Arctic Science Summit Week

25 - 29 April 1999, Tromsø, Norway

Joint Science Day: Marine Climate of the Arctic

Norsk Polarinstitutt
INTERNRAPPORT
Nr. 3 - Tromsø 2000

Internrapport nr. 3

Arctic Science Summit Week
Joint Science Day

Compiled by Olav Orheim

25-29 April 1999
Tromsø, Norway

Abstracts

European Polar Board

IASC

The Norwegian Polar Institute is Norway's main institution for research and mapping in Norwegian polar regions. The Institute also advises Norwegian authorities on polar environmental management.

Norsk Polarinstitutt
2000

Addresses:

Norwegian Polar Institute
Polar Environmental Centre
N-9296 Tromsø
Norway

The International Arctic
Science Committee, IASC
P.O.Box 8100, Dep.
N-0032 Oslo
Norway

European Polar Board
European Science Foundation
1 quai Lezay-Marnésia
78080 Strasbourg Cedex
France

Technical editor:	Anne Kibsgaard/Gunn Sissel Jaklin
Layout:	Dag Rydmark
Cover photo:	Ian Gierz
Cover design:	Jan Roald
Printed:	February 2000
ISBN:	82-7666-269-6

ARCTIC SCIENCE SUMMIT WEEK

25 - 29 April 1999, Tromsø, Norway

JOINT SCIENCE DAY

MARINE CLIMATE OF THE ARCTIC

27 April 1999

Venue: Conference Hall, Polar Environmental Centre

AGENDA

Chairman: Olav Orheim, Director, Norwegian Polar Institute

09:00-09:10	**Opening** David J. Drewry, President of IASC
09:15-09:40	**Setting the Stage: The Arctic Ocean and Global Climate** Bert Bolin, past Chairman of IPCC and Vice President of IASC, Institute of Meteorology, University of Stockholm, Sweden
09:40-10:10	**The Transition of the Arctic from a Mesozoic Warm Stagnant Pool to a Late Cenozoic Ventilated Ice-Covered Deep-Sea Basin** Jørn Thiede, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
10:10-10:35	**Biogeochemical Processes and Arctic Climate** Leif G. Anderson, University of Gothenburg, Sweden, and University of Bergen, Norway
11:35-12:00	*Coffee break*
12:00-12:25	**The Role of Climate on Arctic Marine Biota** Harald Loeng, Institute of Marine Research, Bergen, Norway
12:25-12:50	**Sea Ice Variations in the Arctic During Recent Centuries** Peter Wadhams, Scott Polar Research Institute, University of Cambridge, UK

12:50-13:15	**The Recent Arctic Ocean Warming** E. Peter Jones, Bedford Institute of Oceanography, Dartmouth, Canada
13:15-14:15	*Lunch*
14:15-14:45	**The Influence of the NAO on the Nordic Seas and North Atlantic, and Some Suggestions for the Further Study of Arctic-Subarctic Exchanges** R.R. Dickson, Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, UK
14:45-15:15	**Fresh Water Balance and Arctic Ocean Stability in Changing Global Climate** Peter Schlosser, Lamont-Doherty Earth Observatory & Columbia University, USA
15:15-15:45	**Regional Climate Modelling** Erland Källén, Institute of Meteorology, University of Stockholm, Sweden and Trond Iversen, Department of Geophysics, University of Oslo, Norway
15:45-16:00	*Break*
16:00-17:00	**General Discussion**
17:00-17:45	**Special Announcements (each 10 min)** by representatives of International Permafrost Association (IPA) International Tundra Experiment (ITEX) International Union of Circumpolar Health (IUCH) Others

Members of the Scientific Steering Committee for the Joint Science Day:

Olav Orheim, Norway – Chairman

Bert Bolin, Sweden

Howard Cattle, United Kingdom

Jørn Thiede, Germany

Acknowledgements

The conference was hosted at the recently established Polar Environmental Centre, and supported by the University of Tromsø, the visitor centre Polaria, and by the Norwegian Polar Institute.

Introduction and Executive Summary

David J. Drewry — President, IASC
Olav Orheim — Conference Chairman

The Joint Science Day, with the topic "Marine Climate of the Arctic", was a central component of the first Arctic Science Summit Week held in Tromsø, 25-29 April 1999. The idea of an ASSW evolved from the perceived and growing need to coordinate the activities of several of the organisations responsible for international scientific programmes in the north. Thus at an early stage IASC invited other bodies to express interest and participate in such an enterprise combining both business meetings and an opportunity to jointly explore an important and timely scientific issue. The response to this invitation was positive and unequivocal. The annual business meetings were scheduled for IASC Council and Regional Board, the European Polar Board (EPB), and the newly-formed Forum of Arctic Research Operators (FARO). There was furthermore official representation of IASSA, IPA, IUCH, ITEX and AOSB. The meetings were preceded by a two-day workshop on "Impacts of Climate Change in the Arctic". Additional *ad hoc* meetings were arranged for attendees of other groupings.

The "Joint Science Day" was arranged to give all the participants of the various business meetings and other interested scientists the opportunity to explore a scientific topic of common interest. The theme chosen was one of increasing concern. The report from the 1995 European Networking Conference on Research in the North ("European research in the Arctic – looking ahead") identified several key marine research issues, including the importance of the Arctic Ocean processes on the living conditions in the entire north-western Eurasia. A recent study by the NSF ("Marine Science in the Arctic: a strategy") has re-enforced the growing recognition of the important role of the Arctic Ocean in global climate through its physical and biogeochemical systems, and that it is a region of documented recent change and one of high variability. The health of the Arctic marine environment is essential to the proper functioning of economically important ecosystems. Numerous questions present themselves:

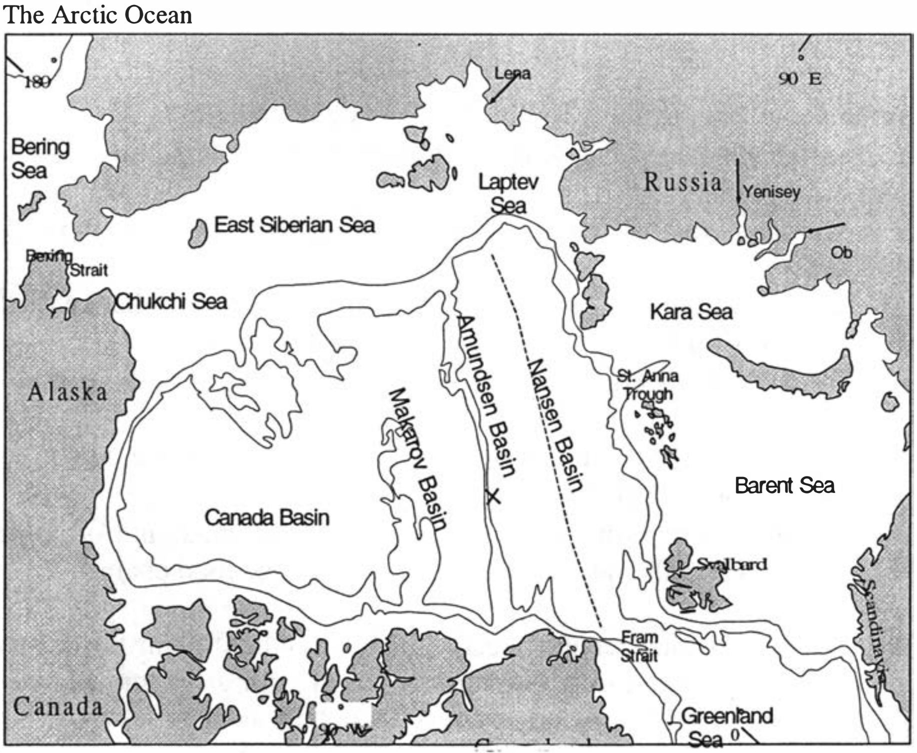
- How was the polar basin formed, where are the plate boundaries?
- What has been the detailed palaeo-climatic history of the high Arctic ocean during the last 1 million years?
- Do decreases in ice extent and upper stratification of the ocean signal a different sea ice regime?
- What is the stability of the sea ice cover, what are the effects of radiative feedback in the Arctic and how do they modulate global ocean circulation?
- What is the role of the continental shelves in the cycling of C,N,Si and other chemicals?
- What is the productivity of the Arctic ocean, and what is the structure and diversity of higher tropic levels?
- What are the effects of environmental change, both of climate and of pollutants and contaminants such as the introduction of POPs into the food chain?

The answers to such questions require clearly framed studies set in the context of national and, importantly, international programmes such as those promoted by IASC. The Joint Science Day provided an opportunity to obtain an overview of some of these key issues and methodologies currently being developed, and identified gaps in knowledge. Extended abstracts of the presentations are given in this report. Some of the actions identified for advancing marine research in the Arctic were:

- placing the Arctic ocean in the context of understanding global atmosphere-ocean variability
- acquisition of additional data, especially long-time series (e.g. sea ice thickness, a range of oceanographic observations based on the Global Ocean Observing System protocols, new biogeochemical information, synoptic studies, palaeoclimatic information on a variety of timescales)
- extending and improving models (e.g. better representation of atmosphere-ice-ocean boundary layer), linking of in-situ measurements with modeling analyses, validation of models, and data assimilation studies
- improvement to understanding contemporary processes, particularly on the continental shelves (e.g. fresh water and sediment fluxes)
- link variations in ocean climate to biological productivity and hence to renewable resource availability
- developing and applying new technologies

Effective international cooperation and access to the entire marine Arctic is essential for a healthy research environment in the Arctic. Two aspects are important: initiating coordinated programmes of observation and specified experimental research (e.g. mesoscale heat balance of the Arctic Ocean) and developing an integrated approach to an international Arctic Ocean/climate programme which will co-ordinate national activities and link to international global programmes (eg. WCRP's CLIVAR and ACSYS/CLIC programmes). These functions can be assisted through bi- and multi-lateral agreements, close logistical coordination and the sharing of research platforms and equipment. Joint bids for funding from both the public and private sectors can be made, supported by the dependence of Arctic coastal communities on the marine environment.

The Arctic Ocean



Setting the Stage: The Arctic Ocean and Global Climate

Bert Bolin
Institute of Meteorology, University of Stockholm

Climate change in the Arctic should be viewed in a global perspective and conversely, changes in the Arctic region may have important implications for the global climate. For examble, the Gulf Stream penetrates into the Northern Atlantic and contributes significantly to the heat balance of the Arctic region, and on the other hand deep water formation in the Norwegian Sea is of fundamental importance for the rate of turn over the Atlantic Ocean with implications for the oceans as a whole.

We know that the global mean surface temperature of the earth has increased by 0.6-0.8 degrees C during the last century, see Fig.1. The analysis also shows that this change is larger and has occurred more rapidly than changes associated with natural variations of the global mean temperaturw during the last millennium. The crucial question that then is being asked is, whether and to what extent this recent change may be due to human emissions of greenhouse gases. An answer is important because a significant human-induced change of climate becoming detectable now also implies that considerably larger changes may be expected in the future if human-induced emissions continue to increase at the rate previously recorded during this 20th century.

