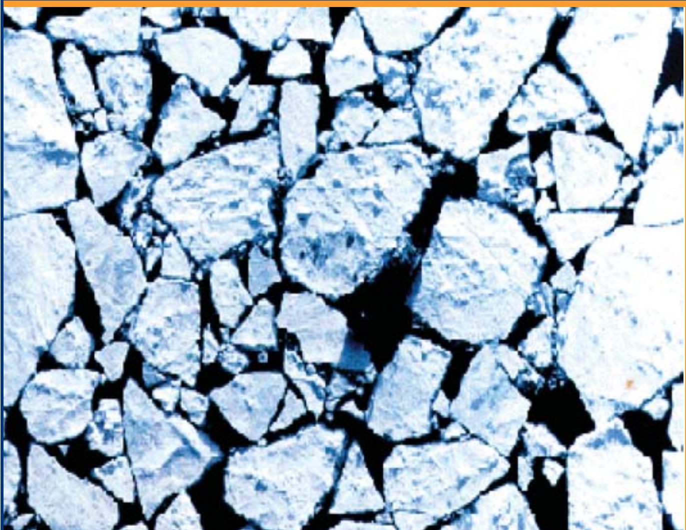
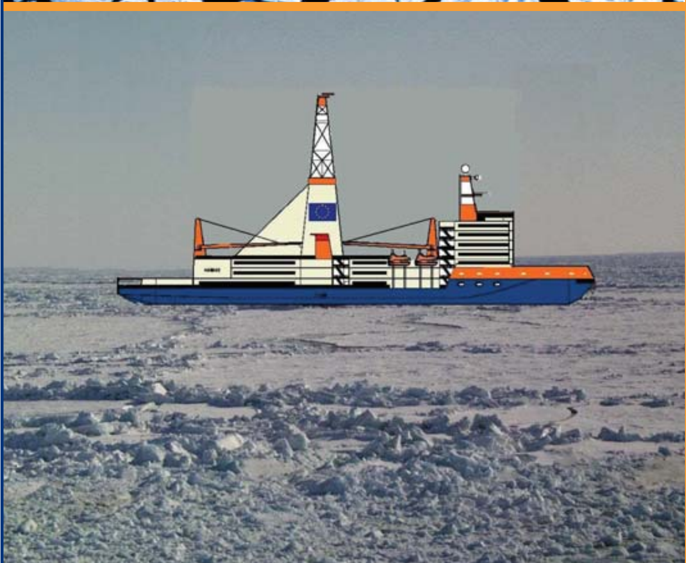
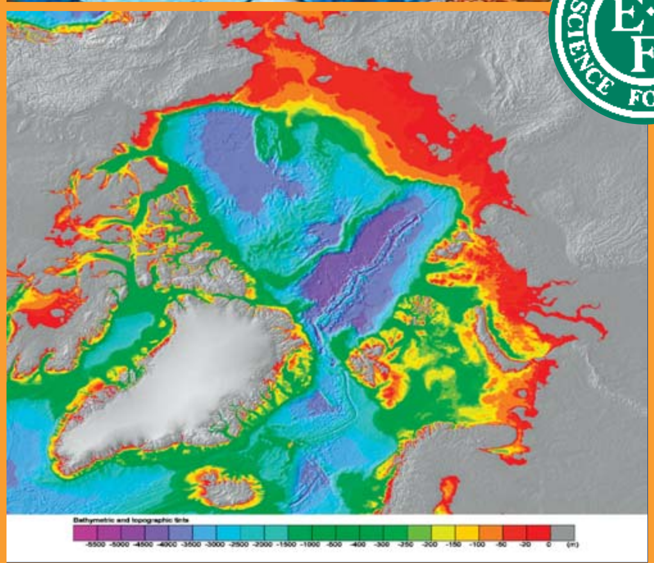
European Polar Board (EPB)
An ESF Expert Committee

AURORA BOREALIS:

A Long-Term European Science Perspective for Deep Arctic Ocean Research 2006-2016







June 2004

The European Science Foundation (ESF) acts as a catalyst for the development of science by bringing together leading scientists and funding agencies to debate, plan and implement pan-European scientific and science policy initiatives. It is also responsible for the management of COST (European Cooperation in the field of Scientific and Technical Research).

ESF is the European association of 76 major national funding agencies devoted to scientific research in 29 countries. It represents all scientific disciplines: physical and engineering sciences, life, earth and environmental sciences, medical sciences, humanities and social sciences. The Foundation assists its Member Organisations in two main ways. It brings scientists together in its Scientific Forward Looks, Exploratory Workshops, Programmes, Networks, EUROCORES (ESF Collaborative Research Programmes), and European Research Conferences, to work on topics of common concern including Research Infrastructures. It also conducts the joint studies of issues of strategic importance in European science policy and manages, on behalf of its Member Organisations, grant schemes, such as EURYI (European Young Investigator Awards).

It maintains close relations with other scientific institutions within and outside Europe. By its activities, the ESF adds value by cooperation and coordination across national frontiers and endeavours, offers expert scientific advice on strategic issues, and provides the European forum for science.

European Polar Board (EPB)

The European Polar Board established in 1995, is the ESF Expert Committee on issues of polar sciences. It is the only European polar organisation that covers science policy issues in both polar regions. EPB is composed of the directors and senior managers of European polar nations and enables cooperation between European national funding agencies, national polar agencies and research organisations. EPB is engaged in dialogue and cooperative actions with important international partners such as the United States and Russia. It provides strategic advice on polar science policy to the European Commission, national governments and international polar bodies.

Acknowledgements:

Principal Editors:
Professor Jörn Thiede and Dr Paul Egerton

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Overhead image of Icebreaker Nansen Arctic Drilling Project; IBCAO Arctic Bathymetry Map; AURORA BOREALIS Research Icebreaker HSVA; IBCAO Digital Bathymetry Map.

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June 2004

Foreword

This Science Perspective document of the European Polar Board and ECORD has been developed by participants from over 20 countries throughout Europe and represents a truly pan-European project highlighting some of the major scientific challenges in the Arctic over the next 10 years. Scientific investigations in the central Arctic, including an understanding of the evolution of the climate record and structure of the Arctic Basin through deep drilling, will be critical in the next phase of European and international research efforts in the Polar Regions.

The international working group involved in this project proposes a unique and novel infrastructure: AURORA BOREALIS, a dedicated European research icebreaker with a deep drilling capability. This facility would enable Europe and its international partners to achieve an unparalleled understanding of the dynamic processes of this sensitive region, which is so critical for understanding the impact of global climate change.

The forthcoming International Polar Year (IPY) 2007-08 provides an opportunity to launch such a groundbreaking and truly European project.

Professor Bertil Andersson
Chief Executive, European Science Foundation
Strasbourg, 2004

Executive Summary

Polar Regions and in particular the properties of northern and southern high latitude oceans are currently a subject of intense scientific debate and investigations because they are (in real time) and have been (over historical and geological time scales) subject to rapid and dramatic change. Polar Regions react more rapidly and intensively to global changes than other regions of the Earth. Observations showing the shrinking of the Arctic sea ice cover, potentially leading to an opening of sea passages to the north of North America and Eurasia en route to a "blue" Arctic Ocean, as well the calving of giant table icebergs from the ice shelves of Antarctica are examples of these modern dynamics.

Until now it has not been clear whether the profound change in all parts of the Arctic is a natural fluctuation or is due to human activity. Since this change is a phenomenon of decades, long time data series of atmospheric and oceanic conditions are needed for its understanding and prediction of further developments. Despite the strong seasonality of polar environmental conditions, research in the central Arctic Ocean up to now could essentially only be conducted during the summer months when the Arctic Ocean is accessible to the currently available research icebreakers.

European nations have a particular interest in understanding the Arctic environment with its potential for change because highly industrialised countries spread into high northern latitudes, and Europe is under the steady influence of and in exchange with the Arctic environment. In addition, considerable living and non-living resources are found in the Arctic Ocean, its deep sea basins and their adjacent continental margins. Modern research vessels capable of penetrating into the central Arctic are few. A new state-of-the-art research icebreaker is therefore urgently required to fulfil the needs of European polar research and to document a multinational European presence in the Arctic. This new icebreaker would be conceived as an optimised science platform from the keel up and would enable long, international and interdisciplinary expeditions into the central Arctic Ocean during all seasons of the year.

Global climate models demonstrate the sensitivity of the polar areas to changes in forcing of the ocean climate system. The presence or absence of snow and ice influences global heat distribution through its effect on the albedo, and the polar oceans are the source of dense, cold bottom waters, which influence thermohaline circulation in the world's oceans. This global conveyor is a major determinant of global climate.

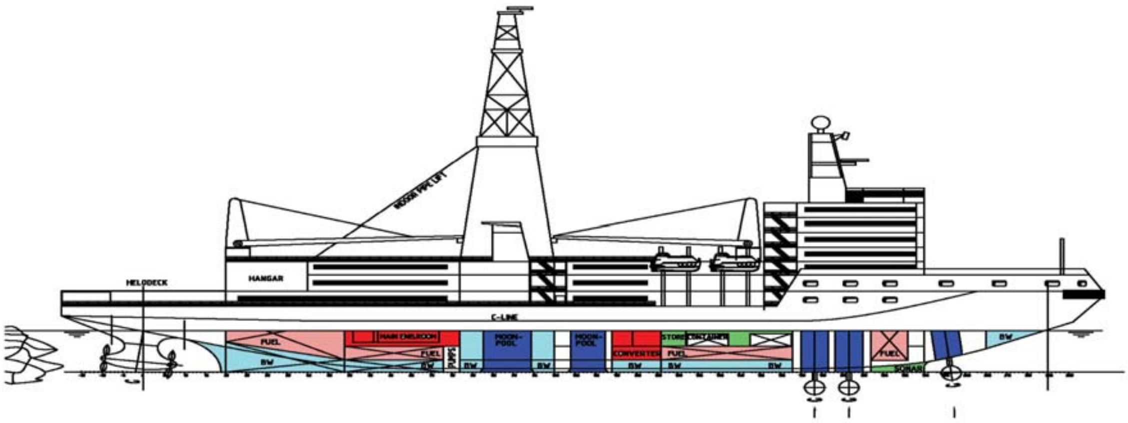
In spite of the critical role of the Arctic Ocean in climate evolution, it is the only sub-basin of the world's oceans that has not been sampled by the drill-ships of the Deep Sea Drilling Project (DSDP) or the Ocean Drilling Program (ODP), and its long-term environmental history and tectonic structure is therefore poorly known. This lack of data represents one of the largest gaps of information in modern Earth Science, also relevant for the field of hydrocarbon exploration. Therefore, the new research icebreaker AURORA BOREALIS **(Fig.1)** should be equipped with drilling facilities to fulfil the needs of the IODP (Integrated Ocean Drilling Program, begun in 2003) for an alternative platform to drill in deep, permanently ice-covered ocean basins. The icebreaker must also be powerful enough to keep on-station against the drifting sea ice cover and will have to be equipped with dynamic positioning.

The AURORA BOREALIS will be a novel all-season research icebreaker with no national or international competitor because of its drilling capability, its sophisticated modularised mobile laboratory systems allowing mission-specific laboratory selections, its moon pools for drilling and for the deployment of remotely operated vehicles (ROV) and autonomous underwater vehicles (AUV) for sub-ice surveys, its propulsion and dynamic positioning systems and its capability for polar expeditions into high latitude ice-covered deep sea basins also during the unfavourable seasons of the year.

An effective use of the new research icebreaker requires the formation of a consortium of European countries and their polar research institutions to ensure a high quality of science and efficient employment of the research vessel during all seasons of the year. Extensive and well-developed Arctic research programmes exist in several European countries, particularly in the Scandinavian countries, Russia and Germany. Different organisations or working groups, with rather diverse structures and domestic impact, exist in each individual country. The construction of AURORA BOREALIS as a joint European research icebreaker would result in a considerable commitment of the participating nations to co-ordinate and expand their polar research programmes in order to operate this facility continuously and with the necessary efficiency. If AURORA BOREALIS is eventually established as a European research icebreaker for the Arctic, European polar research will be strengthened; and Europe will be able to contribute to meeting the Arctic drilling challenge within IODP.

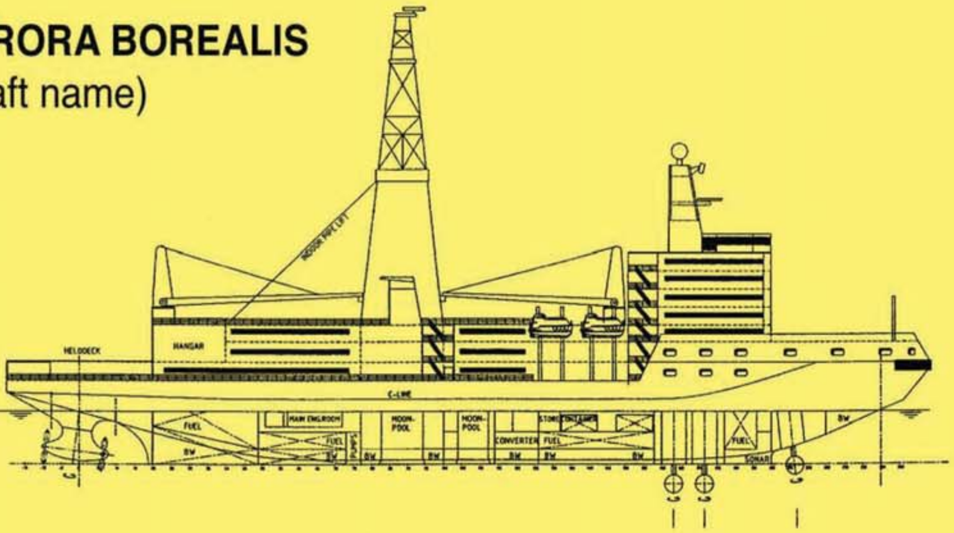
However, from a long-term perspective, the AURORA BOREALIS could also be used to address Antarctic research targets, both in its mode as a regular research vessel as well as a polar drill-ship. The international nature of the Arctic research perspective and of IODP should also be open to participation by non-European countries.

Ideas for a new research icebreaker for the Arctic have been developed by several groups. The sketch below demonstrates the initial HSVA design of the AURORA BOREALIS:



PROPOSAL FOR A NEW DEDICATED EUROPEAN ARCTIC RESEARCH ICE BREAKER (WITH A DEEP OCEAN DRILLING CAPABILITY)

AURORA BOREALIS
(Draft name)



Designed by HSVA

Scientific and Economic Objectives

- The high latitude oceans are subject to rapid changes with vital environmental consequences and also with economical opportunities. The latest example is provided by the news about the shrinking of the Arctic sea ice cover, which could lead potentially to an opening for the sea traffic through the sea routes to the north of North America and Eurasia.
- The central Arctic Ocean has not been visited by a deep-drilling research vessel (DSDP/ODP) and therefore its long-term environmental history as well as the tectonic structure are poorly known. A European contribution to IODP is urgently needed.
- A new dedicated European research ice breaker with a deep ocean drilling capability would provide the opportunity to conduct international, interdisciplinary expeditions during all seasons of the year and to penetrate into permanently ice-covered basins of the central Arctic Ocean.

Dimensions (draft design) and Capabilities of the new ice breaker

- Length LPP 132.00 m; displacement 23,000 t.
- Ability to serve the needs of the polar science disciplines: meteorology, glaciology, oceanography, biology, geology and geophysics as well as marine technology. Capacity of laboratories and electronic areas is 2300 m^2.
- Ability to endure winter and spring expeditions to the permanently ice-covered central Arctic Ocean. Ice breaking performance of more than 2 m and dynamic positioning in ice.
- Deep drilling and coring capability in up to 4 km water depths penetrating into the sea floor up to 1 km.

The European Aspect

- Promotion of the continuity for European polar research programmes and of the internationally successful competition about the leadership in Arctic research.
- The new research ice breaker is thought of as an alternate platform in the European contribution to the successor of the Ocean Drilling Program, the Integrated Ocean Drilling Program (IODP).
- The formation of a European Consortium of interested institutes/countries is required to share the responsibility for the planning and construction of the Arctic ice breaker and to coordinate the scientific programmes.

Fig. 1: The AURORA BOREALIS project.

A Vision of European Collaboration in the Arctic Region

...The critical role of the Arctic in regulating and driving the global climate system is one that requires elucidation in all its complexities. This is necessary to predict future environmental changes and determine strategies that must be adopted by nations to protect the functioning of the Earth system...

European nations have a particular interest in understanding the Arctic environment with its inherent sensitivity to change. The Arctic Ocean contains considerable living and non-living resources. The interactions and effects of human influence must be understood in order to develop adequate means of protection and potential scientific and economic use of this unique environment. The development of a dedicated European research platform icebreaker will enable the study of physical, chemical and biological processes in the Arctic regions during all seasons of the year and will promote internationally integrated and multidisciplinary science programmes based on a unique large research facility. The AURORA BOREALIS project is a core element of the European Polar Board's strategic framework EUROPOLAR and is a concept which enables strengthening, expansion and commitment to the organisation and implementation of European polar research.

Global climate change amplified in the high Arctic has a profound effect on circumArctic populations. This is particularly seen in the social and economic damage arising from more frequent climate-induced extreme events. Anthropogenic feedbacks into the cryosphere-atmosphere-ocean system need to be investigated and evaluated with much greater precision. A dedicated European scientific research platform will significantly contribute towards observation and monitoring of changes in the environment at high latitudes. Polar marine research over the next 10 to 15 years will concentrate on the long-term natural variability within the ecosystems of the Arctic Ocean. This will focus on the feedbacks between atmosphere, sea ice, ocean and biological systems. In particular the propagation of anomalies through the system is used to understand the pelagic ecosystems during the different seasons, the response of planktonic systems and benthic biota to variations in sedimentation and river supply as well the distribution pattern of anthropogenic contaminants in the Arctic.

Climate models demonstrate the sensitivity of the Arctic Basin to changes in forcing of the ocean climate system. Snow and ice cover influence global heat distribution and the polar oceans are the source of dense, cold bottom waters that influence thermohaline circulation in the world's oceans. The global conveyor is a major determinant of climate. In spite of the critical role of the Arctic Ocean for climate evolution in the Northern Hemisphere, it is the only sub-basin of the world's oceans that has not been sampled by any scientific drill–ship, and its long-term paleoenvironmental history and tectonic structure is poorly known. This lack of data represents one of the largest gaps of information in modern Earth Science. Drilling and sampling of the Arctic Basin will be one of the major scientific and technological challenges of this decade and one in which Europe will play a key role. It could form a major European contribution to IODP (Integrated Ocean Drilling Program) and the AURORA BOREALIS could be considered one of the premier European alternative platforms.

The main strength of the AURORA BOREALIS project is that it is a unique research platform providing the solution to several multidisciplinary scientific demands. The concept provides a pathway to the development of a European Research Area in Arctic system science and is at the heart of European cooperation in polar scientific research and operational capabilities. The implementation of a European Arctic Observing System using AURORA BOREALIS will open up long-term perspectives to international programmes and enable greatly enhanced knowledge and sound policy advice to be given to governments on the status of changes to the global environment.

This Science Perspective will provide a basis for future scientific investigations of the High Arctic and define a decadal forward-looking strategy for European cooperation in Arctic science.

The present Science Perspective developed by the European Polar Board has mainly an Arctic focus because sufficient research capabilities will be available in Antarctic waters for the coming decade. However, considering the bipolar research interest of many of the European and polar research programmes, it is clear that the AURORA BOREALIS project also has the ability to conduct all-season research and deep sea drilling activities in the ice-infested waters of the Southern Ocean. The annual transit of research icebreakers between Arctic and Antarctic waters is not an efficient mechanism. Once a decade of dedicated research has been carried out in the Arctic Ocean, an assessment will be made of the scientific capability of the AURORA BOREALIS for mission-specific purposes in the Southern Ocean, and whether it could provide an efficient and modern research platform for those waters.

June 2004

Jörn Thiede

Chairman of the AURORA BOREALIS International Science Planning Committee and former Chairman of the European Polar Board of ESF with 20 member nations

The Science Perspective - Introduction

The AURORA BOREALIS project addresses two scientific communities which in part overlap and in part have divergent interests. The first one is the general polar science community, which requires a research vessel for conducting its field and sea work throughout all seasons of the year, hence with wide scientific perspectives. The other is the deep sea drilling community, which would use the ship mainly during the summer months to study the structure and properties of the oceanic crust and the history of the oceanic depositional environments that can be deduced from the oceanic sediment cover. This has never been carried out in a systematic way in the permanently ice-infested waters of the Arctic, whereas around Antarctica substantial progress has been achieved by using the drilling platforms of the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) during the ice-free seasons and by using a small drill rig from the landfast sea ice very close to shore (CRP, Cape Roberts Project).

As outlined later, AURORA BOREALIS is currently thought of as an Arctic research vessel with a deep drilling capability. In the long term, however, it also has an Antarctic perspective because neither the CRP-tools nor the conventional drilling vessels, which cannot enter ice-infested waters, are able to cover all desirable drilling locations off Antarctica. Many of these locations have not so far been investigated, mainly due to the lack of a suitable ice-capable drilling platform. These scientific targets will now receive renewed attention.

Europe requires new and additional research capabilities to venture into the deep, permanently ice-covered Arctic Ocean. The novel research vessel AURORA BOREALIS will provide such a facility and it should be planned as a European infrastructure unit. It has to be supported by a core group of European countries with relevant research interests; for example, problems in basic research or highly applied research such as fossil hydrocarbon exploration.

From the romantic and heroic times of the early explorers, science in the Polar Regions has evolved into a modern, quantitative branch of the natural sciences, which employs large groups of researchers and sophisticated, expensive instrumentation contributing indispensable data for better understanding the extreme habitats of the Polar Regions as well as their impact on the global environment. The fact that much of the necessary data can be collected only by dedicated research vessels, from permanently manned stations or during expeditions involving many different disciplines and substantial logistic efforts, has resulted in complex interdisciplinary experiments, which can be co-ordinated only under the framework of close international cooperation.

Most of today's scientific polar research problems are thematically oriented and require inter- and multidisciplinary cooperation. They comprise elements of fieldwork, of modelling and of application and a close cooperation with many national and international partners. Hence, this document contains a comprehensive, though not necessarily complete, science perspective for Arctic and, to a lesser degree, also Antarctic research. However, it must be clear, that planning a large and novel research icebreaker results in a scientific programme that is focused on research disciplines and activities that require a ship with the capability of year-round operations in the central Arctic.

The Science Perspective is organised following a thematic scheme, but also identifies the main technical, managerial and organisational aspects of the AURORA BOREALIS project, whose developments have to be science driven. They have not been developed to the same depth as the science plan. In particular, the details of technical planning will require much further refinement, which cannot be provided by scientists, but which will have to come through a separate technical design study. Managerial, financial and organisational structures for running the ship are outlined in a preliminary form. Detailed management concepts need the input of the international science community and relevant agencies committed to the AURORA BOREALIS concept.

High latitude polar oceans and land areas have a high impact on the global environment; they actually control large segments of the global environment and they can be considered drivers of global climate change. This holds true in particular for Europe and for the Arctic Ocean because the interplay between the North Atlantic Ocean and the Arctic Ocean results in a large anomaly of the climatic zonation of the Northern Hemisphere. Hence, European nations have an all-important interest in understanding the Arctic Ocean, its properties and their natural variability as well as their interaction with the adjacent temperate ocean basins. Many European nations therefore support polar research not only in Antarctica but in the Arctic as well and it is indeed a special characteristic of many of the European polar research programmes to have a bipolar perspective.

The urgency of opinions and decisions about the future of the global environment has resulted in large polar research efforts in many nations. At the present time the perspectives of polar research for the coming decades in the Northern and Southern Hemisphere high latitude regions are evaluated, defined and strengthened in many ways.

The science perspective of the AURORA BOREALIS presents a strategy of deploying a powerful tool for carrying out research in the central Arctic Ocean throughout the entire year for a decade or more in this poorly known ocean basin. All indications point to a time of rapid change in the Arctic, and some scientists speculate about a “blue” Arctic Ocean in 50 years from now. The coming decade will be a critical phase in this development especially in the light of the proposed International Polar Year 2007-08 as a platform for an enhanced focus on the Polar Regions.

