciences)
NSF-Earth System History Program Office

Program Schedule for the CAPE 2000 meeting
Kirkjubæjarklaustur, Iceland

2 June, Friday

11:00 CAPE/ICAPP 2000 Participants arrive at Kirkjubæjarklaustur
12:00 Lunch
1:00 Welcome and Charge to the Participants

Session 1: Historical Perspectives on Icelandic Sea Ice Variations

Anne Jennings, Session Chair

1:10 ***Keynote: Astrid Ogilvie: Historical records of sea-ice variability from Iceland.***
1:40 *Martin Miles*: Time scales of sea ice variability in the Atlantic Arctic.
2:00 *Thor Jakobsson:* Sea ice in Icelandic waters in this century.
2:20 *Ingibjörg Jónsdóttir:* Of ice and indices: Icelandic sea ice indices for the period 1850-1999.
2:40 *Elisabeth Isaksson:* A new ice core record from Lomonosovfonna, Svalbard: viewing the data between 1920-1997 in relation to present climate and environmental conditions.
3:00 *Peter Wadhams:* Historical perspectives on sea ice variations.
3:20 Discussion: Lessons from the historical past.
3:40 Break: A guided hike to Systrafoss, a beautiful waterfall close to Kirkjubæjarklaustur.
5:30 Snack and strong coffee for the jetlagged.

Session 2: Sea ice in the Climate System: The challenge of modeling sea ice.
Gifford Miller, Session Chair

6:00 ***Keynote: Bette Otto-Bliesner: Modeling sea ice.***
6:30 *Mark Johnson:* Arctic ice-ocean decadal and multi-decadal variability.
6:50 *Steve Vavrus:* The impact of sea ice motion on Arctic climate sensitivity.
7:10 *Christoph Oelke:* Sea-ice coverage of the Barents Sea in response to changes in ocean characteristics.
7:30 *L. Micaela Smith:* Sensitivity of the climate system to sea ice during the Holocene and LGM based on GCM modeling.
7:50 *Tony Broccoli:* Orbital forcing of Arctic climate during the past 135,000 years.
8:10 Discussion: Current status and future developments in modeling sea ice.
8:30 Dinner

3 June, Saturday

7:00 Breakfast
8:00 **Plenary Discussion**: How well do we know the role of sea ice in the climate system, and what does the modeling community need from the paleodata community?

Session 3: Sea ice variability: The Quaternary record

Anders Elverhøi, Session Chair

9:00 *Keynote:* ***Anne de Vernal: Late Quaternary variations of sea ice and sea-surface conditions in the Arctic and circum-Arctic based on dinocyst assemblages: preliminary results and methodological issues.***

North Atlantic/North America

9:30 *Gerard Bond:* Did Arctic sea ice transport IRD that defines the North Atlantic's 1500 year cycle?
9:50 *John Shepherd:* How regular are the millennial oscillations in North Atlantic data on ice-rafted debris ?
10:10 *Gifford Miller:* Sea ice inferences from lake sediment records in the Eastern Canadian Arctic.
10:30 Coffee
10:50 *David Fisher:* Marine and Continental Record Chemical Signatures From Penny Ice Core Shows Effects of Long Wisconsinan Flow Lines and Early Holocene "Pollution" of Atlantic Surface Water by Melt Water From the Retreating Laurentide Ice Sheet.
11:10 *R. M. Koerner:* The Penny Ice Cap Ice-core Sea Salt Record for the Holocene
11:30 *Alison Murphy:* Relationship Between a Devon Ice Cap Glaciochemical Record and Sea Ice in the North Water/Baffin Bay Region of the Eastern Canadian Arctic.
11:50 *C. M. Zdanowicz:* Ice-Core Microparticles as Paleoenvironmental Indicators: The Holocene Dust Record from the Penny Ice Cap, Baffin Island.
12:10 Discussion
12:30 Box lunches and a short bus ride to the Laki Volcanoes (Skaftáreldafire) and canyons; some nice hiking routes are accessible here.
3:30 Light meal, coffee

Session 4: Iceland and the Nordic Seas

Áslaug Geirsdóttir, Session Chair

4:30 *Keynote****: Nalan Koc: Reconstructing the sea ice limit in the Nordic Seas through the last 14 ka using diatom sea ice assemblages.***

5:00 *Stein Johansen:* The origin and the transport of driftwood into the North Atlantic Ocean unveiled by dendrochronological and woodanatomical methods – a synthesis.
5:20 *Dierk Hebbeln:* Flux of ice-rafted detritus from sea ice in the Fram Strait.
5:40 *Anne Jennings:* Mid-Holocene shift in Arctic sea ice variability on the E. Greenland Shelf.
6:00 *Ole Bennike:* Holocene sea ice variability in northern Greenland.
6:20 *John Andrews:* The carbonate content of cores on the N. Iceland shelf: high-resolution records for the last 5 ka of surface productivity and sea-ice.
6:25 *Chris Caseldine*: Correlating Holocene offshore-onshore sequences in northern Iceland.

Session 5: The Arctic Ocean

Anne de Vernal, Session Chair

6:45 *Keynote:* ***Henning Bauch: Last glacial to Holocene shelf and deep-sea sediment records from the Arctic: implications for changes in ice regime, fluvial runoff, and surface water circulation.***

7:15 *Dennis Darby*: Sea Ice Rafting Events – Present and Past: Global Climate Significance.

7:35 *Stephanie Pfirman:* Annual to Millennial Variations in the Origin and Fate of Sediment-Laden Sea Ice.

7:55 *Christoph Vogt:* Sediment mineralogy and sea-ice development in the Arctic Ocean during the last 20.000 years.

8:30 Dinner

4 June, Sunday

7:00 Breakfast

Session 6: The Barents, Laptev, and Kara Seas

Henning Bauch, Session Chair

8:00 *Leonid Polyak:* Holocene evolution of paleoceanographic environments in the eastern Barents Sea as inferred from sediment records with a submillennial resolution.
8:20 *Dave Lubinski:* Marine and terrestrial constraints on Holocene summer sea-ice conditions in the northern Barents Sea, 80°N.
8:40 *Ivar Murdmaa:* A high-resolution sedimentary record from Russkaya Gavan', a Novaya Zemlya Fjord: inferences for paleoclimatic conditions in the northeastern Barents Sea during the past millennium.
9:00 *Jacobus Zeeberg:* Glacier response on north Novaya Zemlya to NAO-controlled fluctuations of temperature and precipitation in the twentieth century
9:20 Coffee
9:40 Discussion: Beyond CLIMAP: How well can we constrain Late Quaternary sea ice limits? What are the main uncertainties in reconstructing Quaternary sea ice variations, and can they be overcome? Establish main discussion topics for Break-Out groups.
11:00 Group outing to Svartifoss (The Black Waterfall) and to Jökulsárlón, the ice-dammed glacial lagoon, to sail amongst the icebergs; sack lunch provided.

6:30 Conference Gala Dinner
8:30 Poster Session

5 June, Monday

7:00 Breakfast
8:00 Break-out groups meet; rotation of participants at mid-morning coffee.
12:00 Box Lunches and time for hiking, horse-back riding, fishing, or even golf.
4:00 Light meal, coffee and cakes
5:00 Plenary session: Summaries by break-out group leaders. What have we accomplished? Where are the primary data and modeling holes? Where do we go from here? Discussion
8:30 Dinner

6 June, Tuesday

7:00 Breakfast
8:00 Final Plenary session: Development of recommendations for future research (round table discussion).
10:30 Bus leaves for Reykjavik; arrive Reykjavik 1:30 PM, and arrive airport in time for late afternoon departures to North America. European participants can explore Reykjavik in the afternoon and catch public transportation to the airport for evening departures to Europe.
10:30 Post-conference excursion departs Kirkjubæjarklaustur.

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Abstracts

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A field of pancake ice in the Greenland Sea in March 2000.
Sea smoke and clouds in the background

The carbonate content of cores on the N Iceland shelf: high-resolution records for the last 5 ka of surface productivity and sea-ice

John T. Andrews[1], Gu›run Helgadóttir[2], ÁslaugGeirsdóttir[3], Jórunn Har›ardóttir[4], Gréta B.Kristjánsdóttir[4], Laryn M. Smith[1], Anne E. Jennings[1], and Árn‡ Sveinbjörnsdóttir[5]

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Records of the carbonate content of a series of cores on the N.Iceland shelf show a remarkable consistency in the pattern of carbonate accumulation over the last 5,000 years (e.g. Fig. 1). The chronologies for the three cores is based mainly on molluscs; core B997-328 has 11 AMS dates, whereas -327 has 4, and -330 6 dates. The sediment accumulation rates average 10, 15, and 12.6 yrs/cm, respectively. Thus our common sampling interval of 5 cm results in one sample every 50 to 75 yrs, indicating that we can resolve century-scale variations. Estimates of dry unit sediment densities were also obtained at 5 cm intervals. Mass accumulation rates ($MAR_{carbonate}$) of gCarbonate/cm^2.100yr can thus be derived.

The carbonate content of marine cores can be associated with three major life forms, the molluscs, foraminifera, or the phytoplankton. Since our proceedure effectively excludes molluscs then the source of the variation in carbonate content must be caused by changes in either in the sand-size foraminifera, or the < 63 µm fraction which would be primarily coccoliths. A more accurate calculation can be made for 328 as here we have numbers of foraminifera/g dw. Based on the weight and numbers of foraminifera submitted for AMS ^{14}C dating, the average weight of a benthic foraminifera is estimated to be 0.022 ± 0.003 mg. Converting forams/g to forams/cc and taking the average foram weight led to an average $MAR_{foraminifera}$ of 0.02 gCarbonate/cm^2.100yr, or an order of magnitude less than the total $MAR_{carbonate}$.

Using the program "Analyseries" the degree of fit between the records from cores B997-328, -327, and -330 is > r=0.8. The pattern of carbonate accumulation over the last 4-5 ka is marked by a distinct series of events, or which the most profound is the carbonate minimum, temporally associated with the Little Ice Age, and two carbonate maxima with dates of ca. 2 and 3.8 ka (Fig. 1). Another minima occurs around 4.4 ka. Between these major events are a series of smaller oscillations which appear to correlate. Thus it appears that carbonate values vary on both millennium and centuries scales in this region. Preliminary spectral analysis suggests periodicities of ca. 350, 550, and 1500 yrs. These quasi-periodicities are superimposed on a persistent decrease in $MAR_{carbonate}$ over the last 5 cal ka which parallels the decrease in summer insolation at high northern latitudes.

The vast bulk of the carbonate must be associated with large spring and fall phytoplankton blooms. Thordardottir showed that replacing Atlantic Water with Polar Water off N. Iceland resulted in a significant drop in marine productivity due to the increased stratification of the water column and a reduction in vertical mixing and nutrient supply. Malmberg showed that when surface salinities drop below 34.7 o/oo in winter, then sea-ice can form off N. Iceland. During these periods, such as the Great Salinity Anomaly of the mid and late 1960's off N. Iceland, productivity decreased on average by a factor of 2.

Our hypothesis is thus that the changes in $MAR_{carbonate}$ is a proxy for changes of surface productivity, and sea-ice coverage and formation. Examination and comparisons of other related proxies, such as rock magnetic properties, stable isotopes, and lithic content will be used to enhance the evaluation of the hypothesis.

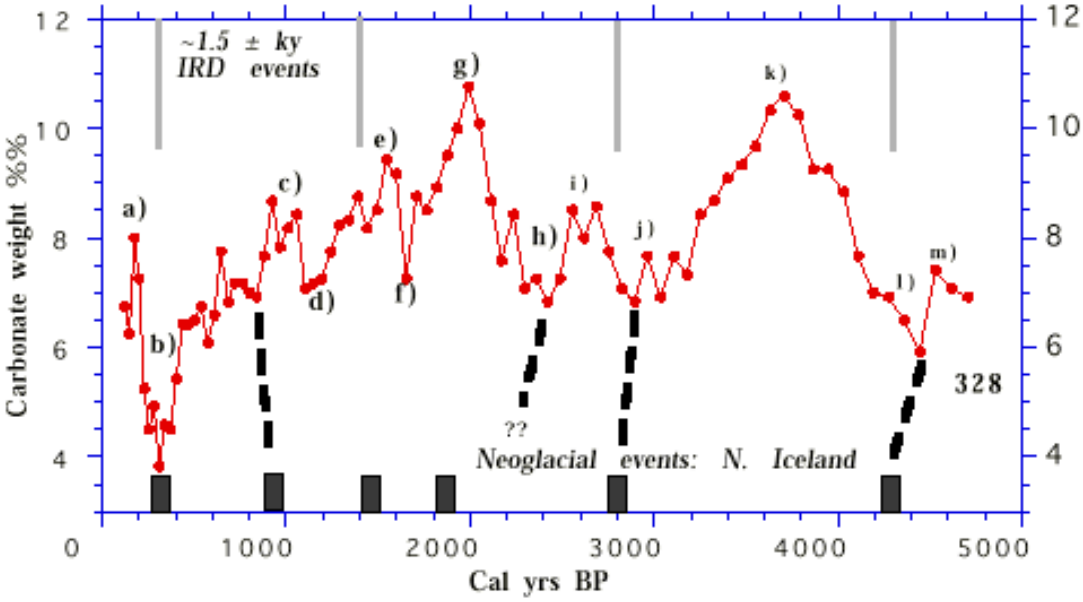

Figure 1: Graph of the carbonate weight % from core B997-330PC from the inner shelf of N. Iceland plotted against time. The black shortbars at the bottom represent the timing of Neoglacial moraines on N.Iceland (Stötter *et al.*, QSR, 1999). The Upper bars represent the timing of IRD pulses in the North Atlantic (Bond *et al.*, Nature, 1997).

Last glacial to Holocene shelf and deep-sea sediment records from the Arctic: implications for changes in ice regime, fluvial runoff, and surface water circulation

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The dispersal and fate of riverine water discharge and its role on Arctic Ocean water mass properties are a central issue in the understanding of past and future climate change beyond the polar region. Tracer studies have shown that a considerable part of the riverine freshwater, delivered to the Arctic Ocean mainly by the large Siberian rivers such as Ob, Yenisey and Lena, is contained in the halocline and overlying sea-ice cover. Since a substantial part of the Arctic sea ice, which drifts across the eastern Arctic Ocean toward Fram Strait within a few years, is also being produced on the broad Siberian shelves, these areas constitute a key element for our environmental understanding. Therefore, from the paleoclimatological point of view, an issue that deserves further study is the critical temporal variability of those environmental factors in the marginal shelf seas that exert the most influence on the surface salinity of the Arctic Ocean and the adjacent Nordic seas.

Due to intensive investigations carried out in the Laptev Sea during the past years, this region is now probably the most comprehensively studied marginal shelf sea in the Arctic. Salinity on this shelf is strongly influenced by the large amounts of riverine runoff discharged during summer, the largest proportion of which stems from the Lena River. On average, this discharge affects mainly the eastern shelf. Based on micropaleontological and geochemical isotope studies, temporal changes in salinity are observed in the shelf sediment records. The downcore distributional pattern of the fossil species assemblages, however, also reflect ecological changes which are strongly influenced by changes in hydrology, nutrients, sea-ice conditions, and sea level. Oxygen isotope ratios measured on calcareous fossil groups are less affected by ecological parameter, thus, rendering this method crucial for the interpretation of past variations in river water discharge. Due to its shallowness, the Laptev Sea shelf was entirely exposed during the last glacial maximum (LGM) limiting the chance to reconstruct the paleoenvironment beyond ~14 ^{14}C ka on the basis of marine sediments. Therefore, Arctic Ocean deep-sea sediments are used to infer older paleoenvironmental changes.

In addition to planktic •^{18}O- and •^{13}C records, flux records of planktic foraminifers, ice-rafted debris, bulk calcium carbonate, and grain size composition are important proxies to reconstruct paleoenvironmental conditions in the Arctic Ocean. They give evidence about changes in water-mass properties, ice cover, and terrestrial influx (glaciations/deglaciations, shelf area exposure/drowning, river input... etc.). For the LGM it is suggested that major parts of the Arctic Ocean were covered by a dense and rather stagnant sea ice cover limiting planktic productivity and bulk accumulation rates. In the southwestern part of the Eurasian Basin facing Fram Strait, high sedimentation rates and maxima of planktic foraminifers (including subpolar foraminiferal species) suggest at least seasonally open water conditions, possibly related to the advection of Atlantic waters. A significant gradient (Fram Strait to Arctic Interior) toward lowered planktic •^{18}O values is a persistent feature in both last glacial and most recent sediments. This may indicate that significant riverine freshwater was supplied to the Arctic Ocean also during the LGM. However, uncertainties remain because the residence time of the surface water mass, the freshwater influx, and the import/export of water masses through Fram Strait may have been different.

The initial deglaciation can be traced in the eastern and central Arctic Ocean by a prominent •^{18}O meltwater spike as early as 15-14 ^{14}C ka. This event supports the idea of an early deglacial Northern Hemisphere meltwater/iceberg calving event which had a very limited impact on the global sea-level record. The marine-based Barents Sea Ice Sheet is the most likely source of this early meltwater event.

Due to the rising sea level and atmospheric changes during the last glacial to Holocene transition it is expected that environmental conditions changed dramatically in the Arctic Ocean and its marginal regions. During this time the shelf seas began to develop, leading to an increase in sea-ice production, river runoff, and shelf sediment supply as well as to an intensification of water mass circulation. At the Laptev Sea continental margin, a major freshwater spike is recognized in planktic foraminiferal •^{18}O at about 11.5 ^{14}C ka. The timing of this event is intriguing since the freshwater event may be responsible for the ensuing climate cooling known as the Younger Dryas. There are indeed indications from the Nordic seas that deep water formation may have been affected at the same time when this event occurred in the Laptev Sea.

During the further course of the Holocene development the Siberian shelf seas became widely flooded. This process was accompanied by a substantial reorganisation of the sedimentary environment from a dominantly terrestrial-fluvial to a more marine type of sediment deposition. Diachronous changes in sedimentation rates together with geochemical and micropaleontological proxy data give clear evidence of the southwardly transgressing sea until about 6 ^{14}C ka when the main transgressional phase in Arctic Siberia was over. After this time modern-like conditions with its typical sea-ice regime and hydrological pattern fully developed in the Arctic, time-coeval with a now enhanced water-mass exchange with the adjacent Nordic seas through Fram Strait and across the western Eurasian shelves.

Holocene sea ice variability in northern Greenland

Ole Bennike

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The central part of North Greenland is characterised by permanent sea ice, and driftwood is extremely rare on modern beaches. In the eastern parts of northern Greenland at least some fjords break up for some time during the summer, and driftwood is fairly common, although far less common than on Svalbard or Jan Mayen. It is obvious from this geographical distribution that sea ice in the near shore waters hinders deposition of driftwood on the beaches, which is not surprisingly.

From the limited data available, it appears that driftwood on raised beaches are most common in fjords in eastern North Greenland, whereas raised beaches at the outer coast are devoid of driftwood. In some areas driftwood is concentrated, which must have to do with local current patterns. In central North Greenland virtually no driftwood is present on raised marine deposits, which points to permanent sea ice throughout the Holocene. This is also reflected in the lack of beach ridges or other coastal features that depend on open water.