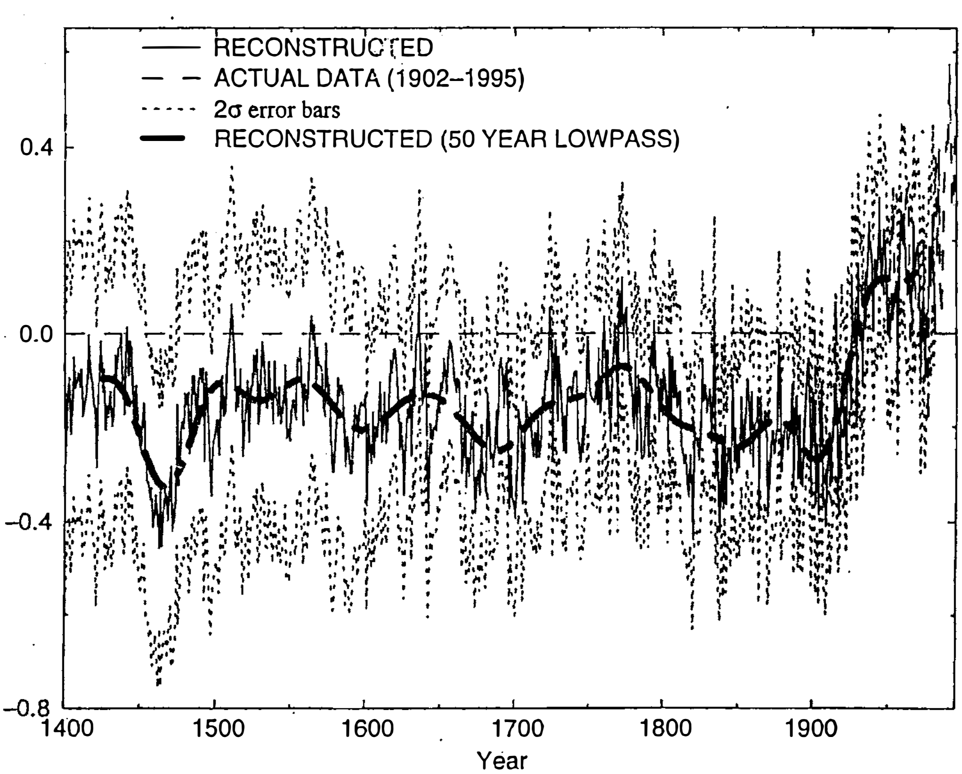


Fig. 1. Changes of the global mean temperature during the last 600 years based on palaeoclimatic data and, during the last 150 years, on an increasing number of direct observations (Mann, et al 1998).

A reasonably reliable answer to this question can only be given on the basis of experiments with climate models. We therefore need good climate models that can simulate the global climate system and its variations well, and with the aid of them attempt to distinguish between naturally occuring variations and those that are being induced by human activities, particularly emissions of greenhouse gases.

The climate system, i.e. the atmosphere, the oceans and its biota, the terrestrial systems, including soils, and the cryosphere, i.e. glaciers, ice sheets and sea ice, is a complex system. Still, the best models are able to reproduce its gross spatial features and seasonal variations fairly well based on our present understanding of key physical, chemical and biological processes that govern its dynamics and specification of the external forcing due to solar radiation. It is, however, more difficult to ascertain their capability to respond realistically to a gradually changing forcing as, for example, caused by changing atmospheric concentrations of greenhouse gases. As a matter of fact, the IPCC still in its most recent report (IPCC, 1996) gave the range between 1.5 and 4.5 degrees C as the expected increase of the mean surface temperature due to a doubling of the carbon dioxide concentration in the atmosphere and I do not see the prospects of this quite large range of uncertainty being narrowed in the near future.

We need, however, data for validation of experiments with models to test the different hypotheses that have been advanced to explain observed past changes. Ingenious methods for determining the climate in past centuries, millennia and even back through the most recent variations of climate between interglacial and glacial periods have been developed in recent years. Still, our ability to resolve the spatial characteristics of these changes decreases rapidly the further back in time we go. We therefore still have to limit ourselves to using the data from the last century or two to be able to use climate models with good resolution. This period is also the one of particular interest.

Climate variations during the last centuries to a millennium are to some extent an expression for the internal non-linear and stochastic variations of the system. In addition, however, variations of solar radiation and volcanic eruption have occurred and, we know, that they may well have had an effect.

In order to quantify their relative importance Bengtsson (1999) has recently carried out a series of model experiments in which he has successively included the variations of the external natural forcing of the system and additionally considered the forcing due to the human-induced emissions of greenhouse gases and aerosols. The transient runs show internal variations of the global mean temperature on the decadal to half century time scale before the beginning of this century that are of about the magnitude as those observed during the last millennium. The inclusion of changes of solar radiation and volcanic eruptions improves the agreement between model results and reality. It is, however, not possible to reproduce properly the global warming that has taken place during the latter part of the 20th century without also including the forcing brought about by the increase of greenhouse gases and aerosols.

Even though it thus seems likely that a human-induced climate change is ongoing, our ability to determine what will happen in the future is limited.

- We do not yet know precisely how sensitive the climate system is to human forcing. The IPCC conclusions derived already in its first assessment in 1990 and cited above still remain essentially unchanged.

- A global warming will not be equally distributed over the globe. Rather, deviations from the global mean change may be considerable and probably larger the smaller the scale of change in space or time.
- Stochastic and unpredictable variations will still occur and are also probably larger when compared with smaller spatial scale features of the change.
- The global climate system is a non-linear and to som degree non-deterministic system, or as it is commonly called, chaotic. The regular seasonal variations at middle and high latitudes are of course predictable, but for example droughts and floods of modest spatial extension may to some extent be stochastic. IPCC emphasized this feature of the climate system in its first assessment by the statement: ”You can never exclude surprises.”

There may, however, be special structures of changes of the climate system that appear as surprises but that may possibly be predicted, if we understand the inherent mechanisms. The El Niño is an interesting example. Even though we are not able to predict the timing of its occurrence well in advance, we may learn what determines the frequency of its occurrence and the changes of its strength.

The Arctic region is influenced by the ”North Atlantic Oscillation” which seems to occur on the time scale of decades. What are the mechanisms that govern its behaviour? Will we be able to predict it or perhaps its statistical characteristic? We do of course not know at present.

The climate record is characterised by sometimes rather ”abrupt” changes, where, however, the concept of abrupt may not be abrupt in a human perspective but rather imply a major change within a few decades to a century. Some of these seem to have been global, others are of a more regional nature. The most well-known one is, of course, the rapid return to a glacial climate in the North Atlantic sector during a period of 400-500 years, the so-called Younger Dryas event, about 11 000 years ago. On that occasion the Gulf Stream slowed down and rather found its way across the Atlantic at about the latitude 40°N rather than penetrating into the Norwegian Sea.

This may have been due to a freshening of the surface waters in the North Atlantic, possibly caused by a rather sudden release of large water masses from a glacial lake in eastern Canada in turn due to the gradual withdrawal of the Laurentide ice sheet.

The climate system may well have other semi-stable states than the one that the human race has experienced during Holocene, that we presently know nothing about. It is probable, however, that the further the system is ”pushed away” from its present structure that maintains an energy blance between incoming solar radiation and infrared radiation back to space, the more likely it becomes that ”surprises” might occur, not necessarily global in nature but anyhow causing major regional changes.

In the light of what I have summarized above we must not consider changes derived with the aid of transient computations using global climate as predictions of the future. They are indicative of what might happen if the concentrations of greenhouse gases in the atmosphere continue to rise, but the range of uncertainty is too large, at least beyond half a century or so into the future, to call them predictions. They should rather be viewed as scenarios that span a range of possible future courses. But it is of course important to realize that this uncertainty does not diminish the risks for a serious climate change, it simply becomes more difficult to assess its magnitude.

It should of course also be recognized that we are not able to predict the future emissions of greenhouse gases in the true sense of the word, but are again only able to present sets of scenarios. The global socio-economic system is perhaps even more chaotic than the climate system. Predictions over 50-100 years with the aid of a macro-economic model are hardly meaningful if viewed as predictions, but sets of scenarios of this kind reflect the implications of various assumptions about population increase, alternative energy supply systems, exploitation of natural resources, etc. They provide in that way an insight into the kind of issues that may arise in the future if no precautionary measures to limit the greenhouse gas emissions will be taken.

Returning finally to the analysis of climate change in the North Polar region and particularly its impact on nature as well as people, I wish to conclude by emphasizing that such analysis should be expressed in terms of risk scenarios, even though it still is difficult to assess such risks quantitatively. As our knowledge increases we should gradually be able to become more specific in this regard. These may then in turn be interpreted in terms of action priorities about protective and adaptive measures.

References

Bengtsson, L., E. Roeckner and M. Stendal, 1999: Why is the global warming proceeding much slower than expected? J. Geophys. Res. 104, D4, 3865-3876.

Mann, M., R. S. Bradley and M. K. Hughes, 1998: Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392, 23 April, 779-787.

The Transition of the Arctic from a Mesozoic Warm Stagnant Pool to a Late Cenozoic Ventilated Ice-Covered Deep-Sea Basin

Jørn Thiede
Alfred Wegener Institute for Polar and Marine Research

The Arctic Ocean and its paleoclimatic history has been the subject of intense debates about its role in the evolution and variability of Cenozoic Northern Hemisphere glaciation (Thiede et al., 1990). Major hypotheses invoked the development of the thick ice sheet covering the entire deep-sea basin during Glacials (Hughes et al., 1977) contra the existence of a more or less ice-free Glacial Arctic Ocean which could then act as a moisture source for the build-up of the ice-sheets. Because of the lack of suitable sediment cores, knowledge about the preglacial history of the Arctic Ocean and its transition into a glaciated stage did not exist; the Nansen Arctic Drilling Program (NAD Science Committee, 1992) has proposed drill sites in the central Arctic Ocean to resolve these questions, but for various reasons has been slow to execute its plans.

Evidence from the few available sediment cores from the Alpha Ridge (Clark, 1988) and from ODP drilling in the Norwegian Greenland Sea (Thiede et al., 1998) proves that the Arctic Ocean and the adjacent deep-sea basins were ice free during Mesozoic and Early Cenozoic times. The records of pelagic microfossils suggest the presence of productive, well ventilated and relatively warm, fully marine surface waters covering deeper and oxygen-deficient bottom waters; the question of the seaways connecting this early Arctic Ocean to the adjacent basins of the world ocean, their location and water depth remains unresolved. The cores from Alpha Ridge have been collected in areas where slide scars have exposed older sediment sequences, they are short and difficult to date in the required precision.

The new ODP sites from the Norwegian-Greenland Sea including the southern Fram Strait (Myhre, Thiede, Firth et al. 1995) confirm the fragmentary evidence from the central Arctic Ocean that the Palaeogene was characterized by relatively warm surface waters and oxygen-deficient bottom waters; while it remains unknown where seaways could cross the then very young and probably emergent Greenland-Scotland Ridge. Only during the Oligocene and Early Miocene did the Norwegian-Greenland Sea palaeoenvironments suggest continuous cooling until the first ice appeared. Ice-rafted terrigenous detritus (IRD) has been observed in Quaternary and Pliocene sediments of the Arctic Ocean, Norwegian-Greenland Sea and North Pacific Ocean. A substantial increase in its frequency in ocean sediments at approx. 2,7 Ma has been interpreted as marking an intensification of ice-sheet formation on the circum-Arctic continents. The interpretation of the modest microfossil records of the ODP drill sites on the Yermak Plateau and in Fram Strait suggests that the climate remained cold since then with the exception of a spell of temperate conditions during the mid-Pliocene (Spiegler, 1996). The detailed record of the ice-rafting in ODP Site 909 in the central deep Fram Strait (Thiede et al., 1998) even indicates that the first climatic events resulting in the occurrence of ice over the ocean can be dated to the Early-Middle Miocene, but the ice must have existed only intermittently and for relatively short time intervals. For the time after the Pliocene increase in ice-rafting from the Arctic Ocean cores as well as from the Norwegian-Greenland Sea suggest the evolution of a highly variable, but dominantly glacial hydrographic regime which apparently was rarely interrupted by interglacial conditions. The latter was sometimes accompanied by an extension of the Gulf Stream system which advected waters from the temperate North Atlantic into high northern latitudes and whose vestiges can sometimes be traced in the occurrences of planktonic foraminiferal faunas and coccolith floras in Arctic sediments.