The central deep sea basins of the Arctic Ocean have yet to be visited by a scientific drill-ship and it is henceforth paramount, under the auspices of IODP, to deploy platforms to solve the following mysteries:

- the plate tectonic origin of the Arctic Ocean
- the nature of the major structural highs as well of the oceanic crust on the other parts of the Arctic Ocean
- to probe for long sediment cores of undisturbed stratigraphic sequences recording the properties of a warm Arctic Ocean prior to the onset of the Northern Hemisphere glaciation
- the traces of the earliest ice covers sometime during the Miocene
- the variability of the glacial and interglacial climate system during the latest part of the Cenozoic.

The technical requirements necessary for the intended research require a large and powerful research vessel that can endure very unfavourable weather and ice situations, is able to position itself dynamically against a drifting sea ice cover mainly without the assistance of other icebreakers and which is strong enough to hold its position precisely enough to be able to carry out deep sea drilling. It also calls for the routine deployment of novel, strong propulsion systems as well as for the development of a large icebreaker with one to two moon pools for the deployment of the drilling instrumentation, ROVs and AUVs as well as deployment of sensitive instrumentation during very unfavourable weather conditions. The dual-purpose research vessel will require flexible laboratory arrangements and it is intended to develop a system of modularised and containerised labs, which can be designed and modified according to the needs of a variety of missions.

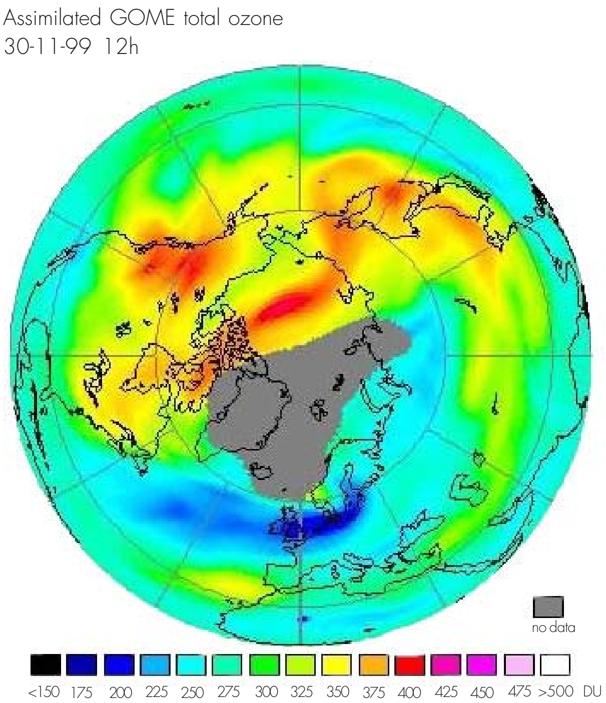
The AURORA BOREALIS would be the first true European research vessel. A decision to build and run it will require large and well-coordinated efforts of the interested countries. With a view to being part of IODP and of the multinational polar research programme, it will not only lead to harmonisation of the polar research programmes but it will encourage the participating nations to look jointly for perspectives in polar research resulting in synergies and efforts hitherto unknown. It will enable data collection and probing of the environment at times when the Polar Regions have never been visited before (mainly during the harsh late autumn, winter and early spring seasons) and will allow European nations to maintain their leading position in Arctic and Antarctic research.

At the same time the AURORA BOREALIS can be considered as a floating laboratory bringing together a sizeable scientific community during an uninterrupted series of multidisciplinary/ interdisciplinary and multinational/international expeditions. It can indeed be considered a floating university and it will be spacious enough to allow the indigenous people of the Arctic–rim countries to contribute and participate in this research, which will collect data and gain insight into the environment on which they depend.

The AURORA BOREALIS will be globally the most advanced research platform with state-of-the-art technology for polar research. With its all-season capability it will provide a platform for tackling major scientific challenges, which hitherto has not been possible. It would be a floating European university in polar sciences. It would promote the idea of the European Research Area and it would result in substantial competitive advantages. In addition, it would help in the collection of data to advance the definition of the continental margins from an EEZ point of view (and it would increase safety in Arctic operations). Besides basic research, it would provide an opportunity to look for non-living Arctic resources such as gas hydrates or other fossil hydrocarbons. It would also give the European nations an advantage in the planning, construction and deployment of large icebreakers in the Arctic, which seems to be developing into one of the most important regions in the Northern Hemisphere.

Part 1

The Arctic Ocean and Global Climate Change – Atmosphere, Sea Ice & Ocean



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The Arctic Ocean and Global Climate Change – Introduction

The temperature increase in the Arctic during the last 50 years is three times larger than the global average and can be taken as an indicator of global change in the Arctic. The Arctic atmosphere-sea ice-ocean system reacts to and modifies these changes. Marine biota, CO_2-fluxes and human living conditions are affected. Improved understanding of this system is needed to distinguish between the natural and anthropogenic variations and to build up predictive capabilities.

The coupled atmosphere-sea ice-ocean system in the Arctic represents an integral part of the global climate system by its effect on the heat balance which is strongly affected by atmospheric and sea ice conditions in the Arctic as well as by the formation of dense water masses which spill over the sills into the North Atlantic Ocean and feed into the global overturning circulation (Houghton et al., 2001). Sea ice and ocean waters give home to a variety of biota, which are supplied through river and aeolian input with materials (and nutrients) from the land. The vertical flux of dissolved and particular organic and inorganic matters into the deep sea provides a basis of benthic life (Fig. 2).

The Arctic Mediterranean Sea comprises the Arctic Ocean with the adjacent shelf seas and the Nordic Seas (Aagaard et al., 1985). It consists of a series of ocean basins separated by ridges, and its internal circulation is to a large extent determined by the basin structure (Aagaard et al., 1985; Aagaard and Carmack, 1994; Rudels, 2001) (Fig. 3). Relatively warm and saline water enters the Nordic Seas from the North Atlantic and is advected through the Fram Strait and the Barents Sea into the Arctic Ocean (Rudels et al., 1994). The Atlantic water re-circulates along different paths in the Arctic Mediterranean, undergoing extensive modification (Rudels et al., 1999a). River runoff from the continents adds a significant volume of freshwater,

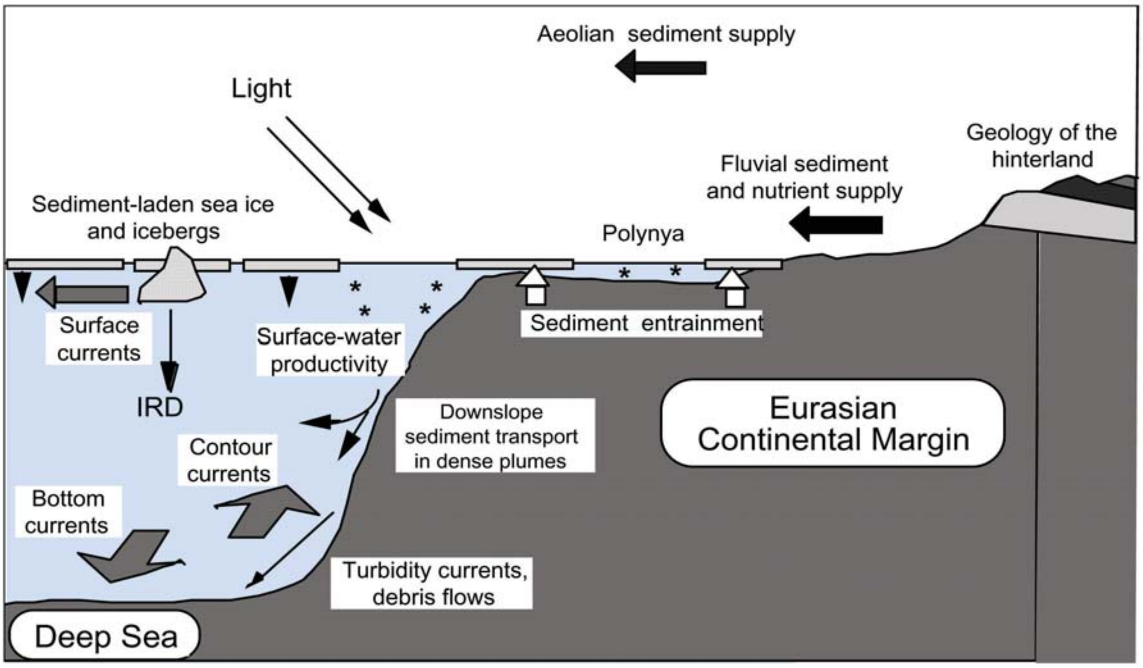


Fig. 2: Factors controlling the Arctic Ocean environment and sedimentation along the Eurasian continental margins and in the adjacent deep sea with implications for ecosystems.

Arctic Ocean Circulation

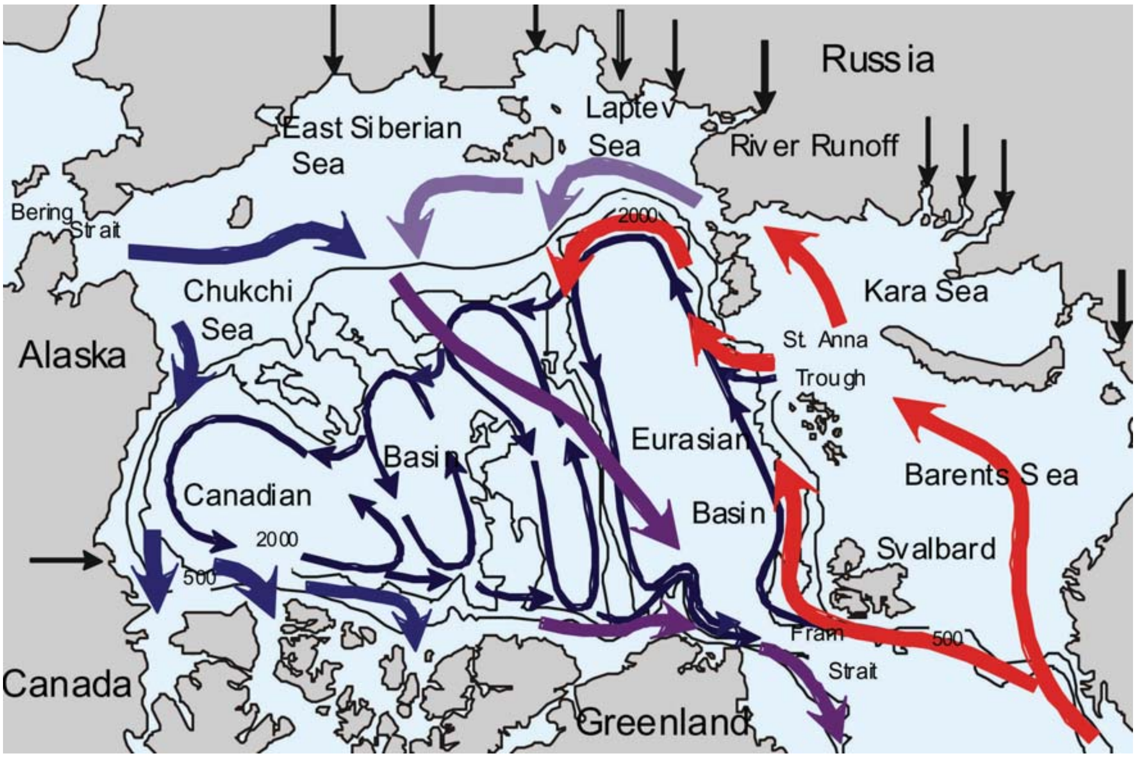


Fig. 3: Schematic circulation of upper layer water (thick arrows) and intermediate water (thin arrows). The flow of Atlantic water follows the red arrows, the return of freshwater from the Pacific Ocean to the Atlantic Ocean the dark blue arrows originating at the Bering Strait. The straight arrows represent the mouths of the major rivers (Anderson, 2002).

and water of lower salinity is supplied by the Pacific through the Bering Strait (Carmack, 2000). Due to the large-scale sea level inclination there is a net transport of low salinity water from the Pacific to the Atlantic which, in spite of its comparatively small volume, constitutes a major control in the global freshwater cycle (Jones et al., 1998). The severe climate, with winter temperatures far below 0^{o}C and the strong stratification in the upper part of the water column caused by the freshwater input leads to ice formation and to the maintenance of a seasonally variable, but currently perennial ice cover in the Arctic Ocean (Wadhams, 2000).

The circulation in the Arctic Mediterranean is driven by wind and by thermohaline processes. The air pressure distribution is basically determined by a high-pressure system over the Beaufort Sea and a low-pressure system over the Nordic Seas leading to an anticyclonic atmospheric circulation pattern over the Arctic Ocean (Przybylak, 2003), which induces a large-scale oceanic circulation (Proshutinsky and Johnson, 1997). The seasonally varying ice cover responds to the winds and the ocean currents, and the anticyclonic circulation of the Beaufort gyre and a less developed cyclonic counterpart in the European Arctic feed into the Transpolar Drift, which provides the major export of sea ice and low salinity upper waters through the Fram Strait. Upper, less saline, water masses also exit the Arctic Ocean through the Canadian Arctic Archipelago into the Labrador Sea.

The Fram Strait is the only deep connection between the Arctic Ocean and the Nordic Seas, where exchanges of intermediate and deep waters take place (Rudels et al., 2000; Fahrbach et al., 2001). The denser water masses eventually leave the Arctic Mediterranean as overflow waters and supply the source waters for the North Atlantic Deep Water, which plays a significant role in the global overturning circulation (Dickson et al., 2001).

The export of both dense and less dense water from the Arctic Mediterranean allows it to exert control on the meridional overturning circulation (MOC) of the global ocean in two ways: 1) the dense overflow drives the lower limb of the MOC; and 2) the low salinity outflow affects the stratification and thus the deep water formation in the North Atlantic which also contributes to the MOC (Rudels, 2001). Variation in these two outflows thus has consequences reaching far beyond the local conditions in the Arctic Mediterranean (Fig. 4). Paleoclimate records suggest that such "rapid changes" could have occurred over time scales of a few decades (Seidov et al., 2001).

During recent years significant changes have been observed in the Arctic, and decadal variations in the atmospheric conditions, sea ice and water mass distribution, and in the oceanic circulation are evident (Thompson and Wallace, 1998; Dickson et al., 2000; Proshutinsky et al., 2002; Dukhovskoy et al., 2004). A decrease and eastward shift of the Beaufort high in the 1990s is described as part of the Arctic Oscillation (AO), which is related to the North Atlantic Oscillation (NAO). The NAO reflects the variations of the pressure difference between the Azores high and the Icelandic low (Hurrell, 1995). Changes in atmospheric forcing modify ocean circulation and sea ice export, which influence the residence time and the ice thickness in the Arctic Ocean, and the exchanges between the Arctic Ocean and the Nordic Seas.

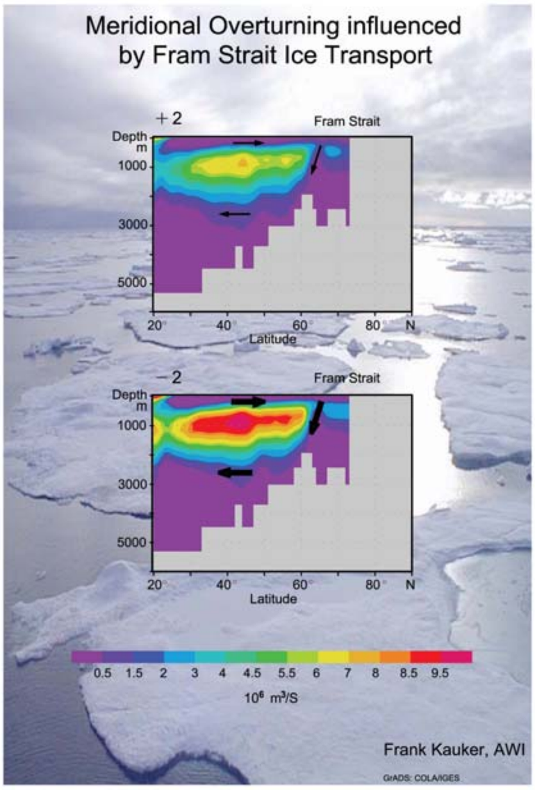


Fig. 4: Meridional overturning is apparently under the heavy influence of the Fram Strait ice transport.

The changes in the Arctic during the last decade, including their impact on human life, are subject to intense research efforts such as the Arctic Climate Impact assessment (ACIA) initiated by the Arctic Council and such as SEARCH http://psc.apl.washington.edu/search/, ACSYS/CliC, CLIVAR, ASOF. A basic prerequisite for a substantial study is the existence of long, spatially well resolved, time series of ocean, atmosphere and sea ice parameters and fluxes, and an improved understanding of the physical processes active in the Arctic Mediterranean, and how they respond to varying conditions. Both time series and process studies are mandatory for any serious attempt in modelling possible future changes.

The severe conditions in the Arctic Ocean, in particular its ice cover, make even the exchange of moored systems, deployed to measure transports at "choke points", difficult, and to obtain, regularly, hydrographic sections to World Ocean Circulation Experiment (WOCE) standard in the interior of the Arctic Ocean is largely beyond the capability of the existing research vessels. The dynamically active period in the Arctic Ocean, as well as in the Nordic Seas, is winter. During winter the dense water formation on the shelves takes place, and much of the sinking of dense water down the continental slope may occur before summer. Winter is also the time when extensive cooling of the surface water occurs and the wind is strong, supporting an intensive uptake of atmospheric carbon dioxide. Furthermore, during this season the haline convection in the basin interior is expected to penetrate through the halocline into the Atlantic Layer, should the stratification in the upper, interior Arctic Ocean weaken.

To study these processes when they are active, not just record traces of their presence, an icebreaker of exceptional capabilities is required, and not just for one winter but for extended periods. The Arctic Ocean is large and what are the most active and important areas have not yet been determined. The relevant investigations are strengthened by multidisciplinary studies, including chemical tracer work with the need to sample waters during the winter season. This sampling must be performed under conditions that avoid the samples freezing; for example. through a moon pool.

Biological studies in the Arctic Ocean aim on seasonal aspects of sea ice and pelagic biota at ice- covered high latitudes. Investigations of the deep Arctic Ocean will include:

- investigations on hydrothermal vent communities along the Gakkel Ridge
- studies on bacterial communities inhabiting in the deep biosphere of ocean basins characterised by low productivity
- research on cold seeps along the Eurasian continental slope
- the installation of long-term observatories at key locations in the ice-covered Arctic Ocean.

The majority of past expeditions to the Arctic were conducted during the summer season. Therefore, a sound database on the biology of organisms inhabiting the sea ice, the water column or the seafloor is available for many regions of the Arctic Ocean and its surrounding shelf seas during this period of a year. In contrast there are only few and randomly scattered samples taken in the central Arctic Ocean and very little information is available on seasonal aspects such as reproductive cycles, overwintering strategies and metabolic adaptations during winter. Additionally, we have only limited information about species composition and distribution in the three marine sub-systems (cryosphere, pelagic and benthic realm) for the central Arctic. Any profound discussion about latitudinal gradients in marine biodiversity needs more systematic sampling, as well as the identification of shifts in distribution patterns of species due to any effects of global change.

The Arctic Ocean system also plays an important role in taking up carbon dioxide from the atmosphere (Anderson and Kaltin, 2001). The mechanisms controlling this uptake is twofold: the cooling of the surface water increases the solubility of carbon dioxide, and the extensive primary production in some regions decreases the partial pressure of carbon dioxide of the water surface. The combination of extensive uptake of atmospheric carbon dioxide and deep-water production makes the area a significant sink of anthropogenic carbon dioxide.

The changes observed during the last decades have a visible impact on natural conditions and on human life in the Arctic and will have dramatic consequences for the socio-economic conditions in the Arctic which will be clearly noticeable in NW Europe (McCarthy et al., 2001). Ship traffic through the Northern Sea Route will flourish with the reduction of transport costs within northern Europe and between Europe and Asia and improving accessibility of wide areas in the European Arctic and beyond. Exploitation of natural resources in the Arctic Ocean will be greatly facilitated in the case of further warming and sea ice retreat. However, it is still not clear that changes in the Arctic are part of a natural variability or if they are the consequence of human impact. Neither can it be said whether the trend will continue or if we are faced with a decadal fluctuation. There is an urgent need to understand change in order to predict further developments. The warming period in the Arctic during the 1920s and 1930s gave rise to similar expectations, and a rapid subsequently cooling endangered hundreds of ships in the late 1930s. Therefore there is a fundamental need for a substantial understanding of climate change which requires the availability of long time series of ocean, atmosphere and sea ice studies.

Atmosphere

Atmospheric Forcing, Clouds and Composition of Arctic Air Masses

The atmospheric circulation and radiation properties as clouds and aerosols are major elements of the global heat budget and have to be included realistically in global climate models. Arctic data are urgently needed.

The Arctic atmospheric circulation and the interaction between atmosphere, ice and ocean form the physical interactive processes controlling the climate in the Polar Regions, extending their reflections south to sub-polar regions. Significant changes in atmospheric parameters become obvious (Serreze et al., 2000; Comiso, 2003). In terms of global climate change the importance of the Arctic atmospheric circulation and atmosphere ocean interaction may be compared with the crucial role of ocean convection and overturning of the Arctic waters, as driving forces for the thermohaline circulation and hydrography of the world ocean.

In recent years, working tools have been introduced to characterise the physical behaviour of the Arctic atmospheric circulation and the atmospheric forcing, such as the Arctic Oscillation Index (AO) and North Atlantic Oscillation Index (NAO) (Thompson and Wallace, 1998, 2000a & b; Dickson et al., 2000).

The best coupled atmosphere-ocean models suggest the Arctic Polar Regions to be most exposed to global warming (Houghton et al., 2001; Pryzbylak, 2003). The main reasoning for this lies in the role of polar radiation balance and clouds (Fig. 5). Increased atmospheric moisture and cloudiness and changes in the composition of the polar atmosphere decrease the polar thermal (long-wave) radiation out to space, and thus enhance the greenhouse effect. Clouds, on the other hand, have also an opposite effect because the upper clouds reflect the down-welling solar radiation out from the Earth's atmosphere. Changes in the composition in the atmosphere, such as aerosols, have an important role in this overall balance but are not too well known and modelled. Special aerosols and chemicals, additionally, play a major role in the cold polar stratosphere and in the ozone hole context (Harris et al., 1998).

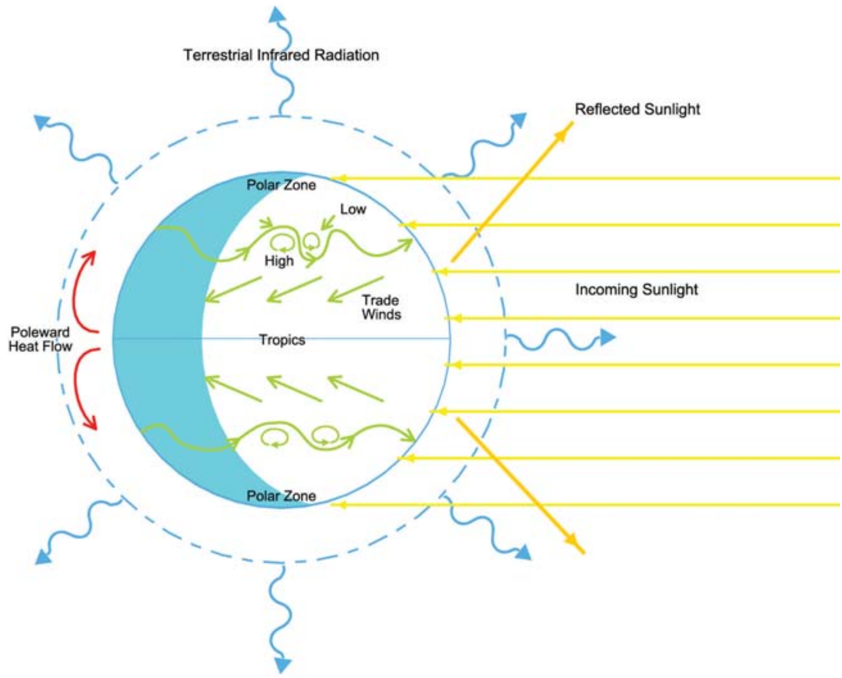


Fig. 5: Schematic illustration of the main features of global atmosphere circulation and radiation patterns.