A total of 42 radiocarbon dates are available on Holocene driftwood from northern Greenland. Many of these have been made on wood, often charred, from archaeological ruin sites. Attempts have been made to date the driftwood located at the highest elevation in different areas. This has resulted in some records for oldest driftwood dates in eastern North Greenland, with the oldest piece dated to 6880 ± 110 ^{14}C years BP (c. 7.7 cal. ka BP). It seems that driftwood is exceedingly rare, if at all present, on early Holocene raised beaches, even in areas that were deglaciated between 9 and 10 cal. ka BP. This is not because trees did not grow in the source area at this time, since early Holocene driftwood is present in Svalbard and arctic Canada. The question is whether there was too much sea ice in the near shore areas, or whether there was too little sea ice in the Arctic Ocean to transport the driftwood all the way to North Greenland? The journey from Siberia to North Greenland lasts about five years, and a driftwood log can only stay afloat for c. one year, so the wood is carried over the ocean by the pack ice. From other evidence it would seem likely that the pack ice of the Arctic Ocean was thinner and less extensive during the early Holocene than at present. However, it also seems that deglaciation of some parts of North Greenland lasted well into the early Holocene. The deglaciation process could well have led to the formation of permanent sea ice in the fjords.

It appears that driftwood on raised beaches is becoming more and more common during the mid and late Holocene. Driftwood was certainly an important fuel resource to the Palaeo-Eskimos that inhabited the area. However, in some fjords driftwood entry came to an end after the development of floating glaciers. The largest is around 80 km long and 25 wide, and it was formed some time after 4.5 cal. ka BP. The youngest driftwood found adjacent to this floating glacier tongue is 5.4 cal. ka BP, and it could be that permanent sea ice in the fjord hindered driftwood entry after this time, prior to the formation of the floating glacier.

Only limited data is available from dated bones of whales and seals. Seven finds of large whales have been dated, which are all records of large whales from a non-archaeological context. The oldest is about 8 cal. ka old. There is also one dated narwhal bone, and a few dated walrus and ringed seal bones.

Did Arctic sea ice transport IRD that defines the North Atlantic's 1500 year cycle?

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Both the interglacial and glacial climates of the North Atlantic over at least the past 200 kyrs were punctuated by a persistent climate cycle that had an average pacing of about 1500 years. The most robust and consistent indicators of the cycle are proxies of ice rafting, including both the concentrations and the mineralogical compositions of IRD (ice rafted debris).

The ice-rafting proxies defining the cycle have been widely regarded as evidence of IRD transport by icebergs calved from tidewater glaciers. While that interpretation cannot at the moment be disproved, an alternative view that the IRD was transported by sea ice, much of which may have originated in the Arctic, appears to be equally consistent with the evidence in hand. First, grain sizes of material in modern coastal sea ice can be quite large, ranging well into the sizes typically associated with glacial icebergs (e.g. coarse sand, pebbles and even gravel). Second, a new record of IRD deposited during the Little Ice Age in the northwestern North Atlantic indicates that off the Scotian coast sea ice deposited IRD that is texturally and compositionally indistinguishable from that conventionally assumed to have come from glacial icebergs. Third, a new record of Holocene ice-rafting in the Laptev Sea, a major Arctic sea-ice factory, reveals a series of ice-rafting cycles over the last 8,000 years that are correlative with the Holocene 1500-year ice-rafting cycles during the same time interval in the subpolar North Atlantic.

As an alternative, the sea-ice transport mechanism has the advantage that sea ice is extremely sensitive to even subtle climate changes such as must have been the case during the interglacial phases of the 1500-year cycle. In addition, rather large increases in fresh water fluxes presumably would have been associated with increased sea-ice transport from the Arctic into the North Atlantic. That would provide a plausible mechanism for altering the North Atlantic's fresh-water balance and inducing shifts in NADW production such as have been identified in association with the 1500 year cycle during both glacials and interglacials.

Orbital forcing of Arctic climate during the past 135,000 years

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We examine the effects of changes in Earth's orbital configuration on Arctic climate in a long integration of an atmospheric general circulation model coupled to a simple slab ocean. The model simulates the temporal evolution of climate in response to continuous variations in orbital forcing from the last 135,000 years, which are accelerated by a factor of 30 to reduce the computational expense. Marked decreases in potential ablation and increases in snowfall are simulated during three periods near 26,000, 73,000, and 117,000 years ago, when aphelion was in late spring and obliquity was low. Both thermal and dynamical effects contribute to the increases in snowfall during these periods, through increases in the fraction of precipitation falling as snow and increases in storm activity. These "glaciation-friendly" periods correspond to three prominent phases of terrestrial ice growth as indicated by the marine •^{18}O record.

Correlating Holocene offshore-onshore sequences in northern Iceland

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Of central importance to developing a robust understanding of Holocene environmental change in the North Atlantic region is the ability to correlate offshore sequences with evidence onshore, especially within the wider framework of the high resolution palaeoclimatic evidence now available from Greenland ice core records. Northern Iceland lies in a potentially sensitive area for establishing such relationships, and is an environment, which is affected by the location and extent of sea-ice, as shown over the last 180 years from meteorological observations, and over the last millennium from documentary sources.

There are however a number of issues which need to be resolved before a detailed Holocene record of offshore-onshore can be adequately determined:

Scale – high temporal resolution in the ice cores, and now appearing in recent marine cores collected as part of the IMAGES project, is as yet not matched by comparable resolution in the terrestrial record. There is a pressing need to find and examine terrestrial sequences at, as a minimum, decadal levels of resolution. The improving glacial sequence is still only poorly resolved chronologically.

Quality of the terrestrial record – not only is the glacial sequence limited in its quality but the same is true for the palaeoecological record, which relies almost entirely on pollen data. Because of the limited flora, with only *Betula* as an arboreal taxon of possible palaeoclimatic significance, and concerns over the taphonomic influences of the various terrestrial deposits analysed, the palaeoecological record has so far proved of limited palaeoclimatic value.

Dating – Iceland has the enormous benefit of a detailed tephrochronological stratigraphy that is now well developed. The actual dating of this tephra framework is however still radiocarbon based and even the most prominent and widespread marker horizons have dates which are, at best, averages of several radiocarbon dates. Discovery of geochemically provenanced tephra shards in the Greenland ice cores has provided at least 5 more precisely dated horizons (although 2 were already historically dated). Correlation of offshore and onshore sequences will however almost certainly still rely in the future on radiocarbon and there are different views of marine corrections to be used around Iceland, as well as the issue of the accuracy of calibration when correlating to ice core years.

There is a pressing need for improving the terrestrial record to keep up with the improving offshore records and to try to establish the nature of the interaction between sea-ice and climate over the longer time period. One possible way to look at this, given the potential detailed tephrochronology in Iceland, would be to look in detail across events such as the 8200 cal BC Greenland event to identify the terrestrial impact, as well as trying to develop a long but less well defined terrestrial record for the Holocene as a whole.

Sea ice rafting events – present and past: global climate significance

Dennis A. Darby

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The annual average volume of sea ice exported through Fram Strait over the last 15 years is about 2.3×10^3 km^3 or more than twice the yearly volume of ice exported to the N. Atlantic through Hudson Strait during the peak of a Heinrich Event (Laurentide ice sheet collapse). Over at least the last 33 kyr, the volume of sea ice increased by 4-5 times the modern average during major sea-ice export events through Fram Strait. This is based on the abundance of detrital Fe oxide grains in a core from the west-central Fram Strait that were matched to important entrainment areas for sea ice. These grains were matched to similarly analyzed source areas of the circum-Arctic using the electron microprobe measurement of each grains chemical composition. The most important entrainment areas are the shallow shelf areas of Banks Island, the Chukchi Sea, and the Laptev Sea. These export events occur every 2.5-5 kyrs and each lasted less than a thousand years. Several shelf areas contributed ice-rafted detritus (IRD) during these events but not always at exactly the same time. At least two of these nine events involved IRD that was coarser than normally transported by sea ice and represented near shore ice entrainment events. During one of these sea ice export events, more than 8×10^3 km^3 per year of ice might have drifted into the Greenland Sea and probably even the N. Atlantic before melting. This would be more than enough ice to freshen the surface layer of the important ocean areas that impact the production of N. Atlantic Deep Water and thus decreasing the convection of warm water to high northern latitudes.

The IRD sampled from sea ice floes over the last 19 years in the Arctic Ocean can be matched to sources using the same technique. Nearly 30 of these floes contained adequate numbers of Fe oxide grains to determine precise sources. All floes contain Fe oxide grains from many sources indicating the importance of shelf to shelf transport of IRD by sea ice. The ice floes from the Beaufort Sea are dominated by Fe oxide grains from Banks Island (16% of 431 grains from six floes) but there are significant (9%) grains from the Laptev Sea. Two-thirds of these Beaufort Sea ice floes are from a single source, Banks Island. The Chukchi Sea area contains ice floes from Banks Island and the Laptev Sea as well as other sources such as the northern Queen Elizabeth Islands shelf area. The Laptev source even dominates one ice floe for the Chukchi Shelf-edge area. The source of these floes with multiple sources is problematic because a floe cannot easily entrain sediment from more than one area. Thus sediment from several shelves are first deposited in a common shallow shelf area and then entrained by sea ice. This occurs on all Arctic shelves, but is particularly significant on the Chukchi Shelf because ice can drift from Siberia and North America and melt here each year. This shelf comprises about 250,000 km^2 of shelf sufficiently shallow for sea ice entrainment. The fact that five of six floes sampled in the central Arctic Ocean between the Chukchi Sea and the Lomonosov Ridge contained Fe oxide grains from both Banks Island and the Laptev Sea strongly suggest the Chukchi Sea as the last entrainment site.

Late Quaternary variations of sea ice and sea-surface conditions in the Arctic and circum-Arctic based on dinocyst assemblages: preliminary results and methodological issues

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In order to document changes in sea-surface conditions, notably in the extent of sea ice cover over the Arctic and sub-Arctic, extensive studies of organic-walled dinoflagellate cysts (dinocysts) in surface sediments and late Quaternary cores were undertaken at GEOTOP, in collaboration with several other institutions. Dinocysts constitute sensitive tracers of past sea-surface conditions in such environments because their distribution patterns are closely related to seasonal changes in the sea ice cover, in addition to temperature and salinity conditions. Moreover, dinocysts are well preserved in these sediments, and they yield relatively abundant and diversified assemblages, unlike many other microfossils. The development of a dinocyst data base permits the use of transfer functions for the reconstruction of sea-surface conditions throughout the northern North Atlantic during the last glacial maximum (cf. de Vernal et al., Can. J. Earth Sci., 2000, vol. 37)**.** This data base also allows us to establish a late Quaternary time~~s~~ series of paleoceanographic changes in subpolar environments.

The establishment of an international working group specifically focused on dinocysts from the Arctic and circum-arctic seas has given access to surface sediment samples that are used to develop an accurate reference data base. The working group also contributed to the establishment of standardized systematics, which is a prerequisite for the establishment of reference data bases to be used in transfer functions. The development of the "modern" dinocyst data base is in progress; it presently includes about 650 reference sites, and the validation exercise yields reasonably accurate results for the "polar" domain, allowing application of transfer functions in the Arctic for reconstruction of past conditions. In order to improve the accuracy of the reconstruction some methodological issues are currently being addressed.

(1) The actual hydrographical and sea ice data used for the calibration (NODC 1994 for temperature and salinity, and NCDC 1953-1990 for sea ice) include many extrapolations and are not very accurate throughout the polar domain. They need to be better constrained. A comprehensive compilation of newly available data is underway that includes the joint U.S. Russian Atlas of the Arctic Ocean, and the National Snow and Ice Data Center, in addition to the NODC and NCDC data.

(2) Among the taxa which seem to be diagnostic of harsh Arctic conditions and which are most important in both qualitative and quantitative reconstructions of sea ice and temperature, are morphotypes of ubiquitous species (notably *Operculodinium centrocarpum* and *Algidasphaeridium* ? *minutum*). These morphotypes are probably phenotypes adapted to Arctic environments. Therefore, they require more attention, through systematic morphometry and image analyses, in order to improve the accuracy of the dinocyst sensitivity for hydrographical reconstructions in polar environments.
(3) One of the weaknesses of the statistical approach presently used for the reconstructions (i.e., the analogue method) is the heterogeneity in the spatial distribution of the reference data base. Alternative approaches are currently being explored to get around this limitation and to improve the accuracy of the reconstructions. Among these approaches, the artificial neural network seems to be particularly promising.

Despite some uncertainties, reconstructions can be made on the basis of dinocyst assemblages from the Arctic seas. In particular, a few Holocene series spanning approximately the last 8000 years are available from three regions: northernmost Baffin Bay, the Barents Sea, and the Chukchi Sea. Rich dinocyst assemblages occur at these three locations, indicating a high productivity, at least during the middle and late Holocene. The transfer functions indicate variations in sea-surface temperature and the extent of sea ice cover, but they do not show identical trends at all sites. In the western Arctic there are indications of reduced sea ice cover and much warmer conditions than at present, notably around 3, 5, and 6-7 ka, and for a late Holocene cooling (cf. Darby et al., CAPE 2000 meeting). In northernmost Baffin Bay, there is also evidence for a mid-Holocene minimum in sea ice cover and for a late Holocene cooling trend. However, in the Barents Sea, the results show similar conditions during the mid-Holocene to those obtaining at present with only minor fluctuations (cf. Polyak et al., CAPE 2000 meeting). These results are preliminary, but they demonstrate the variability in time and space of the sea ice cover during the Late Quaternary.

The origin and the transport of driftwood into the North Atlantic Ocean unveiled by dendrochronological and woodanatomical methods – a synthesis

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A total of 1629 driftwood samples dominated by *Pinus* (65%) and *Picea* (15%) logs were sampled at nine geographically widely dispersed locations in the North Atlantic region. The logs were analysed by dendrochronology and woodanatomical methods. Dendrochronological dating show that 402 pine logs originate in the Yenisey/Angara region in Siberia and 149 *Pinus* logs came from the White Sea region. The White Sea region is found to be the chief source of *Picea* logs, dated with a total of 114 logs. The age distribution of the *Pinus* and *Picea* samples dated are concentrated in the period 1940-1970 coinciding with the phase in the development of logging activities in the Yenisey/Angara basins and in Northwest Russia (White Sea region). As most driftwood specimens dated lack bark, the exact transit time from sources cannot be established by dendrochronological dating. The shortest transport time recorded was four years or less from the Lower Angara region to northern Norway, while six years or less were recorded for logs from Northwest Russia sampled in northern Norway and on Iceland. A survey of wood anatomical data from 992 samples of recent driftwood trees determined by their wood anatomy and collected from 10 geographically widely dispersed locations in the North Atlantic region reveal a strong influx of *Larix*, mainly from sources east of the Urals. A review of data published on the tree genera represented among 412 recent and 471 subfossil radiocarbon dated driftwood samples from the western Barents sea indicate invariant transport routes and source area representation since about 6000 yrs. B.P. The Transpolar Drift Stream and its Siberian branch is the main transporting agent and its driftwood load is a good indicator of the ice-drift from Siberian sources. The results indicate that the major transport routes of the Yenisey/Angara driftwood take place both by ice-export from the Kara Sea north of Novaya Zemlya into the Barents Sea and with the Transpolar Drift Stream into the Fram Strait. Preliminary results from dendrochronological dating of pine and spruce logs from northern Novaya Zemlya indicate an exchange of driftwood released into the eastern Barents Sea with wood in the northern Kara Sea released by the Yenisey.

Table 1. Correlation values between *Pinus* driftwood chronologies from various locations in the North Atlantic region (no. 1-6) dated with chronologies from driftwood (no. 7) and living trees in Yenisey-Angara basins (no. 8). 1) Jan Mayen (Johansen 1998), 2) west coast of south Norway (Johansen unpublished), 3) north Norway (Johansen 1999), 4) northern Svalbard (Eggertsson 1994b), 5) Iceland (Eggertsson 1995), 6) Baffin Island (Eggertsson & Leayendecker 1995),
7) driftwood chronology from middle Yenisey reaches (Eggertsson unpublished), 8) chronology based on living trees in the lower Angara region (E. Vaganov pers. comm. 1995). The t-values are in the upper right part and the sign test values in the lower left part of the table. All sign test values at 99.9% significance.

	1	2	3	4	5	6	7	8
1	**X**	12.47	19.36	15.21	14.59	7.00	14.35	10.62
2	77.3	**X**	12.72	11.34	12.79	5.00	11.74	7.89
3	79.9	79.0	**X**	18.64	16.22	6.99	16.49	11.39
4	75.2	75.9	78.0	**X**	16.44	7.45	12.23	6.70
5	78.5	77.6	80.4	77.8	**X**	7.34	13.22	7.03
6	70.4	64.9	68.2	68.4	66.2	**X**	9.80	4.55
7	74.8	76.6	79.8	73.0	75.1	75.6	**X**	9.28
8	71.3	71.0	66.8	64.9	66.4	64.0	68.7	**X**

Table 2. Correlation values between *Picea* driftwood chronologies from various locations in the North Atlantic region (no. 1-5) dated with chronologies from driftwood (no. 6) and living trees (no. 7) in northwest Russia. 1) Jan Mayen (Johansen 1998), 2) north Norway (Johansen 1999), 3) northern Svalbard (Eggertsson 1994b),
4) western Svalbard (Eggertsson 1994b), 5) Iceland (Eggertsson 1995), 6) driftwood chronology from the Northern Dvina delta (Johansen unpublished), 7) chronology based on living trees in the eastern drainage area of Northern Dvina, Voroncy (F. Schweingruber pers. comm. 1995). The t-values are in the upper right part and sign test values are in the lower left part of the table. All sign test values at 99.99% significance

	1	2	3	4	5	6	7
1	**X**	7.85	6.85	9.01	10.83	13.15	10.82
2	73.4	**X**	11.70	9.59	8.58	9.00	11.63
3	73.3	72.5	**X**	12.12	10.60	9.19	8.09
4	73.7	73.9	74.4	**X**	10.93	7.75	11.33
5	78.5	70.3	73.4	77.1	**X**	11.45	10.26
6	77.5	76.9	66.6	70.1	75.4	**X**	13.61
7	73.1	77.5	66.6	74.6	71.3	76.8	**X**

Late Quaternary variations in sea surface productivity and sea ice cover based on fjord, shelf and lake cores, Northwest Iceland

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The northern North Atlantic has been the location of numerous studies during the last decades that show the area to be of primary importance in delineating changes in deep water formation and sea-ice extent. Most of these studies have taken place in the deep sea beyond the Icelandic shelf, but only few studies are available from the shelf where high-resolution records are to be expected. We present and compare data from several sediment cores obtained during two cruises in 1997 (B9-97) and 1999 (IMAGES V). The cores lie on a transect from the northwest shelf of Iceland (Djúpáll) through a fjord system (Ísafjar›ardjúp, Jökulfir›ir, Skötufjör›ur), and are correlated to a lake core obtained from a lake located 125 m a.s.l. within the innermost part of the fjord system. This area is affected by the southward flowing East Greenland Current of Polar Water origin (≤0°C), and the northward flowing Atlantic Water in the Irminger Current (>4°C; S>35). The fluctuating position of the boundary between these two opposing currents greatly affects the ocean physical and chemical characteristics in the region, including sea surface temperature (SST), salinity and sea-ice extent. It is also well known that changes in the extent and duration of sea ice NW and N of Iceland has direct impact on land temperatures as has been demonstrated by events over the period of instrumental records and historical accounts. We, therefore, believe that there is a measurable link between marine and terrestrial environments within this region that records changes in the sea-surface condition and flux of Polar water.