Cyclic changes in the bulk density of sediments deposited during the Early Quaternary in the southern Norwegian and Greenland Seas have recently been interpreted to be related to the regular fluctuations of the obliquity of the earth´s axis in its orbit around the sun, one of the important Milankovitch frequencies whose impact on Late Cenozoic climate variability had previously been documented in ocean sediment cores from low to temperate latitudes. In the Arctic Ocean and in the Norwegian-Greenland Sea with dominantly terrigenous sediment records, these frequencies seem to be related to changes in the mode of sediment transport from the surrounding continents and henceforth to their record of glaciation. The dominance of the obliquity-signal (with approx. 41 000 y. periodicity) gave way to the eccentricity-dominated signal (with approx. 100 000 y. periodicity) shortly after the Brunhes-Matuyama magnetic boundary. Despite the regularity of palaeoceanographic changes as indicated through the emergence of the Milankovitch frequencies in Arctic sediment cores large and irregular differences have been observed in the characteristics of sequences of glacials and interglacials (Spielhagen et al. 1997), with no obvious explanation.

Lately attention is being paid to Arctic continental margin records with high sedimentation rates and their correlation to the Late Quaternary history of their continental hinterlands. The ESF-program QUEEN (Quaternary Environments of the Eurasian North) has just published the proceedings of its first workshops, with a substantial number of papers addressing issues of Arctic palaeoclimatology including synthesis of the now well-documented margins of the Weichselian ice sheet in Eurasia (Svendsen et al., 1999).

References

Clark, D. L., 1988: Early history of the Arctic Ocean. Paleoceanography 3, 539-550.

Donn, W. L. and M. Ewing, 1966: A theory of ice ages III. Science 152, 1706-1712.

Hughes, I. J., G. H. Denton and M. Grosswald, 1977: Was there a late Würm arctic ice-sheet? Nature 266, 596-602.

Myhre, A., J. Thiede, J. Firth and ODP Leg 151 Shipboard Scientific Party, 1995: Proc. ODP (Ocean Drilling Program), Init. Rep. 151, College Station.

NAD (Nansen Arctic Drilling) Science Committee, 1992: The Arctic ocean record: Key to Global Change (Initial Science Plan). Polarforschung 61/1, 1-102.

Olausson, E. and U. C. Jonasson, 1969: The Arctic Ocean during the Würm and early Flandrian. Geol. Fören. Förh. 91, 185-200.

Spiegler, D., 1996: Planktonic foraminifer Cenozoic biostratigraphy of the Arctic Ocean, Fram Strait (Sites 908-909), Yermak Plateau (sites 910-912), and East Greenland Margin (Site 913). Proc. ODP (Ocean Drilling Program), Sci. Res. 151, 391-405.

Spielhagen, R. F., G. Bonani, A. Eisenhauer, M. Frank, T. Frederichs, H. Kassens, P. W. Kubik, A. Mangini, M. Nørgård Pedersen, N. R. Nowaczyk, S. Schäper, R. Stein, J. Thiede, R. Tiedemann and M. Wahsner, 1997: Arctic Ocean evidence for late Quaternary initiation of northern Eurasian ice sheets. Geology 25, 738-786.

Svendsen, J. I., V. I. Astakhov, D. Yu. Bolshiyanov, I. Demidov, J. A. Dowdeswell, V. Gataullin, Ch. Hjort, H. W. Hubberten, E. Larsen, J. Mangerud, M. Melles, P. Möller, M. Sarnisto and M. J. Siegert, 1999: Maximum extent of the Eurasian ice sheets in the Barents and Kara Sea region during the Weichselian. Boreas 28(1), 234-242.

Thiede, J., D. L. Clark and Y. Herman, 1990: Late Mesozoic and Cenozoic paleoceanography of the northern polar oceans. In Grantz, A., L. Johnson and J. F. Sweeney (eds.): The Arctic Ocean Region: The geology of North America, Vol. L., 427-458, Boulder.

Thiede, J., A. Winkler, T. Wolf-Welling, O. Eldholm, A. Myhre, K.-H. Baumann, R. Henrich and R. Stein, 1998: Late Cenozoic history of the polar North Atlantic: Results from ocean drilling. Quat. Sci. Rev. 17, 185-208.

Biogeochemical Processes and Arctic Climate

Leif G. Anderson
Department of Analytical and Marine Chemistry
University of Gothenburg

The majority of water that enters the Arctic Ocean does so over the large shelves. The warm salty Atlantic Water that flows into the Arctic Ocean through the Barents Sea, loses heat to the atmosphere and part of it gets increased salinity from brine released during sea ice production. The resulting increase in density makes much of this water, of Atlantic origin, penetrate depth below 500 m, when it enters the central Arctic Ocean through the St. Anna Trough [e.g. Swift et al., 1983; Schauer et al., 1997]. Except for this Atlantic Water, nearly the same volume enters through Fram Strait [e.g. Rudels, 1987; Phirman et al., 1994] and follows the continental slope to the east. There has been an extensive variability in both the properties and magnitude of the inflow of Atlantic water during this century [Dickson et al., 1999].

The Pacific Water flows over the Bering Sea shelf, through the Bering Strait and over the Chukchi Sea shelf before entering the deep Arctic Basin. Within both the Bering and Chukchi Seas shelves extensive heat loss take place. This, together with substantial primary production drives an air - sea flux of carbon dioxide. At the sediment surface decay products are released to the bottom water, a bottom water that at places have had its salinity increased by brine from sea ice production.

The Arctic shelf seas also receive a lot of river runoff; the major rivers entering the Eurasian sector are the Ob, Yenisey and Lena. The latter enters the Laptev Sea, while the two others enter the Kara Sea. However, most of the runoff entering the Kara Sea flows to the east along the continent, into the Laptev Sea, before flowing into the central Arctic Ocean [e.g. Olsson and Anderson, 1997]. In the Kara Sea the runoff is mixed with water of Atlantic origin that flows east over the shelves from the Norwegian Sea to at least the Laptev Sea [e.g. Jones et al., 1998]. The runoff supplies the shelf seas with decay products from the drainage basins, including nutrients and dissolved inorganic as well as organic carbon [e.g. Cauwet and Sidorov, 1996; Anderson et al., 1990]. Furthermore, the runoff adds freshwater, with an enormous spring peak which, together with sea ice melt, maintains stratification of the surface water during the productive summer season.

Emission of anthropogenic carbon dioxide from the burning of fossil fuel and deforestation has increased the atmospheric concentration of CO_2 during the last two centuries from around 280 to 365 ppmv. The atmospheric inventory of anthropogenic carbon dioxide is only about half the emission, primarily as a result of oceanic uptake. Estimates of the oceanic sink based on both GCM models [e.g. Sarmiento et al., 1992] and field measurements [e.g. Tans et al., 1993] do not match the difference between emission and atmospheric inventories [Siegenthaler and Sarmiento, 1993]. The "missing sink" can either be terrestrial sinks or oceanic sinks not considered in earlier estimates.

Because of its ice cover the Arctic Ocean has not been considered as a sink of anthropogenic carbon dioxide. However, in a scenario with decreased ice cover as a result of global warming, it has been proposed that the annual biological pump in the Arctic Ocean might increase from ~0.1 to 1 Gt C [Walsh, 1989]. The direct uptake of atmospheric CO_2 within the Arctic Ocean in pre-industrial times has been estimated by Anderson et al. [1998a] at 0.024 Gt C yr^{-1}. By applying a plume-entrainment model, the sink of anthropogenic carbon dioxide was estimated to 0.026±0.009 Gt C yr^{-1} [Anderson et al. 1998b], of which 0.019 is attributed to the Atlantic sector and 0.007 to the Pacific sector.

The biological activity in the central Arctic Ocean is small, while the shelf seas are quite productive. The biological production in the Barents Sea is extensive with a concentration along the marginal ice zone [Sakshaug and Skjoldal, 1989]. As a result of the patchiness no estimate of the mean export production for the whole Barents Sea is available based on measurements. However, the vertical carbon flux at 75 m as simulated by a 3-D model generally varied between 10 to 30 gC m^{-2} yr^{-1} for a cold year (1981) and 20 to 40 gC m^{-2} yr^{-1} for a warm year (1984) [Slagstad and Wassman, 1996]. Olsson et al. [1998] investigated the deficit of carbon and nitrate in sections north of the Kara and Laptev and used this to estimate the export production in the Barents, Kara and Laptev Seas to 0.022±0.007 Gt C yr^{-1}. Similarly, Fransson et al. [1999] evaluated the consumption of nitrate and dissolved inorganic carbon in the Barents Sea, by comparing the concentration in the outflowing (St. Anna Trough) with that of the inflowing water (western Barents Sea continental slope). Their estimate gave a new production of 0.011 Gt C yr^{-1} and an uptake of atmospheric carbon dioxide of 0.010 Gt C yr^{-1}.

Making a similar evaluation of the shift in nutrients and dissolved inorganic carbon for the Bering Strait region is somewhat more complicated. First it is not possible to use nitrate as this is also consumed by denitrification. Second the variability in water masses is more complicated than for the Barents Sea. Anyway, if the surface water at GEOSECS station 219 in the southern Bering Sea is used as source water, together with river runoff, the new production gets 0.008 Gt C yr^{-1}, based on the consumption of phosphate. The concentration of the outflowing water is taken at the Chukchi shelf break, as observed during the Canadian – USA transpolar expedition. Comparing the shift in dissolved inorganic carbon with the consumption of that new production, demand an uptake form the atmosphere of 0.016 Gt C yr^{-1}.

For the central Arctic Ocean an estimate of the new production can be made by comparing the observed concentration of phosphate with the preformed one. This preformed concentration can be computed by taking the observed concentration at the Chukchi shelf break, at the mouth of the St. Anna Trough and that of the river runoff. The fraction of Pacific and Atlantic source waters is computed from the phosphate – nitrate relationship [Jones et al., 1998], while the fresh water contribution is computed from the salinity. The mean shift in the upper water (<100m) of the deep central Arctic Ocean corresponds to a new production of 0.002 Gt C yr^{-1}. All above carbon fluxes together with estimates from the Greenland Sea are summarized in Table 1.

Table 1. Summary of the carbon fluxes.

	Carbon flux, Gt C yr^{-1}		
	Sea - Air	New productic	Anthropogenic CO_2 (deeper than 500 m)
Pacific sector	-0.016	0.008	0.007
Atlantic sector	-0.010	0.011	0.019
Central A. O.	?	0.002	0?
Greenland Sea	-0.015[1]	0.010[1]	0.005[2]
Total	-0.041	0.035	0.031

[1] From Anderson et al. [1999b] [2] From Anderson et al. [1999a]

The sensitivity of the above fluxes to a climate change can at present only be speculated. However, we know the response to some of the forcing, like:

- Increased temperature of the inflowing water will decrease the solubility and thus the air–sea flux.
- Changes in the volume flux will affect the capability of the air – sea flux both by change in the inventory of the dissolved inorganic carbon, as well as by the supply of nutrients.
- An increased melting of sea ice during summer gives the possibility of increased primary production by increased stratification and thus light availability. On the other and this will hamper vertical mixing and thus the supply of nutrients during the productive season.
- If the summer sea ice cover decreases, the heat loss during the winter season increases and thus more brine is produced. This will increase the ventilation, resulting in increased sequestering of anthropogenic carbon dioxide.

The difficulty is to evaluate the relative importance of all these effects. This is an essential task as these feedback mechanisms are not incorporated in climate models. The variability in the inflowing water mass properties and strengths that has been observed at both connections of the Arctic Ocean with the rest of the world oceans makes the years to come an unique opportunity to study these questions with the goal of elucidating these issues.

References

Anderson, L.G., D. Dyrssen and E.P. Jones, 1990: An assessment of the transport of atmospheric CO_2 into the Arctic Ocean. J. Geophys. Res. 95, 1703-1711.

Anderson, L.G., K. Olsson and M. Chierici, 1998a: A carbon budget for the Arctic Ocean. Global Biogeochem. Cycl. 12, 455-465.

Anderson, L.G., M. Chierici, A. Fransson, K. Olsson and E.P. Jones, 1998b: Anthropogenic carbon dioxide in the Arctic Ocean - inventory and sinks. J. Geophys. Res. 103, 27,707-27,716.