Observations of clouds and composition of the polar atmosphere can be carried out by remote sensing and special automatic stations. Satellite methods have good spatial and temporal coverage. However, most of the quantities wanted are derived by inverse methods and remain too inaccurate because of incomplete ground check and validation. Therefore, in-situ observations and vertical soundings of the physical and chemical composition and mechanisms of the atmosphere over the Arctic Ocean are necessary in a sustained manner. In practice, those observations can be made only from mobile marine platforms. Because observations and monitoring are necessary over all seasons and regions, a strong ice-going polar ice research vessel is needed as a quasi-permanent platform.

Sea Ice

Albedo Radiation and Atmosphere -Ice-Ocean Heat Exchange

Sea ice and albedo play a central role in the Arctic Ocean heat budget because sea ice limits the heat exchange between ocean and atmosphere and the albedo determines the reflection of incoming radiation.

The sea ice and albedo of sea ice play the central role in the ocean-ice-atmosphere interaction and heat exchange (Eicken and Lemke, 2001). A high summertime albedo, reflecting the most part of the global radiation back to the atmosphere, is the precondition to formation of multiyear sea ice (Maykut and Untersteiner, 1971). On the other hand, even slight changes in the Arctic albedo may change the sea ice conditions, atmosphere-ocean interaction and heat exchange drastically. Actually, modelling and estimation of the polar albedo remains one of the most crucial issues for predicting scenarios of global climate change. Unfortunately, the albedo in the Arctic is still rather poorly known, quantitatively. Some fixed measured time series over the seasons exist but as they result in a set of complex physical processes the variations in albedo are not properly known and modelled (Curry et al., 2001). A related difficulty is a high spatial and temporal variability and patchiness (Fig. 6). A good part of the patchiness is caused by local differences in sea ice structure, snow thickness and atmospheric forcing. Rough estimates of large- and regional-scale albedo can currently be retrieved from satellites, but they cannot serve as a basis for modelling and prediction; local observations and physical modelling efforts are still necessary. Additionally, the derivation and prediction of the Arctic albedo is, most likely, connected with the progress of global change, and therefore to new facets of study and time scale predictions.

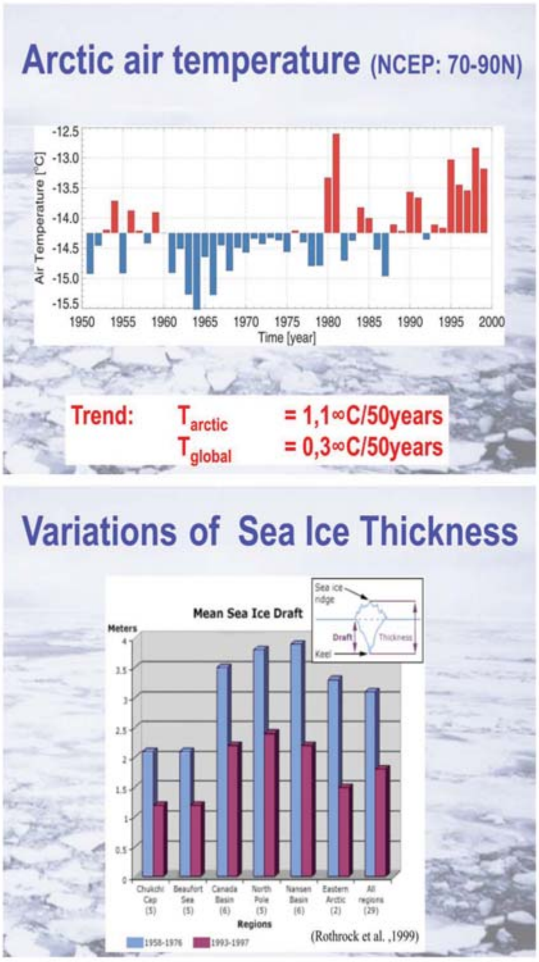


Fig.6: Top panel: Arctic air temperature (NCEP: 70-90N). Bottom panel: Variations of sea ice thickness for various Arctic Ocean regions. Cf. also Fig. 7.

During recent years, retreat and thinning of the Arctic sea ice has been reported (Vinnikov et al., 1999; Rothrock et al., 1999; Wadhams and Davis, 2000; Comiso, 2002; Rothrock et al., 2003). In those reports, the changes have been (surprisingly) rather distinct. However, the characteristics of the regional distribution of time-scale variations make it difficult to distinguish between natural variability in decadal time scales and the potentially human-caused climate change. Only sustained measurements will allow convincing conclusions. However, the example below should give an idea of the importance of accurate and realistic information of the Arctic sea ice cover.

The studies referred in Houghton et al. (2001) conclude the summertime Arctic sea ice extent to have been decreased from the late 1950s to l990s by 10-15%. Accordingly, if we assume the snow-covered Arctic sea ice albedo to be of the order of 0.8, the above decrease in the sea ice extent would mean an order of 30% more short-wave radiation gain in spring and summer in the whole Arctic Ocean, compared with the previous conditions.

Accurate determination of structure and concentration of sea ice in the broken Arctic ice fields is necessary for modelling sea ice dynamics, with regard to energy exchange between the ocean and the atmosphere. We know that the turbulent ocean-atmosphere exchange of heat and moisture from leads and cracks is the most intense (Launiainen and Vihma, 1994). Accordingly, fluxes via leads and cracks of 5% of the area are comparable to those from the sea ice-covered areas. Therefore, the sea ice concentration should be determined more accurately than is currently carried out using the best satellite image-derived algorithms.

The necessary field studies for better investigation and modelling of albedo, sea ice structure and concentration, snow properties and ocean-ice-atmosphere exchange can only be made from marine/sea ice platforms, available all year round and able to operate in large areas.

The Role of Upper Ocean Processes for Extent and Thickness of the Sea Ice Cover

Extent and thickness of the Arctic sea ice cover are affected by heat fluxes from the upper ocean, which can vary due to changes in the stability of the water column caused by changes of the water mass properties.

The strong stability of stratification in the upper part of the Arctic Ocean water column limits the depth of winter convection and allows for cooling of the surface water to freezing temperature and to ice formation (Rudels et al., 1999b). The heat content of the intermediate depth layers of Atlantic water has a capacity to melt about 20m of ice, should it be brought to the sea surface and in contact with the ice cover. However, this requires intensive stirring and turbulent entrainment and may occur only at the continental slope where the rapid flow and topographically trapped and enhanced motions increase the turbulent activity and bring the Atlantic water closer to the sea surface. This is the case at the Eurasian slope in the Nansen Basin. At the slope beyond the Laptev Sea and in the interior of the deep basins, excluding the Nansen Basin, a halocline with temperatures close to freezing is located between the upper Polar Mixed Layer and the Atlantic water. Cold, not warm water is entrained into the mixed layer and no melting takes place.

Recent observations have indicated that the halocline occasionally, and with time perhaps permanently, may disappear in the interior of the deep basins, allowing for direct entrainment of warm Atlantic water into the mixed layer (Steele and Boyd, 1998). This would increase the oceanic heat flux to the ice and cause a thinning (Fig. 7) and possible disappearance of the Arctic Ocean ice cover, generating a "blue" Arctic Ocean with unknowable consequences, not just for the Arctic, but for the global climate. However, in such a scenario one question is of utmost importance: "What mechanisms drive the entrainment of water from below into the mixed layer?" Is the necessary turbulence in the mixed layer generated by the mechanical stirring caused by wind and drifting ice, or is it created by the haline convection induced by freezing and brine release during winter?

Regardless of process, the winter is the only period when entrainment into the Polar Mixed Layer occurs, since a low salinity melt water layer is present at the surface in summer (Rudels, 1999b, 2001). No significant atmospheric cooling is present and the stability in the upper part of the Polar Mixed Layer is too strong for wind-generated turbulence to reach the lower boundary of the Polar Mixed Layer and no entrainment takes place. In winter the stabilising melt water layer is removed by freezing and entrainment of underlying water into the Polar Mixed Layer becomes possible. In the absence of a cold, intermediate halocline entrainment, warm Atlantic water would reduce the ice formation and thus also reduce the release of salt. The decrease in stability at the lower boundary of the mixed layer during winter then becomes smaller than when cold water is entrained.

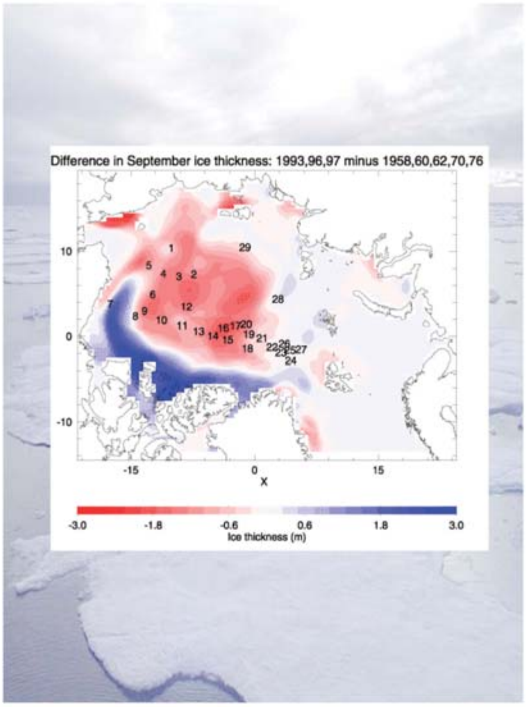


Fig. 7: Difference in September ice thickness: 1993 / 96 / 97 minus 1958/ 60/ 62/ 70/ 76.
(Holloway and Sou, 2002)

The strength of the entrainment depends inversely upon the stability at the base of the mixed layer, and the interactions with the ice cover, induced by entrainment of warm water, provides a negative feedback that acts to reduce the entrainment.

In the special case when the turbulence driving the Atlantic water into the mixed layer is generated by convection, strong entrainment of warm water could temporarily shut down the ice formation and thus the convection, causing the turbulence in the mixed layer to weaken and the entrainment to disappear. Furthermore, convection is a poor mixing mechanism, and much of the cooling of the Atlantic water could actually occur at the lower boundary of the mixed layer when dense, haline plumes penetrate into the underlying warmer Atlantic layer. The heat of the Atlantic water is then not brought to the surface to supply heat to the atmosphere and to melt ice, but is used to heat the cold plumes within the water column.

To understand the complex interactions between sea ice and the underlying waters, observations from numerous sites in the interior of the Arctic Ocean during the active winter season are required. Observations that best can be made from an icebreaking vessel, either directly or from the ice with the ship as a base.

The Dynamics of Biological Systems in a Sea Ice-Covered Arctic Ocean

Sea ice provides a unique habitat for a variety of organisms, which can serve as a food source or seeding stock for marine life on higher trophic levels.

The first trophic pulse in the Arctic Ocean is represented by phytoplankton primary production, which varies considerably and is described as being dependent upon the day length, the hydrological, hydrochemical and biological factors, as well as the cover and thickness of sea ice.

To improve our understanding of sea ice biota, long-term observations on the development of sea ice communities are needed. For better estimates of the production of the sea ice (sympagic) floral and faunal data are are needed for late autumn, the complete winter and early spring. These are critical seasons since we have no idea of how long the growing season is for sympagic organisms. To obtain quantitative data, stationary ship time at selected flows for 2-3 weeks at a time has to be allocated during those critical seasons.

It is still not clear if sympagic organisms serve as food source for pelagic organisms during wintertime, as was found to be the case for Antarctic sympagic algae. The Antarctic krill (*Euphausia superba*) depends during wintertime on the sympagic production. Similarly the Arctic cod (*Boreogadus saida*) may use sympagic amphipods in the same way.

There is growing evidence that sympagic algae serve as *inoculum* for the initiation of the spring bloom in Antarctic waters. Evidence for the Arctic is extremely sparse and contradictory. Data should be obtained from repeated long-term (3-4 weeks) quasi-stationary ship observations in early spring. Certain amphipod species (for example *Apherusa glacialis*, *Gammarus wilkitzkii*) live only at the underside of Arctic sea ice. After thawing of the ice the fate of these crustaceans is unknown. Are they lost (exported) from the sea ice-covered regions? Again only repeated long-term investigations (3-4 weeks) from a drifting ship during early spring will answer these questions.

For all the above projects we need a dedicated research icebreaker during times when, up to now, no ship is available in the Arctic. Second, for all these investigations longer-termed more or less stationary phases are needed, which have not been not granted in the past on other research vessels.

In winter, nutrients in the water column are abundant as a consequence of vertical mixing, but light is not sufficient for phytoplankton growth (Fig.8). The spring increase of incident irradiance and day length, trigger the start of the growing season. At first the amount and quality of light entering the water column below is strongly reduced by the ice cover: for this reason phytoplankton metabolism under the pack ice is

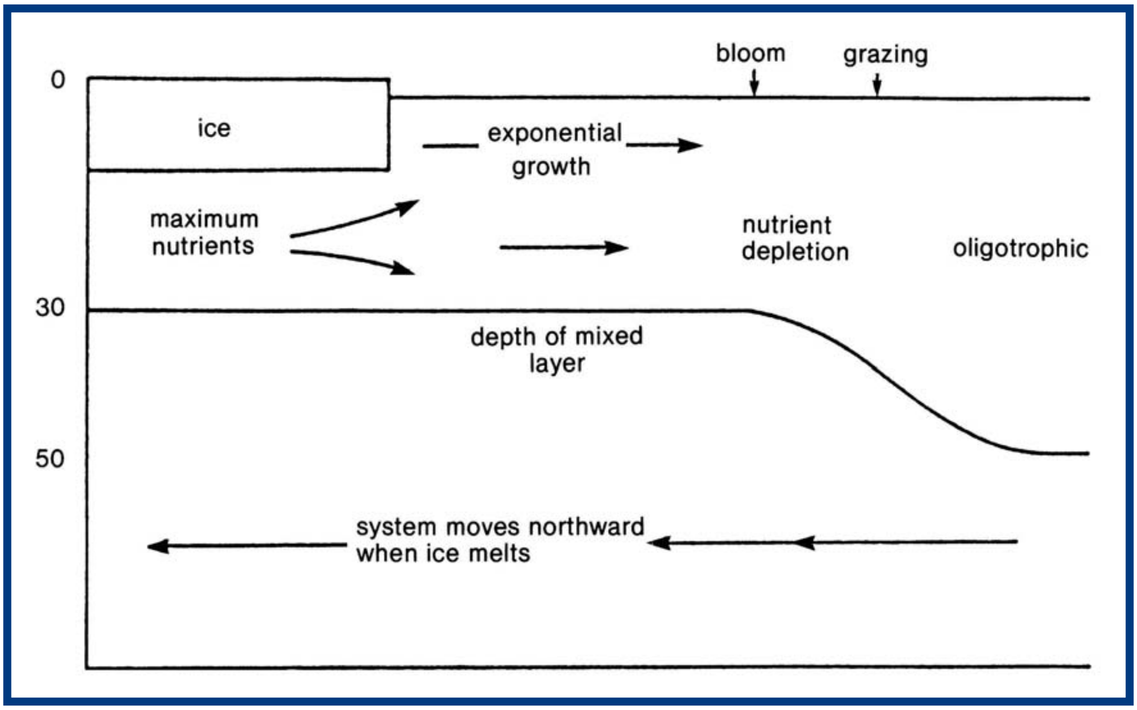


Fig. 8: Schematic illustration of the ice-edge effect. (from Sakshaug, 1990).

very low and most of the algae are found in the ice, clustered in long chains from the undersides of ice, and the communities are mainly represented by colonial chain-forming diatoms (for example *Melosira arctica*). The major input of organic carbon in these ice-covered regions is therefore produced by under-ice flora and also most of zooplankton grazing activity has been observed here (Syvertsen, 1991). The ice melting gives rise to the following changes in the water column: 1) increased light penetration; 2) inoculation of algae from ice; and 3) enhancement of vertical stability that is due not only to freshwater inputs but also to reduced wind stress. Phytoplankton bloom phases, pulsed by diatoms and the prymnesophicaean *Phaeocystis pouchetii*, start at the ice edge but throughout the summer move northwards (Rey and Loeng, 1985; Strass and Nöthig, 1996). Primary production measurements in the marginal ice show high values (up to >1 g C m^{-2} day^{-1}), during the growth season, for example in the Barents Sea (Savinov, 1992), in the Fram Strait (Codispoti et al., 1991) and in the Canadian Arctic (Pesant et al., 1996).

Zooplankton (mainly copepods and protozoans) appears to be able to respond immediately to any increase in phytoplankton biomass and hence grazing reduces the standing stock (Hansen et al., 1995). In the same way the ice melting leaves nutrient-impoverished water behind (Fig. 8). To the south of the ice edge the nutrient depletion at the surface of the open waters is often very pronounced and phytoplankton biomass becomes low, while a deep chlorophyll maximum occurs at the nutricline depth (Sakshaug, 1990). Species composition in open waters is typical of a post-bloom state, mainly represented by auto- and heterotrophic flagellates, large heterotrophic dinoflagellates and several ciliates (Owrid et al., 2000). In these waters the contribution of regenerated production seems to support consistently the net community production within the euphotic layer (Luchetta et al., 2000). Sedimentation rates of living cells from the euphotic zone are low in the open waters and under the thick pack ice and the sinking material consists mainly of faecal pellets (Andreassen et al., 1996), further illustrating the importance of zooplankton grazing (Hulth et al., 1996). It is only at the ice edge that the zooplankton community seems unable to control the spring phytoplankton bloom and the sedimentation of living phytoplankton is therefore dominant and represents the main source of carbon for the benthos.

There is little information for ice-covered regions during the winter; for instance one of the most studied areas in the Arctic (the western and northern waters of Svalbard) lacks the ecological information of the winter periods (Strömberg, 1989). Biologically, sea ice provides a unique environment that is exploited by wide variety of organisms, from bacteria to mammals. The best known of the ice-associated assemblages is that of the ice algae although information on ice fauna and bacteria has been gradually accumulating (Horner, 1990). For this reason winter measurements in the regions north of 80°latitude appear necessary in order to know the ice algae distribution and metabolism and the biology of the water column under the thick pack ice.

Therefore the chance offered by a research vessel working during wintertime can greatly enhance our capabilities to understand the biological dynamics in the Arctic system on a all year-round basis.

Satellite Remote Sensing

Sea ice properties on basin scale can be obtained only by remote sensing techniques which need permanent ground-truthing to assure their quality.

A central task for detecting and understanding the Arctic Ocean system is to determine the sea ice budget. Remote sensing is of outstanding importance in this respect. The following aspects have to be considered:

- extent and area are well observed by satellite microwave data (since 1978) (Gloersen et al., 1992)
- thickness is poorly observed and the main reason why the ice budget is not well known

- present data on thickness are scarce and insufficient to understand the regional and seasonal variability (Wadhams, 2000)
- fluxes through straits are being investigated (Vinje et al., 1998), but are more accurate estimates required?
- what is the contribution of sea ice to the freshwater budget? This brings up the need for more oceanographic data
- how well are coupled ice-ocean models driven by atmospheric forcing able to reproduce realistic sea ice extent and thickness? Validation of such models is of high priority, but availability of good validation data sets is again a key issue
- the relevance of MIZ processes for Arctic ecosystems
- the contributions of sea ice growth, deformation and drift to the redistribution of ice masses in the Arctic Ocean.

Besides the well-established passive microwave system SSM/I which provides data on sea ice concentration and extent, three types of sea ice remote sensing observations are used.

Radar altimetry: CRYOSAT, which will be launched by ESA in 2004 and operate for three years, will be the first satellite which can measure sea ice thickness distribution over practically the entire Arctic Ocean and adjacent seas. The principle of measurement is to estimate the height difference between thick ice (multiyear and thick first-year ice) and open water between ice floes, (Fig. 9). This difference represents the freeboard, which furthermore can be translated into thickness. The assumption for doing this is based on knowledge of ice density and snow cover, but the relation between freeboard and thickness is not yet well established. A single height measurement by CRYOSAT will have an accuracy of about 0.50m, but averaging many measurements in space and time will increase the accuracy to a few centimetres.

Validation of this methodology is essential and can be done only by use of observations obtained from icebreakers, helicopters, fixed-wing aircraft, drifting and moored buoys, etc. A validation programme for CRYOSAT should include:

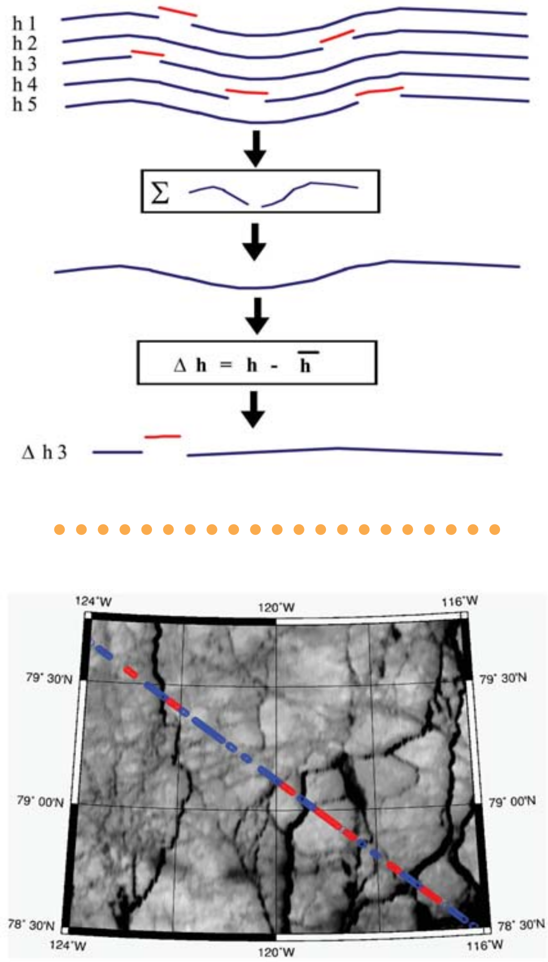


Fig. 9. Classification of radar altimeter signals from ice versus open water/leads.
Top: Specular returns (blue) are used to generate a mean sea surface, which is then removed from individual passes. The elevation difference between diffuse (red) echoes and residual sea surface height is then used to estimate ice freeboard. Currently up to 60 profiles are averaged to obtain a mean sea surface.
Bottom: ERS-1 altimeter footprints crossing sea ice in the Canadian Arctic superimposed on an infrared satellite image. The blue points represent specular reflection from open water or thin ice in leads, while red points represent the return from ice floes giving diffuse echoes (Laxon, 1994).

- ice thickness and surface topography profiles including freeboard data from helicopter using the EMI technique (Haas, 2002)
- snow depth/composition and ice density data to determine the relation between freeboard and thickness
- spatial/temporal statistics on these parameters
- specific data in the transition period between freezing and melting when the radar signal returned from the snow/ice surface is changed.

Laser altimetry: ICESat, launched by NASA in 2002, provides laser measurements of the sea's ice surface. These data can provide information about freeboard in a similar manner to radar altimeter under cloud-free conditions and when there is sufficient light. The laser altimeter will measure the snow surface, whereas the radar altimeter will measure the interface between ice and snow, at least during dry conditions. Estimation of snow depth can, in principle, be done by combining data from ICESat and CRYOSAT. A validation programme for ICESat will be similar to that for CRYOSAT.

SAR imagery: Large amounts of SAR imagery over sea ice have been obtained since 1991 using ERS-1/2 and RADARSAT. However, the validation of SAR signatures of various ice processes (melting, freezing, deformation, etc.) has been done only in a few field experiments. With the launch of ENVISAT and later RADARSAT 2 and 3, there will be new capabilities from the SAR systems (that is, dual polarisation, variable incidence angle, etc.) which will improve the possibility of making a more accurate ice classification and retrieving other ice parameters (leads, ridges, etc.). Validation experiments using icebreakers are needed to establish relations between these ice parameters and the new SAR data. SAR ice classification based on ENVISAT data, for example, can be established as a routine procedure in operational ice monitoring in Europe, similar to that which the US and Canadian Ice Centers are doing by using RADARSAT data. One specific application of the SAR data will be to identify and classify open water/thin ice in leads along the lines of CRYOSAT/ICESat and compare the altimeter signature with the SAR signature. These data will be useful for improvement of the ice thickness-retrieval algorithm for CRYOSAT/ICESat. Another application of SAR ice validation results is in the use of Scatterometer data for operational ice monitoring in the context of EUMETSAT.