Our proxies of changes in the sea-surface condition are biostratigraphical, physical and chemical analyses on the sediments. Radiocarbon dates have been obtained from the cores showing a high-resolution record for the last ca. 30,000 ^{14}C years in Djúpáll trough and at least 11,000 ^{14}C years within the fjord and the lake system. Radiocarbon dates, sediment accumulation rates, and stacked records on sediment properties from the cores demonstrate that the sites have a centuries to decadal temporal resolution. Vedde ash bearing sediments and Saksunarvatn tephra identified in many of these cores provide a regional isochron ca.10,300± yrs BP and 9000± yrs BP, respectively.

The carbonate content derived from the shelf cores (B997-335, -336, -338) shows cold and low productivity water conditions until approx. 10,300 (using 400 years reservoir correction), at which time the total carbon % starts to increase slowly. Apparent consistency in total carbon % occurs between fjord- (-339, -342), shelf- (-335, -336, -338), and lake cores (97-EDV02) over the last approximately 10,000 yrs. Two abrupt, short-term decreases, at ca. 9,000 ^{14}C years BP and at ca. 7,500 ^{14}C years BP are recorded in the total carbon % with a corresponding increase in the magnetic susceptibility. Ongoing studies aim at evaluating whether the decrease in carbonate content at 9,000 ^{14}C years BP is related to diminished nutrients supply caused by the Saksunarvatn tephra or an increase in sea-ice cover with associated decrease in surface productivity. The ca. 7,500 ^{14}C years BP low in total carbon is associated with strengthening of the East Greenland Current and increase in sea-ice cover. Further lows in carbon content coincide with evidences of mass flow deposits between 7,000-7,500 ^{14}C years BP, and show that the sediment records have been affected by both local and regional processes. The fjord cores record distinct local variations during the late Holocene

that can be directly associated with fluctuations in Drangajökull glacier on the NW Peninsula. However, a clear decrease in total carbon % is detected in both marine and lake cores at ca. 6,200 and 6,600 ^{14}C years BP with a peak in total carbon % around 4,200 ^{14}C years BP.

Based on the sensitivity of the study area to fluctuating oceanographic boundaries, we anticipate that impending studies on the cores obtained during the 1999 IMAGES V cruise will provide us with a very high-resolution record of sea-ice coverage and information of surface productivity during the late Quaternary. This information can be used to test the inferred signal of millenium- and century scale changes in sea-ice conditions in the North Atlantic.

Flux of ice-rafted detritus from sea ice in the Fram Strait

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In the permanently and partly ice covered seas of the high latitudes ice-rafted detritus (IRD) is an important sediment component. During recent years IRD records from the North Atlantic and the Nordic Seas have been widely discussed with emphasis on the longterm history of northern hemisphere glaciations, on the so-called Heinrich events and their possible Nordic Seas relatives, and on high resolution reconstructions of ice sheet behaviour.

Normally the term IRD is defined to be the terrigenous coarse fraction (>500 µm or sometimes >63 µm) found randomly distributed in deep-sea sediments. Besides ice-rafting there seems to be no other possible way for such coarse particles to reach the deep-sea floor. In addition to coarse IRD, most of the material transported by sea ice consists of silt and clay sized particles, which contributes substantially to the overall sediment accumulation in ice covered seas. However, this material is difficult to identify as IRD and consequently hard to quantify.

As coarse IRD (e.g. >500µm) is relatively rare in sea ice but common in icebergs, most of the above mentioned investigations focus on the reconstruction of iceberg drift patterns. However, much more important for paleoclimatic studies is the sea ice extension, which covers a much wider area than drifting icebergs and which consequently has a much greater impact on the albedo of the oceans and, thus, on the global climate.

For investigating the impact of sea ice on the sedimentation, the Fram Strait, northern Nordic Seas, is an especially well suited region, due to a dynamic and diverse sea ice cover. A three year particle flux record from the eastern Fram Strait revealed a rather untypical seasonal flux pattern compared to other particle flux studies from the Nordic Seas. In the eastern Fram Strait this pattern is characterised by a sudden four- to sixfold increase of the particle flux in January, when no daylight is available to support any biological productivity. Comparison with sea ice distribution maps led to the conclusion, that the sudden increase in the flux is due to ice-rafted detritus released from sea ice, which originated from the Svalbard archipelago and from the northern Barents Sea. Detailed grain size analyses of the silt fraction indicated the >10 µm fraction of the lithogenic matter to be clearly enriched due to IRD input. Even more important is the observation that lithogenic material >40 µm has been found exclusively during the ice-rafting event and, therefore, appears to be a suitable indicator for IRD transported on sea ice. Thus, in addition to coarse IRD (e.g. >500 µm), which is mainly derived from icebergs, the analysis of fine IRD (>40 µm) in deep-sea sediments can be used to reconstruct paleo-sea ice extensions.

Sea ice services in Icelandic waters

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Sea ice monitoring of Icelandic waters as well as archiving of sea ice observation data is looked after by the Icelandic Meteorological Office. Icelandic waters are defined as the economic zone around Iceland, extending outwards to a 200 nautical miles distance from the coast or to the midline between Iceland and Greenland in the Denmark Strait. The variability of sea ice extent in Icelandic waters is displayed by examples of sea ice charts, based on sea ice reconnaissance flights of the Icelandic Coast Guard and supplemented by ship reports and other available information. Recent and planned research projects dealing with physical processes in this complicated meteorological and oceanographic area and further north are mentioned.

Annual extension of sea ice in the vicinity of Iceland fluctuates between open sea across the Denmark Strait in late summer to sea ice in the Strait in late winter covering the ocean at the coast of East Greenland half way towards Iceland. Much of the sea ice is advected by the East Greenland Current from the Arctic Ocean and the Northern Greenland Sea but considerable amount forms during winter along the coasts of Greenland further south. Besides variable amount being brought south by the East Greenland Current, year-to-year fluctuations in surface ocean conditions in the Denmark Strait and the Iceland Sea give rise to different sea ice extent in Icelandic waters. However, the final cause at present times resulting in sea ice reaching as far east as sailing routes around Northwest and North Iceland, and even to the coasts, is the effect of prevailing winds, i.e. the atmospheric pressure configuration over the North Atlantic. In earlier centuries of colder climate, with more extensive sea ice in the Greenland Sea, Icelandic coasts were visited by sea ice more frequently.

Mid-Holocene Shift in Arctic Sea Ice Variability on the East Greenland Shelf

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Neoglaciation is a term describing a widespread time-transgressive climatic cooling in the Arctic beginning during the mid Holocene (Williams et al., 1995). Recent climatic oscillations such as the "Little Ice Age" and the "Medieval Warm Period" occurred during the Neoglacial interval and have been associated with increases and decreases, respectively, in the export of arctic sea ice in the East Greenland Current (EGC) (Jennings and Weiner, 1996). East Greenland vegetation, ice core, and marine sediment core records consistently show Neoglacial cooling beginning between 6 and 4 cal. ka (e.g. Andrews et al., 1997). We report new century-scale records of iceberg rafting and multi-century scale records of paleo-hydrography from two sediment cores on the East Greenland shelf under the flow of the EGC, JM96-1206/1-GC and JM96-1207/1-GC. Benthic foraminiferal assemblages (Vigen Hansen, 1998), stable isotope analyses on the planktonic foraminifer Neogloboquadrina pachyderma (s), and changes in the flux of ice-rafted, carbonate-bearing lithic grains indicate a shift from warmer ëAtlanticí conditions toward colder, lower salinity ëPolarí conditions c. 5 cal ka. Decreasing salinity in the EGC became especially pronounced during the last 2 cal. ka.

A new proxy of iceberg rafting on the East Greenland Shelf is the flux of calcium carbonate (TIC). Measurements of TIC flux in JM96-1207 at 100 yr intervals reveal pronounced peaks in carbonate flux. Sedimentary rock fragments with calcite cement observed in the > 1 mm fraction of the core are considered to be the source of the carbonate. There is a change in the regularity and spacing of the carbonate flux peaks at c. 4.7 cal ka in JM96-1207, coinciding very closely with the 4.7 cal. ka onset of Neoglacial cooling in the Renland ice core •18Ocarbonate peaksuniformand spacing.ofcorrespond with increases in sea salt Na as would be expected in windier, colder, drier climatic intervals. But, prior to the 4.7 cal ka shift, the association between sea salt Na and carbonate peaks is inconsistent. We propose that the carbonate flux peaks younger than 4.7 cal ka are related to sea-surface cooling such as would occur with increased flux of Polar water. Under these conditions, icebergs calved in the fjords would retain their debris farther onto the shelf (where it would be recorded in JM96-1207), rather than losing their debris to melting within the fjords.

There are six detrital carbonate peaks and five detrital carbonate troughs between 4.7 and 0.4 cal. ka. We propose that the peaks reflect advances of the polar front during the Neoglacial interval, associated with strengthening of the EGC and increased deposition of IRD on the shelf. Such Neoglacial coolings have also been interpreted from deep sea cores. For example, Keigwin (1996) interpreted a 1•C cooling during the LIA and during a similar event 1700 years ago, and a warming of 1•C during the MWP. He recognized another cool interval associated with increase ice rafted debris beginning between 4 and 5 ka, suggesting that this event marks the beginning of Neoglacial cooling. Similar sea-surface coolings c. 1.5, 3.0, 4.5 ka were recorded by Bond et al. (1997) in cores off Ireland. The coolings interpreted in East Greenland core JM96-1207 correspond with these in time, but additional peaks centered around 2.4 and 3.8 cal. ka, were also resolved, suggesting that the shelf site captures higher frequency events which may not be recorded in the deep sea records. In addition, the appearance of the pronounced detrital carbonate peaks c. 4.7 cal ka may that severe arctic sea

ice events began in the Neoglacial interval, and that earlier Holocene cool events in the deep sea records are associated with different processes, for example the catastrophic drainage of glacial lake Ojibway-Barlow at 8.2 cal ka (Barber et al., 1999).

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Arctic Ice-Ocean decadal and multi-decadal variability

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Half-century integrations of a coupled ice-ocean model of the Arctic Ocean were completed for the period 1946 through 1997. The model, forced by daily winds, seasonally varying atmospheric climatology, and transports through open boundaries, produces realistic seasonal and interannual variability of ice cover and the upper ocean. A decadal (12-15 year period) and a multi-decadal (50-60 years) oscillation evident in the model results compares well with observations. The effects associated with heat and freshwater exchange between the Arctic Ocean and the Laptev, Barents, and GIN Seas are studied. Our model results show that ice export anomalies greatly influence the stratification in the North Atlantic and are not unique but rather frequent events which coincide with the two Arctic climate regimes (cyclonic and anticyclonic) described in our previous work. In this study, we examine the thermohaline sequences associated with these two Arctic climate states. We show that the long-term variability of intermediate arctic waters is sensitive to wind regimes due to both variability of water exchange with surrounding basins and to internal variability of the Arctic system. Mechanisms driving these variations will be discussed along with possibly similar mechanisms that drive much longer term variations.

Of ice and indices: Icelandic sea-ice indices for the years AD 1850 to 1999

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In the preface to his book "The East Greenland Ice" Lauge Koch (1945) wrote: "Nobody knows better than myself the uncertainty of much of the material utilised in the present paper; even information on the ice conditions within the present century should often be employed with great criticism."

This statement is still valid, even to people that are presently working on sea-ice monitoring using real-time sea-ice data obtained by satellites. The various sources of sea-ice information are of different nature and quality and the ice conditions can change very rapidly. It is therefore not only the sea-ice regions but also the sea-ice data that have been associated with 'fog and harsh conditions for navigation'.

This paper discusses the general purpose of sea-ice indices and the different methods of establishing them. The limitations of such indices, partly due to the nature of the sources upon whom they are based and partly due to the characteristics of the ice cover, are emphasised.

Icelandic sea-ice indices for the period 1850 to 1999 are presented, showing the great variations in the amount and persistence of ice off Iceland during this time. The indices have been derived from sea-ice information in farmer's diaries, sealer's logbooks, various reports and books, and, for the second half of the 20th century: ice reconnaissance flights and passive microwave images. The indices are based on a grid with an interval of 1˚ in Latitude by 2˚ in Longitude and with a time resolution of one month. The main ice parameter reflected in the indices is the maximum ice extent, however, other features of the ice cover such as coverage and type, have been added to a database.

There is an urgent need to bring together the many sea-ice indices for the North Atlantic region, and preferably digitise them so a flexible database based upon a Geographical Information System can be built.

Reconstructing the sea ice limit in the Nordic Seas through the last 14 ka using diatom sea ice assemblages

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Diatoms have been known from sea ice for nearly 150 years. The diatom assemblages associated with the sea ice are found mainly a) as an interstitial assemblage that occurs in the bottom of the ice, b) as a sub-ice assemblage consisting of algae floating directly beneath the ice or attached to the underside of the ice and forming strands that trail into the water column. A marginal ice zone (MIZ) assemblage consisting of ice algae, both those found in the ice and those that have been released into the water column, and planktonic species in the water column, occurs in spring and may be present as long as the ice continues to recede. If such an assemblage were to be preserved in the sediments below the MIZ it would provide us with a unique tool to reconstruct the position of the ice limit through time.

Factor analysis of surface sediment diatom species from the Nordic seas reveals an assemblage that maps along the present MIZ in the area. This sea ice assemblage consists primarily of *Fragilariopsis oceanica*, *Fragilariopsis cylindrus*, *Thalassiosira hyalina*, *Thalassiosira gravida* (spores), *Thalassiosira nordenskioeldii* and *Bacterosira fragilis*. Several well dated sediment cores from the Nordic seas are investigated for reconstructing the surface paleoceanographic conditions in the area since 14,000 yr BP based on their diatom record. Results show that a N-S extending sea-ice-free corridor had opened along Norway already at 13,400 yr BP, indicating a northward flow of a branch of the North Atlantic Drift (Fig. 1). However, the central and western parts of the area were still under sea ice cover for most of the time. During the Younger Dryas the waters of this corridor were mainly dominated by the sea ice assemblage indicating the position of the MIZ along the eastern Norwegian Sea. A major change of climatic conditions occurred over the Nordic seas around 9000 yr BP, when the sea ice cover and the oceanic fronts retreated to a northwestly position along Greenland and the ocean temperatures rose. The first half of the Holocene is recorded as the warmest period during the last 13,400 yr BP in the area, and during this time the sea ice cover was at its minimum. The second half of the Holocene is characterized by a cooling trend in step with the decreasing insolation, and a clear increase in the sea ice cover is observed since then.

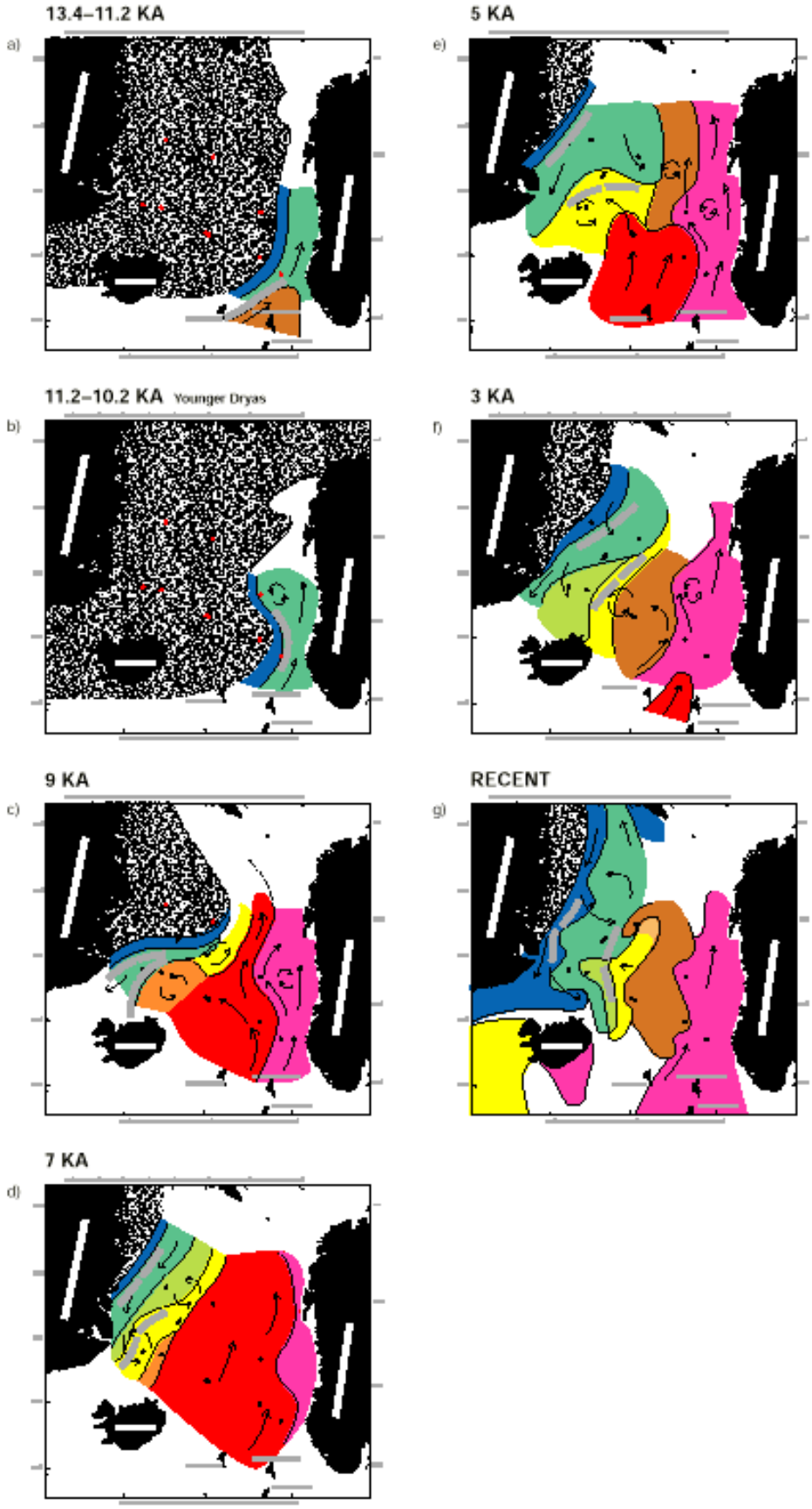
13.4–11.2 KA
a)
11.2–10.2 KA Younger Dryas
b)
9 KA
c)
7 KA
d)
5 KA
e)
3 KA
f)
RECENT
g)

Figure 1(a-g). Reconstructions of paleoceanographic conditions of the Nordic seas at 13.4-11.2 ka (a), 11.2-10.2 ka (b), 9 ka (c), 7 ka (d), 5 ka (e), 3 ka (f) and the Recent (g) (Koç et al., 1993). The recent distribution of the diatom assemblages are redrawn from Koç Karpuz and Schrader (1990). Plotted are the sites of the cores used (dots), polar and arctic fronts with surface ocean circulation denoted by arrows and sea ice cover with broken pattern. Also plotted are the reconstructions of the areal distribution of the various factors; Factor 1-Norwegian-Atlantic Current assemblage (pink), Factor 2-Arctic Waters assemblage (green), Factor 3-Sea-ice assemblage (blue), Factor 4-Arctic-Norwegian Waters Mixing assemblage (yellow), Factor 5-Atlantic assemblage (red), Factor 6-Norwegian-Arctic Waters Mixing assemblage (brown). Areas of overlaps are indicated by the mixture of the two overlapping colors.