Anderson, L.G., M. Chierici, E. Fogelqvist and T. Johannessen, 1999a: Flux of anthropogenic and steady state carbon into the deep Greenland Sea. J. Geophys. Res., accepted.

Anderson, L.G., H. Drange, M. Chierici, A. Fransson, T. Johannessen, I. Skjelvan and F. Rey, 1999b: Annual variability of carbon flux in the upper Greenland Sea, as evaluated from measured data and a box model. Unpubl.

Cauwet, G. and I. Sidorow, 1996: The biogeochemistry of Lena River: Organic carbon and nutrient distribution, Mar. Chem. 53, 211-227.

Fransson, A., M. Chierici, L.G. Anderson, I. Bussman, G. Kattner, E.P. Jones and J.H. Swift, 1999: The importance of shelf processes for the modification of chemical constituents in the waters of the eastern Arctic Ocean. Cont. Unpubl.

Dickson, B., L.G. Anderson, M. Bergmann, R. Colony and P. Mälkki, 1999: Arctic-subarctic linkages to form a new focus of AOSB activity. News from the Arctic Ocean Sciences Board, May.

Jones, E.P., L.G. Anderson and J.H. Swift, 1998: Distribution of Atlantic and Pacific waters in the upper Arctic Ocean: Implications for circulation. Geophys. Res. Lett. 25(6), 765-768.

Olsson, K. and L.G. Anderson, 1997: Input and biogeochemical transformation of dissolved carbon in the Siberian shelf seas. Continental Shelf Res. 17, 819-833.

Olsson, K., L.G. Anderson, M. Frank, A. Luchetta and W. Smethie, 1999: Carbon utilization in the Eurasian sector of the Arctic Ocean. Limnology and Oceanography 44(1), 95-105.

Pfirman, S.L., D. Bauch and T. Gammelsrød, 1994: The Northern Barents Sea: Water mass distribution and modification, p. 77-94. In O.M. Johannessen, R.D. Muench and J.E. Overland (eds.), The polar oceans and their role in shaping the global environment. American Geophysical Union, Washington DC.

Rudels, B., 1987: On the mass balance of the Polar Ocean with special emphasis on the Fram Strait. Nor. Polarinst, skr. 188, 1-53.

Sakshaug. E. and H.R. Skjoldal, 1989: Life at the ice edge. Ambio. 18(1), 60-67.

Sarmiento, J.L., J.C. Orr and U. Siegenthaler, 1989: A perturbation simulation of CO_2 uptake in an ocean general circulation model. J. Geophys. Res. 97, 3621-3645.

Schauer, U., R.D. Muench, B. Rudels and L. Timokhov, 1997: The impact of eastern arctic shelf water on the Nansen Basin intermediate layers. J. Geophys. Res. 102, 3371-3382.

Schlosser, P., G. Bönisch, M. Rhein and R. Bayer, 1991: Reduction of deepwater formation in the Greenland Sea during the 1980s: Evidence from tracer data. Science 251, 1054-1056.

Siegenthaler, U. and J.L., Sarmiento, 1993: Atmospheric carbon dioxide and the ocean. Nature 365, 119-125.

Slagstad, D. and P. Wassmann, 1996: Climate change and carbon flux in the Barents Sea: 3-D simulations of ice-distribution, primary production and vertical export of particulate organic carbon. Mem. Nat. Inst. Pol. Res. 51, 119-141.

Swift, J.H., T. Takahashi and H.D. Livingston, 1983: The contribution of the Greenland and Barents seas to the deep water of the Arctic Ocean. J. Geophys. Res. 88, 5981-5986.

Tans, P.P., J.A. Berry and R. Keeling, 1993: Oceanic $^{13}C/^{12}C$ observations: A new window on ocean CO_2 uptake. Global Biogeochem. Cycles 7, 353-368.

Walsh, J.J., C.P. McRoy, L.K. Coachman, J.J. Goering, J.J. Nihoul, T.E. Whitledge, T.H. Blackburn, P.L. Parker, C.D. Wirick, P.G. Shuert, J.M. Grebmeier, A.M. Springer, R.D. Tripp, D.A. Hansell, S. Djenidi, E. Deleersnijder, K. Henriksen, B.A. Lund, P. Andersen, F.E. Müller-Karger and K. Dean, 1989: Carbon and nitrogen cycling within the Bering/Chukchi seas: Source region for organic matter effecting AOU demand of the Arctic Ocean. Prog. Ocean. 22, 277-359.

The Role of Climate on Arctic Marine Biota

Harald Loeng
Institute of Marine Research, Bergen

Climate variability and change have become important issues in the Arctic region over the past few decades. They have also prevailed in the international scientific and political scene for over a decade through major programmes of scientific research, through intergovernmental assessments and through international treaties, protocols and conventions. The results of scientific research and indigenous knowledge have increasingly documented climate-related changes that are more evident in the Arctic region than in other regions of the world or are critical to our understanding of global-scale climatic processes. The effect of climate variability on the ecosystems around the Arctic is of major concern, and the present contribution focuses on variability in the marine climate and its role on Arctic marine biota illustrated by a few examples.

The thermohaline circulation dominated by the Arctic Ocean and Nordic Seas is responsible for as much as half of the Earth's poleward heat transport. Alterations of this circulation, as have been observed during climatic changes of the past, can affect global climate and in particular the climate of Europe and North America. (Broecker et al. 1985). The latest main changes seem to be these: that in the late 1980s-early 1990s, a warmer, fresher and probably stronger transport of Norwegian Atlantic Water was carried north to the Fram Strait and Barents Sea. Entering the Arctic, the Atlantic derived sublayer shoaled and warmed up to 2°C in the Eurasian Basin and extended in distribution by about 20% (Dickson 1999, Dickson et al. 1999). There are clear indications of covariance of variety of aspects of the North Atlantic Ocean and the overlying atmosphere and, perhaps crucially, suggestions of a participation of oceanic advection in that covariance in such a fashion as to have a potential for oceanic feedback to the atmosphere.

Regime shifts in the ocean will have impact on distribution of commercially important fish stocks. There are several examples of such impact, especially on species living in the marginal area where very small changes may have large influence on stocks. One example is the northward migration of cod along the west coast of Greenland during the warming from the 1920s up to the late 1930s (Jensen 1939). The warm period came to an end in the late 1960s and the subsequent period consisted of three extremely cold periods attributed to different geophysical events. The West Greenland cod stock has not produced any good year classes since the cooling (Buch et al. 1994). Another example is the Norwegian Spring Spawning Herring. During the warm period that lasted from 1920s up to mid 1960s, this herring stock had its feeding migration to Iceland. However, a marked climate shift with a decrease of about 1°C had the consequence that the herring gradually disappeared from Iceland (Vilhjalmsson 1997).

In the Barents Sea, rich year-classes of cod occur only in years with relatively high temperature on the spawning ground and the areas of their distribution during the first half-year of their lives. Feeding distribution of cod, haddock and capelin depend on the climatic conditions with more easterly and northerly distributions noted in warm years than in cold ones. The growth of fish also seems to depend on the environmental temperature, but the temperature/growth relationships are probably not simple. The climatic fluctuations also influence the plankton production and thereby the food conditions for all plankton feeders. Temperature effects linked to the variability of food may therefore be as important as the direct effect of temperature on the biological conditions of fish (Loeng 1989).

Since Arctic sub-regions can have widely differing characteristics, a comprehensive circumarctic integration of impacts will not be easy. For example, while the Bering Sea and the Barents Sea are similar in many respects, they also show pronounced differences. This is shown in table below (due to Egil Sakshaug and taken from Weller and Lange, 1999) which compares some general parameters of both regions.

PARAMETER	BARENTS SEA	BERING SEA
Water Depth	Shelf (aver. 200m)	Very shallow to deep
Horizontal Circulation	Counter clockwise	Counter clockwise
Deep Water Formation	In neighbourhood	Rarely
Ice Cover Biology		
Year to Year Variations	Extreme	Extreme
Seasonal Variations	Extreme	Extreme
Plant Nutrients	"Atlantic"	2x "Atlantic"
Primary Production	High (shelf)	High - Very high
Fisheries	Average Rich	Rich - Very rich
Ecosystem Structure	◄——— Different	———►

Sakshaug and Walsh (1998) have speculated about what might be the impacts of climate change on these two seas. Assuming that the Arctic ice cover will be reduced, the phytoplankton growth season will be lengthened. If in addition the vertical mixing and structure of the water column changes, this may result in threefold increase or more in "new" primary production. This will again influence the zooplankton production and finally the feeding conditions for fish.

References

Broecker, W. S., D. M. Peteet and D. Rind, 1985: Does the ocean-atmosphere system have more than one stable mode of operation. Nature 315(6014), 21-26.

Buch, E., S.A. Horsted. and H. Hovgard, 1994: Fluctuations in the occurrence of cod in Greenland waters and their possible causes. ICES Mar. Sci. Symp. 198,158-174.

Dickson, R.R., 1999: All change in the Arctic. Nature *397*, 389-391.

Dickson, B., L. Anderson, M. Bergmann, R. Colony and P. Mälkki, 1999: Arctic-subarctic linkages to form a new focus of AOSB activity. News from the Arctic Ocean Science Board 3(2), 1-5.

Jensen, A.D.S., 1939: Concerning a change of climate during recent decades in the Arctic and sub-arctic regions from Greenland in the west to Eurasia in the east, and contemporary biological and geophysical changes. Det Kgl. Danske Videnskapbernes Selskab. Biologiske Medd. XIV.

Loeng, H., 1989: The influence of temperature on some fish population parameters in the Barents Sea. J. Northwest. Atl. Fish. Sci. 9, 103-113.

Sakshaug, E. and J. Walsh, 1998: Biomass, productivity distribution and their variability in the Barents Sea and the Bering Sea shelf: A summary. BASIS workshop report.

Vilhjalmsson, H., 1997: Climatic variations and some examples of their effects on the marine ecology of Icelandic and Greenland waters, in particular during the present century. Rit Fiskideildar, Journal of the Marine Research Institute, Reykjavik Vol XV no 1, 9-29.

Weller, G. and M. Lange, 1999: Impacts of global climate change in the arctic regions. International Arctic Science Committee.

Sea Ice Variations in the Arctic During Recent Centuries

Peter Wadhams
Scott Polar Research Institute, University of Cambridge

Introduction

We present a survey and review of observational evidence concerning the extent and thickness of Arctic sea ice, and how it has varied during the period when it has been observed by mankind. The oldest such evidence comes from the early settlement period in Iceland in the 10th Century, and Icelandic records have been continuous since then. Sporadic records were obtained during the search for the Northwest Passage from the 16th Century onwards, followed by records from whalers in Baffin Bay and the Greenland Sea. More systematic observations from the Greenland and Barents Seas, the Russian Arctic and the Bering Sea, recorded on an institutional basis, began in the 19th Century. The quality of observations improved greatly when airborne ice reconnaissance became common from the 1950s onwards, while real global synoptic continuous data have been obtained only since the satellite era began, and most usefully since 1973 when the first passive microwave sensor went into orbit. Quantitative observations on ice thickness distribution began only in 1958 with the first nuclear submarine voyages to the Arctic. Submarine data from the US and UK have since been supplemented by moored upward sonar data, but the ice thickness dataset still remains sparse in comparison with the ice extent dataset, since no satellite technique for mapping ice thickness directly has yet been successfully developed.

Present-day variability

Sea ice extent in the Arctic varies in a typical year from 16.0 million km^2 in winter (February) to 9.0 million km^2 in summer (August). This variation is not as great as the winter-summer change of area of Northern Hemisphere snow cover (46.3 to 3.7 million km^2) which dominates snow and ice albedo-feedback effects; the climatic effects of sea ice are manifested mainly by its effects on heat and moisture fluxes and by the oceanic impact of salt fluxes from sea ice production. The winter maximum area varies greatly from year to year, both regionally due to varying cover in marginal and subarctic seas such as the Bering, Labrador, Greenland and Barents Seas, and in overall magnitude. However the summer extent appears to be more stable, and the summer minimum basically covers the deep part of the Arctic Basin only.