Optical satellite data: The major use of optical satellite data occurs through the AVHRR, MODIS and MERIS systems. They provide high resolution visible images of the sea ice which are used to determine sea ice concentration, extent and small scale processes. Use of ocean colour data from satellites can be important for studies of chlorophyll in the open water outside the MIZ, for sediment transport from rivers and other processes in the ice-free parts of the Arctic Ocean. Most of the satellite-derived data will need ground-truthing experiments during all seasons of the year, in the marginal zone as well as in the central Arctic Ocean.

Remote Sensing Validation

Winter Ground-Truth and other Uses of Remote Sensing Data

AURORA BOREALIS will be used as a platform for a variety of satellite remote sensing validation measurements. These are mostly performed by means of helicopter surveys, or in-situ ice core drilling and analysis. Helicopter measurements are most essential for the validation of CRYOSAT thickness retrievals.

- Ice thickness will be surveyed by means of helicopter EM sounding on length scales of > 100km. As the ship serves as a moving landing platform, daily surveys from different take-off locations can enable basin-scale surveys.
- Pressure ridge frequency and distributions and other surface roughness information will be obtained along these profiles as well by means of laser altimetry.
- Nadir video and still photography will also be performed on those flights, allowing for the determination of ice concentration and ice type.
- Systems under development include snow thickness radar and scatterometers, which provide additional information important for the validation and interpretation of CRYOSAT thickness retrievals and SCAR ice signatures. These can be obtained on >100km scales as well.
- Since snow thickness is one of the most important parameters for the accuracy of CRYOSAT thickness retrievals, snow thickness distributions will be measured on ice floes along the ship's track by means of ruler measurements.

- Similarly, ice type, salinity, crystal and pore texture, and density and their spatial variability will be measured with ice cores obtained from floes along the ship's track.
- AURORA BOREALIS as a research platform will permit repeated, systematic thickness profiling across key regions ("hot spot sampling") such as in the Fram Strait or between Greenland and the North Pole, to directly observe the spatial and temporal variability of the ice thickness distribution.

AURORA BOREALIS will contribute to the Global Monitoring for Environment and Security (GMES) ESA/EU programme to promote usage of Earth Observation data for operational monitoring) by obtaining in-situ ice data for monitoring and validation purposes.

Ocean

Arctic Ocean Circulation

Ocean circulation transports heat, freshwater, nutrients, gases and pollutants within the Arctic Ocean and across its boundaries. Variations of these transports affect all elements of the Arctic Ocean system as well as the adjacent ocean basins and have a particularly strong impact on Europe.

The large-scale circulation in the Arctic Ocean consists mainly of basin-scale gyres which are interconnected (Fig. 3). The exchange between the basins may occur either through gaps in the ridges as lenses associated with eddies (Schauer et al., 2002b) or by the boundary current which leads relatively warm and saline water of Atlantic origin from the Nordic Seas through the Fram Strait and the Barents Sea into and around the Arctic Ocean. The Atlantic water recirculates along different paths (Rudels and Friedrich, 2000; Rudels, 2001), undergoing extensive modification. River runoff from the continents adds a significant volume of freshwater, and water of lower salinity is supplied by the Pacific through the Bering Strait (Roach et al., 1995). Deep water from the Eurasian and Canadian basins leaves the Arctic Ocean through the Fram Strait. Upper, less saline, water masses also exit through the Fram Strait and the Canadian Arctic Archipelago into the Labrador Sea.

During recent years significant changes have been observed in the Arctic. They include decadal variations in the atmospheric conditions which affect the Arctic Ocean circulation. A decrease and eastward shift of the Beaufort high in the 1990s is described as part of the Arctic Oscillation, which is related to the North Atlantic Oscillation. Shifts in hydrographic fronts (Carmack et al., 1995; McLaughlin et al., 1996; Morison et al., 1998; McLaughlin et al., 2002) illustrate the effect of variations in the circulation, which can be evidenced in particular for the Beaufort gyre in models (Proshutinsky and Johnson, 1997; Maslowski et al., 2000).

Our present knowledge of the circulation is mostly based on the interpretation of the distributions of water mass properties and on models. Only a few direct measurements exist from moored instruments, which are able to resolve the spectrum of relevant time scales (Aagaard and Carmack, 1994; Woodgate et al., 2001). Those measurements are local and of too short a duration to address climate time scales. Variations on interannual to decadal time scales are evidenced by the variations in the water mass properties. However, due to the observational gaps of up to several years, a serious aliasing problem exists (Karcher et al., 2003). A better coverage exists at the boundaries where current meter measurements are carried out in the Fram Strait (Fahrbach et al., 2001), the Barents Sea opening (Ingvaldsen et al., 2002), the Bering Strait (Roach et al., 1995) and part of the Canadian Archipelago.

To address the variability of the Arctic Ocean circulation large-scale repeat sections (Fig. 10), moored instruments and Lagrangian measurements are needed (Fig. 11a and b). Besides temperature and salinity, natural or anthropogenic tracers (for example Iodine 129) can supply additional information (Smith et al., 1999, Smethie et al., 2000). To map the flow of Atlantic water in the Eurasian Basin, regional surveys along the Eurasian continental slope north of Siberia, extending from the Yermak Plateau to the Lomonosov Ridge with CTD casts from surface to bottom would be needed. SOFAR floats released in the Atlantic core around the Yermak Plateau together with SOFAR tracking stations on moorings are necessary to determine the speed and pathway of the Atlantic water. Sea ice-tethered ocean observation instruments deployed in the Siberian branch of the Transpolar Drift north of Franz Josef Land up to the Laptev Sea would supply temperature, salinity and velocity profiles in the surface mixed layer and the halocline down to the Atlantic layer. Profiling floats for use under ice would be able to extend the observations to deep layers. They are currently under development.

The profiling float deployment has to be repeated over several years and will complement the survey of the global ocean by the ARGO programme. Each CTD survey should be repeated once a year during springtime. New ice-tethered drifters and SOFAR floats should be released every year at the initial positions and the tracking stations should be serviced at the same time.

The required ship time for a transArctic survey is approximately 60 days. However, this will depend strongly on the ice conditions. For the regional surveys about 30 days plus transit time are needed. A particular need is the deployment and recovery of moorings under sea ice, which requires a powerful icebreaker.

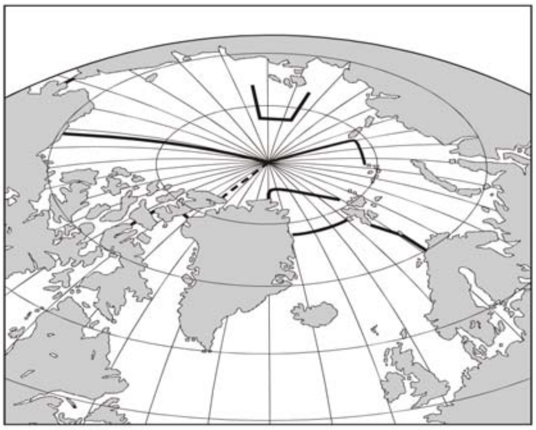


Fig. 10: Hydrographic repeat sections to detect the variations of the water mass properties suggested by the CliC project.

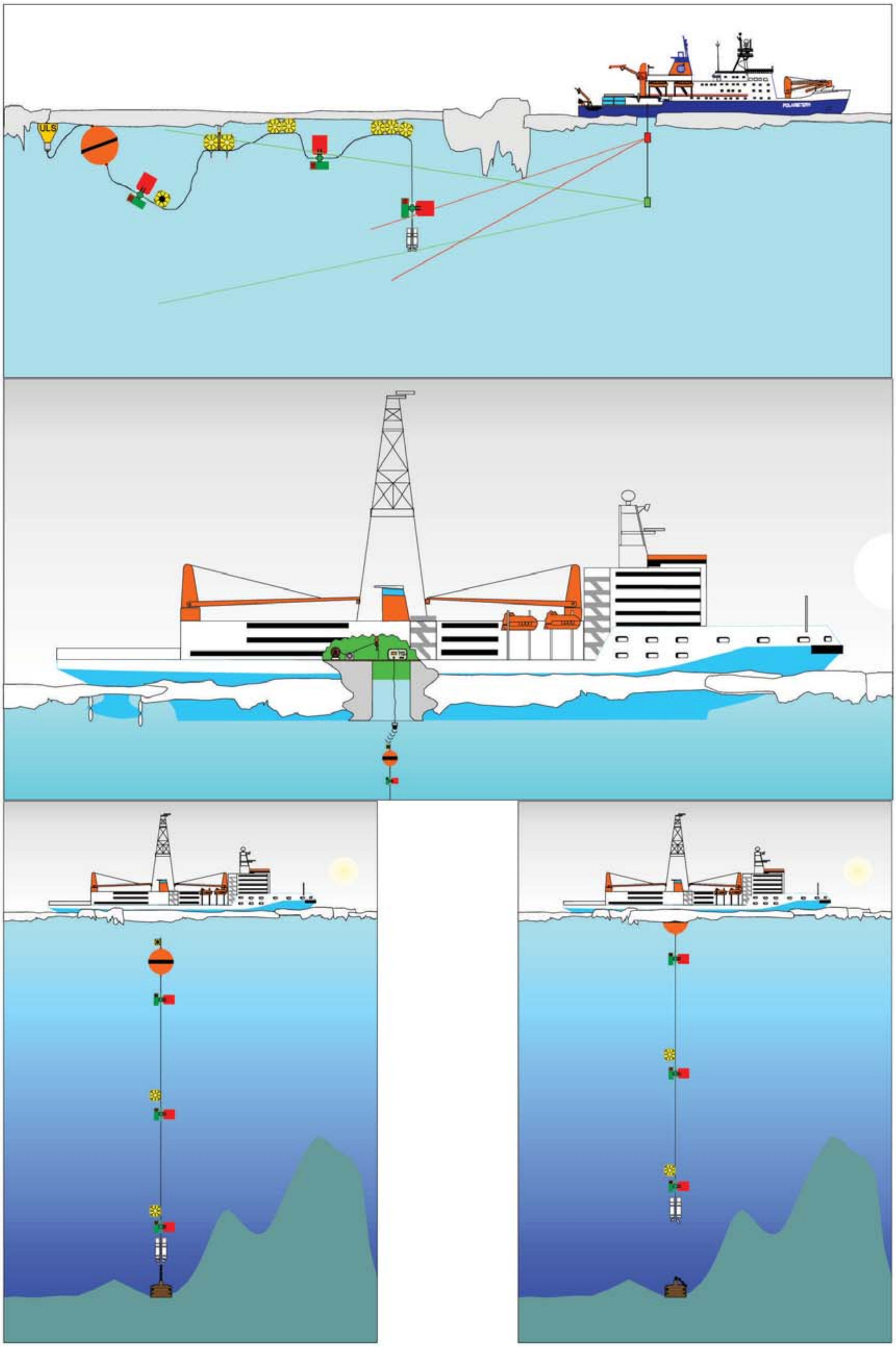


Fig. 11a: see figure legend on the next page (Fig.11b).

Hybrid Arctic Float Observation System – "HAFOS"

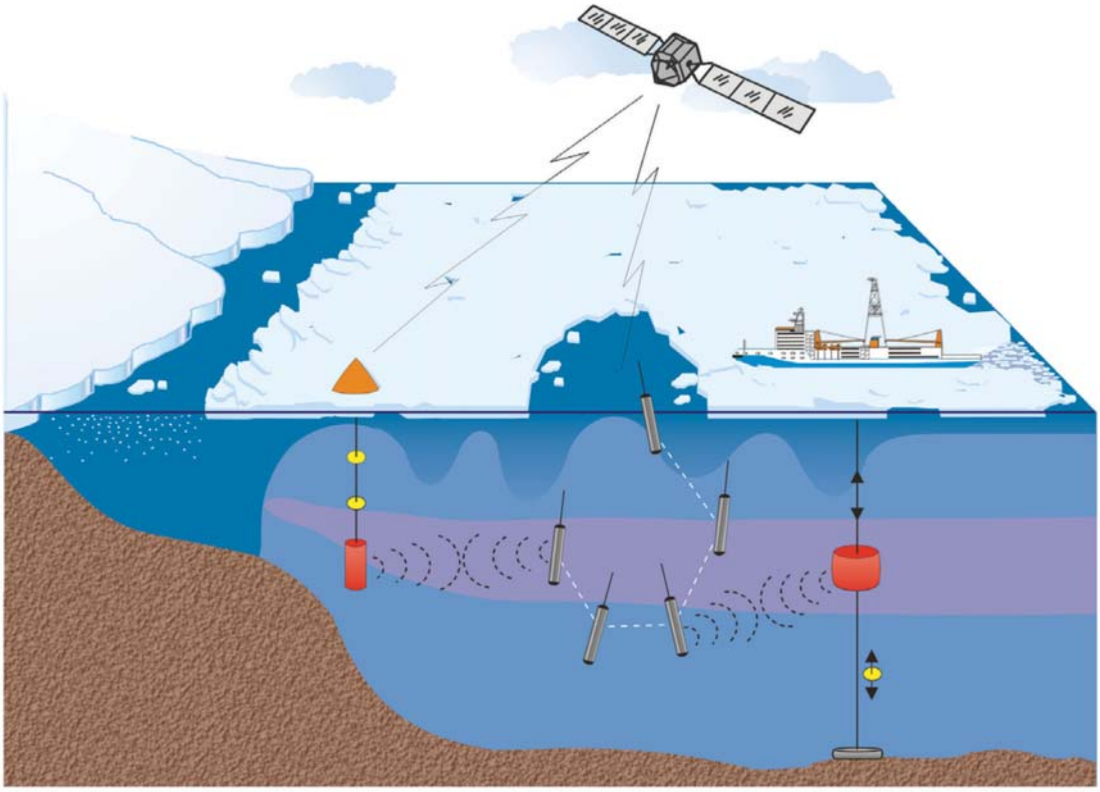


Fig.11 b: Combined observation system with moored instruments, sea ice-tethered ocean instruments and profiling floats in the Arctic Ocean.

Water Mass Conversions on Arctic Ocean Shelves

Water mass conversions on the Arctic shelves control the water properties of the interior Arctic Ocean.

Ten percent of the global river runoff discharges into the Arctic shelf seas. The distribution and modification of this huge freshwater supply are expected to strongly affect the global thermohaline circulation. With the exception of the deep Fram Strait, exchange between the Arctic and the Atlantic and Pacific oceans also takes place across shelf seas (Schauer et al., 2002a; Roach et al., 1995; Gerdes et al., 2003). Before the freshwater input from rivers and the Atlantic and Pacific inflows enter the central Arctic and eventually leave it, they are strongly modified through various processes taking place on the shelves (Bauch et al., 2003; Harms et al., 2003). Depending on the atmospheric wind regime (Atlantic Oscillation), the river water is retained and circulating on the shelves for several years or it enters the central Arctic Ocean more directly (Maslowski et al., 2000).

Shelves are shallow so that tide- and wind-induced mixing may affect the whole water column and convective mixing easily extends to the bottom. Furthermore, latent heat polynias, generated by wind-driven ice divergence, are localised by islands, coasts and landfast ice, which are features of the shelves (Midttun, 1985). Admixture of freshwater and salt release during ice formation are counteracting processes which determine the density of shelf water and thus their ability to ventilate the upper, intermediate and deep layers of the ocean and thereby contribute to the thermohaline circulation.

In contrast to the deep basins, the shelves of the Arctic Ocean are almost ice free in summer (Gloersen et al., 1992). In autumn the water cools rapidly to freezing temperatures and ice is formed. The open water allows larger ice formation per unit area than the ice cover in the interior Arctic Ocean. However, ice is also imported from the deep basins and melts on the shelves. The net annual mean ice production in the deep basins and on the individual shelves and the corresponding freshwater/salt balance is not known.

Many of these processes have been inferred theoretically but detailed observations of the different steps are still lacking. This concerns freezing and brine rejection, convection and dense water accumulation, as well as the mixing and dilution of the dense bottom water with ambient water masses and its advection towards the shelf break. To study these processes, field work during the active winter season is necessary. Ice camps cannot be used without excessive hazard in the marginal ice zones connected with polynias and leads. To reach and operate in these areas in winter requires an icebreaker.

The Role of Polynias for the Water Mass Conversions of the Arctic Ocean

Polynias are areas of extreme atmosphere-ocean interaction, which results in water mass conversions and affects on marine biota.

The sea ice cover of the Arctic Ocean forms an isolating sheet, which effectively inhibits the temperature and gas exchange between the ocean and the atmosphere. In some areas and during certain events, however, the closed ice cover opens and the surface water is exposed to the atmosphere (Lemke, 2001). These open water areas are called polynias when they occur repeatedly at the same location. They form a “window” to the atmosphere where intense thermodynamic exchange can take place (Pease, 1987; Winsor and Björk, 2000).

Polynias are maintained free of ice by two different physical processes (Smith et al., 1990). Heat-sensitive polynias form when relatively warm water upwells towards the surface where it melts the ice cover or prevents ice from forming. Latent heat polynias form in areas where ice diverges as soon as it is formed due to the wind or current field. This process often happens in the lee of islands or along shorelines in the presence of offshore winds (Drucker and Martin, 2003).

During winter, wind-induced latent heat polynias experience strong heat loss to the atmosphere and intense thermodynamic ice production. Brine release and subsequent convection lead to strong vertical mixing which affects the hydrographic structure of the stratified ambient waters below the ice. Latent heat polynias play an important role in water mass transformation and the formation of dense bottom water in the Arctic Ocean and its marginal shelf seas (Cavalieri and Martin, 1994).

Because of severe weather conditions or inaccessibility of appropriate areas, the hydrographic structures in and near latent heat polynias during winter are hardly known. One recurrent latent heat polynia exists in Storfjorden in southern Svalbard where the outflow of dense water was intensively studied (Haarpainter et al. 2001; Schauer and Fahrbach, 1999; Fer et al., 2003). Furthermore, in Whalers’ Bay north of Svalbard the other type of polynia is present. Here the warm Atlantic water of the West Spitsbergen Current encounters and melts sea ice formed in the Arctic Ocean and transported towards the Fram Strait. The melt water is stirred into the Atlantic water transforming its upper part into a cold, less saline layer above the warm, saline core of the Fram Strait inflow branch. This upper layer is believed to be the embryo of the halocline located above the Atlantic layer in the interior of the Arctic Ocean (Rudels et al., 1996), which inhibits the vertical transport of heat from the Atlantic layer to the ice cover and the atmosphere. The primary aim of studying polynias is to especially investigate latent heat polynias and to evaluate their relevance for the climate of the Arctic Ocean. Such studies involve several disciplines. The purpose of the oceanographic work is to:

- capture the mesoscale hydrographic structure in a latent and a sensible heat polynia
- investigate turbulent salt, momentum and heat fluxes during ice formation
- determine temporal and spatial scales of convection and dense plume formation
- observe the temporal and spatial scales of outflow of dense bottom water
- determine the dynamics which control bottom plume propagation and mixing.

Measurements have been possible only since the advent of new ship- and airborne electromagnetic (EM) sensors for accurate ice thickness sounding. The measurements should be performed along extended transects parallel to the main ice drift direction to observe thickness gradients. The thickness measurements should be complemented by measurements of vertical profiles of ice salinity and temperature. Another aim of the measurements is to gather ground-truth data for the development of algorithms to retrieve the relevant sea ice parameters (surface temperature and roughness, thickness) from satellite data (NOAA AVHRR, ENVISAT AATSR and ASAR).

During 2001 the news media reported the disappearance of the ice over the North Pole and the generation of huge open channels. These news reports generated much excitement all over the world although it was due to a natural process. This news event clearly illustrates the ignorance about processes of the formation and maintenance of polynias in the Arctic sea ice cover, in particular during the unfavourable seasons of the year. Multidisciplinary field studies resolving the annual cycle will be needed to study their dynamics.

Ventilation of Arctic Ocean Waters by Shelf-Basin Exchange

Water masses formed on the shelves descend the continental slope in short-lived and small-scale plumes to intermediate and deep layers.

The shelf edge forms a boundary for shelf-typical processes and determines the mechanisms by which central basin and shelf water masses are exchanged. Instabilities of fronts allow upper layer waters to cross the shelf-break and transfer shelf water into the interior Arctic Ocean gyres (Swift et al., 1997). Submarine canyons, such as the St Anna Trough, channel the drainage of dense shelf water and also allow water from central basins to enter the shelf.

The strong stability of the water column in the interior Arctic Ocean limits the local convection to the upper 100m, and the deeper layers are ventilated by advection of dense waters from the Nordic Seas or by dense shelf water convecting down the continental slope. The shelf-basin interactions occur as two types: 1) as injection of water advected from outside the Arctic Ocean; and 2) by the input of dense water, created on the shelves by brine rejection and haline convection in winter.

The strong flow down the St Anna Trough is essentially an inflow from the Nordic Seas, cooled and transformed in the Barents Sea, which merges isopycnally with the Fram Strait inflow branch in the boundary current north of the Kara Sea (Schauer et al., 2002b). The inflow through the Bering Strait is similar to the inflow of the Barents Sea branch, but because of its lower salinity the Pacific water cannot ventilate the deep Arctic Ocean, unless it experiences a salinity and density increase on the Chukchi Shelf caused by ice formation and brine rejection. A density increase partly takes place also in the Barents Sea but ice formation is not necessary for the Barents Sea branch to ventilate the intermediate layers.

Slope convection proper occurs as thin intermittent boundary plumes of highly saline and dense shelf water sink into the deep (Rudels and Friedrich, 2000). Few deep plumes have been observed in the Arctic Ocean and most of what is assumed about their physics and dynamics has been inferred from differences in temperature/salinity characteristics between the deep and intermediate waters in the Arctic Ocean and in the Nordic Seas (Anderson et al., 1999). The slope plumes must, in contrast to the St Anna Trough inflow, be strongly entraining. This implies a substantial one-way exchange between the upper layers and the deep ocean, even if the amount of water that leaves the shelves is small. Slope convection is the main cooling mechanism for the Atlantic layer, either by plumes reaching their terminal depth at the Atlantic layer and merging with the Atlantic water or by denser plumes sinking through the Atlantic layer, entraining and transferring warm water downwards. The high initial salinity of the shelf bottom waters and the entrainment of warm Atlantic water determine the characteristic temperature/salinity properties of the Arctic Ocean deep waters.

To test if the plume hypothesis is tenable, winter and early spring observations at the continental slope are needed, especially close to areas of persistent polynias, where dense water formation is expected to take place.

Determining details of the inflow of the Barents Sea branch in the St Anna Trough (Schauer et al., 2002a) is of equal importance. The Barents Sea branch mainly supplies water to the 200-1 200m layer, but it could occasionally have a denser bottom layer which separates from the main inflow and sinks down the slope into the deep Nansen Basin. Since it enters at a much greater depth (1 000m) than the shelf water it would not entrain the less saline upper water or the warm Atlantic water. It could therefore reach great depths without a strong temperature increase and without having the excessive initial salinities required on the shallow shelves.

The study of slope convection requires the capability to reach the shelf break and the slope in specific regions during winter and also to be able to follow plumes should these be encountered. The ice conditions are expected to be severe. This task cannot be completed from a drifting ice station but only with a manoeuvrable strong icebreaker.

Biodiversity in the Central Arctic Ocean

Since biodiversity cannot be quantified in the central Arctic Ocean the effect of global change on marine life cannot be estimated.

The majority of past expeditions to the Arctic were carried out during the summer season. Therefore, a sound database on the biology of organisms inhabiting the sea ice, the water column or the seafloor is available for many regions of the marginal Arctic Ocean and its surrounding shelf seas during this period of the year. In contrast there are only few and randomly scattered samples taken in the central Arctic Ocean and very little information on seasonal aspects such as reproductive cycles, overwintering strategies and metabolic adaptations during winter is available. Additionally, there is only limited information about species composition and distribution in the three marine sub-systems (cryosphere, pelagic and benthic realm) for the central Arctic. There is scientific evidence from terrestrial ecosytems that higher diversity may keep a system more resilient to disturbances than less diverse systems. Whether or not this holds true for marine systems is uncertain. The few quantitative zoobenthos samples taken in some of the permanent ice-covered regions of the Arctic gave moderately high diversity indices for the macrozoobenthos. Because large motile epifauna organisms modify and structure the sediment surface “benthic engineering”, thus creating microhabitats for smaller species, any loss of large species should consequently also lead to a loss of such habitats and their inhabiting species. Among this systematic sampling of the Arctic marine biosphere one of the main objectives of future research should focus on the possible effects of loss of key species at different trophic levels of the ecosystem as well as on the effects of invading ("alien") species favoured by environmental changes. Special attention has to be paid to the bacterial communities because of their significant contribution to organic matter transformation.