Marine and terrestrial constraints on Holocene summer sea-ice conditions in the northern Barents Sea, 80°N.

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The northern Barents Sea (78°-82°N) is a sensitive setting for recording fluctuations in summer sea-ice extent and duration, largely because the present mean summer sea-ice limit extends over its northernmost portions. This setting is particularly useful for delimiting periods of less-than-present summer sea-ice cover (i.e. the early Holocene), when many sample sites experience dramatic transitions from heavy cover to sparse or absent cover. The northern Barents Sea is also a valuable region for studying past interactions of ocean, atmosphere, and sea ice; this region is heavily influenced by inflows of relatively warm Atlantic-derived water and extreme insolation forcing during the Holocene. The latter forcing includes a >10% higher-than-present July receipt - one of the largest insolation anomalies for any latitude during the past 100,000 years. Furthermore, the northern Barents Sea is affected by northeastward-tracking cyclones that bring relatively warm and moist air from the Nordic Seas/North Atlantic region. Although the entire northern Barents Sea was covered by grounded glacier ice during the Last Glacial Maximum, the shelf was completely ice free by 10 ka. Thus, unlike the Eastern Canadian Arctic, early Holocene sea-ice conditions were not strongly influenced by the presence of an ice sheet.

A series of Holocene paleoenvironmental datasets assembled in the last decade from eastern Svalbard, Franz Josef Land, and the adjacent continental shelf areas provide both direct and indirect constraints on the temporal pattern of summer sea-ice variations for the northern Barents Sea. The vast majority of the data furnish useful information on a multi-century to millennial timescale. Most data are consistent with a relatively heavy summer sea-ice cover during the earliest Holocene, minimum cover c. 8 ka, a still poorly defined trend toward more severe ice conditions during the middle Holocene, and a late Holocene with relatively severe but fluctuating conditions. Proxies that provide quantitative estimates of these sea-ice changes are rare. Rarer still are studies providing sub-century timescale paleoenvironmental data constraining sea-ice cover - such as summer air and sea-surface temperature (SST). More definitive time-series records should be available in the next year or two as more dinoflagellate cysts are counted in marine cores and high-resolution ice core studies are completed. The outlook for reconstructing spatial variations in sea-ice cover within the northern Barents Sea is not as bright given the scarcity of reliable records. More energy should clearly be focussed on developing a plan for defining spatial variations. Providing important constraints on sea-ice conditions for eastern Svalbard are a dozen 14-C dated occurrences of the thermophilous pelecypod *Mytilus edulis*. They range in age between 8.8 ka and 5.0 ka, showing a lengthy period when coastal summer SST's tended to be elevated above present (Hjort et al., 1995). Higher temperatures are consistent with pelecypod and glacier extent data from western Svalbard (Salvigsen et al., 1992; Svendsen and Mangerud, 1997) and with the apparent lack of early Holocene ice in Svalbard ice cores (Koerner, 1997). This data provide indirect evidence for less severe sea-ice conditions than at present for much of the early Holocene.

In Franz Josef Land, there are a number of constraints on coastal and open-ocean sea-ice cover including new dinoflagellate cyst samples for one marine core (DZ92-GC2), Bowhead whalebones from a series of raised beaches, benthic foraminifera in five marine cores (36 AMS 14C ages), and glacier extent records from 16 margins (Lubinski et al., 1998; 1999; in prep). The earliest Holocene is characterized by a lack of Bowhead and low percentages of

the foraminiferal species *Cassidulina reniforme*; more direct evidence is provided by sea-ice dominant dinoflagellate species. These data suggest relatively heavy ice conditions in the earliest Holocene. Subsequent conditions changed considerably given that all proxies are consistent with the least sea-ice cover for the entire Holocene at c. 8 ka. For example, foraminifieral species *Elphidium clavatum* reaches its minimal values at this time. Likewise, available dinoflagellate data suggest the fewest total calendar months of sea-ice cover. More dinoflagellate studies are ongoing to quantify this early Holocene change. Bowhead whales first appear on Franz Josef Land beaches at c. 9.5 ka only to diminish again by c. 8.9 ka. They remain scarce until until c. 7 ka, after which they are common up to the present. I interpret the scarcity of Bowhead from c. 8.9 to 7 ka to reflect a northward retraction of the summer sea-ice margin and a corresponding migration of whales to locations north of Franz Josef Land. This interpretation is consistent with all available proxies, including glacier margins. Glaciers were behind present limits throughout the early to middle Holocene, apparently reflecting elevated summer temperatures (Lubinski et al., 1999). The middle Holocene interval appears to be a period of transition toward heavier sea-ice cover. The exact timing of this transition is poorly known. Most proxies imply relatively severe but fluctuating sea-ice conditions in the late Holocene. However, most proxies are not particularly good at defining conditions more severe than present. Dinoflagellate cyst transfer functions do not have this problem, but very low concentrations of cysts in late Holocene marine sediments have hindered our understanding of this interval. The low concentration may reflect reduced surface water productivity associated with severe ice.

The similarities between sea-ice related proxies throughout the northern Barents Sea region on a multi-century to millennial timescale suggests similar climate forcings and responses over a broad region. Both the paleoenvironmental data and climate model simulations (e.g., TEMPO, 1996) imply that decreasing summer insolation during the Holocene was a dominant forcing. Also important were variations in oceanic northward heat transport by the Atlantic water system. The largest fluxes appear to have occurred c. 9 to 5 ka, overlapping with the c. 8 ka sea-ice minima. Determining the affect of Atlantic water influxes on sea-ice cover in the northern Barents Sea is difficult given masking by the strong isolation forcing and the frequent insolation of the sea ice from the warm Atlantic water by a heavily stratified water column. Additional forcing factors requiring future study include the flooding of the Laptev Sea shelf with sea-level rise, which probably affected the source and strength of sea-ice formation in the Arctic Ocean.

Acknowledgements: This abstract is based on several recently completed and ongoing collaborative projects in the Franz Josef Land region as well as a large number of published studies in the northern Barents Sea by many authors. My collaborators for the Franz Josef Land work include Leonid Polyak (BPRC, Ohio State University), Steven Forman (Univ of Illinois at Chicago), Anne de Vernal (GEOTOP, Montreal), Sergey Korsun (Shirshov Institute of Oceanology, Moscow) and Gifford Miller (INSTAAR, Univ. of Colorado).

Time Scales of Sea Ice Variability in the Atlantic Arctic

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Introduction

A consensus in the climate modelling community is that global warming will be enhanced in the Arctic, with the predicted arctic warming ~3 °C during the next 50 yrs, along with a substantial retreat of the sea ice cover. Modern sea ice data serve as spatially integrated indicators of arctic climate change. However, the record is brief compared to the natural variability of the ice cover on longer time scales. The objectives of this presentation are to synthesise recent variability in arctic sea ice in the context of long-term climate change, including a treatment of:

- Recent variability and trends in arctic sea ice parameters derived from remote sensing data
- Significant time scales of sea ice and climate variability in the sub polar North Atlantic, with emphasis on quasi-periodic behaviour and ice-ocean-climate interactions

The first objective is addressed through a synthesis of recent research based on satellite data from the past two decades, focusing on seasonal-to-interannual time scales. The second objective is based on preliminary results of a Nordic research project on "Interannual-to-decadal climate changes in the Atlantic Arctic", with reference to other recent observational research.

Sea ice variability in the Arctic

Sea ice data are derived from various sources, each with their particular spatial and temporal sampling and other limitations. Sea ice charts extend back over 100 years in many regions including the Atlantic Arctic, and gridded datasets of arctic ice extent since 1901 have been produced, albeit with some inherent uncertainties. The most reliable, homogeneous part cover the period since 1953 and are derived from operational ice charts including those based at least partly on satellite images. Available since 1978, multi-channel microwave data are used to calculate total ice concentration (the percent of ice-covered ocean within an image pixel), from which total ice extent, total ice area and open water area are derived. The consensus is that there has been a 2-3% per decade decrease in the areal extent of sea ice in the Arctic (Bjørgo *et al*., 1997), with large regional anomalies in the Atlantic and Siberian seas. Perennial, multiyear ice (i.e., having survived a summer melt) ice is ~3 times thicker than first-year or seasonal ice (~1 m), such that changes in their distribution could also both reflect and effect climate change. Multiyear (MY) and first-year (FY) ice have different microwave radiative properties, permitting their during the winter months when their signatures are relatively stable (Figure 1).

From 1978-98, the observed 0.031 x 10^6 km^2 yr^{-1} decrease in winter MY ice area represents a proportionally large (~7% per decade) reduction in MY ice area 1978-98, compared with an ~2% per decade decrease in the total ice area in winter (Johannessen *et al*., 1999). The apparent 14% reduction in MY ice area over two decades is corroborated by other analyses. The balance of observational evidence indicates a sea ice cover in transition, which could eventually lead to a different ice-ocean-atmosphere regime in the Arctic, altering heat and mass exchanges as well as ocean stratification. However, 20 years of microwave satellite data are insufficient to establish that this is a long-term trend rather than reflecting decadal-scale

atmosphere-ocean variability such as the North Atlantic Oscillation (NAO) (e.g., Hurrell, 1995.)

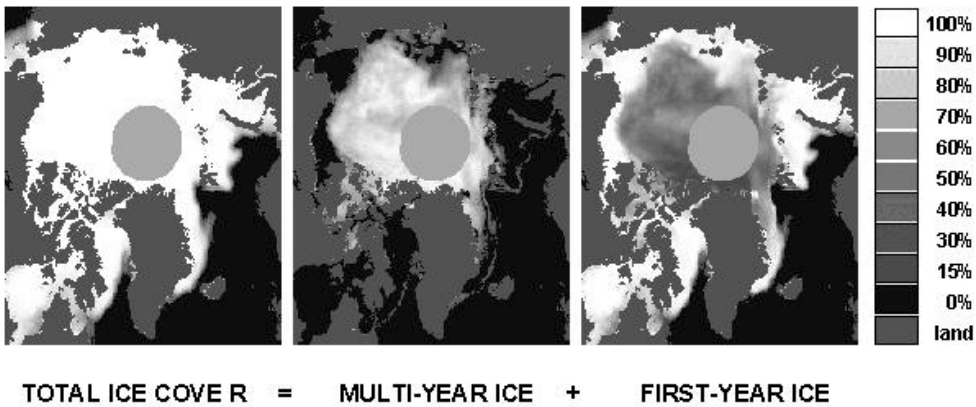

Figure 1. The arctic total sea ice cover and its components, multiyear (MY) and first-year (FY) ice, as derived from satellite microwave data in winter. The scale indicates the concentration (percentage) of each ice type in an image pixel. (E.V. Shalina, Nansen International Environmental and Remote Sensing Center, St. Petersburg, Russia.)

Sea ice and climate variability in the Atlantic Arctic

The characteristics of quasi-periodic oscillations around the Atlantic Arctic are investigated on biennial-to-interdecadal time scales, including the NAO and its influence on sea ice and climate fluctuations. Observational data analyses have led to a number of conceptual models of ice-ocean-atmosphere feedback loops on decadal to interdecadal time scales (e.g., Slonosky et al., 1992; Mysak and Venegas, 1998). To better determine the nature of such variability, multiple methods are applied to decades long, spatially distributed time series of sea ice and climate data, including the modern part of the Icelandic sea ice index, which is representative of large-scale (regional) ice conditions (Kelly et al., 1987).

Preliminary results (e.g., Dretvik and Miles, 2000) suggest an intriguing set of overlapping modes of biennial-to-decadal oscillatory behaviour in the regional sea ice cover and climate, though neither their spatial extent, significance, nor relationship to the ocean have been determined. Periodicities are found at 12-14, 7-8, 5.7-5.9, 5, 3-3.5, 2.5-2.9 and 2.2-2.4 yr in the air temperature data – cf. the main spectral peaks at 7-8, 5.8, 3.2, 2.8, 2.3-2.4 yr in the Hurrell NAO index. The strong 5 yr peak in the Icelandic sea ice data is evident in many temperature records, mostly in the north. This variability appears distinct from the NAO, and speculatively may be linked to a 10 yr ice-atmosphere feedback loop proposed by Mysak and Venegas (1998).

Acknowledgements. *The research summarised here involves many colleagues: O.M. Johannessen, Nansen Environmental and Remote Sensing Center, Bergen, Norway; E.V. Shalina, Nansen International Environmental and Remote Sensing Center, St. Petersburg, Russia; G.L. Dretvik, Department of Geography, University of Bergen, Norway, and T. Jakobsson, Icelandic Meteorological Office, Reykjavík, Iceland. The Norwegian Research Council and the Nordic Council of Ministers have supported this research.*

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What can lacustrine records from the Eastern Canadian Arctic tell us about sea ice?

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Although it has not yet been possible to isolate a direct proxy for sea ice from lacustrine sediments adjacent to ice-covered seas, the status of regional vegetation and the lake's aquatic biota are closely correlated with summer temperatures and the length of the growing season. For the past decade, we have been analyzing sediment cores from lakes on Eastern Baffin Island, Arctic Canada, to reconstruct environmental changes on glacial/interglacial timescales, and on decadal timescales within the Holocene. We have focussed our analyses on the record of biological proxies such as pollen, diatoms, and chrionomids, on the physical characteristics of the sediment, and on the stable isotopes preserved in aquatic macrofossils.

It has long been recognized that Baffin Island, lying at the NE margin of the former Laurentide Ice Sheet, was not completely inundated by the ice sheet during the Last Glacial Maximum (LGM). Consequently, lake basins lying outside the ice limits should preserve continuous records that span more than 30 ka. We have now successfully cored six lakes that contain more than 50 ka of lacustrine sediment without intervening diamict. Luminescence dates indicate that the oldest sediment above a basal diamict is about 100 ka old. The pattern of sedimentologic and biotic change through the cores is similar in most of these lakes. The oldest lake sediments record highly productive lake ecosystems and minimal clastic input, reflective of ice-free summer conditions. Terrestrial vegetation was sub-Arctic in character, whereas it is has been in the mid-Arctic vegetation zone throughout the Holocene. Abundant midges preserved in the earliest phase of the oldest lake cycle reflect conditions much warmer than at any time in the Holocene. We interpret the older lake cycle to reflect long, warm summers with substantially reduced sea ice, presumably during the last interglacial (*s.l.*). Sedimentation apparently ceased with the onset of full-glacial conditions that terminated this warm interval.

When sedimentation commenced again in the lake, conditions were starkly different. The overlying unit is dominantly minerogenic, contains few biotic proxies and the midges indicate cold water, and brief ice-free summers. Dating is still uncertain because much of the dissolved organic carbon is apparently reworked, and macrofossils are rare. The available data suggest that the minerogenic unit was deposited relatively rapidly, in perhaps a few thousand years, at the end of the LGM. As summer temperatures rose above freezing and slope processes were reinvigorated, the lack of significant vegetation allowed transport of substantial clastic material to the lake basins. In the earliest phases pollen is absent, subsequently dominated by pioneer species and only by 9 to 10 ka is the modern Arctic tundra established. We interpret this sequence to indicate that the unglaciated regions of Baffin Island experienced extremely cold summers beginning more than 40 ka. Conditions were so cold that geomorphic activity essentially ceased in the drainage basins, and what vegetation could survive reproduced asexually. As summer temperatures increased beginning about 14 ka BP, hillslope processes were active in some basins, because vegetation cover was so thin. This interpretation implies permanent sea ice in the adjacent oceans beginning before the LGM and persisting until at least 14 ka ago.

Finally, higher resolution records sampled at 30 to 50 year intervals for the past 5000 years suggest that Neoglaciation began about 5000 years ago, and that summer temperatures began an additional decreasing trend beginning about 2500 years ago. Although summer insolation has been decreasing throughout the Holocene, the step-wide nature of Holocene climate change suggests a combination of sea ice and Labrador Sea deep-water convection modulated the smooth insolation trend.

A high-resolution sedimentary record from Russkaya Gavan', a Novaya Zemlya fjord: inferences for paleoclimatic conditions in the northeastern Barents sea during the past millenium

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Russkaya Gavan' (Russian Harbour) is a glacier-influenced fjord at the northwestern coast of the Novaya Zemlya archipelago that bounds the Barents Sea on the east. For over 60 years, Russkaya Gavan' was the site of a weather station, which provided one of the few meteorological archives for the eastern Barents Sea, the area of intense Arctic-Atlantic oceanic and atmospheric interactions. The glacial regime of Shokal'ski Glacier, which drains into Russkaya Gavan', has been repeatedly studied since 1933 (Chizhov et al., 1968; Mikhaliov & Chizhov, 1970). These unique high-Arctic data sets, combined with high-resolution sedimentary archives that are expected in glaciomarine fjord environments, make Russkaya Gavan' a key site for studies of paleoclimatological and paleoceanographic changes in the Barents Sea.

Sea-bottom sediment sampling, acoustic penetration and sidescan profiling, and oceanographic measurements were performed in Russkaya Gavan' from R/V's Akademik Sergei Vavilov (ASV) in 1997, and Ivan Petrov in 1998. A 6-m long gravity core ASV-987 was collected from the central, deep part of the fjord at a water depth of 170 m and at a distance of ~5 km from the glacier front. The core was investigated for water content, grain size, total organic carbon (TOC) and carbonate contents, foraminifers, stable-isotopes in foraminiferal calcite, and enzyme activity of organic matter. Age control was provided by four AMS ^{14}C datings.

Acoustic penetration data show that stratified glaciomarine sediments deposited above a subglacial diamicton are ~20 m thick near the ASV-987 site and increase in thickness to >>30 m towards the glacier. This ice-proximal sedimentary wedge consists of three units separated by two prominent reflectors, which possibly indicate the two most recent glacier advances. As measured in September 1997, the concentration of suspended sediment in surface water varied from ~60 mg/l near the glacier front to 13.5 mg/l near ASV-987 and to ~5 mg/l at the fjord mouth. The pattern of suspended-matter and bottom-sediment distribution along the fjord indicates that sedimentation in Russkaya Gavan' is largely controlled by glacier meltwater.

The summer meltwater discharge strongly affects hydrographic conditions in the fjord by forming a stratified water column with low-salinity, suspension-rich surface water and saline, suspension-poor deep water that flows into the fjord from the open Barents Sea. In winter, the temperature regime is a likely control on hydrographic conditions in Russkaya Gavan', as illustrated by a correlation of sea-ice melting time with winter air temperatures (Mikhaliov & Chizhov, 1970). In turn, winter temperatures reflect regional hydrographic and atmospheric patterns, which is demonstrated by a multi-decadal covariation between winter air temperatures at the western side of Novaya Zemlya with water temperature and ice cover in the Barents Sea.