Sea ice extent variation in the satellite era

Hemispheric

Since the late 1960s sea ice extent in the Arctic has been mapped by satellite, initially from low-resolution visual band sensors then, since 1973, from passive microwave sensors which penetrate cloud and darkness and which give ice concentration in pixels of a few tens of km resolution. Since 1978 multifrequency passive microwave sensors (SMMR then SSM/I) have given improved coverage, and most analyses of sea ice variation have made use only of the most recent 21 years of record from these two sensors. Two independent analyses, by Bjørgo et al. (1997) and Cavalieri et al. (1997), have shown that the sea ice area and extent in the Northern Hemisphere have shown a decline since 1978 which can be fitted by a linear relationship of slope -2.9% per decade (Fig. 1). This is in contrast to Antarctic sea ice, which has remained basically stable (Bjørgo et al.) or shown a barely significant growth of 1.6 % per decade (Cavalieri et al. 1997).

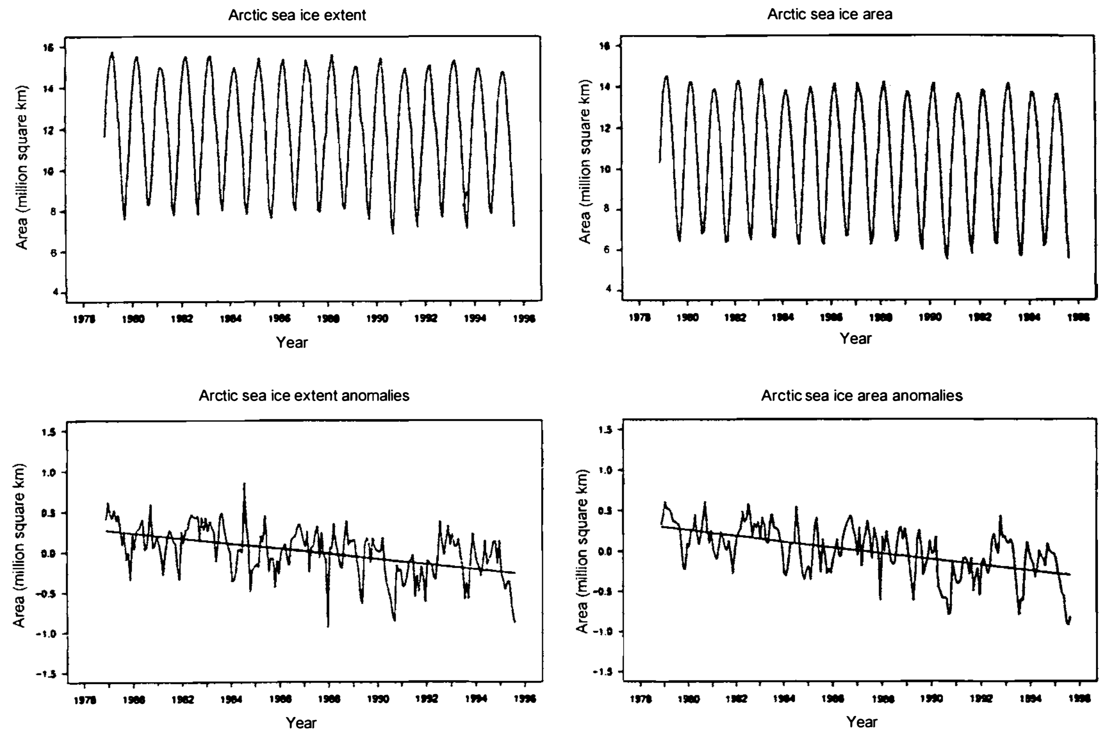


Fig. 1
Monthly averages (top) and anomalies (bottom) of Arctic ice extent and ice area, November 1978 – August 1995. Linear regressions from least squares fitting are shown (after Bjørgo et al., 1997).

Regional

The steady hemispheric decline masks more violent regional changes. In the Bering Sea there was a sudden downward shift of sea ice area in 1976 (Niebauer, 1998), indicating a regime shift in the wind stress field as the Aleutian Low moved its position. In the Arctic Basin a passive microwave analysis (Parkinson, 1992) of the length of the ice-covered season during 1979-1986 showed a see-saw effect, with amelioration in the Russian Arctic, Greenland, Barents and Okhotsk Seas and a worsening in the Labrador Sea, Hudson Bay and Beaufort Sea. Many other passive microwave studies show large regional trends and cycles which, when combined together, give the slow declining trend seen hemispherically.

Sea ice thickness variation in recent decades

Basinwide sea ice thickness data adequate to test whether Arctic ice thickness is changing are scarce. Wadhams (1990) was able to compare datasets obtained from two submarine cruises in the Greenland Sea and Eurasian Basin, in 1976 and 1987, finding a 15% decrease in mean ice thickness between the two (Fig. 2). Later data from the same area in 1996 (in preparation) confirm a continuing downward trend. Yearly datasets from UK cruises from 1988 to 1994 have now been made available, which when analysed will improve the resolution of trends or cycles in mean thickness over this region of the Arctic. For trends in the Canada Basin we must await publication of thickness data obtained from the annual US SCICEX cruises from 1993 onwards. Wadhams (1997) has also found, by examining the varying nature of the ice thickness distribution in a profile running from the North Pole to the Greenland Sea, that the development of the distribution can be best fitted by a melt process which is thickness-dependent (ridges decay faster than level ice) and which begins at the Pole itself rather than just north of Fram Strait as was previously assumed to be the case.

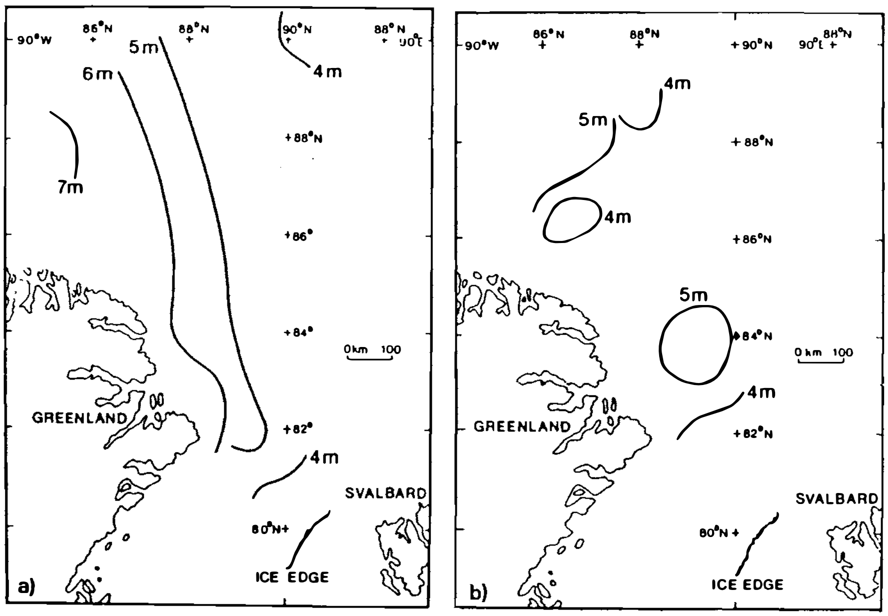


Fig. 2
Contours of mean sea ice draft in the Eurasian Basin from October 1976 and May 1987 (after Wadhams, 1990).

Sea ice flux variability

The most critical passage for mapping fluxes is Fram Strait, since this transports most of the ice exported from the Arctic Basin. A line of moored upward sonars has been in place across the Strait since 1990, and when combined with satellite data on velocities this has enabled flux variability to be measured. Studies by Vinje et al. (1998) and Kwok and Rothrock (1999) show mean values of some 2000 km^3 a^{-1} but with large interannual variabilities and a peak in 1994-5. The annual maximum usually occurs in December. There is a positive correlation with the NAO index, since the anomaly associated with a positive index tends to drive more ice through the Strait.

The 19th Century - Danish and Norwegian records

When we seek evidence from the period before satellite or aircraft observations yet after the beginning of systematic worldwide meteorological observations (i.e. about 1860-1950) the best institutional sources are Danish and Norwegian records. The Danish Meteorological Institute (DMI) was founded in 1872 and began the systematic collection of sea-ice information in 1885, from the captains of ships sailing to Greenland. From these reports monthly ice charts were issued covering the sailing season (May-October). Information was also sought from other nations, especially Norwegian sealers, and from 1895 ice charts were published covering the whole of the Nordic Seas. An early compilation of ice variability data was a book by Carl H. Ryder (1896), on ice conditions during 1877-1892. DMI became the agreed international centre for sea ice information in 1899, and still continues to publish regular ice charts. From 1959, when the passenger ship "Hans Hedtoft" disappeared off Cape Farewell, ice reconnaissance flights in Greenlandic waters were used to supplement other sources of information.

The Norwegian Meteorological Institute was established in 1866, setting up meteorological stations in Svalbard (1912), Bear Island (1920), Jan Mayen (1921) and Hopen (1945). The Institute collected sea ice information from Norwegian whalers and sealers, and data on early years was assembled by Otto Sverdrup and A. Hermansen, but not published. Recently G. Kjaernli and T. Vinje of Norsk Polarinstitutt have systematically compiled this early information into a digital dataset as an ACSYS project, and it will shortly be published. Fig. 3 shows an especially interesting case from the 19th Century, the extraordinary year of 1881 when the ice in the Nordic Seas advanced further towards the European coast than in any other recorded instance. Icebergs were sighted off South and North Norway during this winter.

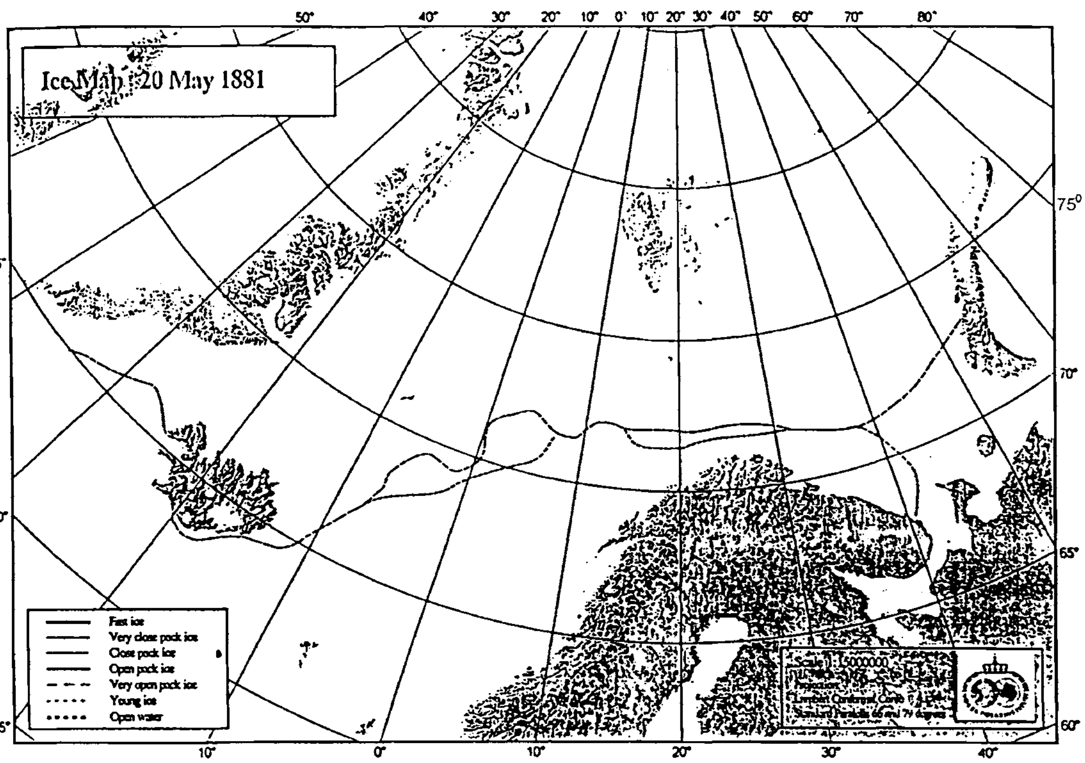


Fig. 3
The extreme ice limits reached in the Nordic Seas on 20 May 1881 (after Vinje et al., 1996).