For studies on seasonal aspects of marine biology at high latitudes, the access to a new icebreaking research vessel with a moon pool, the opportunity to operate ROVs and standard sampling instruments would allow the installation of long-term observatories at key locations in the ice-covered Arctic Ocean. Such long-term data is urgently needed to evaluate the actual status of the Arctic ecosystem and to develop prognostic models about its future development. AURORA BOREALIS would be the single research platform which guarantees regular access to pre-selected key locations where interdisciplinary measurement programmes could be initiated. Where to install such observatories will be decided later but the deep basins, the ridges and locations at the continental margin should be considered for this Arctic network. These observatories will include pre-programmed moorings and lander systems, the use of AUVs and ROVs, the latter for video-controlled sampling and experiments (Fig. 12).

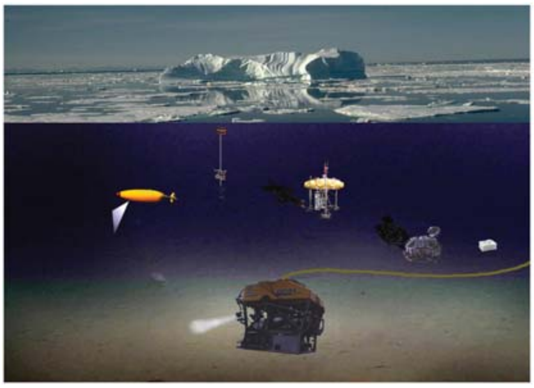


Fig. 12. Illustration of possible instrumentation and vehicles to be used at specific locations in the Arctic Ocean for long-term measurements.

Interactions between Arctic Shelf, Slope and Deep Sea Bio-systems

The transport of dissolved and particulate matter from the Arctic shelves over the slope into the deep sea determine the development of Arctic marine ecosystems.

In contrast to the Antarctic, the North Polar Region is surrounded by landmasses. This peculiarity of the Arctic Ocean implies intense interactions between continental landmasses and the ocean. About 10% of the global river runoff takes place in the circumArctic region, which represents 25% of the world ocean's shelf area. Freshwater discharge has significant relevance for the role of the Arctic Ocean in the global climate system because sea ice formation, primary production and water mass distribution is strongly influenced by river runoff. Additionally, huge amounts of sediments, nutrients and pollutants are introduced from the river mouths via estuaries into the shelf seas and the adjacent deep basins. For the Eurasian Arctic a total annual discharge of 2 960km^3 freshwater containing 115 million tonnes of total suspended matter were calculated (Gordeev et al., 1996). Past European projects such as OMEX (Ocean Margin Exchange) clearly indicated the importance of particulate matter transport from the shelves into the deep sea ecosystem. In the Arctic, the freshwater mixes with marine water on its way to the north, and transformation and sedimentation of dissolved and particulate matter occurs. Marine ecosystems have to evolve along these strong gradients built up by such transformation and mixing processes.

During numerous international expeditions, biological samples were taken and analysed with regard, for example, to species distribution, primary and secondary production during summer months in the ice-free areas of the Arctic shelf seas. Because of the severe ice conditions in winter and beyond the marginal ice zone in summer very little is known about the ecology of biological communities both in winter and in the central Arctic Ocean. Virtually nothing is known about overwintering strategies of pelagic and benthic species, the relevance of fluvial material during winter and how much of the fluvial matter passes through the marginal filter entering the deep basins (Fig. 5) under recent conditions. There is some evidence that the river runoff regime in the Kara Sea is changing, and is most likely explained by enhanced groundwater infiltration due to permafrost retreat (Vörösmarty et al., 2001). However, the gap in current knowledge makes it difficult to assess the role of the Arctic Ocean in the global carbon cycle; for example, does the Arctic act as a net sink for carbon and other material?

Long-term stations at key locations along the continental margins and in the deep basins could be visited for some days or weeks and sampled at regular intervals. Among aspects on how much particulate matter enters the central Arctic, by whom and how it is used and transformed, and what fingerprint does it leave in the sediment record, many biological issues with regard to high Arctic ecosystem functioning could be addressed.

Air-Sea Carbon Dioxide Flux Feedbacks in a Changing Arctic Ocean

The Arctic Ocean takes up carbon dioxide by physical solution and consumption by primary production. Deep water production makes it a significant sink of anthropogenic carbon dioxide.

Today we have a good knowledge of the large-scale fluxes of carbon dioxide in the Arctic Ocean, including the fluxes with adjacent seas and with the atmosphere. For instance the flux of carbon dioxide from the atmosphere to the Arctic Ocean and the Nordic Seas is in the order of 30 x 10^{12} g C yr^{-1} (Anderson et al., 1998, 2000). This is in the order of the world ocean areal average, indicating that the quantitative importance of an ocean depends on its size. What distinguishes the Arctic Ocean from most other oceans is that many of the changes suggested in a global change perspective will have a substantial effect on the air–sea fluxes. We know that a changing sea ice cover could have an effect on the flux, as can a changing transport of warm water from the Atlantic. Furthermore, a change in the climatic environment will likely affect the biological production, also affecting the driving forces of the air–sea carbon dioxide flux. Lastly, a shift in the ventilation of deep and intermediate waters will change the transport of carbon dioxide from the surface waters into the deep, contributing to the sequestration of anthropogenic carbon dioxide.

However, we have no knowledge of the magnitude of these carbon dioxide flux changes, and in some instances we do not even know the direction of such changes. A simple back-of-the-envelope calculation of how much carbon dioxide could be taken up by the central Arctic Ocean if it became ice free resulted in 500 x 10^{12} g C (Anderson and Kaltin, 2001). This is a substantial amount, corresponding to about 10% of the annual anthropogenic emission. This estimate has large uncertainties, but it points to the potentially significant feedbacks that a climate change can have on air–sea fluxes in the Arctic Ocean. Such feedbacks are not included in ocean–atmosphere coupled global climate models.

In order to pin down the quantitative estimates of the fluxes at hand we need to perform two types of field studies. One will be in cooperation with physical oceanographers, looking at the carbon system of the surface waters in conjunction with winter investigations of potential deep water formation regions. The second would be a more biochemically oriented investigation, evaluating how the biota would react to changes in the climatic environment. How will changes in temperature and salinity affect the biological species composition and thus also the vertical transport of particulate organic matter. Also how will the nutrient supply change both the advective input by rivers and oceans as well as through the effects on the strength of the vertical mixing. As in the rest of the global oceans we also have the uncertainty of how the biota will react to a lowering of pH, caused by the uptake of carbon dioxide from the atmosphere. The environmental conditions that could have a feedback on the air–sea flux of carbon dioxide are schematically illustrated in Figure 13.

Much of this research can be performed only by a research vessel capable of doing research all year round in ice-covered parts of the Arctic Ocean. Winter activities are likely to be performed in the rim areas of the Arctic Ocean; while there might be a need to complement these by some field campaigns in the deep central Arctic Ocean, but not necessarily in the coldest part of the year.

In a 10-year perspective there is a need to have three to five field studies for the investigation of each of the above scientific topics. The effect of changes in the physical conditions should be studied in cooperation with physical oceanographers and should be carried out in the autumn, winter and spring. They should focus on three regions, one being the inflowing Atlantic water over the Barents Sea, one a polynia area and one the continental margins of the central Arctic Ocean in areas where shelf-basin interaction is expected. The latter includes the waters north of Severnaya Semlya, north of the East Siberian Islands and the Chukchi shelf slope.

Studies of the biological response require a substantial field programme, which includes the study of how the supply of nutrients is affected both by vertical mixing and by input of seawater and rivers, as well as more biologically oriented studies during early spring. The first type of investigations should be more hydrographically oriented and cover both the shelf seas and the deep ocean, and be performed all year round. The biologically oriented field activities should focus on the early spring to autumn period that also covers the summer season. The area of interest includes the marginal ice zone and the permanent ice-covered waters.

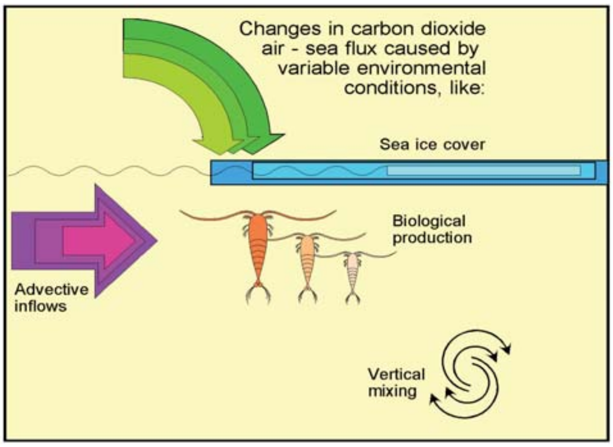


Fig. 13. The air–sea carbon dioxide flux might be affected by changes in the volume flow or properties of inflowing seawater and river runoff, by changing sea ice cover, changing biological productivity, changes in vertical mixing and changing ventilation due to modification in brine production.

Contaminants

Contaminants are transported by atmosphere, ice and ocean circulation through the Arctic Ocean system and affect human, terrestrial and marine life.

The Arctic is a focus for major atmospheric, fluvial, and marine pathways, which result in the long-range transport of contaminants into and within the Arctic. The Arctic is, therefore, a potential contaminant storage reservoir and/or sink. Various processes remove these contaminants from the atmosphere, ocean and rivers and make them available to plants and animals. Food chains are the major biological pathways for selective uptake, transfer, and sometimes magnification of contaminants by Arctic plants and animals, many of which are subsequently consumed by Arctic peoples.

Ocean waters are a major storage reservoir and transport medium for water-soluble persistent organic pollutants (POPs). Sea ice may be important in transporting POPs and other contaminants from coastal sediments during the winter, and from deposition out of the atmosphere, with subsequent redistribution during ice melt. The Arctic Monitoring and Assessment Programme (AMAP) has identified a need for knowledge of ocean transport processes for different contaminants, including ice transport and subsequent contaminant release in melting (focusing) zones. Information on contaminant levels and trends is lacking for certain contaminants and media in the Arctic Ocean. Furthermore, regarding seawater, little is known about concentrations of most organic contaminants in offshore areas within the Arctic Ocean and adjacent seas, especially for PCBs and toxaphene. Profiles of these contaminants, with depth, which would allow estimation of the total mass of these chemicals in the ocean, are lacking. The general lack of information on organochlorines (OCs) in the Norwegian Coastal Current and East Greenland Current is especially critical because of the importance of these currents for inputs to and outputs from the Arctic Ocean. There is no information on fluxes of OCs to marine sediment for any area of the Arctic Ocean. Knowledge of losses via sedimentation and burial are critical to make accurate budgets of PCBs and may also be important for some toxaphene components. It is recommended that sediment cores should be collected at key locations in the Arctic Ocean.

Modern Geodynamics and Hydrothermalism

Part 2

AWI/AMORE

Modern Geodynamics and Hydrothermalism – Introduction

In 1999 and 2001 active volcanoes were discovered at Gakkel Ridge deep beneath the Arctic ice cover, with substantial hydrothermal activity influencing bottom waters.

As an important end member of the global ridge system, as the last geologically and biologically unsampled ridges, as a unique combination of tectonic forcing functions, the Arctic Mid-ocean Ridges are extremely interesting for research. Arctic hydrothermal systems in general have a high probability of supporting novel fauna based on both the relative youth of the basin and ridge system, and their isolation from deep waters of Atlantic and Pacific Basins. The success of future programmes in the ice-covered Arctic depends on new technologies such as the use of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) through a moon pool of a research vessel.

The slowest opening rate of the active global submarine ridge systems is found at the Gakkel Ridge in the Eurasia Basin of the Arctic Ocean with the assumed lowest melt production of the world's mid-ocean ridge systems. The Gakkel Ridge is a continuation of the North Atlantic Mid-ocean Ridge and has been active for the last 56 million years. Its slow opening rate implies extremely low melt production. Geophysical surveys of the oceanic crust generated at the spreading centre suggest thin crust, but a major rock-dredging effort by two icebreakers during the Arctic Mid-Ocean Ridge Expedition 2001 indicated a far more complex situation (Michael et al. 2003; Jokat et al., 2003; Thiede et al., 2002).

Sampling at special sites of scientific interest such as hydrothermal vents (Edmonds et al., 2003) or cold seeps need appropriate techniques. ROVs are proven systems for this kind of video-controlled work even at high latitudes and AUVs are currently underway to become reliable new platforms for a huge variety of sensors. At proposed long-term stations in the Arctic Ocean the installation of autonomous instruments, the deployment of experimental devices, the recovery of data and targeted sampling also needs ROVs. To elucidate the interactions between the broad shelf areas and the deep basins with regard, for example, to the fate of fluvial matter originating from the large Siberian rivers, such observatories are necessary because the transport of freshwater, nutrients, dissolved and particulate organic matter underlies strong seasonal fluctuations. Moreover, according to long-term measurements it seems that the river runoff regime changed over the past decades in a way that more freshwater enters the estuaries because of increased groundwater infiltration due to the retreat of the permafrost.

However, ice cover hampers the use of remotely operated and autonomous vehicles because either the ROV cable is most vulnerable to the ice or the AUV cannot surface after its pre-programmed mission. These problems can be overcome by using a research vessel with a moon pool large enough to launch and recover vehicles up to about 6m in length. Underwater docking stations for AUVs were recently developed and successfully tested in North America and in Europe, hence recovery even under ice cover is possible.

Vent and Seep Communities in the Arctic

Vents and cold seeps can act as major conduits of greenhouse gas methane into the ocean where it is destroyed through microbially mediated anaerobic oxidation.

In 1998 samples were taken by *Polarstern* at the continental slope of the Laptev Sea containing hydrothermal vent fauna specimens. In 2001, during the joint AMORE (Arctic Mid-Ocean Ridge Expedition) expedition of *Polarstern* and the US Coast Guard Cutter *Healy,* a promising list of further indications for active hydrothermal activity at the Gakkel Ridge was found (Edmonds et al., 2003; Snow et al., 2001); for example, many hydrothermal plumes, abundant fresh lava, fresh sulphides probably part of "black smoker" chimneys, the latter verified by a deep sea camera and sensor package lowered to the seafloor from the *Polarstern* that showed intact sulphide chimneys and recorded warm water vents (Snow et al. in: Thiede et al., 2002). As an important end member of the global ridge system, as the last geologically and biologically unsampled ridges, together with a unique combination of tectonic forcing functions, the Gakkel Ridge is extremely interesting for research. The Gakkel Ridge as the northern prolongation of the mid-Atlantic Ridge (Kristoffersen et al., 1982) system has a high probability of supporting novel fauna based on both the relative youth of the basin and ridge system, and their isolation from deep waters of Atlantic and Pacific Basins. Hence, it is likely but yet unproven that other species and life forms evolved under these special evolutionary conditions.

Ten years earlier than the discovery of hydrothermalism in the Arctic, the Håkon Mosby Mud Volcano (HMMV), a methane-releasing point source was discovered northwest of Norway (Klages et al. in preparation.). This cold seep was unexpected because the location of the HMMV is at a passive continental margin whereas many other known mud volcanoes are to be found at active margins. Microbially mediated anaerobic oxidation of methane (AOM) takes place here and is the major biological sink of methane in marine sediments. Hence this process is crucial in maintaining a sensitive balance of our atmosphere's greenhouse gas content. However, a fundamental understanding of the associated biology is still lacking, preventing a thorough biogeochemical understanding of an integral process in the global carbon cycle. In several sedimentary environments AOM can be the dominant sulphate-consuming process; for example, in sediments above gas hydrate and at methane seeps, as well as in the deep biosphere. No data are yet available from mud volcanoes, which are another important geological source of methane. An updated compilation of AOM rates shows that the consumption of methane in gassy sediments is probably several times higher than previously estimated. Detailed studies on cold seeps at either known or yet undiscovered locations along the continental margin of the Arctic Ocean are urgently needed to improve our understanding of the processes and turnover rates which take place there.

The investigation at cold seeps and hydrothermal vent fauna in the Arctic is just at its beginning. Sampling at these special sites of scientific interest with low areal coverage of some square kilometres only, needs appropriate techniques. ROVs are proven systems for this kind of video-controlled work even at high latitudes **(Fig. 14)**. AUVs are currently underway to become reliable new platforms for a huge variety of sensors enabling, for example, the detection of methane plumes or fluids coming out of "black smokers". However, ice cover hampers the use of ROVs and AUVs because either the ROV cable is most vulnerable to the ice or the AUV cannot surface easily after its pre-programmed mission. These problems can be overcome by using a research vessel like AURORA BOREALIS with a moon pool large enough to launch and recover vehicles up to about 6m in length. Underwater docking stations for AUVs were recently developed and successfully tested in North America and in Europe; hence recovery

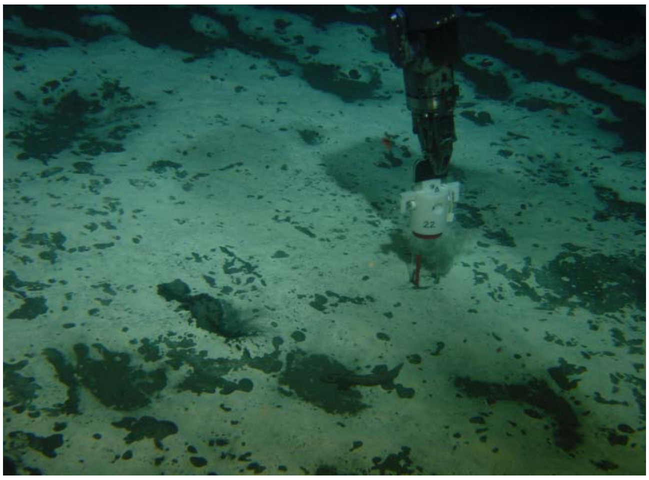


Fig. 14: Image taken at 1 250m water depths northwest of Norway at the Håkon Mosby Mud Volcano (HMMV) in August 2001. The sediment surface is covered with white mats of sulphide oxidising bacteria (probably *Beggiatoa)* which are sampled with a tube corer handled by one of the manipulator arms of the ROV VICTOR 6000 for later analysis in the laboratory. Photo Klages/AWI.

of such vehicles even under ice cover will be possible in future.

Because of the isolated location of the vent fauna along the Gakkel Ridge their investigation offers a unique opportunity to study the evolutionary development of vent organisms comparing the data obtained by applying modern molecular techniques with data from other known vent fields in the Pacific and Atlantic Oceans. This approach would also contribute to answering the question of whether the colonisation of Arctic vent fields is driven by drifting larvae of Pacific/Atlantic origin or not. As in other future research areas, long-term observation at selected vent fields should be possible with AURORA BOREALIS, giving a better understanding of the reasons for temporal variability in fluid flow, its composition and possible effects on associated biological communities.

The Deep Biosphere beneath an Ice-Covered Ocean

The bacterial populations beneath the seafloor are part of an extreme habitat that reaches much deeper than previously thought.

Recent results of ocean drilling revealed that bacterial populations are present to at least hundreds of metres depth beneath the seafloor. This sub-seafloor biosphere is a substantial new habitat on Earth contributing, according to first estimates, about 10–30% of the total biomass on our planet. The bacteria existing there are not just surviving, they are thriving in extreme conditions at these depth reaching surprisingly high abundances of about 10^9 cells cm^{-3} (Fig. 15). They are assumed to have a high but unknown diversity of life forms and biomolecules and are well adapted to life at the extremes. The upper temperature limit of these bacteria is between 100 and 120° Celsius. Therefore, these microbes are presumably involved in several geochemical processes such as modification of minerals and methane formation.

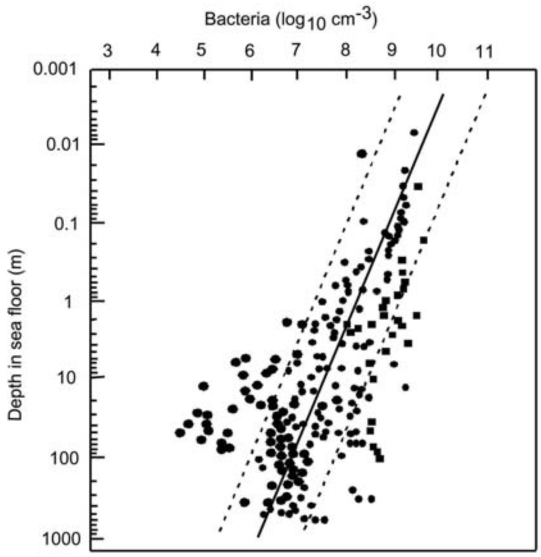


Fig. 15: Depth distribution of bacteria at five locations in the Pacific Ocean (after Parks et al., 1994).

Large bacterial populations were found in close proximity to fossil hydrocarbon stocks suggesting an involvement in hydrocarbon modification. In order to get a better understanding of the processes and organisms involved in the deep biosphere, this discovery is one of the six explicit scientific themes in the long-range ODP plan. The first choice for a deep biosphere-dedicated microbiological ODP leg in 2002 was the Peru Margin because of its extremely organic-rich sediments which receive high amounts of primary produced marine matter from upwelling. A future choice for comparison could be Arctic Ocean sediments because of the strong environmental differences compared to an upwelling system. Among these differences are: 1) central Arctic Ocean sediments receive less amounts of primary produced organic matter; 2) rather low sedimentation rates were measured; and 3) ice-rafted and riverine terrigeneous material distinguish Arctic Ocean sediments from other ocean sediments.

With its drilling capacity AURORA BOREALIS would offer the unique opportunity to sample the deep biosphere in the Arctic with its wide range of sediment types (hemipelagic muds, black shales, siliceous oozes and volcanic materials). With such a technology in the background and the work on hot vents/cold seeps in the Arctic, European scientists would further develop their leadership in the investigation of some of the most extreme habitats on Earth. First sampling sites could be selected in close cooperation with geologists according to their drilling objectives. Some of the main research objectives will be the investigation of microbial methanogenesis at great sediment depth, the identification of physiological and phylogentic differences of bacteria including studies on the limiting factors (temperature, substrate, pressure, etc.) for microbial life in the deep biosphere.

Impacts of the Siberian Shelf Seas

The Arctic system is a sensitive indicator of environmental changes. Understanding the evolution towards the present state of Arctic climate as well as its feedback on the global system is necessary to decipher processes controlling climatic changes.

For a simulation of future development of the Earth's climate after taking into account a greenhouse effect, it is necessary to reconstruct the Arctic environment over the very recent geological time. The Arctic Ocean is surrounded by the largest continental shelves on Earth (Jakobsson et al., 2000). Being both large and shallow, these shelves remain sensitive to sea-level fluctuations. Very large rivers drain onto these shelves, influencing sea ice cover and depositional environments. The shelves, in particular the Laptev Sea and its Siberian hinterland, are considered to constitute a key source for the Arctic halocline's freshwater budget and a major ice production area, linking the Siberian shelves to the Arctic Ocean and the Nordic seas.

There are many areas of land-sea interaction in the Siberian Arctic about which we have little understanding. For instance, our knowledge of the climatic impact on sea ice formation is very limited, making it difficult to predict possible future global climatic changes. This holds true in particular for the Siberian Shelf Seas (Kassens et al., 2002), which, for logistical and political reasons, have long been inaccessible to the international scientific community.

Ecosystems of the coastal zone are extremely sensitive to anthropogenic activities, which drastically increased in scale and rate during the last century. Commercial usage of the Northern Sea Route, extraction of non-renewable resources, particularly oil and gas developments, projects of new infrastructure complexes created new types of interaction between natural and anthropogenic systems.

We need to evaluate the impact of global changes in social and economic systems as well as the response of economic activity and their impact on natural systems. Such assessments will be the scientific basis for an integrated management of the coastal environment.

Overall Research Goals

1. Land-sea connection: present and past natural processes on the Arctic continental margin with particular reference to the effect of riverine and other coastal fluxes.
2. Forcing functions: rate and degree of environmental changes.
3. Arctic processes and climatic change: databases and models for reconstructing the past, understanding the present, and predicting the future.