Based on four ^{14}C ages, we estimate the time span of sediment core ASV-987 as ca. 800 years, from 1200 AD to present. The sediment generally consists of olive gray to blackish,

silty-clayey mud with an unevenly distributed admixture of sand and coarse clasts. Distinct lamination occurs at some intervals, whereas diffuse contacts disturbed by bioturbation are more common. Down-core distribution of grain-size fractions, TOC, foraminiferal numbers, stable isotopes, and enzyme activity show significant variations on a century to multi-decadal scale reflecting changes in sedimentary and/or hydrographic environments. Foraminiferal numbers, TOC, and enzyme activity may covary, but at some core levels they show differing patterns reflecting a complexity of controls, which include glacier meltwater and sediment discharge, sea-ice conditions, and water exchange with the open sea. Stable-isotopic •^{18}O and •^{13}C values show a strong covariation, which indicates that they are controlled by inputs of meltwater that presumably descent to the fjord bottom with brines during sea-ice formation.

The lower part of ASV-987, prior to ca. 1500 AD, is characterized by fine sediment and relatively heavy •^{18}O and •^{13}C values and contains three broadly co-occurring spikes of foraminiferal numbers, TOC, and enzyme activity. We believe that these features generally indicate glacier-distal settings with century-scale variations in productivity that were, in turn, related to sea-ice conditions. The time interval of ca. 1500 to 1700 AD is distinguished by an elevated concentration of coarse granulometric fractions, with several pronounced spikes, and an associated low water content; stable-isotopic values at this interval are characteristically low. We suggest that these changes in sediment deposition resulted from pulses of icebergs and/or debris flows combined with meltwater releases, and thus indicate abrupt changes in the glacier front position. This assumption is corroborated by morainic features at the coasts of Russkaya Gavan' that attest to a recent advance and retreat of the Shokal'ski glacier. The maximum age of the advance is controlled by a ^{14}C age of ca. 1350 AD, obtained on a bivalve shell embedded in a moraine (Zeeberg and Forman, in press), and is consistent with ASV-987 stratigraphy. The timing of this glacier advance in Russkaya Gavan' generally corresponds to the Little Ice Age cooling in other high-latitude sites. The evidence for LIA cooling in the Barents Sea region includes a tree-ring series from the Polar Urals (Briffa et al., 1995) and the latest glacier expansion on Franz Josef Land (Lubinski et al., 1999). The upper part of ASV-987 was likely deposited in relatively glacier-distant environments, consistent with regional warming and a general retreat of sea-ice margin after ca. 1800 AD (Vinje, 1997).

Acknowledgment: This study is partially supported by the NSF grant OPP-9725418.

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Sea-ice coverage of the Barents Sea in response to changes in ocean characteristics

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1. Ocean Characteristics

We show first analyses for a comprehensive new data base of ocean temperature and salinity. The Barents and Kara Seas Oceanographic Data Base (BarKode) (*Golubev et al., 1999*) contains 206,300 station profiles for the Barents and Kara Seas during the 100-year time period 1898-1998. Both recently declassified military data, and from a variety of civil sources have been quality- and redundancy-checked. The result is the most complete data set available for this Arctic shelf region. BarKode is being prototype tested in April 2000. The final CD-ROM together with the data report will be available from the International ACSYS/CLIC Project Office in the near future.

The surface water gets more saline during the past 75 years for all months of the year (Fig. 1) whereas surface temperature decreases for all but the summer months. The importance of analyzing long time series becomes obvious in negative ocean temperature trends for the last 75 years, but strongly positive trends for the past 20 years. The salinity trend is positive for the whole year except of July. Salinity is also increased throughout most of the water column (Fig. 2) whereas the strongest signal appears at the surface. Ocean temperature on the other hand is, on average, decreased for all depth levels. The negative temperature trend is smallest at depths 25 and 50 m. The temperature trend for all water levels is strongly positive for the last 20 years (1978-1998).

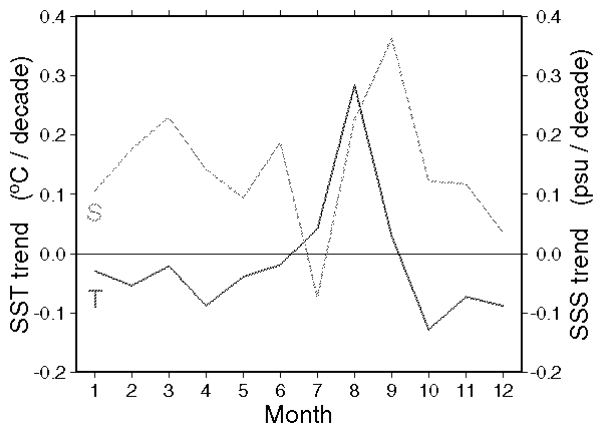

Figure 1: Decadal trends for sea surface temperature (SST) and sea surface salinity (SSS) for the Barents and Kara Seas, 1921-1997.

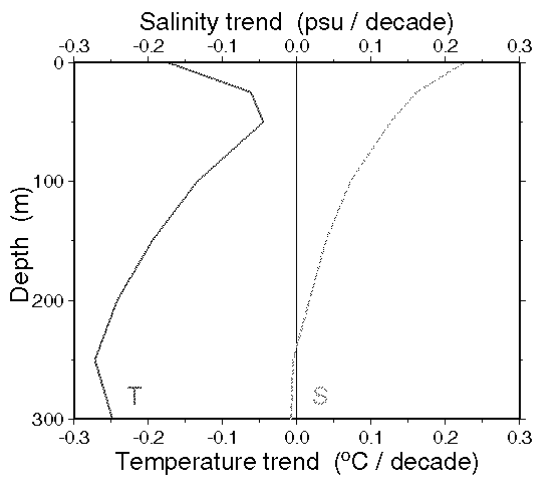

Figure 2: Decadal trends of ocean temperature and salinity with depth (0 to 300 m) for the Barents and Kara Seas, 1921-1997.

2. Historical Sea-Ice Charts

The Norwegian Polar Institute compiled a 400-year time series of sea-ice extent for the Nordic Seas with good temporal and spatial coverage for the period 1853-1999. Ice edge and ice type information from sealers, other ship traffic and land observations (before 1950) is supplemented with aircraft and satellite data (after 1950).
Here we analyse the April and August ice extents for the Barents Sea (10-70˚E). April ice extent is reduced by 10% from 1920-1998, August extent by 62%. We find a correlation of -0.15 between the average winter temperature (January to April) for depths 0 to 50 m, and sea-ice extent. The correlation rises to -0.36 when correlating with only ocean temperatures from the western Barents Sea inflow area of Atlantic water (30-40ºE, 72-76ºN). The highest correlation with winter salinity of -0.28 is found for a time lag of 1 year. Higher salinity in one year leads to lower ice extent the year thereafter. Studies of *Vinje (2000)* reveal a minor effect of atmospheric warming on sea-ice extent that can be explained by the difference in heat capacity of air and sea water. But if oceanic and atmospheric effects remain positively correlated (like during the past 30 years) considerable extension or contraction of the ice extent would be expected.

3. Future Plans

ACSYS/CLIC (Arctic Climate System Study/Climate and Cryosphere) is one of the 5 sub-programmes of the World Climate Research Programme (WCRP). An important task is the compilation of all existing observations and proxy data of sea-ice distribution that are scattered in different archives, institutions and countries (e.g., Norway, Denmark, Germany, England, Iceland, Russia, the Netherlands, Canada, USA). We plan to initiate a project on historical sea-ice charts for the past 400 years that cover the Labrador and Nordic (Greenland, Barents and Kara Seas). This would lead to longer, more complete and thus more reliable records of sea-ice extent which are needed to evaluate climate variation and possible climate change.

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Historical Records of Sea-Ice Variability from Iceland

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INSTAAR and the Stefansson Arctic Institute

The sea-ice record from Iceland, based on historical data, has long been known as an excellent proxy record for past environmental and climatic changes. In this presentation, the sea-ice data will be discussed on an annual to decadal basis and compared to the earlier Koch ice index. Koch's "The East Greenland Ice" (1945) remains a classic work, and was a pioneering effort. However, this is based on another work (Thoroddsen, 1916/17) which, although another pioneering work, contains many errors. Furthermore, many new sources of information have now been discovered. Historical data on sea ice are to be found from around AD 1145 onwards, however, they do not become continuous until around AD 1600. For the period from this time to the present, the data suggest that the decades with most ice were the 1780s, early 1800s and the 1830s. From 1840 to 1855 there was virtually no ice off the Icelandic coasts. From 1855 to 1860 there was frequent ice again, although the incidence does not seem to have been as heavy as in the earlier part of the century. Further clusters of sea-ice years occurred again from ca. 1864 to 1872. The 1880s contained several very severe sea-ice years. Some sea-ice years occurred in the 1890s, but far less than in the 1880s. From 1900 onwards, sea-ice incidence declines dramatically. It is clear that, in comparison with the entire period AD 1600 to 1900, sea ice off Iceland has occurred less frequently in the twentieth century. It is interesting to note that there appears to have been a relatively ice-free period during the years ca. 1630 to 1680. This coincides with a period when independent documentary evidence shows that mainly mild temperatures predominated in Iceland. This is in contrast to the marked coldness of the seventeenth century in Europe. Indeed, this century has often been regarded as the height of the so-called "Little Ice Age". For the Iceland sea-ice record, however, the most severe interval in recent times would appear to be from c. 1780 to 1920. This presentation will also consider impacts of sea ice on the human population, particularly during the period AD 1650 to 1850. The presence of sea ice affected people in a variety of ways; not all of them negative. Useful products, such as driftwood and marine mammals, for example whales and seals, could accompany the ice. However, the lowering of temperatures associated with the presence of the ice mainly affected the growth of the important grass crop. A lack of hay with which to feed the livestock meant that they were likely to die of starvation. As the Icelandic economy was based largely on animal husbandry, the loss of the livestock frequently meant loss of human life as well. Other social consequences could follow such as the desertion of farms. The presence of the sea ice off the coasts caused other problems such as the prevention of fishing and access by trading vessels.

Modeling Sea Ice

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Arctic ice cover has a mean thickness of 3-4 meters but varies in thickness from open water to pressure ridges tens of meters thick. Current models of sea ice consider not only how sea ice grows and melts but also drifting due to winds and currents. Sea ice models, depending on their complexity, can contain four components: thermodynamics, ice thickness distribution, ice rheology, and momentum balance. The thermodynamic component specifies the growth and decay rates of various ice thicknesses. The ice thickness component treats the evolution of the ice thickness characteristics by thermodynamic and dynamic effects. The momentum balance component takes into account the stresses induced by the atmosphere and ocean, within the ice, and due to Coriolis and inertial forcing. The ice rheology relates the ice stress to ice deformation and ice thickness.

The NCAR Climate System Model (CSM) is a coupled atmosphere-land-ocean-sea ice model which incorporates a sea ice model with thermodynamic and momentum balance components. Simulations for present, pre-industrial, Mid-Holocene, and Last Glacial Maximum conditions have been completed. The mid-Holocene simulation has reduced sea ice compared to present in the Arctic and northern Atlantic and Pacific Oceans as a result of delayed formation in the fall and earlier melting in the spring. Annual surface temperature over continental areas rimming these oceans are warmer than present as a result of the diminished sea ice. At Last Glacial Maximum, the CSM predicts sea ice in the North Atlantic significantly more than present but less than reconstructed by CLIMAP.

Annual to millennial variations in the origin and fate of sediment-laden sea ice

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In the Arctic today, sediment-laden sea ice that forms over shallow shelf regions, may be incorporated in the central Arctic ice pack and delivered several years later to the marginal ice zones of the Greenland and Barents sea. This study examines variations in sediment sources and fate from 1979 to 1994+ using simulations of ice drift from the International Arctic Buoy Program database, and from 18,000 to today using bathymetric reconstructions from a combination of the Peltier (1994) and ETOPO5 databases. Results indicate large spatial and temporal variations in likely sources (and therefore composition, Elverhoi et al., 1989) of sediment laden ice, transport pathways and potential contributions to Arctic and North Atlantic sediment flux.

Presently, highest sediment concentrations in sea ice are associated with sediment incorporation by suspension freezing (Reimnitz et al., 1992; Nuernberg et al., 1994; Eicken et al., 1997). Resuspension of sea floor sediments and entrainment in forming ice is favored by shallow water depth (<25-30 m), a weakly stratified water column, cold winds blowing over a fetch >20 km, and bottom sediments that are fine but not cohesive (Reimnitz et al., 1998; Sherwood, 2000; Smedsrud, 2000). Long range transport of sediment-laden ice is only possible when the ice is entrained in a mobile perennial ice pack and drifts for several years. Thus sediment incorporation in the fall and early winter and at a location close to the multiyear ice border will favor long range transport (Rigor and Colony, 1997). At present, the main source for sediment-laden ice in the Arctic is the region north of the New Siberian Islands, where all of these conditions are fulfilled (Pfirman et al., 1997).

Once entrained in the multiyear pack, the trajectory of sediment-laden ice is governed by the general circulation of the ice. Interannual variations in ice drift forced by environmental changes associated with the Arctic Ocean Oscillation (Proshutinsky and Johnson, 1997; Pfirman et al., submitted), will transport sediment-laden ice along different pathways in different circulation regimes. For example, Pfirman et al. (submitted) have shown that in some years, ice from the northern Kara Sea is transported directly into the Barents Sea, south of Franz Joseph Land. In other years, most of this ice circulates first to the east, toward the Laptev Sea and the New Siberian Islands, and then drifts back to the west and into Fram Strait with the Transpolar Drift Stream. Such variations in ice drift have a major impact on spatial and temporal variations in composition and flux of sediments deposited from sea ice. Some sediment is lost by drifting floes during summer melting and ice rafting, and contributes to sedimentation along the drift trajectories. However, the bulk of the sediment load is likely to be deposited when the floe trajectory intersects the marginal ice zone.

In this study, we use the drift trajectories of Pfirman et al. (submitted) to simulate sedimentation at 79°N in the Fram Strait and Barents Sea. This analysis shows that sea ice originating in the Kara, Laptev and East Siberian seas undergoes marked variations in exit location, resulting in interannual changes in the mineralogy and concentration of exported sediment (figure 1).

The next step is to look back in time, and assess likely locations for sediment entrainment Shallow water depths (0-20m, 20-25m, and 25-35m) were highlighted for each 1 ky from 18 kyBP to today. Sites favorable for sediment entrainment in sea ice are identified in North

Atlantic and Arctic regions, with marked shifts in potential source areas as deglaciation progressed. While this analysis is dependent on many uncertainties (distribution of glacier cover, sea level changes, erosion, wind and sea ice conditions, etc.), it does raise some interesting possibilities.

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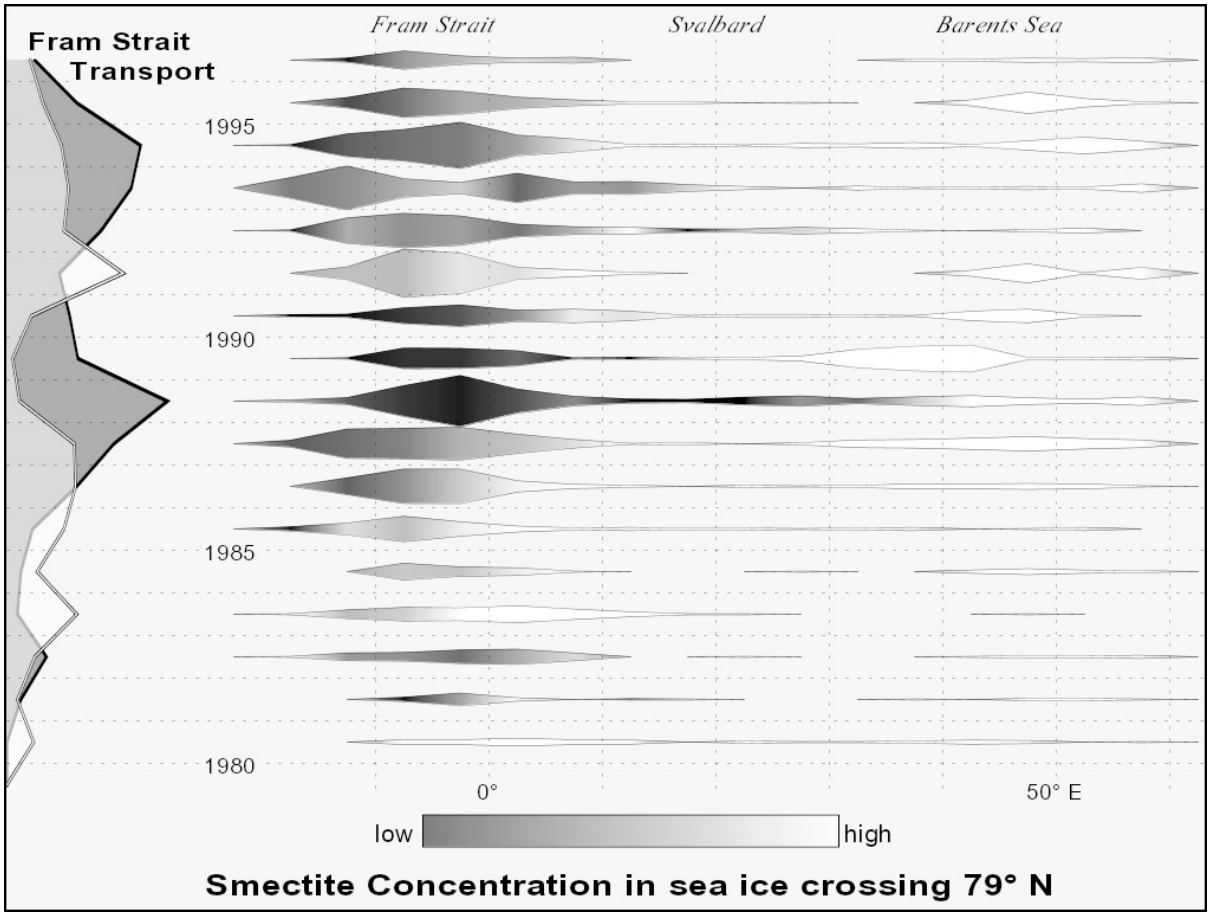
Fram Strait
Transport
Fram Strait
Svalbard
Barents Sea
1995
1990
1985
1980
0°
50° E
low
high
Smectite Concentration in sea ice crossing 79° N

Holocene evolution of paleoceanographic environments in the eastern Barents Sea as inferred from sediment records with a submillennial resolution

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Of all the Arctic regions, the Barents Sea has the highest amplitude of interannual variations in the sea-ice cover, which occur on a decadal scale (e.g., Mysak and Manak, 1989). This variability is related to fluctuating inputs of warm and saline Atlantic water, of about 1.6 Sv on average, which control the winter limits of sea ice (e.g., Loeng, 1991). To understand a long-term development of these Arctic-Atlantic interactions, we investigate sediment cores from the eastern Barents Sea that have been collected from sites with elevated Holocene sedimentation rates, providing a submillennial resolution. Sediment cores have been logged for physical properties (density, p-wave velocity, and magnetic susceptibility) and are investigated for grain size, organic matter content and composition, foraminiferal and palynomorph assemblages, and stable isotopes in foraminiferal calcite. The modern dinocyst database developed at GEOTOP was used for calculating surface water conditions (de Vernal et al., this volume). Age control is provided by AMS ^{14}C datings of foraminifers and small mollusks.

Cores for detailed studies were selected from sites representing minimal, maximal, and mean modern winter sea-ice limits in the southeastern Barents Sea (Fig. 1). The winter ice edge corresponds to the boundary between Arctic and Atlantic water masses and is marked by the Polar Front (PF) – a zone of high biological productivity, especially pronounced over the shallow areas. Episodes of elevated paleo-productivity in sediment records can be interpreted as indications of the PF proximity. In combination with lithological and paleobiological sea-ice proxies, the productivity records can thus be used for reconstructing winter ice limits.