The Icelandic sea ice record

Iceland has been settled for more than 1100 years, and information on sea ice conditions around the island can be obtained over most of that period, from parish records and, in early times, from the sagas. In recent times (since 1970) the occurrence of ice upon the coasts of Iceland in winter has been a rarity, and it is clear that ice upon the coast represents an extremum of the sea ice variability in the Greenland Sea. It is therefore unclear what general implications, if any, can be drawn from a single ice year.The general trend, however, should show some correspondence to the trend of ice severity in the European sector of the Arctic as a whole. A compilation of Icelandic data since 1600 has been carried out by Astrid Ogilvie, with a more intensive study of the period since 1850 by Ingibjorg Jonsdottir. Their joint curve (provisional) is shown in fig. 4, where the coastal region of Iceland is divided into four sectors, with four possible seasons for ice occurrence and a 5-year sampling time. Thus a "score" of 80 represents year-round ice engulfing Iceland. The apparent amelioration before 1800 may be due to greater scarcity of records before that time, so only the last two centuries should be regarded as fully compatible. The steady amelioration during the last half of the 19th and first half of the 20th centuries is very clear, as is the short-lived return of heavy ice conditions in the late 1960s, corresponding to the large pulse of ice into the Greenland Sea that created the "great salinity anomaly".

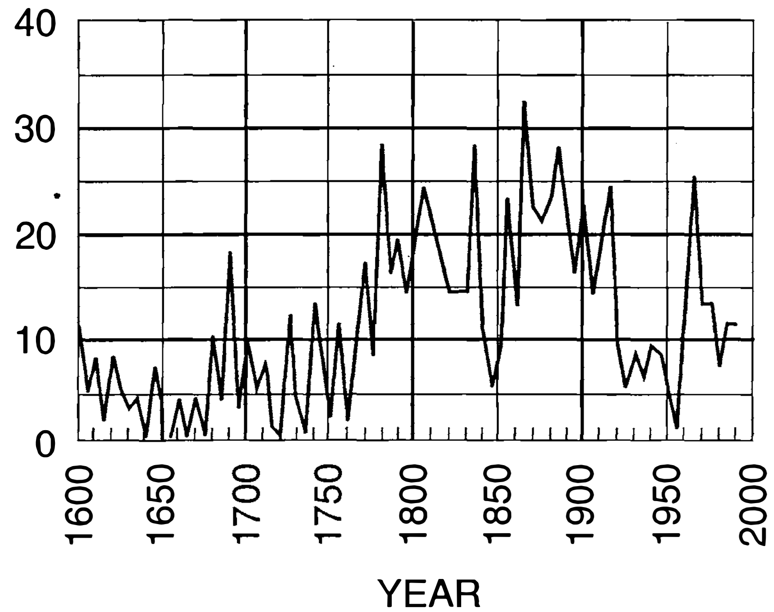


Fig. 4
Ice severity around Icelandic coasts, 1600 - present. Five-year summations of ice occurrence in four offshore sectors over four seasons per year (maximum score 80). Compiled by A. Ogilvie and I. Jonsdottir (personal commun., 1999).

It is clear that there should be a close negative correlation between average air temperature and sea ice severity in Iceland - not because cold temperatures cause ice, but because the winter air temperature is strongly dependent on whether or not sea ice surrounds the island. A bold attenpt to correlate these quantities was made by Bergthorsson (1969), who found a relationship between temperature and sea ice severity extending back to the start of good temperature measurements (1846), and then for earlier periods used a sea ice severity index which he had compiled back to 900AD to derive air temperatures back to the same date. This is a rare attempt to derive climate from sea ice extent rather than vice versa. In general terms the results showed the mild climatic optimum period of 1050-1200 and more severe conditions from 1300 to 1800.

The Storis

The Storis is the Danish name given to polar ice which is exported from the Arctic Basin. In particular, it refers to polar ice which is advected around Cape Farewell and up the west coast of Greenland - another extremum of the Greenland Sea ice distribution. Fabricius et al. (1999) collected and analysed data back to 1820 on the latitude reached by the Storis up the west coast, benefiting from local records kept in Greenlandic settlements. The data agreed with Icelandic datasets in showing moderatly heavy ice conditions in 1820-1880, a peak in the early 1880s, then a decline until about 1950 since when they have been fairly stable except for the 1969 peak. Autocorrelation analysis showed a strong negative correlation at one year lag, implying that a bad ice year on the west coast tended to be followed by a good one.

Future needs in ice mapping

The main need in ice mapping is to develop a satellite-based remote sensing technique which will enable ice thickness to be mapped synoptically. When combined with ice velocities which can already be mapped from satellites, it will then be possible to map ice fluxes throughout the Arctic Basin. I anticipate that a combination of existing sensor data (passive and active microwave) interpreted in new ways, and new sensors such a radar and laser altimeters, will provide a way forward towards this goal.

It is also vital that all possible submarine sonar datasets, extending back to the earliest cruises, be processed and analyses published, and that ice thickness data collection from submarines be continued.

References

Bergthorsson, P., 1969: An estimate of drift ice and temperature in Iceland in 1000 years. Jokull 19, 94-101.

Bjørgo, E., O.M. Johannessen and M.W. Miles, 1997: Analysis of merged SMMR-SSM/I time series of Arctic and Antarctic sea ice parameters. Geophys. Res. Letters 24, 413-416.

Cavalieri, D.J., P. Gloersen, C.L. Parkinson, J.C. Comiso and H.J. Zwally, 1997: Observed hemispheric asymmetry in global sea ice changes. Science 278, 1104-1108.

Fabricius, J.S., K. Frydendahl and P. Frich, 1999: Polar sea ice off West Greenland - a review. Proc. ASME, in press.

Kwok, R. and D.A. Rothrock , 1999: Variability of Fram Strait ice flux and North Atlantic Oscillation. J. Geophys. Res. 104(C3), 5177-5189.

Niebauer, H.J., 1998: Variability in Bering Sea ice cover as affected by a regime shift in the North Pacific in the period 1947-1996. J. Geophys. Res. 103(C12), 27717-27737.

Parkinson, C.L., 1992: Spatial patterns of increases and decreases in the length of the sea ice season in the north polar region 1979-1986. J. Geophys. Res. 97, 14377-14388.

Ryder, C., 1896: Isforholdene i Nordhavet 1877-92. Copenhagen.

Vinje, T., M. Nyborg and G. Kjaernli, 1996: Sea-ice variations in the Greenland Sea during the Nineteenth Century. European Subpolar Ocean Programme (ESOP): Sea-ice - Ocean Interactions. Tech. Rep., Scott Polar Res. Inst., Cambridge 1, 101-104.

Vinje, T., N. Norland and Å. Kvambekk, 1998: Monitoring ice thickness in Fram Strait. J. Geophys. Res. 103, 10437-10449.

Wadhams, P., 1990: Evidence for thinning of the arctic ice cover north of Greenland. Nature 345, 795-797.

Wadhams, P., 1997: Ice thickness in the Arctic Ocean: the statistical reliability of experimental data. J. Geophys. Res. 102, 27951-27959.

The Recent Arctic Ocean Warming

E. Peter Jones
Bedford Institute of Oceanography
Dartmouth, Nova Scotia

Previous to the last decade or two, the concept of the Arctic Ocean was of a quiet, steady-state ocean not interacting much with the global ocean. With the much more extensive coverage gained through the use of icebreakers and submarines, we have obtained a very different picture. We now know that significant changes in the Arctic Ocean are occurring, and if the trend continues, we will face major environmental issues. Changes include warming of the Atlantic layer, and a retreat of the cold halocline. These raise a concern regarding heat transport to surface layer and the possible diminution of ice cover. There has also been a major shift in the boundary between Atlantic and Pacific waters in the surface Polar Mixed Layer and halocline waters. The new observations, together with evidence of changing circulation patterns in the near surface waters, show that the Arctic Ocean is not a quiescent environment remaining in a quasi steady-state, but exhibits as large a variability as other regions of the ocean. Questions relevant to warming in the Arctic Ocean include where, when, and how much. Also to be answered are what will be the consequences of warming for the surface, i.e. ice melt and interactions with the atmosphere, and whether the observed changes are cyclic or part of a trend.

Warm water from the Atlantic produces a relatively warm layer, the Atlantic Layer that extends throughout the Arctic Ocean. This layer is formed mostly from Atlantic water flowing into the Arctic through Fram Strait, the Fram Strait branch (Rudels et al., 1994), and most of the heat transported into the Arctic Ocean enters via the Fram Strait branch. The recently observed warming is most evident in the Atlantic Layer. An approximately equal amount of Atlantic water also flows into the Arctic Ocean via the Barents Sea, the Barents Sea branch. Near-surface, relatively less dense Atlantic water entering the Barents Sea has its density range expanded by cooling and salt rejection as ice forms. The upper layer in the northern Barents Sea in winter is too saline to supply the winter mixed layer of the Arctic Ocean. The part that flows north enters the thermocline or the Atlantic Layer core, with some of the most dense water going deeper, below the warmer Atlantic Layer. Some dense slope plumes, mostly going through the St. Anna Trough, sink to the deepest regions, entraining surrounding water as they descend. The Barents Sea seems to be the source of much of the water flowing into the Canadian Basin and forming the Arctic Ocean deep water.

The warm surface water flowing in through Fram Strait encounters ice, which cools and freshens it. This modified Atlantic water forms the embryonic halocline (Rudels et al., 1996). Later additions of fresh water from rivers and from the Bering Sea modify and complete the formation of halocline waters.

In 1990, Quadfasel et al. (1991) observed temperatures in the Atlantic layer in the Eurasian Basin that were about 1 degree warmer than those reported earlier (2.8 c.f. 1.7 and 1.8). Warmer temperatures appeared sometime after 1987. In 1993, Carmack et al. (1995) found warm Atlantic water (1.4 degrees c.f. 0.5 - 0.75) in the Canadian Basin over the Mendeleyev Ridge, far past the historical boundary of warmer part of the Atlantic Layer near the Lomonosov Ridge. A comparison of data at the North Pole in 1979 (Moore et al., 1983), in 1991 (Anderson et al., 1994), and in 1994 (Carmack et al., 1997) show warming has occurred at the North Pole, where the temperature maximum was historically near 0.8°. There, the Atlantic Layer has become warmer and thicker, moving higher in the water column. By contrast, in the Canada Basin north of Alaska, the temperature, salinity and density were almost identical in 1985 and 1997, and are consistent with what we think was true in the past. The type of change observed elsewhere had not occurred in this part of the Canada Basin.

Warming in the Atlantic Layer can be related to warming in West Spitsbergen current at South Cape (Swift et al., 1997). Using transit times of the Atlantic Layer water from the Norwegian Sea, they observed that the warmest water over the Eurasian slope coincides with the highest South Cape temperatures in the entire 16-year record. Similarly, the coldest temperatures coincide with the coldest South Cape temperatures. The warming is a result of warming of the source waters in the Norwegian Sea. If the source water variability is in fact largely caused by variability in the winter cooling in the Norwegian Sea, one would expect the source temperature to correlate with the North Atlantic Oscillation, since positive NAO anomalies are associated with warm winters in the region (Hurrell, 1995).