• *Major research foci*

Evaluation of the environmental variability of the Laptev Sea Shelf polynia, in particular in the area of the Northern Sea Route. The Siberian river discharge is of major importance for the Arctic and global ocean systems (Kassens et al., 2002; Stein et al., 2003). The freshwater input contributes significantly to a strong stratification of the near-surface water masses and, thus, promotes sea ice formation. Changes in the freshwater balance would influence the extent of the sea ice cover. The melting and freezing of sea ice results in distinct changes in the surface albedo, the energy balance, the temperature, and salinity structure of the upper water masses, and of the biological processes. Changes in these export rates of freshwater would result in changes of deep water formation and, thus, in global thermohaline circulation and ventilation. Therefore it is necessary to understand the complex interactions in land-estuary-atmosphere-ocean systems.

• *Dynamics and history of permafrost in the Siberian Arctic*

Permafrost is a particularly sensitive indicator of climate (Romanovskii, in press). Some of the conditions affecting its formation are severe climate, sea-level change, glaciation, and geomorphologic change as in Arctic deltas. The potential for climatic change will have serious local and global consequences. Climatic warming will influence permafrost to varying degrees by increasing active-layer thickness, increasing rates of peat and gas hydrate decomposition and the subsequent release of carbon dioxide and CH_4 increasing the amounts of thermoerosion and sediment transport. These responses would have secondary and tertiary affects through changes in channel morphology and transport of nutrients from the terrestrial system, through the aquatic to the marine system.

• *Sinks and sources of carbon and nutrients in high latitude northern Eurasia*

The Arctic rivers transport large amounts of dissolved and particulate material onto the shelves where it is accumulated or further transported by different mechanisms (sea ice, icebergs, turbidity currents etc.) towards the open ocean. Thus, river-derived material contributes in major proportions to the entire Arctic Ocean sedimentary and chemical budgets. However, the sources and sinks of carbon and nutrients from the Eurasian watersheds to the Russian Shelf Seas is poorly known (Stein et al., 2003).

Seafloor Processes with a Geological Impact

The major traits of the gross physiographical features of the Arctic Ocean are shaped by plate tectonics and the impact of sedimentation and erosion along the seafloor. All of these processes are poorly known in the Arctic and need thorough efforts of study.

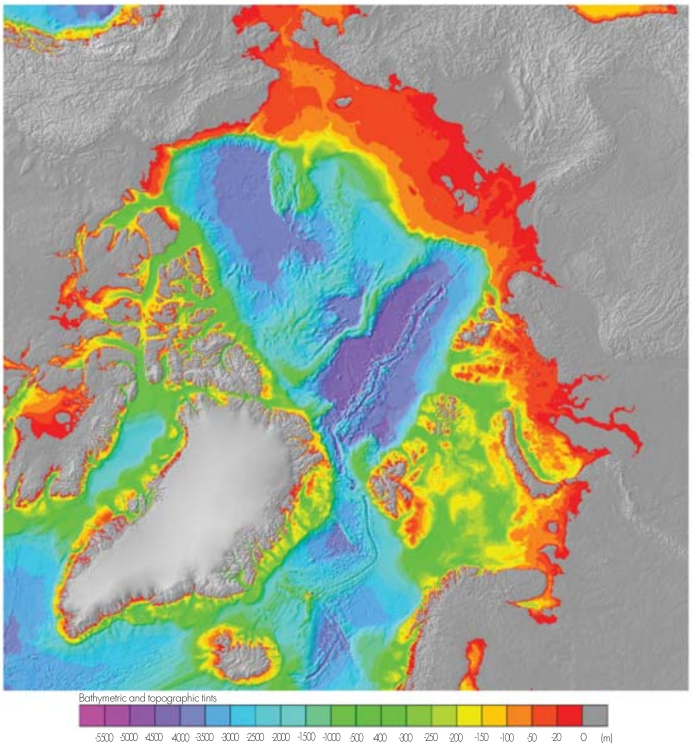
We know that large amounts of fine-grained clastic sediment materials included in sea ice as well as coarse material, transported by icebergs, reach the central part of the Arctic Ocean, where they apparently melt out of the ice and rain down to the seafloor. Neither of these properties is properly quantified (Pfirman et al., 1990; Nürnberg et al., 1994).

Due to the presence of permafrost, large segments of the Arctic coasts and hinterland consisting of ice complexes, which are currently degrading rapidly, plus huge quantities of sediments are made available for sedimentation either in or on the ice or on the shelves infront of the coastal sections. The sediments comprise high proportions of organic materials and they are, together with the sediment load of the river waters, transported out to the shelf where they are distributed or re-distributed. It is unclear how they reach the shelf edge but the morphology of the shelves is either characterised by the relatively recent existence of an ice sheet generating a highly irregular topography, or by wide, shallow shelves, which allow the tracing of former river valleys that existed during the last glacial maximum when sea level was approximately 130m below contemporary levels. Signs of erosion on ridge crests and rises have been observed occasionally and it is yet to be resolved if this erosion is due to the ephemeral existence of ice shelves over the Arctic Ocean, due to giant icebergs or due to bottom scavenging of currents (Jacobsson et al., 2002). The erosion processes, generated under the fast ice along the coast and by the drifting sea ice, need to be defined and further studied. Apparently the presence of the ice and its erosional/depositional effects result in a slightly different hypsograph curve of the shallow parts of the shelf.

The deep basins of the plate tectonically young eastern Arctic Ocean Basin and of the tectonically old Canada Basin are covered by turbidite sequences and the results of the slumping processes along the adjacent continental margins; they have yet to be quantified in terms of timing and regional distribution. Both in the Canada Basin as well as in the eastern Arctic Ocean turbidite sequences are up to several thousand metres thick, their source regions and reasonable detail are yet to be resolved. Many of these questions have to be addressed, probably by detailed studies to be carried out by deep-towed tools or by seismic reflection profiling. The currently available database is far too scant to gain a detailed picture of sediment distribution and their source regions (Weber and Sweeney, 1990). It will require a multiyear effort to establish this database and to relate physiography of the seafloor surface as well as sediment input to the major processes controlling their distribution.

The Arctic Ocean and its Geological History

Part 3



IBCAO

The Arctic Ocean in Geological History – Introduction

The structure and history of the deep Arctic Ocean seafloors can be addressed by means of geophysical measurements as well as by sampling by scientific coring and drilling.

Various aspects of the geological history of the Arctic Ocean have been dealt with many of the planning documents for the Nansen Arctic Drilling Programme (NAD), which published its Science Plan in 1992 (Thiede and NAD Science Committee 1992), by the Arctic Programme Planning Group, who published its Report in 2001 and by the Arctic Detailed Planning Group for Lomonosov Ridge drilling, which published its Science Plan (Fig. 17).

The Arctic Ocean presents a number of aspects that are truly unique in a global context and where the basic approach requires sampling by scientific drilling. A long-term strategy for its investigation will require study (Fig. 16):

- the tectonic evolution of a land-locked deep polar basin containing a distinct polar water mass
- the palaeoceanography and teleconnection to the world ocean
- the Arctic climate history as the global climate changed from general warmth to the Cenozoic "ice house world" of today.

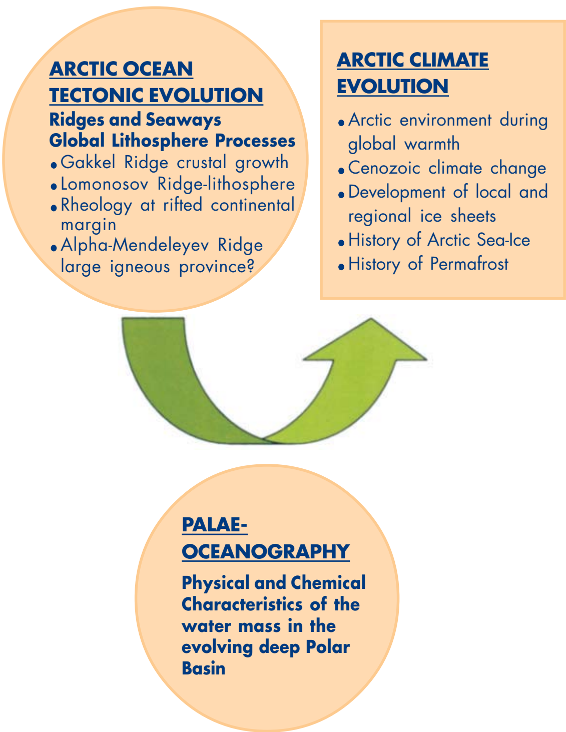


Fig. 16: Arctic geological systems.

The Formation of the Arctic Ocean Basin

It has been postulated that the initial formation of an isolated Arctic polar basin occurred during the Late Jurassic/Early Cretaceous (about 140 million years ago) by rotation of a landmass, comprising the present Alaska and Chukotka, away from the Canadian Arctic islands and creating the Amerasia Basin in its wake.

Almost nothing is known about possible water mass connections to the Pacific, but a shallow seaway was present through North America. Critical events in the geological evolution of the deep polar basin included the formation of three large submarine ridges of alpine proportions (Alpha-Mendeleev Ridge, Lomonosov Ridge and the modern Gakkel Ridge), each manifesting fundamentally different lithosphere processes during plate motion.

• Lomonosov Ridge and lithosphere rheology during the rifting process

Conceptual models of lithospheric strength predict that failure during rifting should occur on the continental side of a continent-ocean crustal boundary. All available geophysical data suggest that the Lomonosov Ridge is a sliver of continental crust and therefore potentially the most outstanding example anywhere in the ocean for testing this hypothesis.

We need to establish the nature of the crustal framework and tectonic history of this 1 500km-long structure by geophysical surveys and scientific drilling. A first attempt at drilling the Lomonosov Ridge will hopefully be attempted by IODP in summer 2004.

• Alpha-Mendeleev Ridge – a large ingeous province or a more complex feature?

Large igneous provinces (LIPs) are accumulations of mafic rocks formed by processes distinct from those associated with plate movements. At times in the past, particularly during the Cretaceous, the mantle flux associated with the emplacement of LIPs, may have exceeded that associated with the global mid-ocean ridge system. Therefore, LIP emplacement is an important factor in determining global geochemical cycles.

The Alpha-Mendeleev Ridge, a lithosphere feature stretching across the Arctic Ocean Basin, may represent a Cretaceous LIP and be coeval with a major magmatic episode in the Canadian and Russian Arctic islands. The principal support for this theory comes from seismic refraction studies, which indicate a crust approximately 40km thick with a structure similar to that of other oceanic LIPs. However, a continental origin of parts of the ridge is also a possibility.

The Alpha-Mendeleev Ridge needs to be sampled by scientific drilling because of its large size compared to other LIPs as well as its importance to meaningful reconstructions of the Arctic Ocean Basin.

Changes in Arctic Hydrography

At present there are only eight rock samples and/or short sediment cores, recovered by chance, to document the Mesozoic Arctic Ocean environment during the initial event when the Amerasia Basin formed.

The occurrence of black shales is considered to represent oxygen-deficient conditions along the flanks of islands on the Alpha Ridge about 80 to 85 million years ago. Subsequently, the presence of laminated siliceous oozes, more typical of environments of temperate latitudes, is indicative of an Arctic Ocean upwelling system. The second event in the birth of the polar basin was the formation of the Eurasia Basin, by extension of the North Atlantic seafloor spreading into the Arctic region between Svalbard and Greenland by about 56 million years ago. A deep teleconnection between the Arctic Ocean and the world ocean was established sometime after about 40 million years ago by the opening of the Fram Strait, and today the polar basin is part of the source region for bottom water renewal in the global ocean. On the Pacific side, the shallow seaway through the Bering Strait formed after about 5.5 million years ago. The change from a temperate Mesozoic and early Cenozoic global environment to the modern extreme is one of the most exciting and least understood chapters of Earth history. In spite of our efforts so far, a key to understanding the Mesozoic and Cenozoic Northern Hemisphere conditions in general, and polar palaeoceanography in particular, is still hidden in the sedimentary sequences of the Arctic Ocean itself.

Extreme Climates – Learning from the Past to Explain the Future

The present-day Earth is in a state of extreme climate condition. To understand how this evolved, how this condition has been maintained and how it might end is a research priority for the international scientific community under the new IODP Plan for the understanding of global change.

Thermal maxima occurred during the period 120–100 million years ago, and at about 50 million years ago. Subsequently, the Earth's climate gradually went into an "icehouse" state with major shifts taking place at about 34, 26, 14 million years ago and 2.5 million years ago. Today, the Arctic Ocean is the primary Northern Hemisphere heat sink and an important challenge is to develop a qualitative understanding of the underlying mechanisms for maintaining polar warmth in the past. The evolution of Northern Hemisphere glaciation is complex and local ice sheets may have developed before 10 million years ago. A dramatic influx of ice-rafted debris from the continents into the ocean basins signalled an intensification of glaciation in the north 2.5 million years ago. Recent surveys by submarines and by sediment sampling demonstrate that icebergs with drafts of up to 1 000 m have ploughed furrows in the bottom sediments on top of the Lomonosov Ridge in the central Arctic Ocean within the last few hundred thousand years. We still know very little about the history of sea ice cover in the Arctic Ocean. The permanent sea ice cover has a tremendous influence on the albedo, atmospheric circulation, and distribution of fresh water. New geological results from areas of high sedimentation rates hold promise for documenting the relative strength of the Beaufort gyre and the Transpolar Drift on a thousand year time scale and provide crucial insight for understanding the variability experienced during historic times. While the recently observed polar warming is dramatic, the new micropaleontological data suggest that mid-Holocene Arctic Ocean water temperatures may have been 5°C warmer only a few thousand years ago. Our primary challenge is to document the high Arctic environment in time and space in order to understand whether the Arctic Ocean influences changes in global climate or how it responds to these changes.

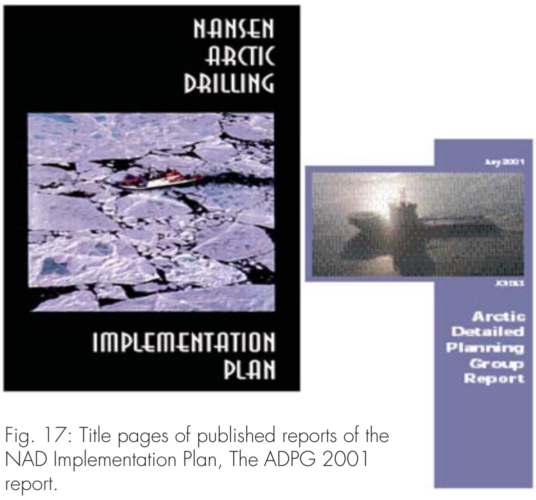


Fig. 17: Title pages of published reports of the NAD Implementation Plan, The ADPG 2001 report.

The Stability of the Offshore Permafrost

Terrestrial permafrost is an important feature of the major landmasses of the high northern latitudes.

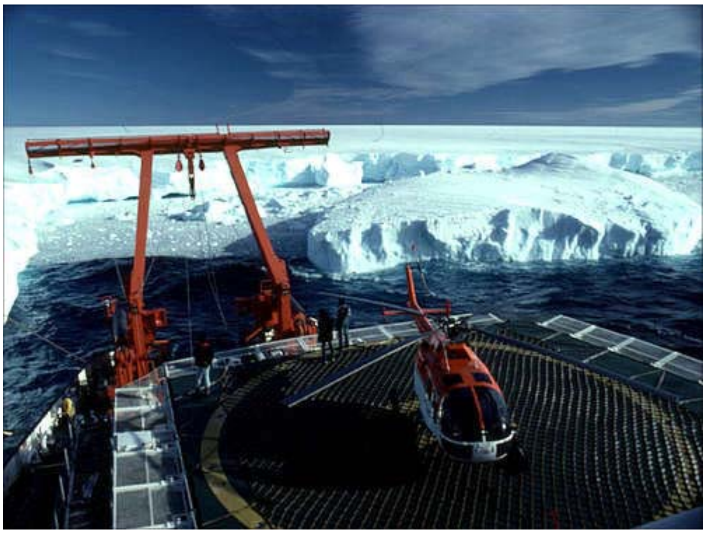
Permafrost extends across Central Asia and central North America far into low latitudes and seems to have evolved as a result of the late Cenozoic climate regime. Relatively recently large tracts of submarine permafrost have been detected in the Arctic Siberian Shelf Seas, which comprise former land surfaces due to the lowered glacial sea levels (Romanovskii, in press).

This must have occurred frequently as a consequence of the repeated glaciations, affecting in particular the large landmasses on the Northern Hemisphere. Permafrost is outcropping in many places at the modern sea surface, and the observations of the karst phenomena in the seafloor and of disappearing islands document the fact that not only the terrestrial permafrost areas are retreating quickly today but that the submarine permafrost areas are also subject to degradation during the modern warming.

The submarine permafrost regions and segments have been sampled only in a few geotechnical drill sites with no real attempts made to date the sediments of the ice complex. Only recently has drilling been carried out in the Laptev Sea, which permitted the dating of the surface layers of the submarine permafrost. C-14 ages of the surface layers pointed to the fact that they developed during the last glacial maximum (Kassens, personal communication). However, very little is known about the extension and thickness of the submarine permafrost areas, in particular nothing much about the timing and the processes of their formation. It would therefore be an important task, both in terms of paleoclimatic studies as well as in terms of documenting the potentially occurring gas hydrates, to investigate the structure, origin and history of the submarine permafrost regions and to compare the features with their terrestrial counterparts. Little can be achieved without having research vessels with a substantial drilling capability at the disposal of the researchers.

Technical Requirements for Achieving Arctic Science Goals

Part 4



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Technical Requirements for Achieving Arctic Science Goals – Introduction

The scientific necessity and the general research requirements for the AURORA BOREALIS project are demonstrated in Parts 1-3 of this report, which provides a scientific vision and justification for a unique infrastructure solution. **The project calls for a multipurpose all-season icebreaking research vessel with a drilling capability.**

The vessel should be able to support experiments for all existing marine disciplines: physical oceanography, biological oceanography, marine geology (including drilling), sea- and air-chemistry, marine geophysics, meteorology and more. As a multipurpose vessel specific equipment will be installed only if it cannot be supplied within specific lab-containers. This implies sufficient space and supplies (water, electricity, data and more). Furthermore it has to be ensured through a modularised construction that future modernisation of the ship and equipment will be as easy as possible.

An absolute condition for such a multipurpose icebreaking research vessel is a very good manoeuvrability on transit as well as on station within open and ice-infested waters – without additional icebreaker assistance. This includes dynamic positioning in open and ice-covered waters and the ability of slow motion for longer time periods. The ship has to be economical, reliable, vibration-free, of low-noise and hydro-acoustically silent.

In a global sense there is no research icebreaker of the required power and capacity available for carrying out year-round scientific missions within the Arctic Ocean. And there is currently no vessel strong enough for drilling and operating automatically in ice-covered waters, such as the central Arctic Ocean. Even when assisted by icebreakers any drill-ship must have a highly ice-strengthened hull to resists the ice pressure of the central Arctic conditions.

This requires the development of a new, tailor-made multipurpose research platform with state–of-the-art equipment such as that proposed in the AURORA BOREALIS project described in more detail below. The scientific requirements of this ship are unique in that the propsed tasks currently cannot be performed from any other research platform in the world. The planning and the final construction therefore implicate different technical solutions: 1) new developments, which should be tested as far as possible beforehand, for example within a study for tendering the ship's construction; 2) developments and the potential of existing technical features; and 3) state-of-the-art technical features, as found on already-existing scientific platforms. In the list below all requirements are listed and graded with **ND** – new development, **DT** – development of existing technical facilities and **SA** – state-of-the-art technical aspects.

Mission Types for the AURORA BOREALIS

As outlined in the science part of this perspective, there is a wide variety of scientific disciplines requiring a range of technical capabilities from this ship, which in general has to be powerful enough to operate year-round in the central part of the Arctic Ocean as well as be able to maintain station by dynamic positioning. Several mission types can be envisaged as deduced from the scientific requirements outlined above:

- ***Summer missions to the Arctic Ocean, for drilling, for site surveying and for classical polar research disciplines.*** The ship will be operating in any waters encountered, both ice-covered and open water, and will have to be able to use its dynamic positioning system and to traverse areas of old ice (that is to say with the mean thickness of 2m and more). The duration of such missions can be from 2 to 3 months.

- ***Summer missions purely for drilling***. The main use during the optimal ice season will be devoted to carrying out the drilling programme as a mission-specific platform for IODP. This will require outfitting the ship with a removable drilling rig, which has to be protected against bad weather and with a suite of laboratories dedicated to the drilling task. The ship needs to carry provisions in terms of fuel and food (for the increased equipment and personnel devoted to science and drilling), as well as lab supplies.
- ***For winter, autumn and spring missions to the central part of the Arctic Ocean.*** These missions will be mostly devoted to the classical polar research disciplines, requiring a floating platform. Some of the disciplines have indicated that they may have substantial use for the lifting capabilities of a derrick and this has to be evaluated if the drilling derrick is removed during each winter season. The ship will be equipped with the mission-specific suite of laboratories and it will be operating in any Arctic waters even under heavy ice conditions.
- ***Year-round mission in the Arctic Ocean.*** At the present time no plans have been developed for a long-term deployment (more than 6 to 12 months) for a ship in the Arctic. Such missions may be needed in the future for Arctic exploration and the ship needs to fulfil its scientific requirements for such missions.
- ***Year-round missions in the Atlantic Ocean.*** The AURORA BOREALIS will also be used as a regular research vessel in ice-margin areas and it needs a reasonable transit speed and securing behaviour (roll-damping devices) as well as dynamic positioning.
- ***Antarctic missions.*** At the present time the AURORA BOREALIS is thought of as a dedicated Arctic research vessel in use for a decade or more. However, if urgent scientific need arises and if the members of the AURORA BOREALIS consortium are willing to devote its ship-time to the Antarctic, it should be able to fulfil the technical requirements of Antarctic research work too. They will be rather similar to the Arctic requirements with the exception that the seas of the Southern Ocean are rougher. A particularly attractive aspect is that the AURORA BOREALIS will be able to address Antarctic deep sea drill sites, which cannot be reached by either the classic type of JOIDES *Resolution* operation or by a system like the Cape Roberts Project (CRP) system, which operates from the sea ice.

Technical Requirements for Marine Geophysics

Marine geophysical surveys and conventional gravity- and giant piston coring (for example with the French Calypso-system) are a prerequisite to selection of optimum sites for scientific drilling. Site definition often requires several seasons of data collection and is urgently needed for justification of a long-term scientific drilling effort in the Arctic Ocean. Foremost, we need to further develop the, technically difficult task of seismic data acquisition from a single vessel to the point where it can be done at maximum propulsion capacity of the vessel with minimum loss of scientific equipment.

The need for a substantial effort to acquire geophysical regional and site survey data was established at a JEODI workshop in Copenhagen in January 2003 (see Appendix II). The site surveys will either cover new regions or will refine and look for new targets based on the drilling results gained with AURORA BOREALIS. The ship must therefore also have the ability to carry out geophysical investigations (seismic reflection and refraction, gravity, magnetic, swath bathymetry mapping system, sediment echo sounder). This includes facilities for remotely operated vehicle (ROV) deployments for precise bottom sampling.

Alternative Solutions

There are naturally a limited number of alternative solutions to fulfil the requirements of the science as defined in Parts 1-4 of this Science Perspective. For example, heavy duty icebreakers can be adapted to scientific work, commercial drilling platforms can sail (or be towed) into the central Arctic under substantial icebreaker assistance, etc. None of these solutions can match a new, dedicated research icebreaker with a deep drilling capability because they:

- will lead to occasional peaks in research efforts in the Arctic, but not to a substantial and continuous, uninterrupted science effort in the central Arctic
- do not comprise the novel technology needed for an effective execution of the envisaged research programme
- do not guarantee the long-term commitment to support a substantial and dedicated drilling effort in the Arctic deep sea
- do not lead to the establishment of substantial research programmes devoted to the central Arctic.

Technical Requirements for a High Arctic Drilling Vessel

The principal requirement is an icebreaking research vessel with the ability to operate in the high, ice-covered Arctic. It must be equipped with a drill rig, heave compensation system, a moon pool, and dynamic positioning. The rig should be able to support a drill string for continuous coring down to 1 000m below the seafloor, ideally in water depths of 3 000m.

The main requirement is a ship with icebreaker capability, equipped with a moon pool, precise dynamic positioning, a drilling system, and excellent heave compensation. Successes in the Cape Roberts Project, where core recovery, even in poorly consolidated strata was well in excess of 90%, showed the value of having an effective riser system.