Core PL96-112, studied in most detail, was collected from 320 mwd between the mean and maximum winter ice limits (Fig. 1). This core spans ca. 7.5 kyr with an average sedimentation rate of 50+ cm/kyr. The oldest part of the record, prior to ca. 6 ka, is characterized by high sediment fluxes accompanied by high sand contents, heavy TOC •^{13}C values, and relatively high concentrations of terrestrial palynomorphs. These features may reflect lower sea levels or higher inputs of river runoff. Dinocyst assemblages attest to stable, relatively warm surface-water conditions, although foraminiferal assemblages lack species indicative of Atlantic waters. The maximum of Atlantic influence is detected at ca. 6 ka by the peak in the content of planktonic foraminifers and the benthic species Cassidulina teretis; this event can be traced into the southeasternmost Barents Sea, in front of the Pechora River estuary.

A pronounced cooling and sea-ice expansion occurred at the PL96-112 site at ca. 4.5 ka. This event can be identified throughout the eastern Barents Sea by a change in sediment lithology and foraminiferal assemblages. Extreme southward advances of the winter ice margin are also reflected in ice-related beach features at the western Kola Peninsula, estimated to have been formed at around 4 ka (Møller et al., 1996). The subsequent evolution of hydrographic conditions in the southeastern Barents Sea is characterized by alternating cooling and warming events. The PF was often located near PL96-112, especially pronounced between 4

and 2 ka; this interval also contains a peak of Atlantic influence. The last major cooling occurred at ca. 2 ka; a less pronounced cooling is detected at ca. 0.5 ka. More precise dating is needed to correlate these episodes to broader climatic events, such as the Little Ice Age. Some sediment characteristics, notably the magnetic susceptibility and content of blackish iron sulfides, cyclically varied after 4 ka with a frequency of ca. 0.5 kyr, presumably reflecting oscillations in the position and/or intensity of the PF. We suggest that the transition from generally warm and stable to an oscillating marine regime at 4-5 ka was caused by a climatic reorganization in the Barents Sea region, possibly related to changes in routes and intensity of Atlantic cyclones.

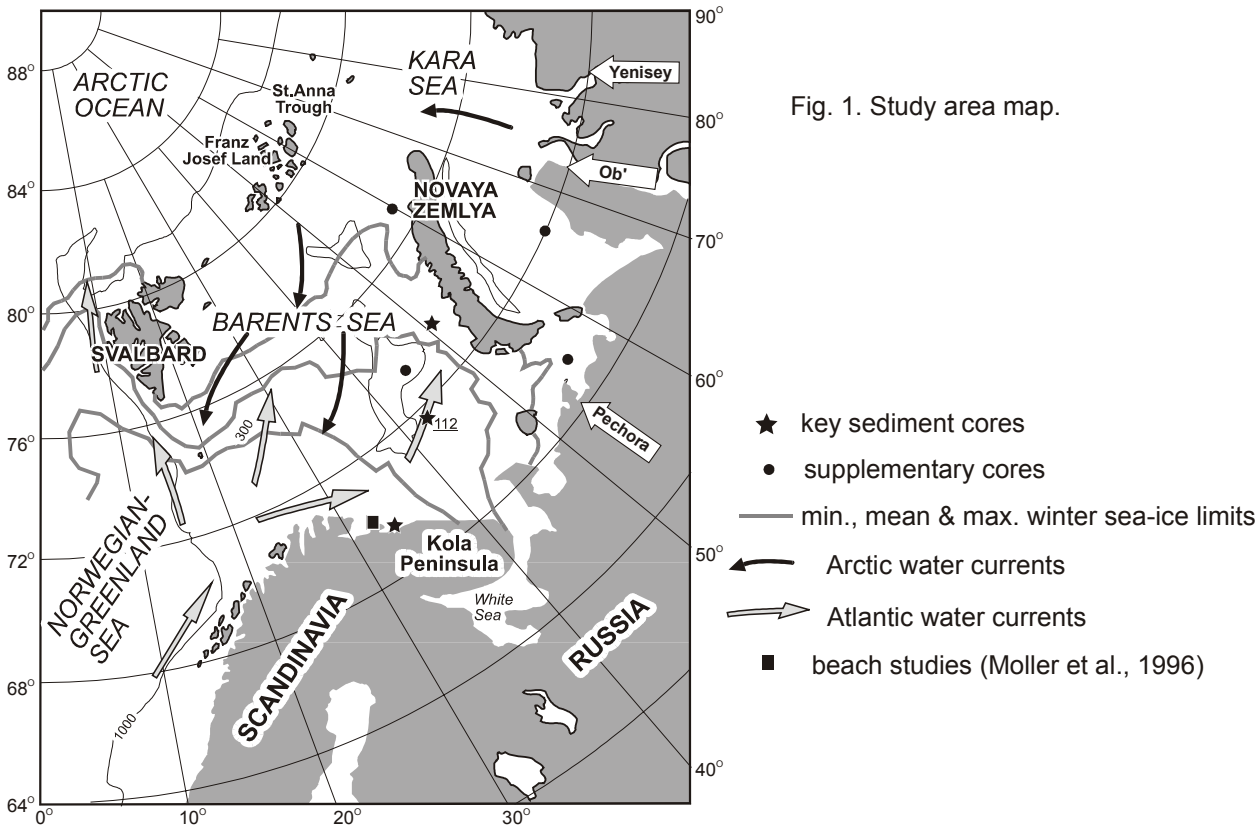

Fig. 1. Study area map.

Acknowledgment: This study is supported by the NSF grant OPP-9725418.

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How regular are the millennial oscillations in N. Atlantic data on ice-rafted debris ?

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Recent high resolution data on ice-rafted debris from several North Atlantic cores (Bond et al, in press) exhibit striking and apparently periodic variations (with a consistent "pacing" period of about 1500 ± 500 years) during both recent glacial episodes and the present interglacial. These are particularly noticeable for counts of hematite-stained grains (Bond et al, loc cit), but the cause of these variations is not known. Their persistence despite the retreat of the major ice-sheets does however make it plausible that they are a signature of a process involving sea-ice. Analysis of the regularity (or otherwise) of these variations may help to determine whether they are truly periodic (suggesting an external driving mechanism, such as astronomical forcing) or quasi-periodic, more indicative of some internal relaxation oscillation of the ice-ocean-atmosphere system.

We have applied several methods of spectral analysis to both the full record and to segments of it, to evaluate as objectively as possible the regularity of the millennial-scale variability. One of these methods (Phase-Sensitive Spectral Analysis) is novel and measures the extent to which the phase of any apparent periodic signal remains coherent (i.e. constant throughout the record). The results indicate that the millennial signal is not highly phase-coherent, and the period varies (apparently unsystematically) between about 1 ka and 2 ka for different segments of the record, consistent with earlier analyses showing a fairly broad peak in the spectrum in this range. We interpret these results as suggestive of some quasi-periodic internal oscillatory mechanism, or some form of stochastically forced relaxation oscillation or stochastic resonance (Alley, pers comm), rather than a genuinely periodic process. This suggests that the source should be sought in coupled ice-ocean-atmospheric processes, and that this apparent cyclicity should not be regarded as a potential clock for dating purposes.

Sensitivity of the climate system to sea ice extents during the Holocene and LGM based on GCM modeling

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We are testing the sensitivity of the climate system to changes in sea ice extent in the Northern Hemisphere for Holocene (6 ka) and Last Glacial Maximum (21 ka) conditions using NCAR's Global Circulation Model (CCM3). The investigation is focused on how the surface temperature, sea level pressure, North Atlantic Oscillation (NAO), snowfall amount, and growing degree day index are influenced by changes in sea ice extent. For the Holocene, we tested three different sea ice limits: 1) present-day sea ice extent (6kP), 2) sea ice less than present-day (6kMin), and 3) CLIMAP's sea ice reconstruction (6kMax). The 6kMin and 6kMax experiments are considered analogous to the Holocene Optimum and the Younger Dryas, respectively. For the Last Glacial Maximum, we tested two different sea ice limits: 1) CLIMAP's sea ice reconstruction (21kMax), and 2) CLIMAP's sea ice limit with a seasonally sea ice-free Nordic Sea and Sea of Okhotsk (21kMin). Table 1 lists the model input parameters.

The 6kMin experiment shows significant warming in the winter in the Eastern Canadian Arctic and along East Greenland compared to the 6kP experiment, but sea level pressure does not significantly change. There are no significant changes in temperature or sea level pressure in the summer. The 6kMax experiment shows significant cooling all year in the North Atlantic and extending downstream into Europe and Asia compared to the 6kP experiment. Additionally, sea level pressure is significantly dampened and strengthened in the North Atlantic and North Pacific, respectively. Comparison of the LGM experiments (21kMin-21kMax) indicates that there is an increase in temperature and strengthening of sea level pressure in the North Atlantic in the winter months with the decrease in sea ice extent in the Nordic and Labrador Seas. There are few significant changes in the temperature or sea level pressure in the summer. Both LGM experiments have a deepened Aleutian Low and weakened Icelandic Low compared to the Holocene experiments.

There are two major results from the sensitivity experiments: 1) for the Holocene experiments, significant changes in temperature and sea level pressure are caused by changes in winter, not summer, sea ice limits in the North Atlantic, and 2) a minor reduction in the annual sea ice limit in the North Atlantic at the LGM significantly alters temperature and sea level pressure. Hence, reconstructing the North Atlantic sea ice limits, especially at the LGM, is critical for paleoclimate interpretations.

Table 1. Input parameters for each modeling experiment.

Model	Sea ice extent	SST	Insolation	Atm Gases[1]	Land&Ice Sheets[2]
6kP	present-day	modern	6 ka	pre-I	Modern
6kMin	< present day	modern	6 ka	pre-I	Modern
6kMax	CLIMAP	modern, except north of 20˚N (CLIMAP)	6 ka	pre-I	Modern
21kMin	CLIMAP, ice-free Nordic Seas	CLIMAP except in Nordic Sea	21 ka	LGM	LGM
21kMax	CLIMAP	CLIMAP	21 ka	LGM	LGM

[1]Values for atmospheric gases (CO2, CH4, CFC, N_2O, ozone) are based on ice core values from Blunier et al. (1995), Fluckiger et al. (1999), Indermuhle et al. (1999), and Raynaud et al. (1993).
[2]Land and ice sheet configuration for the LGM model experiments is based on CLIMAP (1981) and Peltier (1994).

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The Impact of Sea Ice Motion on Arctic Climate Sensitivity

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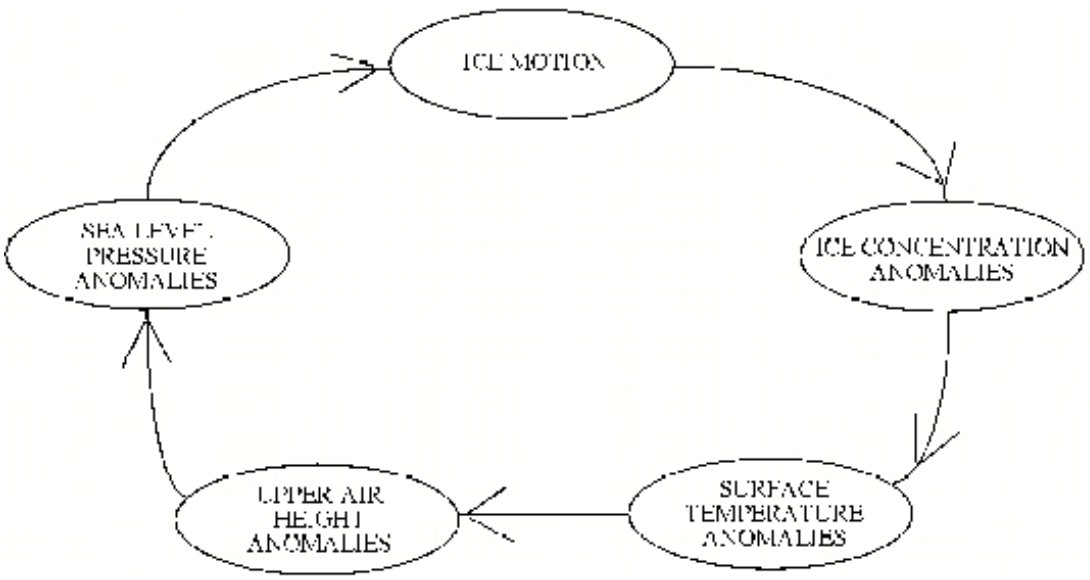
Sea ice dynamics play an important role in the Arctic climate system. Ice export from the Arctic Ocean redistributes fresh water, by increasing salinity locally during ice growth but decreasing salinity downstream as ice melts in the North Atlantic. Sea ice motion is also an important thermodynamic forcing mechanism, because it rearranges the coverage of pack ice across the Arctic-North Atlantic oceans and thus creates regions of relatively thick, compact ice and areas of thinner, more diffuse ice. Because these transports of heat and salt are believed to influence the global thermohaline circulation, they may be relevant for understanding past and future high-latitude climate variability. Less clear is how sea ice motion interacts with the atmosphere to generate climate feedback mechanisms that are important for explaining recent paleoclimates and predicting future climates.

A series of experiments have been run with a global climate model to investigate the role of sea ice dynamics in affecting Arctic climate sensitivity. The GENESIS (Version 2) coupled atmosphere/mixed-layer ocean general circulation model was forced with orbital parameters appropriate for 6 ka (warmer-than-modern Arctic) and 115 ka BP (cooler than present). A pair of simulations was run for each paleoclimate time period and for a modern control case: one with dynamic sea ice (DI) and one with thermodynamic-only sea ice (TI) (no sea ice motion). In addition, a supplementary experiment of the last interglacial (126 ka BP) with dynamic ice was included, as well as a pair of DI-TI simulations for a future climate with doubled CO_2 to corroborate the major feedbacks.

The paleoclimate and future climate simulations indicate that sea ice motion acts as a cooling mechanism in both the warmer and cooler scenarios, due to atmospheric circulation changes which are induced by the presence of a dynamic ice pack. This cooling effect is superimposed on the orbitally forced climate changes, causing approximately $2^{o}C$ less warming of the central Arctic in the warm scenarios (6 ka and 2 x CO_2) and $0.5^{o}C$ greater cooling in the cold scenarios (115 ka). This cooling occurs primarily because dynamic ice spreads the North Atlantic ice margin equatorward more in the altered climates than in the modern simulation. This advective forcing results in a reduced poleward retreat of the ice pack in the warm scenarios and an enhanced equatorward advance in the cooling scenario.

This ice-margin effect stems from complex ice-atmosphere interactions, in which ice cover anomalies create local surface temperature anomalies that propagate into the lower atmosphere. Atmospheric dynamics cause these temperature changes aloft to induce changes of surface pressure and wind, which in turn affect the spatial distribution of the ice pack. These ice-atmosphere interactions generate a low pressure anomaly over the northern Eurasian coast in all experiments, producing enhanced cyclonic winds over Eurasia and the eastern Arctic Ocean. This pattern causes increased outflow of polar air and sea ice from the Arctic to the North Atlantic in all of the DI experiments. By contrast, the simulations without ice motion do not show these kinds of pressure and wind anomalies. Instead, the sea ice anomalies in the TI experiments favor air pressure changes that generate increased inflow of heat and moisture from the North Atlantic to the Arctic in the warm scenarios and produce only minor changes in the cold scenario. These linkages among sea ice-atmosphere

interactions in the presence of a dynamic ice pack may be important for interpreting paleoclimates and are schematically illustrated below.



Hypothesized feedback loop illustrating the interaction among sea ice dynamics and the atmosphere.

Sediment mineralogy and sea-ice development in the Arctic Ocean during the last 20.000 years

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This presentation focuses on sedimentological investigations of sediment cores recovered during the international Arctic´91 expeditions with the German research ice breaker "Polarstern" to the Eurasian Basin of the Arctic Ocean in addition to published data of the Fram Strait. The last glacial/ interglacial change in transport mechanisms and sedimentation is deduced from the clay mineralogy. The clay mineral group smectite has been choosen as an example how sediment mineralogy can be linked with particular source regions (the Kara and Laptev Sea regions), distinct transport mechanism (sea-ice and surface currents) and sedimentation processes (biologically enhanced via fecal pellets). The history of sea-ice development and sedimentation from sea-ice during the last approx. 20,000 years will be discussed.

The Arctic Ocean system is a key player regarding the climatic changes of Earth (Alley 1995). Its highly sensitive ice cover, the exchange of surface and deep water masses with the global ocean and the coupling with the atmosphere interact directly with global climatic changes. The Arctic Ocean is surrounded by the large Northern Hemisphere ice sheets which not only affect the sedimentation in the Arctic Ocean but also are supposed to induce the course of glacials and interglacials. Several of the largest rivers of the world drain into the Arctic Ocean. Terrigenous sediment delivered from the ice sheets by icebergs and meltwater as well as through newly built sea-ice are major components of Arctic Ocean sediments (Clark et al. 1980; Nürnberg et al. 1994). Hence, the terrigenous content of Arctic Ocean sediments is an outstanding archive to investigate changes in the paleoenvironment.

The development of the sea-ice cover is of particular interest as its large extent compared to its small thickness combine to its extreme sensitivity for climatic changes. The production of sea-ice and the entrainment of sediment in the wide and shallow Siberian shelf regions have been extensively investigated lately (see Nürnberg et al. 1994; Kassens et al. 1995, 1997). Predominantly fine grained material is strongly entrained in the shallow shelf regions (< 30 m water depth) of the Laptev and Kara Seas (Nürnberg et al 1994). Polynyas are regarded to be the major regions of sea-ice production and sediment entrainment (Nürnberg et al. 1994; Dethleff 1995).

In the Siberian shelf region the eastern Kara Sea and the western Laptev Sea form a distinct region defined by high smectite, (clino-) pyroxene and plagioclase input (Silverberg 1972; Stein & Korolev 1994; Wahsner 1995; Behrends et al. 1996; Vogt 1997; Wahsner et al. 1999). The source of this signal are the extensive outcrops of the Mesozoic Siberian trap basalts in the Putorana Plateau which is drained by the tributaries of the Yenissey and Khatanga. The eastern Laptev Sea and the East Siberian Sea can also be treated as one source region containing a feldspar, quartz, illite, mica, and chlorite association combined with the trace minerals hornblende and epidote (Silverberg 1972; Stein & Korolev 1994; Wahsner 1995; Behrends et al. 1996; Vogt 1997). Franz Josef Land provides a mineral composition

rich in quartz and kaolinite (Polyak & Solheim 1994; Wahsner et al. 1996; Vogt, 1996, 1997). The diverse rock suite of the Svalbard archipelago distributes specific mineral compositions of highly metamorphic crystalline rocks, dolomite-rich carbonate rocks and sedimentary rocks with a higher diagenetic potential manifested in stable newly built diagenetic minerals and high organic maturity (Elverhøi et al. 1989; Anderson et al. 1996).