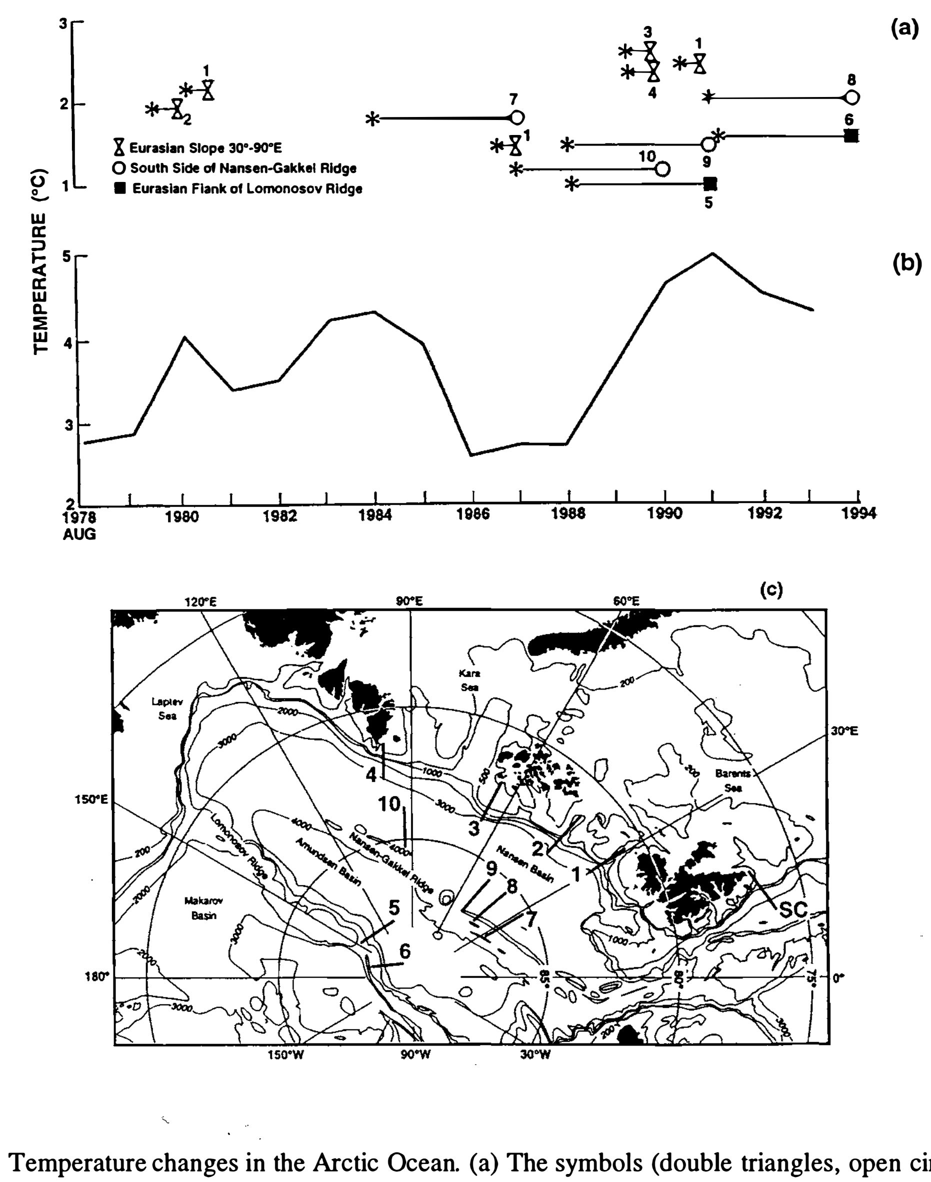


Fig. 1 Temperature changes in the Arctic Ocean. (a) The symbols (double triangles, open circles, filled squares) indicate temperatures in regions of the Arctic Ocean at times on the x-axis in (b). The asterisks indicate the estimated time when the water at a particular location was in the West Spitsbergen Current. (b) The temperature in the West Spitsbergen Current at the times indicated on the x-axis (after Blindheim and Svendsen, 1994). (c) The numbers associated with each symbol refer to the location of the observations within the Arctic Ocean. See Swift et al., 1997, for a detailed discussion.

In addition to warming, two major changes have occurred in Arctic Ocean waters. There has been a reduction of the halocline (Steele and Boyd, 1998), and there has been a shift in the boundary between waters of Atlantic and of Pacific origin (McLaughlin et al., 1996). The halocline is a barrier to heat transport from the relatively warm Atlantic Layer to the surface, where the ice is. If the halocline is removed, or much diminished, there is more than enough heat to melt all of the Arctic Ocean ice. Observations in the Eurasian Basin show an increase in near-surface salinity, with the halocline deepening and disappearing. The barrier depends, initially at least, on where fresh water from rivers goes. More saline near surface water suggests that there has been a change in where the river runoff flows as it enters the Arctic Ocean.

Most halocline water in the Eurasian Basin is of Atlantic origin, though historically (Gorshkov Atlas) and up to two decades ago, there was a strong signal of Pacific water in the halocline of the Canadian Basin extended to the North Pole. McLaughlin et al. (1996) noted that the halocline waters of Pacific origin were no longer where they were previously reported. The demarcation between Atlantic and Pacific water in the halocline had shifted from near the Lomonosov Ridge to near the Alpha-Mendeleyev Ridge. Changes in water mass characteristics and structure of the upper layer nature of Pacific water north of Ellesmere Island have recently been reported by Newton and Soritin (1997). The changes could be explained by an increase in the transport of surface and upper halocline waters from the Canadian basin into the Eurasian Basin along the continental slope.

The recently observed warming and changes in water mass characteristics seem to have begun about 1990 in both the Eurasian and Canadian basins (Quadfasel et al., 1991; Swift et al., 1997; Newton and Soritin, 1997). A temperature maximum north of Ellesmere Island in 1991 was not observed in 1986 (Jones and Anderson, 1990). Annual plots of sea ice drift suggest a major change in atmospheric forcing occurred in 1989.

Whether the observed changes are due to a large, but normal fluctuation, or are part of a trend is not yet known. Higher temperatures in the Atlantic Layer or Norwegian Sea would not, by themselves, lead to a shift in the boundary between the Atlantic and Pacific domains nor to the changes in the halocline. Most striking, the Polar Mixed Layer in the interior of the Eurasian Basin is more saline than historical data (34.3 c.f. 32.7 or 33.2), and it is deeper, 140m c.f. 50 m, and reaches down to the thermocline at the top of the Atlantic Layer. In the near surface water in the Eurasian and Makarov basins, there is less fresh water. Because it doesn't seem that the melting of sea ice has changed greatly in the last decade, this points to the river runoff being redistributed and/or decreased.

How many of the observed changes can be attributed to changes in the atmospheric circulation is still an open question. Recent wind fields could also drive much of the runoff from the Ob, Yenisey and Lena eastward from the Laptev Sea. When the anticyclonic atmospheric circulation is strong, it brings Pacific water from the shelf and slope into the Beaufort gyre and also helps it to extend far into the Canadian Basin. When it is weaker, as it has been in recent years, Pacific water becomes more confined to the area close to the North American continent and would allow the Atlantic water to reach far into the Arctic. Changes in atmospheric circulation can be correlated to changes in the characteristics of the Arctic Ocean. But that may not be the whole answer.

References

Anderson, L.G., G. Björk, O. Holby, E.P. Jones, G. Kattner, K.P. Koltermann, B. Liljeblad, R. Lindegren, B. Rudels and J. Swift, 1994: Water masses and circulation in the Eurasian Basin: Results from the Oden 1991 Expedition. J. Geophys. Res. 99, 3273-3283.

Carmack, E.C., R.W. Macdonald, R.G. Perkin, F.A. McLaughlin and R.J. Pearson, 1995: Evidence for warming of Atlantic water in the Southern Canadian Basin of the Arctic Ocean. Geophys. Res. Lett. 99, 1107-1126.

Carmack, E.C., K. Aagaard, J.H. Swift, R.W. Macdonald, F.A. McLaughlin, E.P. Jones, R.G. Perkin, J.H. Smith, K.M. Ellis and L.R. Killius, 1997: Changes in temperature and tracer distributions within the Arctic Ocean: Results from the 1994 Arctic Ocean section. Deep-Sea Res. 44, 1487-1502.

Gorshkov, S.G., 1983: World Ocean Atlas, Vol. 3, Arctic Ocean. Pergamon, New York, 189 pp.

Hurrell, J.W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, Science 269, 676-679.

Jones, E.P. and L.G. Anderson, 1990: On the origin of the properties of the Arctic Ocean halocline north of Ellesmere Island: Result from the Canadian Ice Island. Cont. Shelf Res. 10, 485-498.

McLaughlin, F.A., E.C. Carmack, R.W. Macdonald and J.K.B. Bishop, 1996: Physical and geochemical properties across the Atlantic/Pacific water mass front in the southern Canadian Basin. J. Geophys. Res. 101, 1183-1197.

Moore, R.M., M.G. Lowings and F.C. Tan, 1983: Geochemical profiles in the central Arctic Ocean: their relation to freezing and shallow circulation. J. Geophys. Res. 88, 2667-26741.

Newton, J.L. and B.J. Soritin, 1997: Boundary undercurrent and water mass changes in the Lincoln Sea. J. Geophys. Res. 102, 3393-3403.

Quadfasel, D., A. Sy, D. Wells and A. Tunik,1991: Warming in the Arctic. Nature 350, 385.

Rudels, B., E.P. Jones, L.G. Anderson and G. Kattner, 1994: On the intermediate depth waters of the Arctic Ocean, in the polar oceans and their role in shaping the global environment, Geophys. Monogr. Ser. Vol. 85, Johanssen, O.M., R.D. Muench, and J.E. Overland (eds.) pp. 33-46, AGU, Washington D.C.

Rudels, B., E. P. Jones and L.G. Anderson, 1996: Formation and evolution of the surface mixed layer and halocline of the Arctic Ocean, J. Geophys. Res. 101, 8807-8821.

Steele, M. and T. Boyd, 1998: Retreat of the cold halocline layer in the Arctic Ocean, J. Geophys. Res. 103, 10,419-10,435.

Swift, J.H., E.P. Jones, K. Aagaard, E.C. Carmack, M. Hingston, R.W. Macdonald, F.A. McLaughlin and R.G. Perkin, 1997: Waters of the Makarov and Canada basins, Deep-Sea Res. 44, 1503-1529.