In the Antarctic, wherever one might be drilling at sea, there must be concerns about interference from icebergs. This applies in the Arctic to a far lesser degree. Therefore, time in the hole should be kept to a minimum. Existing seismic surveys reveal extensive gently dipping sequences that would lend themselves to investigation by a series of short holes(few hundred metres) sited down-dip and with stratigraphic overlap.

A state-of-the-art wireline logging facility is critical to achieving the best possible correlation between holes, as well as providing information on any sections lost in the coring.

With careful selection of sites and targets, the ability to drill to 500m or more below the seafloor would open up enormous possibilities.

AURORA BOREALIS Conceptual Study

A preliminary conceptual study by HSVA showed the general feasibility of the required icebreaking research platform as well as its ability to operate in the central Arctic without additional icebreaker assistance. The main feature of the study is a new hull with strong sloped side walls for sideways breaking during dynamic positioning in ice-covered waters **(Fig. 18)**. The main features and some important particulars are listed below and graded **ND**, **DT** and **SA** whenever necessary and possible.

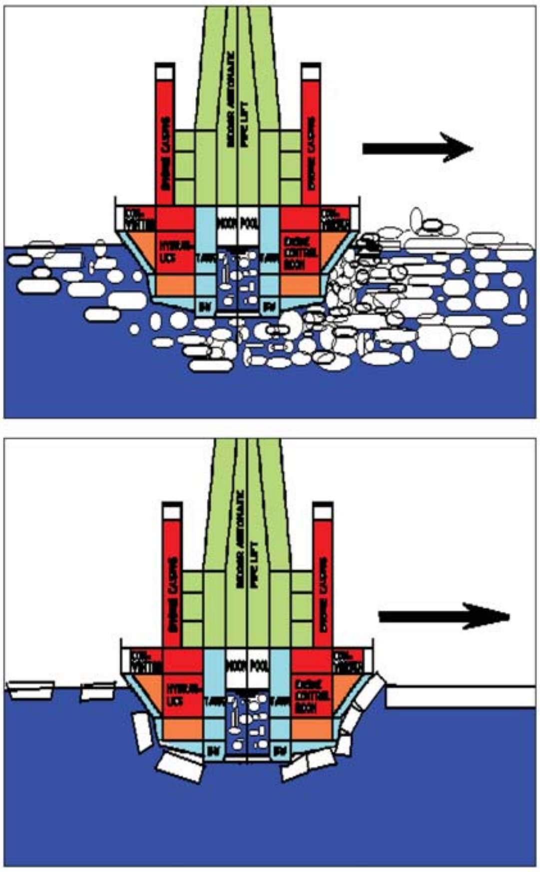


Fig.18: Cross section of AURORA BOREALIS.
Note: (1) the sloped side walls for sidewards ice-breaking during dynamic positioning in ice-covered waters, (2) the double hull for safety of the ship, (3) the derrick with the upper part removable or retractable.

Main dimensions

- Length between perpendiculars Lpp 132.0m
- Beam (main deck) 40.0m
- Beam CWL 36.0m
- Draft CWL 8.5m
- Depth to main deck 13.5m
- Max. displacement approx. 2 3000.0 tonnes
- Ice-class as high as possible (ND)

Mission profile

- Endurance at of total installed power 18000nm (DT)
- Duration 60 days (DT)
- Max. speed 15kn (DT)
- Cruising speed 12kn (DT
- Minimal speed 0 – 2kn (DT)
- Personne total 200 persons
- Fuel Capacity approx. 6000

Icebreaking performance

- Ahead and astern icebreaking (winter ice) 1 Knot >2.0m (DT)
- Dynamic positioning in ice-covered waters (slow-motion ice-breaking) (ND)

Nautical equipment

- 2 radars (SA)
- GPS/Glonass (SA)
- Sonar (SA)
- Speed log (SA)
- Clinometers (SA)
- Gyro and necessary nautical instruments (SA)
- Ice-forecasting system (DT)

Hull design

- New hull with strong sloped side walls for sidewards icebreaking during dynamic positioning with both sterns optimised for icebreaking and open water operations (ND)
- Low noise possibility for seismic work (DT)
- Channel-clearance behind the ship for seismic work (DT)
- Twin hull, ballast or void space for safety reasons (DT)
- Minimum two compartment vessel for safety reasons (DT)
- Helicopter deck and hangar (SA)
- Special painting ('green ship') or stainless steel plated hull (DT)
- Survivability compartment inside the vessel
- Working deck area covered (DT)

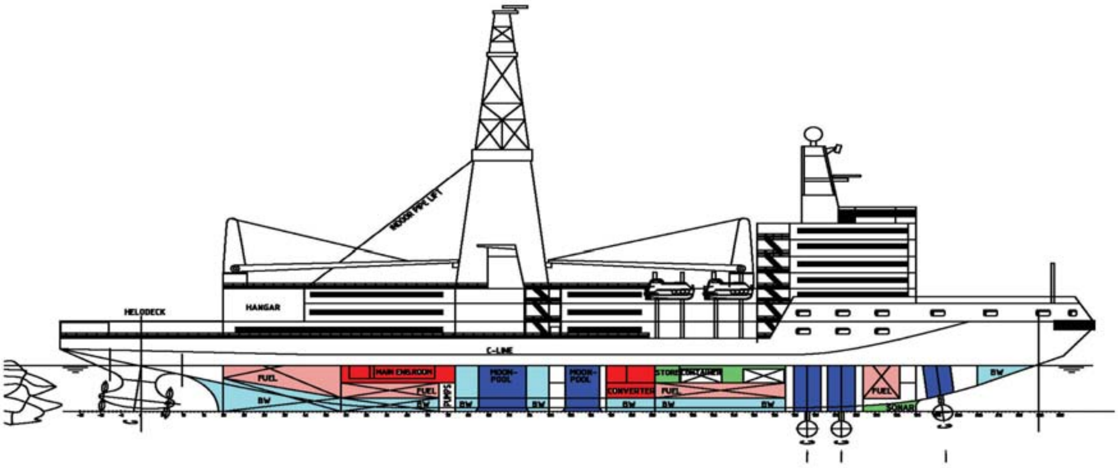


Fig. 19: Side-view of AURORA BOREALIS: Note: (1) covered working deck aft area with sliding beam, (2) azimuth propulsion at stern, azipod with one propeller counting forward during normal operations, turned astern during transit in shallow waters, (3) retractable bow thruster, (4) both sterns optimised for icebreaking and open water operations, (5) derrick with automatic pipe supply.

Machinery

- Diesel electric (see Fig. 19) (SA)
- Diesel generators 6 x 5 MW (SA)
- Diesel generators 4 x 2.5 MW (SA)
- Total installed power 50 MW (SA)
- Redundancy (minimum two engine and two control rooms) (SA)
- Closed (or partly closed) cool water systems (DT)
- Emissions as low as possible (DT)
- Vegetable oil for lubrication and hydraulics (DT)
- Closed water system for grey water (DT)
- Combustion plant (DT)

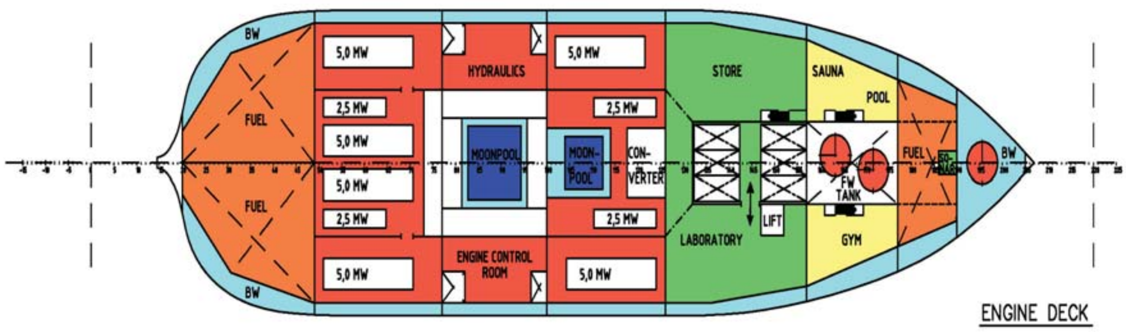


Fig. 20: Engine deck. Note (1) two large moon pools, (2) redundant machinery, (3) machinery in smaller units for economical performance, (4) huge laboratory section.

Propulsion

- Azimuth propulsion at the stern 2 x 25 MW (ND)
- Ice-strengthened retractable azimuth bow thrusters 3 x 3 MW (ND)
- Total installed propulsion and thruster power 35 MW (ND)
- Dynamic positioning DP Class 3 (DT)
- Redundancy for propulsion system (SA)

Safety

- Water-independent fire protection system (DT)
- Rescue satellite (lifeboats) for evacuation on a minimum of one-week survival (SA)
- 4 x 50-person lifeboats, closed, ice resistant (SA)
- Inflatable liferafts (SA)

Multipurpose research *(Fig. 20)*

- Laboratory and electronic area approx. 2300m² (SA)
- Containers (laboratory or storage) 30 (DT)
- Supply for lab-containers (water, electricity, communication) (SA)
- General labs (wet, dry, chemistry) (SA)
- Remote operating vehicle (ROV) handling (DT)
- Autonomous underwater vehicles (AUV) (DT)
- Moon pool (Vehicle and others) 6 x 6m (SA)
- Moon pool clean up system to avoid ice inside (ND)
- Side-ramp for ascent onto ice (DT)

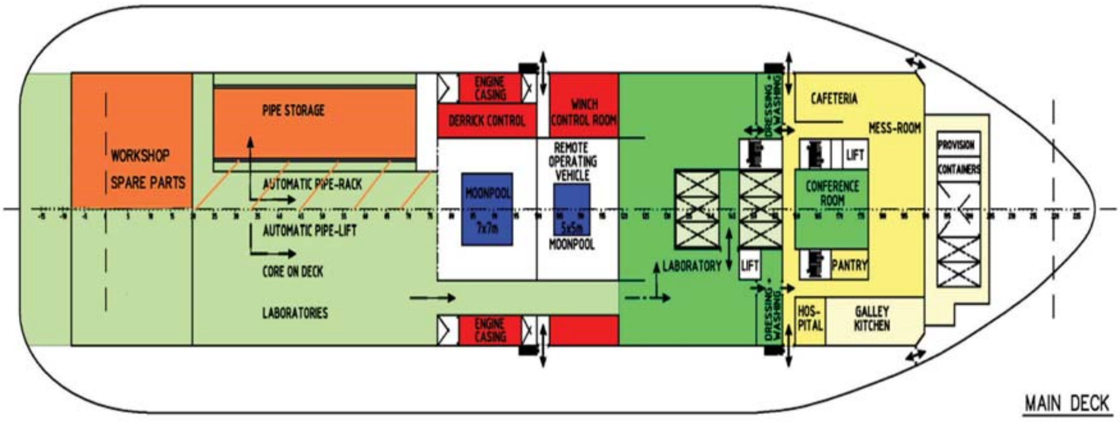


Fig. 21: Working deck. Note: (1) three ship sections from bow to aft: accommodation, science and drilling (machinery), (2) automatic pipe-storage, (3) huge working deck space, (4) large laboratory space, e.g. for lab-containers.

● *Drilling*

- Core drilling (max. 4 000m water depth and 1 000m core) (DT)
- Removable or lowered derrick (ND)
- Reconnectable drilling pipe system (ND)
- Automatic pipe rack (SA)
- Automatic pipe lift (SA)
- Pipe store capacity about 9000m (SA)
- Height of derrick approx. 62m (SA)
- Heave compensation system (DT)
- Moon pool (drilling) 7 x 7m (DT)
- Moon pool clean up system to avoid ice inside (ND)
- Storage for Cores (SA)
- 'Calypso coring system' (DT)
- Option for slim-line riser system (ND)

● *Winches*

• Friction winch (glass fibre)	18mm Ø	6 000m (SA)
• Friction winch (cable)	18mm Ø	6 000m (SA)
• Friction winch (wire)	18mm Ø	6 000m (SA)
• 2 cable winches	11mm Ø	6 000m (SA)
• Several working winches	12mm Ø	4 000m (SA)

- Capstan (SA)
- Heave compensation system (DT)

● *Lifting device*

- Sliding beam (stern) (DT)
- 2 sliding beams (starboard) (SA)
- 2 cranes on deck, range 30m, 25 tonnes (SA)

● *Echosounding, data aquisition and distribution*

- Seabeam (SA)
- Penetr. Echosounder (SA)
- ADCP (SA)
- Real-time data acquisition (ship data, meteorology, echosounder and more) (DT)
- Real-time, fast data transmission system to and from on-shore labs (DT)

Living Quarters (SA)

- Cabins (for one and two persons with shower and WC)
- Conference room
- Mess room
- Cafeteria
- Pantry and galley
- Hospital
- Sauna, pool and gym

Special Technical Aspects of AURORA BOREALIS

The requirements for hull design and testing of a new hull shape that allows turning in ice-covered waters has been described above. However, there are a number of technical requirements, deduced from the scientific demands, that are novel for research vessels and which require a special feasibility study, which will be carried out in the near future. They comprise the following points:

- stability, no-vibration (to permit the on-board use of sophisticated equipment, e.g. "floating floor" labs)
- "Class 100" clean laboratory
- controlled laboratories for the use of radio-isotopes
- no (or minimised) interference for optical measurements (ship paint colour)
- deep freezing cells
- capability to deploy and recover long and heavy moorings
- slow motion capability
- "clean" electrical power (dedicated scientific line)
- on-board Local Area Network
- real-time, fast data transmission system to and from on-shore labs, remote sensing images, etc.
- capability to manage heavy packages, such as benthic observatories, etc.

Development of an ice-strengthened powerful azipod propulsion system

The requirements of the dynamic positioning and of station-keeping against a slowly floating sea ice mass require a very powerful ship and a specific hull-shape as described above. Directional bow thrusters (or azipods) may have to be retractable.

Development of a removable derrick

Derricks for drill-ships are routinely used – as known from many examples. However, in this instance they will have to be used under very harsh climatic conditions, requiring protection against weather for the crew operating the derrick. Several scientific disciplines other than deep sea drilling also requested access to the lifting capacity of the derrick. The derrick should be removable because the ship will be devoted to drilling in the Arctic only during the most favourable season of the year (probably 4 months during the summertime). In general it is envisaged that established IODP technology is transferred to the AURORA BOREALIS without a major need for development. At the present time penetration into the seafloor of no more than 1 000m (probably in most cases only up to 500m into the sediments in the shallow parts of the ocean crust) is predicted. No re-entry is planned at the present time. Most of the drilling will be done in a riserless mode, applying APC-coring or rotary drilling coring.

A close collaboration between IODP and ICDP is under development. Part of the ICDP community has asked whether a removable derrick of the AURORA BOREALIS could potentially also be deployed for ICDP drill science, either in shallow water from barges or even on land. This technical problem has to be solved by the proper specialists.

Long sediment cores

A tool, close to the achievements of Arctic deep sea drillings, has been developed in France and in other countries by means of giant piston coring devices. The AURORA BOREALIS should have the technical facilities to deploy the French Calypso-system, which will in the near future expand its capabilities to 100m seafloor penetration. Since many of the stratigraphic targets in the Arctic Ocean can be approached by a step-wise deployment of such a coring device, AURORA BOREALIS will have to fulfil the technical requirements of being able to deploy this set of instruments.

Classical Polar Research

Sixty to seventy percent of the ship time of the AURORA BOREALIS will be devoted to classical polar research disciplines, requiring a floating platform as their base. The AURORA BOREALIS will therefore have to be equipped as a helicopter base to permit the deployment of helicopters for research purposes. It also has to fulfil the entire suite of geophysical requirements for conducting site surveys and other geophysical research, and it has to accept the winches needed to deploy classical marine polar research instrumentation. This includes all kinds of probes for physical oceanography, the ability to deploy moorings of various natures and to take geological and biological samples.

Moon pools

A drill ship requires a moon pool of substantial size. Several disciplines have in addition, asked for a second separate moon pool to deploy ROVs and AUVs under controlled conditions. The size of the moon pools has to be adapted to the requirements of drilling and deployment of these instruments. Henceforth, the dimensions will be in the order of 5 x 5 metres.

Laboratories

The AURORA BOREALIS will be equipped with a suite of mission-specific, modularised and containerised laboratories. This requires the development of an entire lab-system as well as technical facilities to store the suite of labs on a research vessel devoted to very harsh climatic environments. As a polar vessel, AURORA BOREALIS will have to be equipped with substantial cold storage, cold (climatised) laboratories and temperature-controlled experimental laboratories (aquaria) for marine biological investigations.

There has been an evaluation of the minimal requirements of lab spaces devoted to the mission-specific activities of IODP (see the ODP Working Group report):

Excerpt from [ODP SciMP] Working Group report

"SciMP considers that the minimum laboratory needs for IODP alternate drilling platforms can be met by two 20-foot [approx. 6m] vans that are configured so that they can be used either on the drilling platforms or on nearby drilling-support sites.

Van 1 - Core handling, MST, and special sampling

Functions:

1. *Core sectioning; sampling for density, head-space, and pore-water analysis*
2. *Whole-core MST measurements (ephemeral properties)*
3. *Clean sampling for microbiology*

…

The equipment and facilities required for these functions, consisting of an MST, a glove-box, a core-sectioning stand, and related materials, would fully fill one 20-foot [approx. 6m] laboratory van.

Van 2 - Safety, drilling decisions, and ephemeral properties

Functions:

1. *Head-space gas analysis (drilling safety, ephemeral property)*
2. *Micropaleontology (drilling age control)*
3. *Pore-water analysis (ephemeral property)*
4. *Microbial sample fixing (ephemeral property)*
5. *Moisture and density measurements (ephemeral properties)*

The equipment and facilities required for these functions, consisting of a gas chromatograph, an oven, a balance, a pycnometer, microscopes, sediment squeezers, titrators, a spectrophotometer, and associated materials, would fully occupy one 20-foot [approx. 6m] laboratory van.

General requirements

Both vans should be able to accommodate two persons/shift (van No. 2 may require three persons per shift) and will need to be fully equipped with electricity, running water (hot and cold), climate control, and good ventilation (and both a fume hood and an acid hood for van No. 2). Ideally, the vans should be connected together so that sample flow is facilitated.

At least one additional laboratory van may often be required for leg-specific objectives. Furthermore, a refrigerated van may also be required for core and sample storage, and some samples may need to be frozen for later study of sensitive properties soon after core sectioning."

Environmental Impact and Protection

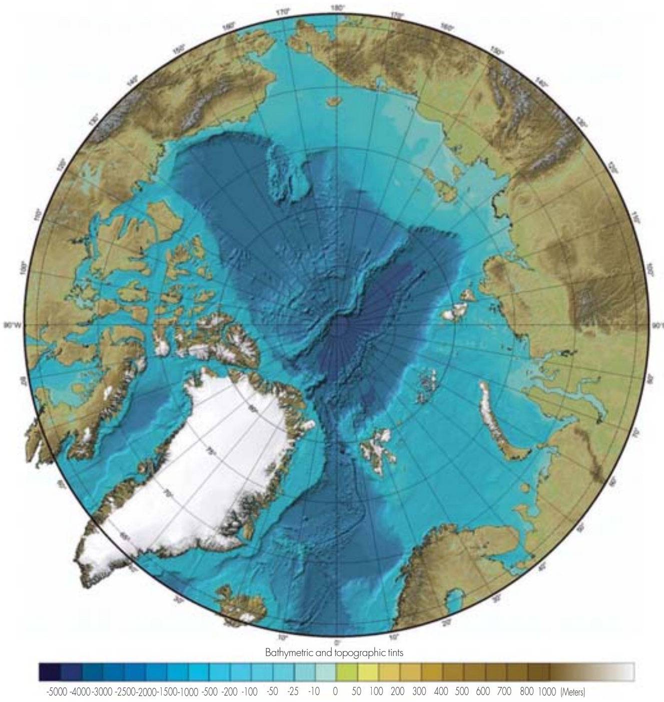
The Arctic environment has a particular sensitivity; it is subject to rapid changes, and its living biota could be affected by human intervention. Using the modern technologies available, utmost attention must be paid to reducing the environmental impact of a ship such as the AURORA BOREALIS operating in the Arctic. This means that it needs a specially protected hull so that its emissions of all kinds (air, exhaust, water and waste, acoustic noise) are kept to a minimum.

Justification for a Technical Feasibility Study

It is clear, after the preliminary results of the conceptual study on the AURORA BOREALIS, that a detailed technical feasibility study for planning the vessel is urgently needed. Ideally this should be part of a tendering process. The study is necessary to assess the potential of such a ship to accommodate the technical requirements deduced from the envisaged science programmes. It is also necessary from the point of view of trying to secure the most modern and efficient solutions to a number of technical aspects of a drilling vessel operating in the Arctic, which have never been addressed before. It would be particularly important to demonstrate that the vessel really can operate autonomously without assistance from additional icebreakers because this would give it a substantial financial advantage. However, science programmes and drilling operations cannot be compromised because of this aspect. Therefore technical solutions have to be found by engineers experienced in planning and constructing icebreakers.

Planning, Financing and Management of a Dedicated European Arctic Research Platform

Part 5



IBCAO

Planning, Financing and Management – Introduction

Many of the arguments collected in this report call for a large powerful novel research icebreaker with a drilling capability.

The principal questions to be answered are:

- Should Europe have a coordinated polar research programme in the Arctic (as well as in the Antarctic)?
- Should we have tools allowing us to do research in the most extreme environments and during the most extreme seasons?
- And if so, is the time ripe for a large-scale international, interdisciplinary effort in the central Arctic?
- And is the topic of Arctic deep sea drilling important enough to warrant the large-scale effort of establishing a decadal drilling programme (which also means great expense in preparative work to define drill sites)? (which also means great expense in preparative work to define drill sites)?

The extensive perspectives articulated in this document suggest that there is sufficient justification that all of these questions can be answered in the affirmative. Therefore the main conclusion of this report is to move ahead with trying to establish a new, technically novel research tool that will allow a substantial effort in the central Arctic Ocean, such as the AURORA BOREALIS project.

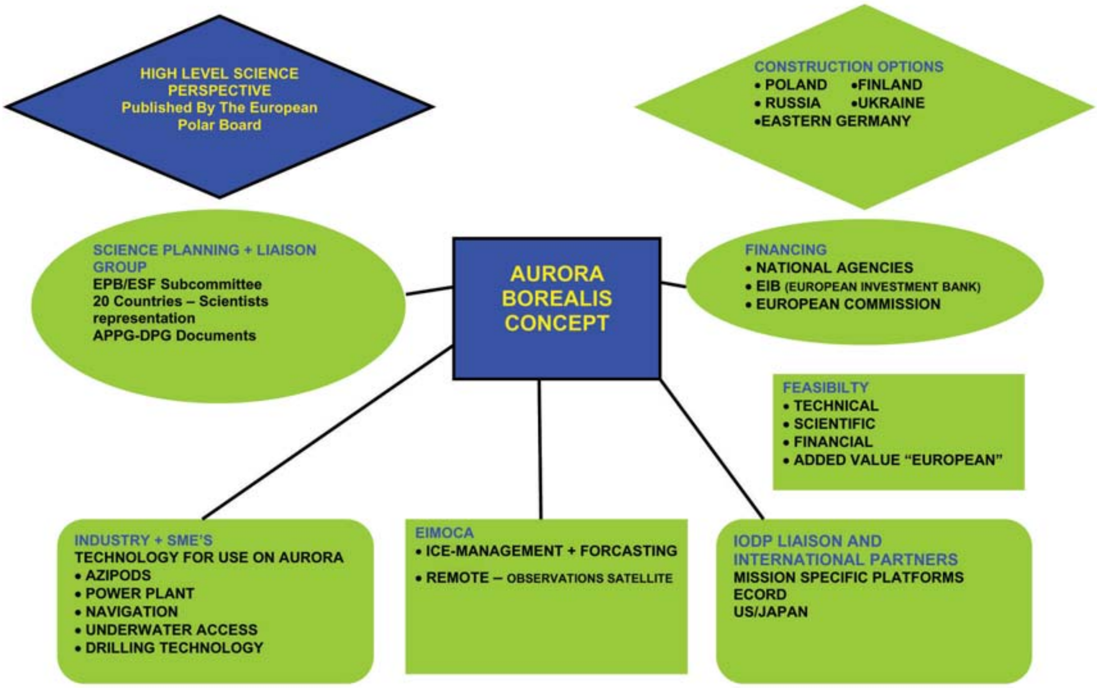
The Concept of the AURORA BOREALIS within EPB EUROPOLAR

The AURORA BOREALIS would be the first only European (jointly owned and run) research vessel dedicated to Arctic research. It would require the establishment of a management structure in Europe and a clear distribution of responsibilities.