Newly produced sea-ice transports smectite-rich sediment from the Laptev and Kara Seas to the Fram Strait through the Southern Eurasian Basin of the Arctic Ocean (Nürnberg et al. 1994; Pfirman et al. 1997). In the northwest of Svalbard relatively warm Atlantic Water of the northward trending Westspitsbergen Current (WSC) submerge at the Polar Front beneath the cold Polar Water which is sea-ice covered. The position of the Polar Front and the sea-ice edge depends on the strength of the WSC and the outflow of the Polar Water (Anderson et al. 1994). The outflow of Polar Water is strongly dependent on the fresh water influx into the Arctic Ocean by the Siberian rivers (Aagaard & Carmack, 1994).

During summer sea-ice melts near the Polar Front in the northwestern Fram Strait and open water conditions extend to the north of Svalbard (Gloersen et al. 1992). At the Marginal Ice Zone primary production is enhanced by algae blooms (Berner & Wefer 1990; Anderson 1995). Increased grazing of copepods lead to strongly enhanced sedimentation of fine grained particles via fecal pellet production (Alldrege & Silver 1988). Fine grained sediment, just released from the sea-ice, is transported to the sea-floor very near to the actual position of the MIZ. Increased smectite contents are observed in sediment traps in the eastern Fram Strait close to the MIZ (Berner & Wefer 1990; Hebbeln & Wefer 1991; Hebbeln & Berner 1993).

Hence, smectite contents in the sediments of the Fram Strait and the Eurasian Basin can give a hint on the position of melting sea-ice and open water position (see also Letzig 1995). In this presentation, this will be investigated for the last 20.000 years.

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Glacier response on north Novaya Zemlya to NAO-controlled fluctuations of temperature and precipitation in the twentieth century

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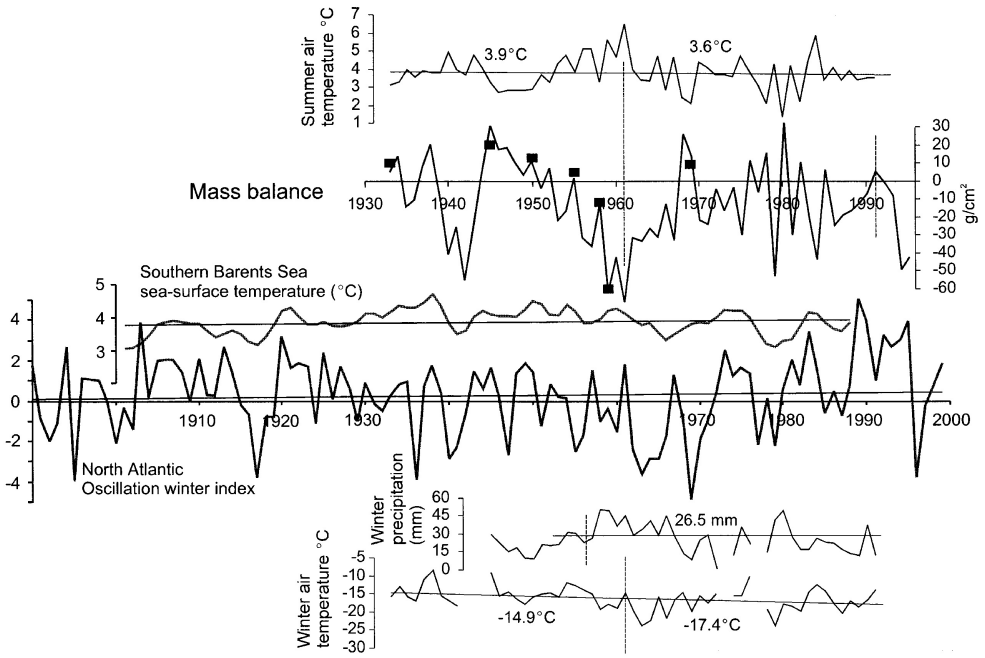
Glacier retreat on north Novaya Zemlya for the past century is documented by registering glacier terminus positions from expedition and topographic maps and remotely sensed images. Recession of tidewater calving glaciers on north Novaya Zemlya in the first half of the twentieth century was relatively rapid (>300 m/year), consistent with post-'Little Ice Age' warming documented by a 122-year instrumental record from Malye Karmakuly. The glaciers completed 75 to 100% of the net twentieth century retreat by 1952. Between 1964 and 1993 half of the studied glaciers were stable, the remainder retreated modest distances of <2.5 km. This stability coincides with decreasing average temperatures, especially during the winter, which is counter to model prediction.

Field-inspected moraines on north Novaya Zemlya were found to be ice-cored and lichen-free, indicating formation connected with the maximum 'Little Ice Age' glacier extent. A ^{14}C age of 660±45 y BP (AD 1300-1400) was obtained on a paired *Astarte borealis*-shell retrieved from a transported block of marine sediments in the lateral moraine of the Shokal'ski Glacier, presently at a distance of ~500 m from the calving margin. This is a maximum age for the latest Holocene glacier advance in Russkaya Gavan'. A paired, juvenile *Chlamys islandica* bivalve collected at 21 m aht from a fresh moraine at the front of the Pavlov Glacier yielded a post-bomb (younger than 1945) ^{14}C age (AA-31368), indicating a small (<200 m) recent advance.

There is a statistically significant covariance of unfiltered winter and summer temperatures from Novaya Zemlya and a smoothed 88-year record of SSTs in the southern Barents Sea (r>0.75). Elevated SST in the Barents Sea appear to reflect increased advection of warm North Atlantic water associated with a positive North Atlantic Oscillation index (NAO). Winter temperatures are periodically correlated with the NAO (r=0.75 to 0.9) reflecting repeated penetration of Atlantic cyclones into the Arctic. There is a delay of 3 to 5 years between a strong increase of the NAO-index and the response of summer temperatures, probably related to transit time of North Atlantic water to the Barents Sea. Hence, summer temperatures have the highest correlation with the NAO during prolonged positive phases (r=0.6 to 0.9).

During the twentieth century, an overall positive glacier mass balance trend at Novaya Zemlya is associated with a positive phase of the NAO, elevated southern Barents Sea SST, and a concomitant increase of winter precipitation. However, when summer temperatures rise <1°C above average, ablation compensates for the added precipitation, resulting in a negative glacier mass balance. Strong NAOs enhance winter precipitation and summer temperatures on Novaya Zemlya and have a variable effect on Novaya Zemlya glaciers. Variable control implies a non-linear glacier response to predicted climate warming. There is a clear need to further monitor glaciers in the High Arctic to determine response to atmospheric and oceanic warming.



Zeeberg, J.J. & S.L. Forman 2000: Changes in glacier extent on north Novaya Zemlya in the twentieth century. *The Holocene* 10, 6 (November, 2000).

Figure caption:
Summer (July-August) and winter (December-March) air temperature and winter precipitation measured at Russkaya Gavan' weather station between 1933 and 1991. Temperature averages are calculated for 1933 to 1961 and 1962 to 1991 (separated by broken lines). Precipitation measurements are accurate since 1956 (indicated by broken line). Black boxes indicate mass balance measurements on the Shokal'ski Glacier. The mass balance time series is calculated from regression formulas of ablation-summer temperature and precipitation-winter temperature. The NAO index was taken from http://www.cgd.ucar.edu/cas/climind/nao_winter.html

ICAPP 2000

Abstracts

Öræfajökull, SE Iceland

Spatial and temporal variations in pollen assemblages of arctic snow: considerations in interpreting pollen records from ice cores

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Pollen deposition in snow was investigated to improve our understanding of pollen deposition in arctic regions and thereby improve our interpretation of pollen records obtained from ice cores. Over the course of several years, the annual snow layer was sampled primarily at sites in the Canadian Arctic, as well as in Greenland, the Russian Arctic, and on the perennial sea ice in the Arctic Ocean between Russia and Canada. At three Canadian ice caps and at one Russian ice cap, the seasonal and annual variations in pollen deposition were studied in more detail.

Pollen assemblages recovered from snow are diverse and consist of pollen grains of arctic tundra plants as well as pollen of trees and herbaceous species growing several hundreds to thousands of kilometres distance from the sample sites. Pollen succession, corresponding to the flowering periods of arctic and southern plants, is evident in the more detailed study mentioned above. Pollen percentages and concentrations are generally related to the density of the regional vegetation and to the distance of the source in more productive regions. The number of long-distance, transported tree and shrub pollen deposited in the Arctic can be highly variable, particularly at the sites closest to the treeline. Nevertheless, regional patterns are emerging and these might be used to define past and present characteristics of atmospheric circulation in the Arctic. For example, the presence of air masses originating in Eurasia can be identified by the increase of pine pollen in Arctic Ocean samples. This suggests that some of the pollen deposited in the northernmost part of the Canadian Arctic could originate from Eurasia. In some respects, this complicates the interpretation of ice core pollen records obtained from the Agassiz Ice Cap, northern Ellesmere Island.

Development of ultra-clean ice-core drilling technology:
Report on a field test on Devon Island, Nunavut, Canada

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Accurate measurement of toxic metals and other trace chemical species in ice cores requires that the level of handling and contamination of the cores prior to analysis be minimized. To this end, most investigators have adopted in-laboratory decontamination procedures that remove the outer layers of ice cores. These procedures have been proved effective and are widely adopted. However, they are time consuming and are inefficient in terms of core utilization. Quite often, a single core may only be used for analysis of a single metal species. Moreover, contamination remains an issue when handling fragile, porous cores drilled in the firn zone of glaciers and ice caps. Accordingly, efforts should be directed at reducing the initial amount of metal (or other) contamination resulting from the ice-core drilling operation itself.

Here we report on the development and testing of a new ultra-clean electro-mechanical drill specifically designed to collect ice cores for trace metal analysis. The new drill is designed to reduce the amount of contact and exposure between the ice cores and the metal components of the sonde. A field test conducted on the Devon Ice Cap, Nunavut, Arctic Canada, in April 2000, successfully demonstrated the new design to be functional, practical and easy to use. Moreover, the new drill design was found to significantly enhance core integrity.

Marine and continental record chemical signatures from Penny Ice Core shows effects of long Wisconsinan flow lines and early Holocene "Pollution" of Atlantic surface water by melt water from the retreating Laurentide Ice Sheet

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O-18 records from Penny Ice Cap have suggested that Wisconsinan flow lines originated far inland and much higher; from the Foxe Dome or even at times from the Keewatin Dome . The evolution of the distance to source and elevation of the flow line origin has a first order effect on the chemical species found in the Penny ice core. In particular the mineral dust indicators like [Ca] are much less sensitive to flow line evolution than the marine indicators eg.[Cl] or [Na], which can gather in more locally derived material than the well matured mineral dusts.

Northern Hemisphere ice cores from places like Summit, Renland and Agassiz have ice age ice with much higher (dust) [Ca] and higher (marine) [Cl] than Holocene. Penny [Ca] in the ice age is about 5-10 times higher than in the Holocene ice, which is similar to other Northern Hemisphere ice core records ,eg. Summit. However ,for ice age ice the marine species like [Cl] are lower than the Holocene except for very cold O-18 events. This difference between the Penny and other sites can be explained simply using the Hansson model combined with the evolution of the flow line origin. Comparisons are made to Summit that has no large "flow line" length change during the last 100 ka.

The only time interval where there is lack of agreement between theory and data is the early Holocene and agreement can be established by invoking early Holocene "(O-18) pollution" of Atlantic surface waters by Laurentide Ice Sheet melt water ,which has very low values. This melt "pollution" effect has been inferred from other lines of investigation comparing melt layer and series .

High resolution multi-proxy-climate records from ice cores, tree rings, corals and cultural sources; reconstructions and eigen vectors; results and significance

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Ideally all the proxy temperature time series used in a given analysis would have the following characteristics:

1. *Be statistically homogenous*
2. *Have well established transfer functions that captured all the temperature series frequency domain .*
3. *Have the same resolution in time .*
4. *Have no time scale errors.*
5. *Have very low ëlocalí noise levels.*
6. *Be numerous ,geographically dense and well distributed.*
7. *Have the same seasonal temperature sensitivity; eg summer (JJA).*

In practice for any given time resolution and interval of study it is unlikely that the suite of available proxy series will have all these characteristics. In order to maximize the number and geographical distribution of series and insure inclusion of series that have a wide spread of frequency sensitivity one has to consider including series with poor or no transfer functions, somewhat different seasonal sensitivities, time scale errors, different resolutions/spectral sensitivities and high local noise levels. The question arises; “How good are the resulting reconstructions and are the compromises worth it ?”. This paper makes these compromises and addresses these questions. The simple answer seems to be that the compromises are worth it and the reconstructions very robust even in the face of very high noise levels of all sorts.

A new ice core record from Lomonsovfonna, Svalbard: viewing the data between 1920-1997 in relation to present climate and environmental conditions

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In April 1997 a 124 m deep ice core was drilled at the ice divide of Lomonosovfonna (78°51'53"N, 17°25'30"E, 1230 m asl), the highest ice field in Svalbard. Radar measurements in the area of the ice core site indicate an ice depth of 126.5 m, suggesting that the bottom of the ice cap was nearly reached. The 137 Cesium content was determined by high resolution gamma spectrometry. The 1963 radioactive layer is situated at 18.7 m, giving a mean annual accumulation of 0.38 m w.eq. for the time 1963-1996. The ice core analysis program also includes DEP, ice structures, oxygen isotopes, deuterium, major ions and MSA. Several of the ion records show clear cycles that appears to be annual. The apparent seasonality of the signals is preserved even in the deeper parts of the core, although amplitude is reduced.

The results from the uppermost 36 m which is corresponding to the time between 1920 and 1997 and is interesting since there are both instrumental and other environmental records available which can then be used to verify the ice core data. The records of $\delta^{18}O$, MSA and melt features from the ice core are correlated with air temperature data from Longyearbyen on a multi-year basis suggesting that this core site reflects the local climate to a large degree.

A close comparison of the MSA record and the sea ice record over the 1920-1997 period suggests that they are closely related. MSA concentrations are higher for warm years with reduced ice cover. Years with little sea ice probably enables more DMS production and thus more MSA, and vice versa. Prevailing easterly winds suggest that conditions in the Barents Sea should have a strong influence on the amount of MSA deposited on Lomonosovfonna. This is confirmed by a comparison of MSA concentrations with Barents Sea sea surface temperature and ice cover. MSA may be influenced to varying degrees by many different parameters, however these results show that on a decadal scale the MSA record is a useful proxy of the climate of the surrounding region.

The Penny Ice Cap ice-core sea salt record for the Holocene

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Two ice cores were drilled to bedrock on the top of Penny Ice Cap in 1995 (334 m) and on a nearby, but lower, isolated dome in 1996 (178 m). This paper discusses primarily the sea salt and •18O time series through the Holocene (0-11.5 thousand years ago). The use of sea salt in an ice core as a sea ice cover proxy, can be questioned from studies showing lower sea salt concentrations during the more open sea conditions of summer (eg Wagenbach et al, 1998). In addition, fractionation of sea salt before, or while, it develops as an aerosol further question the proxy. However, this fractionation now seems to be an effect produced in the formation of sea ice. Therefore, it appears that sea salt may have two major sources: sea ice and the open sea. Sea ice salt is characterized by large sulphate deficits (Gjessing, 1989). The Penny ice core sea salt concentrations, because of their sulphate/sodium signature, can be considered to be dominated by an open water source.

A pattern of declining •18O concentrations through the Holocene, has been found in several ice cores drilled from small ice caps in the circumpolar region. A similar, but weaker, pattern is found in the Penny Ice Cap 1995 core. This is interpreted as evidence for declining temperatures through the Holocene with a thermal maximum 10-11,000 years ago (based also on melt layer evidence from a Northern Ellesmere ice core). The highest concentrations of sea salt in the Penny ice cores occur in ice from the early Holocene. This suggests that despite the disintegration of the adjoining Laurentide ice sheet at that time, and possible high fluxes of calved land ice in Baffin Bay, there was substantial open water. A study of whale-bone remains in the Eastern Canadian Arctic supports this conclusion (Dyke et al, 1996). Thereafter, the Penny record shows continuing declining temperatures (with •18O as a proxy) and an overall decline in sea salt concentrations. Although the sea salt/ sea ice proxy is not too robust, we conclude that with the general cooling there was a similar, though less consistent, increase in sea ice cover until it reached a maximum 150 years ago in the very period when there was a vigorous search for the northwest passage.

Chemical records from the Lomonosov ice core, Svalbard over the past 200 years.

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High-resolution sampling has been performed on the 120 m deep ice core from Lomonosovfonna (1230 m asl), Svalbard, drilled in 1997. The results from the uppermost 60 m of major ions plus MSA and various other species measured using ion chromatography are presented. Most species seem to have been relatively undisturbed by melt. Dating based on the 1963 radioactive layer, the Laki volcanic eruption of 1883 at 67.5 m detected by dielectric profiling in the field, together with the transition from the Little Ice Age detected in stable isotope stratigraphy gives an accumulation rate of about 0.4 m/yr. Detailed chemical and physical stratigraphic analysis of the core reveals that much of the original seasonality has been preserved, providing psuedo-annual peaks in many species. However the calculation of sea-salt ratios in individual 5 cm samples is problematic.

The acid budget in the core is dominated by nitric acid, with lower levels of sulphuric acid, which seems primarily to be of anthropogenic origin over the last few decades. Neutralization of acid species is associated with ammonia from anthropogenic arctic haze and with calcium from local sources of alkaline dust. Terrestrial species such as Ca^{2+} show large peaks in specific localized events in the stratigraphy, that may be related to industrial activity in Svalbard. The ion records seem to reflect 20th Century anthropogenic influence which is in agreement with other cores site sin the Arctic. The nitrate levels started to increase in the late 1940s and remained high until late 1980s and has decreased thereafter. The sulphate levels started to increase earlier, in the 1930s and has decreased during the last 3 decades. Since this is in agreement with the general pattern of emission of fossil fuel combustion on the continent the temporal variability of ions does not seem to have been severely altered by melt water percolation at this core site. The MSA signal in the core shows higher levels in the 19th Century while the sulphate levels were lower than at present, and the MSA/H_2SO_4 ratio has decreased by more than a factor of 2. In contrast sea salt markers such as Na^+ and Cl^- show no apparent trend with the end of the LIA, but show evidence of decline in recent years.

On-going work will complete the ion chemistry and improve preliminary data sets of PAH, NVOC, and metals in the core, which together with stable isotope and detailed physical stratigraphic analysis of the core are intended to be completed within 1 year.

Relationship Between a Devon Ice Cap Glaciochemical Record And Sea Ice in the North Water/Baffin Bay Region of the Eastern Canadian Arctic

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The North Water polynya, located in Smith Sound and extending into northern Baffin Bay of the eastern Canadian Arctic, plays an integral role in the circum-Arctic climate system through its energy budget, feedback mechanisms, and source for precipitation reaching surrounding ice caps. The Devon ice cap's proximity to the North Water and Baffin Bay is especially advantageous for reconstructing a record of past sea ice variability in this region. Glaciochemical records developed from four snow pits, two from the summit of the ice cap and two from the East Dome (approximately 14-km east of the summit), and from a 302-m ice core drilled at the summit of the ice cap in 1998 are used to evaluate the relationship between their sea salt species and sea ice within the North Water and Baffin Bay. Sea salt chemistry is compared with sea ice percentages from the SMMR and DMSP SSM/I 1978-1999 satellite passive-microwave sea ice data set for the North Water, Baffin Bay and Davis Strait regions. We determine that the source for sea salt chemistry is from local marine areas based on calculated excess chloride to total chloride ratios. Initial analysis reveals that a significant inverse relationship exists between changes in summer (June, July, August) sea ice in the North Water and Baffin Bay and Devon annual sea-salt concentrations for 1979-1998. The amount of sea salt species present in the Devon record is not solely a function of the amount of open water available. The additional variability in the sea salt record can be explained by other climatic parameters such as wind direction, wind speed, storm tracks and pressure surfaces that also play a role in the transport of sea salt to the ice cap. These parameters are being looked at for future analysis. Empirical Orthogonal Function (EOF) analysis is also used to look at the common variance between sea-ice percentages in the North Water and Baffin Bay and Devon sea-salt sodium. Initial results from this analysis illustrate that an inverse relationship exists between annual sea-salt sodium with spring, summer and fall sea ice in the North Water and Baffin Bay regions with the strongest relationship with summer sea ice. Forty percent of the variance in annual sea salt sodium from the ice-core, about 80% of the North Water summer sea-ice variance and 75% of the Baffin Bay summer sea-ice variance, as well as 39% of the North Water spring sea-ice variance are accounted for in the first EOF for 1979-1998. These results are promising for our ability to develop a 2000-year record of sea-ice extent in the North Water and Baffin Bay regions.