The Influence of the NAO on the Nordic Seas and North Atlantic, and Some Suggestions for the Further Study of Arctic-Subarctic Exchanges

R.R. Dickson,
CEFAS, Lowestoft

The NAO and its recent extreme variability

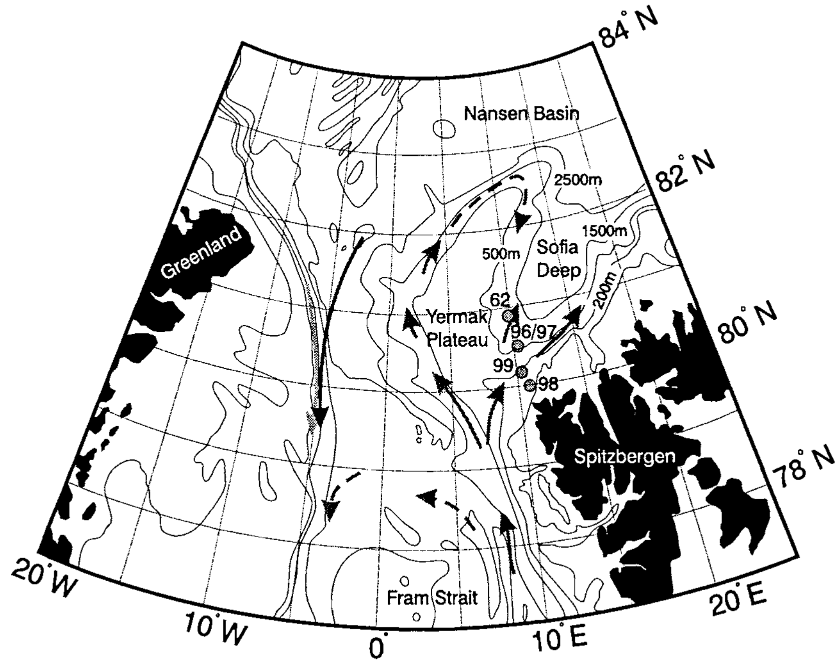
The North Atlantic Oscillation is the dominant recurrent mode of atmospheric behaviour in the North Atlantic Sector and one of the most robust on Earth. Over the period of the instrumental record, (since 1865), the NAO has exhibited considerable long-term variability which appears to be amplifying with time. Thus the 1960s exhibited the most extreme and protracted negative phase of the NAO Index and the late 1980s/early 1990s experienced its most prolonged and extreme positive phase. This talk examines aspects of the Ocean's response, particularly those which appear to have the potential to modulate or control one or other of the processes important to "global change". These differ from one sea-area to another. In the North Atlantic, the issue is whether NAO-induced decadal changes in mode-water formation and in the strength of the main Atlantic gyre circulation are merely the response of a passive ocean to a decadally-evolving atmosphere, or whether and how the ocean might feed back to encourage long-period change in the NAO itself. Further north, the issue concerns the freshening of the Nordic Seas and effects on the thermohaline circulation, as an amplifying NAO increased the winter storm activity and precipitation there brought a decrease in the extent of marginal sea-ice and drove an increased efflux of Arctic ice south through Fram Strait. The increasingly-anomalous southerly airflow that accompanied the amplifying NAO over Nordic Seas is also held responsible for a progressive warming (and freshening) in the two streams of Atlantic water that enter the Arctic Ocean across the Barents Sea shelf and along the Arctic Slope west of Svalbard. Thus the issue in the Arctic Ocean is the warming and spreading of the Atlantic-derived sublayer in the Eurasian Basin, together with the recent dwindling of the cold halocline layer which separates these relatively warm near-surface layers from the Arctic ice.

Priority Requirements for Data

These separate, large scale effects of a single change in the NAO are all of "potential" importance at present, requiring further fieldwork before any actual link to global change can be established. Key elements of the required field programme are suggested to be those which quantify the fluxes of heat and salt, ice and freshwater between the Arctic and lower latitudes, specifically:

Improved estimates of heat and salt fluxes to the Arctic
(a) via Fram Strait

The first perceived gap is that we still need to quantify the heat input contributed by the western (warmer, more saline) branch of Atlantic inflow to the Arctic. The EC-VEINS investigation of the Fram Strait throughflow has been very successful, but needs supplementary measurements if we are to identify that part of the flow which will enter the Arctic Ocean from that which will recirculate southwards without ever entering the Arctic. Figure 1, based on hydrography by F/S Polarstern in summer 1997, (Dr R. Meyers, A-W-I, Bremerhaven, pers comm.) shows the location of a suggested moored array site running northwards across the Slope from the NW tip of Spitsbergen.



Circulation of the Atlantic Water Layer in the Fram Strait.
Numbered dots refer to stations worked by F/S Polarstern - summer 1997
[R.Meyer A-W-I, pers.comm.,1999]

Atlantic Water
upper Canada Basin Intermediate Water
upper Eurasian Basin Intermediate Water

Fig. 1
Circulation of the Atlantic water layer in Fram Strait, kindly supplied by Dr. R. Meyer, Alfred-Wegener-Institute, Bremerhaven. Numbered dots mark the position of hydrographic stations worked by F/S Polarstern in summer 1997, and mark the location of the moored instrument array that is proposed to monitor the inflow of Atlantic water from the eastern Fram Strait to the Arctic Ocean.

This array would cross the warm, saline Atlantic inflow at the earliest point after it has actually entered the Arctic Ocean, where the ice cover is likely to be less problematic than further east and where the warm, saline current core is still well confined against the upper Slope so that the flow can be monitored with a limited array of bottom-mounted gear (well protected against shellfishing activities!). A long term sealevel station nearby at Barentsburg is available to help with the transport estimate.

(b) via the Barents Sea
The present successful EC-VEINS effort to monitor the colder, fresher (Barents Sea) branch of inflow to the Arctic is focused on a moored current meter array across the western entrance to the Barents Sea, but as with the Fram Strait array, our knowledge of heat input to the Arctic from this source is likely to be compromised by an unknown component of westward recirculation. A Norwegian/Russian team has already shown that it is possible to monitor this branch close to its point of entry to the Arctic Ocean (St. Anna's Trough) in their successful recovery of a pioneering long-term current meter array from waters between Franz Josef Land and Novaya Zemlya; the location of the inflow core was clearly demonstrated in the strong, steady flows towards the south side of this passage. Thus the array itself is practicable in technique, location and physical access.

(c) via the Bering Strait
Inflow from the Pacific is a critically important source of low-salinity water and nutrients to the Arctic system. The former is a major component of the Arctic's freshwater budget and halocline, while the latter is key to supporting carbon fixation, particularly on adjacent shelf regions. Modelling efforts suggest that variability in the

flow through Bering Strait reflects fluctuations in the balance between the hydraulic head (northward) and an opposing wind stress. Monitoring such flows has been an ongoing effort of oceanographers at the University of Washington since the 1960's, and in recent years this effort has been joined by oceanographers from Canada's Department of Fisheries and Oceans. Recent observations show a remarkable freshening of the Pacific's inflow, a full unit (psu) in salinity during the present decade.

Improved measurement of the freshwater flux from the Arctic

Achieving a better measure of freshwater flux from the Arctic is one of the targets of EC-VEINS and is being achieved by an Icelandic team using repeat hydrography and new current measurements east of Iceland. However, the important component of freshwater flux under the East Greenland ice-pack has proved elusive and this may be the major component of southward flux. The need to provide a good measure of this flux is underlined by the global importance that coupled models currently assign to relatively minor changes in freshwater distribution at high latitudes. Figure 2 shows the component parts of a new array designed to provide such a measure under the ice of the SE Greenland shelf. Basing the sensor deployment on summer and winter salinity transects during the IGY, the suggestion is that this could be achieved using two moorings each equipped with multiple salinity sensors focussed on the freshest layers of the upper water-column and with current meters of one type or another to provide the necessary detail on the vertical current structure. Development work would largely consist of attempts to design an ice-proof instrument and buoyancy shell so that impact with pack ice would temporarily deflect rather than destroy the moorings. Since recent transects and moored arrays in Barrow Strait (Canada/US JOIS cruise, 1997) have successfully shown the way in measuring the freshwater flux through the Canadian Arctic Archipelago, it makes good sense to make coordinated measurements of both these components of the freshwater flux at the same time, particularly since the most advanced Arctic ocean models now anticipate that their time-dependence may be linked.

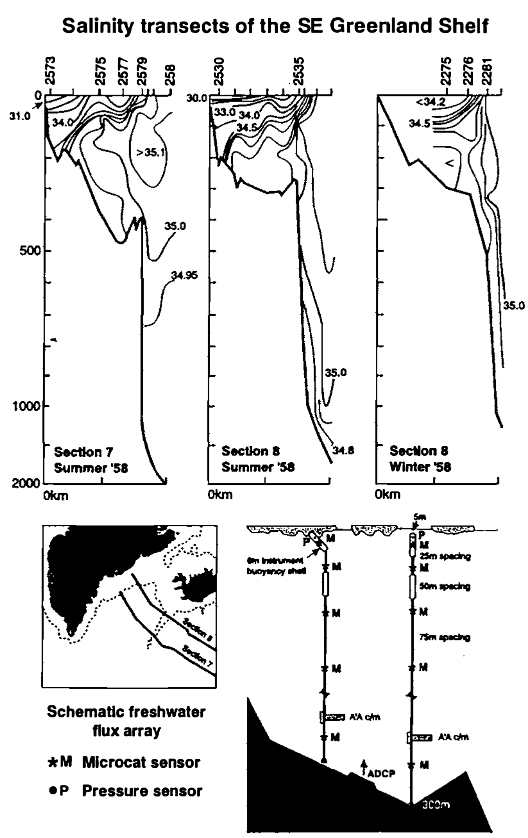


Fig. 2
Schematic diagram of an instrumented array designed to monitor the freshwater flux over the East Greenland shelf. Salinity transects are observations from the IGY.

What caused the earlier Arctic warming?

In many ways, the earlier episode of Arctic warming in the middle decades of this Century was more amplified, more protracted (e.g. Figure 3) and more extensive than the relatively restricted spreading of subsurface warmth that has attracted our attention in the 1990s. This much seems clear from the Report of the ICES Special Scientific Meeting on the subject in 1948 and from its comprehensive bibliography by Arthur Lee. To revisit and continue these early steps toward understanding the warm decade of the 1930s, our own first step is to reassemble the relevant hydrometeorological record. It is proposed to identify ocean and meteorological data from the maritime Arctic for the period 1922-1958, roughly spanning the period from the Maud Expedition to the IGY, - a period of active scientific research throughout the Arctic which included the Second International Polar Year. The geographical region should extend from the Bering Sea, throughout the Arctic Ocean and marginal seas and into the Nordic Seas. The data sets most relevant to our understanding of decadal warming will come from the physical sciences (physical oceanography, meteorology, sea ice and hydrology). However, marine biogeochemistry may also provide direct evidence of the sources of the warming, and such data may support the greater objective of understanding the *consequences* of Arctic warming. Many of these data will already reside in various national and international archives, so that their identification and collation should be relatively straightforward, but other records may well be "lost" or inaccessible in institutional or even private archives, requiring a greater and well-directed effort in data rescue. The International Arctic Research Center, University of Alaska, is proposed to take the lead in assembling all these data, promoting data-archaeology and data-rescue activities where necessary, and producing a CD-ROM for general distribution as well as for submission to World Data Centers. Such a data assembly project is timely, following other recent and present efforts to assemble and distribute sets of Arctic data from more recent decades, mainly 1950-90. We anticipate that the bulk of the useful information could be in the hands of the research community by mid-2001.

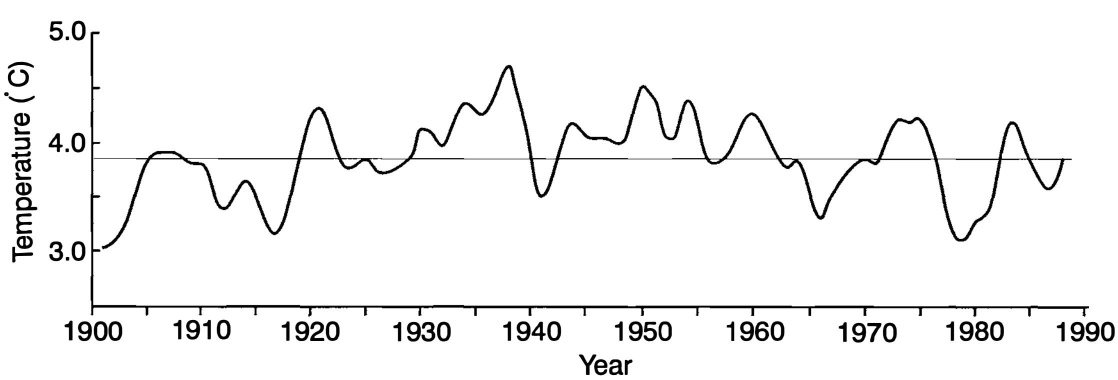


Fig. 3
Three-year running averages of yearly temperature along the Kola Section of the Barents Sea, 1900-90 (from Loeng 1991), clearly illustrating the high-latitude warming that took place in this sector during the middle decades of this century.

To be effective in covering the decadal signals that we now know or suspect to be passing through the Arctic and subarctic seas, these various measurements of "exchange" imply the need for a coordinated pan-Arctic programme with unusual longevity. This in turn confers a particular importance on the international bodies charged with the coordination and funding of Arctic Marine Science.


HANSEN AMUNDSEN SVERDRUP