Studies of textures, fabrics and stratigraphy in the NGRIP deep ice core - in relation to climate history and ice deformation

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Introduction

The GRIP and GISP2 deep ice cores, drilled in Central Greenland in the years 1989-1993, provided the most detailed records available on climatic variation in the Northern Hemisphere during the last 100.000 years. Initial results from the GRIP core, indicating rapid climate shifts during the Eemian interglacial (~130-110 ka BP), could not be confirmed by GISP2 studies or other Northern Hemisphere records. Stratigraphic studies on the cores indicated that flow disturbances had occurred in ice older than 100 ka, but the extent of disturbance in the GRIP record could not be fully resolved.

Intense pre-site surveying by the Alfred Wegener Institute, University of Copenhagen and other groups in the years 1993-95 led to the selection of a promising new deep drilling site in North Greenland, where accumulation is lower than at Summit and the bedrock is unusually flat. These factors, together with a thorough study of internal reflectors traced from Summit to North Greenland, strongly indicate that the Greenland palaeoclimate record can be extended through the Eemian back to 150-200 ka BP with the drilling and analysis of a new core at this site.

The North Greenland Ice Coring Project (NGRIP) was started in 1996 but suffered a severe setback when the drill got stuck at 1370 m depth during the 1997 season. Drilling was restarted from the surface in 1999 and reached a depth of 1750 m after a record-breaking season. Assuming similar productivity next year it seems realistic to assume that bedrock will be reached at 3085 m depth during the 2000 season. The extensive field program will consist of electric conductiviy measurements (DEP and ECM), CFA studies, stratigraphic observations and thin section analysis of crystal size variation. In addition, samples will be cut for laboratory measurements of oxygen-isotope ratios and gas concentrations.

Crystal size and orientation

<u>The crystal size measurements</u> from the uppermost 1700 m reveal the same general features as observed in the GRIP core; normal grain growth down to about 700 m, stable grain size due to polygonization below that, and a decrease across the Holocene-Wisconsin transition. The limiting grain size reached at 700 m is slightly higher at NGRIP, 4.5 mm, as compared with 4.0 mm at GRIP. This is explained by the 1K higher ice temperature at NGRIP, leading to higher grain-growth rates according to a well known relation. During the 2000 season, crystal size measurements will be performed with high resolution across the Dansgaard-Oeschger events in the Wisconsin ice and in the Eemian ice. It is hoped that the results will help establish crystal size as a climate-related parameter measured on ice cores.

<u>C-axis fabrics</u>. The results obtained indicate that the fabric does not evolve towards a vertical single maximum like at GRIP, but towards a Vostok-type vertical girdle fabric; i.e. the c-axes are clustered around a vertical plane. Such fabrics are interpreted as resulting from a combination of vertical compression (which tends to rotate c-axes towards the vertical axis), horizontal tension (which rotates c-axes away from the axis of tension) and likely also

horizontal compression along an axis perpendicular to the tension axis (see Paterson,1994 - p. 196-200).

A fabric of this type has not been observed in any Greenland ice core before, and it seems important to understand its formation as this will give us significant information on the flow regime at the NGRIP site. The most likely explanation is that the axis of tension is across the ice divide, as clearly indicated by surface velocity data.

Stratigraphy

During the 1997 field season, methods for stratigraphic study were tested and carried out on selected parts of the NGRIP core. A newly designed line-scan camera was used to obtain a digital record of core transmissivity, which has been compared to visual observation of layering, crystal size and other data. During the 1999 season, the visual contrast across the Holocene-Wisconsin transition was studied, confirming earlier observations of intense *cloudy banding* in the Greenland Wisconsinan ice. These clearly visible layers are believed to result from a much higher concentration of impurities, clathrates and other inclusions in the glacial ice, and possible also from the reappearence of air bubbles due to core relaxation.

The experience gained with this work will be put to use during an intense stratigraphic study of the lower part of the core during the 2000 season. The results of this work are likely to be of prime importance for the interpretation of the climatic record extracted from the NGRIP core, since the accurate detection of first signs of stratigraphic disturbance indicates to which depth the climate record can be considered reliable.

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A new ice core from Eclipse Dome, Yukon Territory, Canada

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Introduction

A new ice core record is being developed from Eclipse Dome (60.50' N, 139 50'W, 3107 m), Saint Elias Mountains, Yukon Territory, Canada, and should provide new insights on changes in precipitation chemistry in the remote northwestern North America troposphere. Eclipse Dome, with its high accumulation rate and limited melting and windscour, represents a nearly ideal site for development of a high resolution, continuous glaciochemical record. Furthermore, there is a shortage of high resolution, multi- parameter paleoclimate records from northwestern North America. Instrumental records from this region are short, but readily available, providing the opportunity for calibration of our ice core record. This is an important region for climate change research owing to its proximity to centers of action of broad scale circulation patterns, such as the North Pacific Oscillation and Pacific- North American pattern.

Methods

A 160 m firn/ice core was recovered from Eclipse Dome in the summer of 1996. Visible stratigraphy (location and thickness of ice layers) and density measurements were made in the field, then half the core was shipped frozen to the University of New Hampshire. In addition to the core, samples from a 2.5 m snowpit and a fresh snowfall event were collected. The core was continuously sampled in 10 cm segments, generating 1600 samples. Stringent core processing techniques, similar to those used to sample the GISP2, Penny Ice Cap, and Devon Ice Cap cores were used to ensure contamination free samples. Samples were analyzed for major ions (Na^+, $NH4^+$, K^+, Mg^{++}, Ca^{++}, Cl^-, $NO3^{--}$, $SO4^{--}$) using an ion chromatograph in a dedicated laboratory at the University of New Hampshire and for oxygen isotopes at the Stable Isotopes Laboratory in Copenhagen, Denmark. A section of the core from 50m to 76 m depth was also analyzed for beta activity.

Results

Analysis of the beta activity profile and comparison with air measurements from Whitehorse, YT, shows clear identification of the 1961 and 1963 beta activity peaks from atmospheric thermonuclear weapons testing. An average annual accumulation of 1.55 m ice equivalent was determined by identification of the 1963 beta activity peak. Analysis of the snowpit samples shows a strong seasonal signal in the major ion chemistry, with distinct maxima in NH4, NO3, and dust species in summer. Seasonal oscillations in both the major ion and oxygen isotope records are preserved at depth. These oscillations have allowed detailed dating of the portion of the core for which sample analysis is complete via annual layer counting. Several volcanic signatures are apparent in the major ion record, including Redoubt, Alaska, 1989; St. Augustine, Alaska 1976; and Katmai, Alaska, 1912. Preliminary chronology based on annual layer counting and the 1963 and 1961 beta activity reference horizons suggests the age of ice at 100 m ice equivalent depth to be about 1930.

Figure One

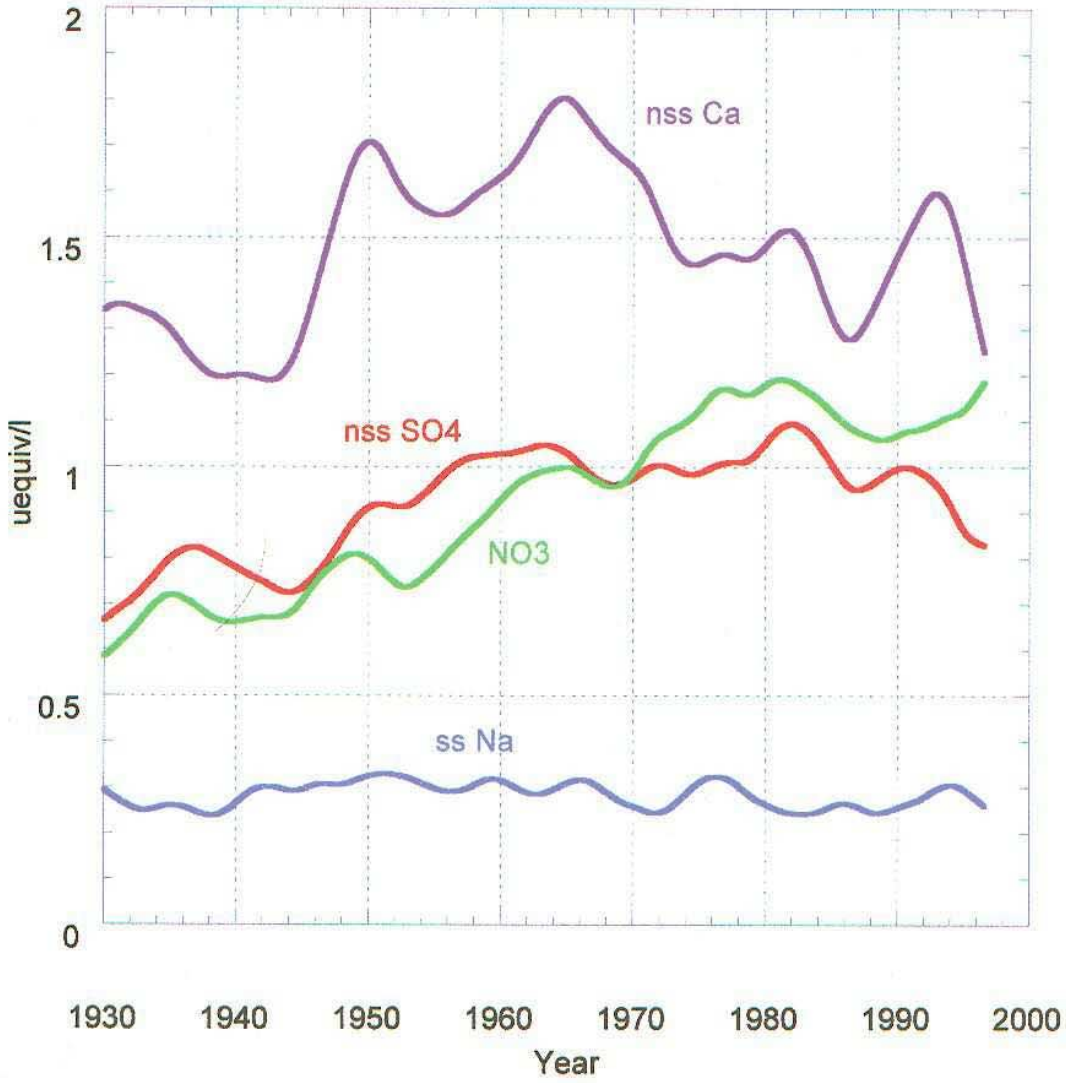
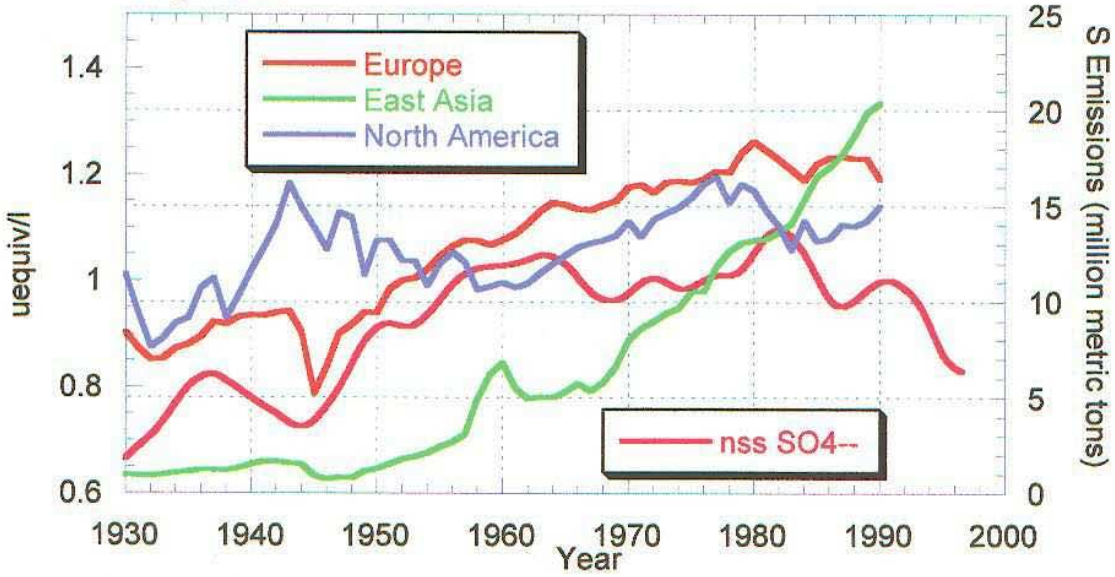


Figure 2



Discussion

Robust statistical analysis of the major ion record has identified trends in the record that can be related to changes in source strength. Robust smoothing of the nitrate and excess sulfate series, along with non-sea-salt (nss) Ca^{++} and sea-salt (ss) Na^{+}, as representative of dust and sea-salt species, respectively, removes seasonal cycles and episodic events from the record. This reveals the trends in background levels of each species (Figure 1). Background levels of ss Na^{+} have not changed appreciably over the period 1930- 1996. Background levels of nss Ca^{++} show elevated levels from 1950- 1970 but no overall trend. Levels of excess sulfate have risen from 0.65 uequiv/l in 1930 to a maximum of 1.10 uequiv/l (a 70% increase) in the mid 1980's and have since dropped to 0.85 uequiv/l. Nitrate has shown a steady increase from 0.60 uequiv/l in 1930 to 1.2 uequiv/l in 1996, a 100% increase.

The increase in background levels of sulfate could have at least two sources: fossil fuel combustion or increased in dust flux to Eclipse Dome reflecting more arid conditions in source regions, a change in circulation patterns, or enhanced transport efficiency. Since the ss Na^{+} flux has not changed appreciably, a significant change in circulation patterns or enhanced transport efficiency can be ruled out. Elevated levels of nss Ca^{++} from 1950 to 1970 indicate that at least part of the increase in excess sulfate over that period may be attributable to increased dust flux; however the remainder of the increase is likely due to anthropogenic emissions. Comparison with estimates of regional sulfur emissions (Figure 2) shows that the sulfate trend in the Eclipse Dome ice core most closely follows the pattern of European sulfur emissions. Trends in nitrate at Eclipse Dome resemble trends in anthropogenic nitrous oxide emissions. Distinct maxima in background levels of nitrate in the Eclipse Dome core may be associated with periods of thermonuclear weapons testing (Holdsworth 1986). Ice cores from the eastern Canadian Arctic (Koerner et al. 1999) and Greenland (Mayewski et al. 1993) show sulfate and nitrate increases of similar magnitude to that observed in the Eclipse Dome core. An ice core recovered from 5430 m on Mt. Logan, 45 km southwest of Eclipse Dome, showed no discernable increase in sulfate or nitrate (Mayewski et al. 1993). This may reflect the difference in elevation between the two sites, with Eclipse Dome sampling polluted mid-troposphere air while Mt. Logan samples air from the remote upper troposphere.

Conclusions

These results suggest that the chemistry of the mid -troposphere over northwestern North America has been impacted by anthropogenic activity. Major ion and oxygen isotope analysis of the remainder of the core should be completed this summer, extending this record about 40 years and allowing a more complete interpretation of these preliminary findings. Future investigations using the Eclipse Dome record will include particle analysis of selected volcanic horizons, trends and cycles in Asian dust loading, variability in the Aleutian Low and North Pacific Oscillation, and trends in trace metal deposition.

Figure Captions

Figure 1. Robust smoothing of the major ion record shows an increase in the background levels of sulfate and nitrate with no change in sea-salt sodium and elevated levels of non-sea-salt calcium confined to the period 1950-1970.

Figure 2. The increase in background levels of excess sulfate in the Eclipse Dome core most closely follows the pattern of European sulfur emissions, though inputs from North America and East Asia are possible. Sulfur emission estimates from Lefohn et al. 1999.

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Ice-Core Microparticles as Paleoenvironmental Indicators:
The Holocene Dust Record from the Penny Ice Cap, Baffin Island.

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The concentration and size distribution of dust microparticles (0.8-12 µm) were measured continuously in a 334-m long ice core drilled through the Penny ice cap on southeastern Baffin Island (67 N; 65 W). The Penny ice-core record spans the entire Holocene epoch and extends into the last glacial period.

Dust deposition on the Penny ice cap was greatest in late-glacial time when the climate was drier and windier than in the Holocene. This finding is in good agreement with results from other ice cores in the northern and southern hemispheres. Microparticles deposited on the ice cap were also finer in late-glacial time (modal diameter • 1 µm) than in the Holocene (• 2-3 µm), suggesting that late-glacial dust sources were further from the ice cap than in the Holocene. This is partly because late-glacial ice originated from the Foxe ice divide of the Laurentide Ice Sheet, ~ 2000 km west of the modern Penny ice cap summit, hence far from any ice-marginal dust sources.

Dust concentration in the Penny ice core dropped abruptly after the late glacial-Holocene transition, but increased markedly again after ca. 7800 yr ago as the Penny ice cap receded and distance from proximal dust sources was reduced. Enhanced transport and deposition of proximally-derived dust to the Penny ice cap is indicated by the transition from a unimodal microparticle size distribution (mode • 2-3 µm) in the early Holocene, to a bimodal distribution (modes at ~2.5 and 5.5 µm) after ca. 7500 yr ago. Time series of non-sea salt calcium (nss-Ca; presumbaly crustal) in the Penny ice core show no discernable trend for most of the Holocene, suggesting that the coarse dusts deposited on the Penny ice cap after ca. 7500 yr ago did not originate from Ca-rich marine sediments. Instead, the dusts may have been deflated from glacial sediments (e.g., outwash, sandurs) derived from the Precambrian substrate that underlies most of southern Baffin Island.

A comparison of Holocene dust and nss-Ca time series in the Penny and GISP2 ice cores reveals a marked divergence between the two ice-core records beginning ca. 7000 to 6000 yr ago, as dust levels in the Penny core increased while nss-Ca in the GISP2 core decreased. This divergence illustrates how the ice-core record from the small circum-Arctic ice caps became increasingly dominated by signals of regional-scale environmental changes (e.g., changes affecting local sources of airborne impurities) during the Holocene. It is the potential for documenting such regional changes through the circum-Arctic that is one of the fundamental drivers of ICAPP.

CAPE/ICAPP

Sea Ice in the Climate System
The Record of the North Atlantic Arctic

Participation List

June 2-6, 2000
Kirkjubæjarklaustur, Iceland