Following the publication of this Science Perspective an implementation consortium would be formed of interested nations. If substantial interest from non-European Arctic countries materialises, we should be open to a wider international participation. The implementation consortium would be tasked to generate a business plan and structures for establishing the scientific parties of interdisciplinary/multidisciplinary programmes involving international science parties. It would have the task of looking at the ship time allotments and to oversee the management of the facility in association with the ESF European Polar Board's evolving European polar entity EUROPOLAR. It would require taking steps to harmonise polar capabilities in the European Research Area, the establishment of segments of a European structure streamlining European polar capabilities. The European Polar Board is developing this approach through a number of elements which comprise:

- **EIMOCA (European Ice Management Observation Capability),**
- **EPICOM (European Polar Infrastructures Committee),**
- **ERICA (European Research Icebreaker Capability),**
- **EPAC (European Polar Air Capability), etc.**

AURORA BOREALIS organisational elements



The Management of the AURORA BOREALIS

The stakeholders in the AURORA BOREALIS project should develop management structures for the icebreaker and its ice-management capability. These management structures will also have to promote integration and a close liaison with national and international programmes such as IODP and others.

Financial Options for the AURORA BOREALIS Project

The currently available estimates for constructing a vessel with the capabilities of the AURORA BOREALIS amount to approximately 250 million euros in terms of construction costs, which have to be shouldered entirely (under the present conditions) by the participating nations. In addition, based on the experience of other ships, we expect expenses of approximately 10-15 million euros a year for the total running costs with 300 days of operation (including the necessary management structure).

Because of the dual use of the ship, approximately 30% of ship time will be used for drilling; the financial support for this share amounts to approximately 5 million euros a year.

The other user group (classical polar scientists) will use approximately 70% of the available ship time and they would have to raise to roughly 10 million euros a year in total. At the present time we consider all members of the EPB as being potentially interested in the AURORA BOREALIS project. (Special inputs in terms of contributions to construction could be expected from Russia, Ukraine and Poland). The AURORA BOREALIS project could potentially be opened to non-European Arctic countries.

We have currently considered the AURORA BOREALIS project from the European perspective because IODP expects the European IODP membership to contribute alternative drilling platforms and because we face the fact that

European participation in IODP warrants lead agency status. However, as the research interest in the Arctic expands, other potential contributors such as, Canada, China, Japan and the USA could be encouraged to cover part of the expenses. Funding could be recruited from national sources, from EU structural funds and potentially through the European Investment Bank, to name but a few.

Since the detailed interests of individual nations have yet to be defined, it is proposed to subdivide the construction costs into 25 shares at approximately 10 million euros a share. Memberships will be distributed according to the size of the country's relevant scientific community: with the larger being allowed a maximum of 10 shares; medium-sized being allowed a maximum of 5 shares, and the smaller 1-2 shares. Membership level (which would be equivalent to the number of shares held) should determine the amount of participation in the scientific use of the AURORA BOREALIS. The suggested 30% of ship time allowed and used by the IODP science community would still leave another 11 000 scientist days per year on board, bearing in mind the 50 "scientific" berths on the ship. Each share would then be the equivalent to 440 scientist days per year.

Logistical Considerations for the AURORA BOREALIS Project

Expertise for the construction of large icebreakers exists in Finland, Germany, Russia, to a lesser degree probably in Denmark, Norway, Poland and the UK. Expertise in icebreaker crewing and icebreaker operations exists in Denmark, Finland, Germany, Russia, Sweden and the UK.

Potential homeports should be located close to the Arctic Ocean – the main area of operations for the coming decade. The following ports seem to be suitable because of the facilities and because of the presence of relevant (scientific) institutions: Bremerhaven, Harstad, Murmansk, Reykjavik, Stavanger, Tromsø.

Probably Trømso in northern Norway has a certain advantage in this context because of its university devoted to polar disciplines, the location of the Norwegian Polar Institute and the proximity of many Arctic specialists. It is also close to the areas under investigation. The only disadvantage is the lack of a suitably large docking facility for handling a large vessel like the AURORA BOREALIS.

The AURORA BOREALIS will have to be attached to a home port with suitable facilities, as close to the area of investigation as possible and as the contributing countries agree. Besides the international management structure it will be important to establish a local office in the home port to handle the ship and to arrange the practical aspects of liaison with port authorities, international clearances, port calls, exchange of scientific personnel, etc.

In addition, we expect that the ship and the drilling operations will be handled through qualified commercial companies.

For medical emergencies and defined air support and procedures, on-board hospital and medical services, as well as a certain amount of psychological welfare for the crews, the ship must be equipped with landing facilities for helicopters (on-board hangar, refuelling facilities, experienced crews). Twin-powered helicopters would be needed for emergency operations but also to extend the experimental operation to an approximately 150 km radius around the vessel.

The vessel will also be used as a platform for a certain amount of ship time devoted to support science (site surveys in preparation of drill sites, which could also be carried out using existing icebreakers or aeroplanes for acquisition of the necessary geophysical data).

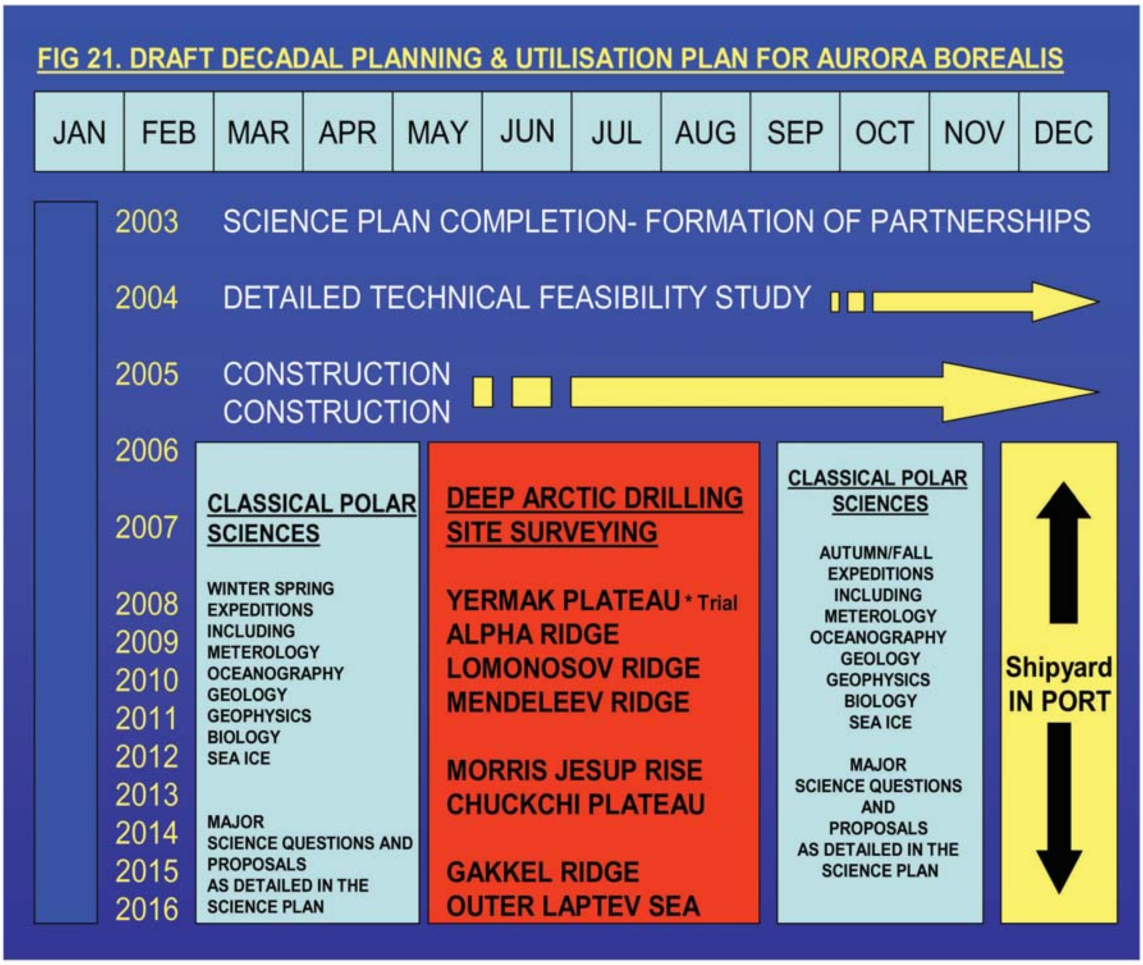


Fig. 21b: A draft decadal plan for the use of the Arctic research icebreaker AURORA BOREALIS.

Ice Management System, Satellite Monitoring

The New ESA platforms such as ENVISAT, CRYOSAT would enable enhanced remote sensing information for Arctic operations. Ice thickness probes can already be carried out from airborne platforms and one would have to generate institutional ice forecasting system within EUROPOLAR and possibly linked to the EU GMES initiative.

A 10-Year Outlook for the AURORA BOREALIS

The central Arctic Ocean and its marginal seas show many signs of rapid change, and it will be paramount to have a modern research platform in place during all seasons to verify the consequences of those changes over the coming decades.

In Figure 21b we have tried to accommodate the interest of the two scientific communities that will make use of the AURORA BOREALIS. After an initial phase devoted to trials and tests of the ship and its technical/scientific facilities the summer season (approximately 3 months) would be devoted to drilling operations following the priorities of the NAD Science Plan and of the report of the JOIDES Arctic Program Planning Group (chaired by A. Hovland, published in 2001). The other seasons would be used according to the ideas developed in this Science Perspective. The AURORA BOREALIS with its power, structural endurance and flexibility to accommodate different science programmes will be a support platform for acquiring data during the seasons of the year and from areas in the central Arctic Ocean that have been impossible to reach before.

Appendices

Appendix I

The Development of the Science Perspective

The project started to develop a science perspective after a short technical feasibility study on the possibility of deep sea drilling from an icebreaker had been completed. The study was carried out by the Hamburg Ship Model Basin (HSVA Hamburg) and resulted in the conceptual design of the AURORA BOREALIS (Fig. 1). This study offered a rough estimate of the size and nature of the ship, novel technologies such as ROV and AUV systems, dynamic positioning, propulsion and moon pools installed in a new heavy-duty research icebreaker.

Following this development, the European Polar Board decided to establish an International Working Group composed of specialists recruited from two scientific communities. The larger group recruited specialists needing a modern research icebreaker for work devoted to the classical disciplines of polar research, the smaller one represented specialists interested in studying the nature and composition of the seafloor in ice-covered deep sea basins by the means of deep sea drilling. Both groups were aided by specialists in icebreaker technology (Table 1). The working group met twice, each time with additional experts, once at the premises of the European Science Foundation (ESF) in Strasbourg (14-15 January 2002, see Table 2) and once at the Danish Polar Centre (18-19 March 2002, see Table 3). Much of the remaining work had to be completed by electronic mail.

The Science Perspective, as presented here, is focusing on major new scientific topics that provide the basis for a decadal strategy of Arctic Ocean exploration, but does not claim complete coverage of all possible disciplines or topics. Since science is defining many of the technical requirements of the intended research and since this novel technology has to be developed and evaluated in great detail by engineers experienced in building icebreakers, the technology of the intended ship is treated relatively in general; it will require a separate detailed treatment. The same applies to the planning, financing and management structures for building the AURORA BOREALIS and for the management, once she has been built. Many of the ideas expressed in the current text will have to be adapted, refined, altered as the interest in the project increases and as the countries interested in contributing to its success make their decisions. It is, however, quite clear, that the structure of the ODP/IODP for science and management is an excellent model, which could be simplified/ or refined and applied to the development and employment of the AURORA BOREALIS for the drilling component.

A preliminary proposal on this project has also been evaluated by the Wissenschaftsrat (WR, the science policy advisory body to the German Government) in a series of evaluations of major infrastructure units for basic research under discussion in Germany from a national perspective (autumn 2001, review published July 2002).

Even though the evaluation of the WR had been carried out from a national perspective, the report offers important and helpful remarks on the project, as cited below.

Excerpt from WR conclusions

.....In the context of global warming and global change, the Arctic regions are the most sensitive to climatic change. Understanding these regions is essential to predicting the evolution of the climate system, the detection and attribution of climate change and its impacts on the European and global environment. Unlocking the history of this region currently contained in sediment cores as well as an accurate description of present ocean and sea ice conditions in the Arctic Ocean and their evolution will underpin this understanding. AURORA BOREALIS is currently the only proposal that will allow the collection of the necessary ocean cores and year-round ocean observations.....

....AURORA BOREALIS is a unique, technically innovative and very challenging project with the goal of deploying a scientific platform for all seasons in the polar region, especially in the Arctic Ocean. The European drilling research icebreaker would satisfy the needs of a drilling ship and a multidisciplinary polar research vessel. There is no other ship of the capabilities proposed for AURORA BOREALIS that would be able to conduct investigations in all seasons. The vessel would be a welcome addition to the proposed IODP. This would open the use of the ship to the international community beyond Europe. The drilling research icebreaker would have a paramount importance for a better understanding of the paleoclimate, the present and the future climate, both regionally and globally.....

Table 1.

The International Working group of EPB and ECORD on the project AURORA BOREALIS

Members of the Scientific Working Group

***Polar Sciences** (nomination via the EPB)*

Andersen, Leif	Chalmers University of Technology (CTH), Gothenburg, Sweden
Elverhöj, Anders	University of Oslo, Norway
Fahrbach, Eberhard	Alfred Wegener Institute (AWI), Bremerhaven Germany
Gramberg, Igor †[1]	VNII Okeangeologia, St Petersburg, Russia
Klages, Michael	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Launiainen, Jouko	Finnish Institute of Marine Research (FIMR), Helsinki, Finland
Mikkelsen, Naja	Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark
Rabitti, Sandro	Institute of Marine Biology, Venice, Italy
Rudels, Bert	Finnish Institute of Marine Research (FIMR), Helsinki, Finland
Thiede, Jörn	Alfred Wegener Institute (AWI), Bremerhaven Germany and Chairman of EPB
Turon, L.J.	University of Bordeaux, France

***Ocean Drilling** (nomination via ECORD)*

Balut, Yvon	French Polar Institute (IPEV), Pluzane, France
Camerlenghi, A.	University of Milan, Italy
Foucher, Jean Paul	French Research Institute for Exploitation of the Sea (IFREMER), Paris, France
Kassens, Heidemarie	Research Centre for Marine Geosciences (GEOMAR), University of Kiel, Germany
Kristoffersen, Yngve	University of Bergen, Norway
Larter, Rob	British Antarctic Survey (BAS), Cambridge, UK (from February 2002)
Thomson, Mike	British Antarctic Survey (BAS), Cambridge, UK (until February 2002)

Icebreaker Technology and Ship Design

Niini, Mikko	Kvaerner Masa Yards Inc., Helsinki, Finland
Rupp, Karl-Heinz	HSVA Hamburg, Germany
Broeckel, Klaus v.	Institute for Marine Research (IfM), University of Kiel, Germany

[1] † deceased in 2002.

Table 2.

Participants of first science meeting at ESF in Strasbourg, France (14-15 January 2002)

Andersen, Leif	Chalmers University of Technology (CTH), Gothenburg, Sweden
Balut, Yvon	French Polar Institute (IPEV), Plouzane, France
Broeckel, Klaus v.	Institute for Marine Research (IfM), University of Kiel, Germany
Egerton, Paul	European Polar Board of the European Science Foundation, Strasbourg, France
Fahrbach, Eberhard	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Grikurov, Garrik	VNII Okeangeologia, St Petersburg, Russia
Kassens, Heidemarie	Research Centre for Marine Geosciences (GEOMAR), University of Kiel, Germany
Klages, Michael	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Knoblauch, Christian	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Kristoffersen, Yngve	University Bergen, Norway
Launianen, Jouko	Finnish Institute of Marine Research (FIMR), Helsinki, Finland
Niini, Miko	Kvaerner Masa-Yards Inc., Helsinki, Finland
Petersen, Hanne	Danish Polar Center, Copenhagen, Denmark
Rabitti, Sandro	Institute of Marine Biology, Venice, Italy
Rudels, Bert	Finnish Institute of Marine Research (FIMR), Helsinki, Finland
Rupp, Karl-Heinz	HSVA, Hamburg, Germany
Thiede, Jörn	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Thomson, Mike	British Antarctic Survey (BAS), Cambridge, UK

Table 3.

Participants of the 2nd AURORA BOREALIS Workshop at the Danish Polar Centre, Copenhagen, Denmark (18-19 March 2002)

Broeckel, Klaus v.	Institute for Marine Research (IfM), University of Kiel, Germany
Egerton, Paul	European Polar Board of the European Science Foundation, Strasbourg, France
Fahrbach, Eberhard	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Gascard, Jean Claude	University of Paris, France
Khristoffersen, Yngve	University of Bergen, Norway
Klages, Michael	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Knoblauch, Christian	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Mikkelsen, Naja	Geological Survey of Denmark and Greenland, (GEUS) Copenhagen, Denmark
Niinni, Mikko	Kvaerner Masa-Yards Inc., Helsinki, Finland
Petersen, Hanne	Danish Polar Centre, Copenhagen, Denmark
Rupp, Karl-Heinz	HSVA, Hamburg, Germany
Thiede, Jörn	Alfred Wegener Institute (AWI), Bremerhaven, Germany
Vanneste, Lieve	British Antarctic Survey (BAS), Cambridge, UK

Table 4.

The members of the WR special international group convened to assess the AURORA BOREALIS project

Berger, Wolfgang H.	Scripps Institution of Oceanography, University of California, USA
Bieri, Stephan	ETH-Rat, Zürich
Church, John	CSIRO Marine Research, Hobart, Australia
Delissen, Thomas	Finanzbehörde, Hamburg
Herzig, Peter M.	TU Bergakademie, Freiberg
Hüttl, Reinhard F.	TU Cottbus - Chairman
Kudrass, Hermann R.	BGR, Hannover
Pearce, Julian	Cardiff University, Wales
Rummel, Reiner	TU, Munich
Scott, Steven D.	University of Toronto, Canada
Soffel, Heinrich C.	LMU, München
Wagner, Hermann-Friedrich	BMBF, Bonn

Additional input was received from various members of European Polar institutions in particular from: Dr C Haas (AWI). All persons involved in preparing this document are acknowledged for their important contributions to this venture.

Appendix II

Abstract of JEODI Arctic Site Survey Workshop

Preparing for Scientific Ocean Drilling in the Arctic: The Site Survey Challenge

was organised by
Naja Mikkelsen (Copenhagen) and Jan Backman (Stockholm), Wilfried Jokat (Bremerhaven) , Yngve Kristoffersen (Bergen), Jörn Thiede (Bremerhaven)

in Copenhagen, Denmark, 13-14 January 2003

The workshop was attended by colleagues from the Canada, Russia, USA and most western European countries with an interest in Arctic deep sea drilling. The workshop results will be documented in a report to be published in Denmark in spring 2004. The workshop participants agreed on the following:

Major Recommendations

- The scientific importance of Arctic deep sea drilling for paleoceanographic, climatic and tectonic goals is well understood, but the lack of adequate site survey data hampers the development of mature drilling proposals. Potential drilling locations were discussed for all major ridges (Gakkel Ridge, Lomonosov Ridge, Alpha-Mendeleev Ridge) as well as for the continental margins and marginal plateaus. The workshop participants recommended a decadal programme of dedicated expeditions to the central Arctic with the aim of completing site surveys over areas of potential drill sites. A letter will be written by the workshop organisers to all operators of scientific platforms and of the necessary geophysical equipment to request action for including site survey activities in their planning.

- While no actual drill site proposals can be developed in the central Arctic Ocean at the present time due to the lack of suitable site data (with the exception of the Lomonosov Ridge proposal), the situation is far better for the Arctic continental margin and marginal plateau areas. The workshop participants encouraged geophysical working groups on the Yermak Plateau, the Chukchi Plateau-Northwind Ridge and Laptev Sea continental margin to formulate and submit preliminary drilling proposals.

- Whereas scientific expeditions to the Arctic Ocean have been organised for the past 25 years mostly on an ad hoc basis, they have lacked long-term, international well-coordinated planning procedures. For the benefit of costly site surveys, which often require two-ship operations, this process has to change into a detailed and well-coordinated planning procedure where results should be reviewed at regular annual or biannual intervals. The Arctic Science Summit Week will provide a suitable venue for such reviewing.

- The upcoming International Polar Year (IPY) 2007-08 would offer a superb opportunity for operating a suite of expeditions to the central Arctic Ocean to conduct systematic site surveys over selected segments of the Alpha-Mendeleev Ridge Complex (the AMEX expedition), employing suitable icebreakers from Canada, Finland, Germany, Russia, Sweden and the USA.

- Recognising that Arctic Ocean geoscientific data relevant for site surveys are at present dispersed over many institutions and countries the workshop participants recommended the establishment of a database to collect all data in a unified and easily accessible format.

- Site survey technology is under constant development; many of the available technologies have to be adapted for use in the ice-covered Arctic waters. The workshop participants recommended requesting from iSSP, iILP and iTAP the establishment of an IODP working group focusing on the development of site survey strategies for the Arctic Ocean. This should be brought to the attention of the three panel chairs soon, in order to be put on the agenda for the Panel Chairs meeting in March 2003.

- Drilling technology for ice-covered deep sea basins has yet to be tested. Proposals for drill ships capable of operating in the central Arctic were discussed and the workshop participants encouraged further development of the plans.

- There is a major need for communication within the Arctic geoscientific community. The workshop participants recommended a follow-up workshop in two years' time. The continuation of the communication can be organised by the existing NAD organisation, which is an associate programme to ODP and which maintains a newsletter (*The Nansen Icebreaker*).

- The workshop participants recommended publication of the detailed workshop results in the *Bulletin of the Geological Survey of Denmark and Greenland.*

Appendix III

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Appendix IV

Acronyms and Abbreviations

- **AATSR** Advanced Along Track Scanning Radiometer
- **ACSYS** Arctic Climate System Study
- **AMAP** Arctic Monitoring and Assessment Programme
- **AMORE** Arctic Mid-Ocean Ridge Experiment
- **AO** Arctic Oscillation
- **AOM** Anaerobic Oxidation of Methane
- **APC** Advanced Piston Coring
- **ARGO** A global array of profiling floats
- **ASAR** Advanced Synthetic Aperture Radar
- **ASOF** Arctic-Subarctic Ocean Fluxes
- **AUV** Autonomous Underwater Vehicles
- **AVHRR** Advanced Very High Resolution Radiometer
- **CLiC** Climate and Cryosphere Project
- **CLIVAR** Climate Variability programme
- **CRP** Cape Roberts Project
- **CRYOSAT** Three-year radar altimetry mission
- **CTD** Conductivity-Temperature-Density
- **DSDP** Deep Sea Drilling Project
- **EPB** European Polar Board (ESF)
- **ECOD** European Consortium for Ocean Drilling
- **ECORD** European Consortium for Ocean Research Drilling
- **EEZ** Exclusive Economic Zone
- **EM** Electromagnetic Radiation
- **EMI** Electromagnetic Interference
- **ENVISAT** European Earth observation satellite
- **ERS** European Remote Sensing Satellite
- **ESA** European Space Agency
- **ESF** European Science Foundation
- **EUMETSAT** European Organisation for the Exploitation of Meteorological Satellites
- **GMES** Global Monitoring for Environment and Security (EU)
- **HAFOS** Hybrid Arctic Float Observation System
- **HMMV** Håkon Mosby Schlammvulkan mud volcano
- **HSVA** Hamburgische Schiffbau Versuchsanstalt Gmbh (Hamburg Ship Model Basin)
- **ICDP** International Continental Scientific Drilling Program
- **ICESat** Ice, Cloud and land Elevation Satellite
- **iILP** Interim Industry Liaison Panel (IODP)
- **IODP** Integrated Ocean Drilling Program
- **iSSP** Interim Site Survey Panel (IODP)
- **iTAP** Interim Technology Advice Panel (IODP)
- **JEODI** Joint European Ocean Drilling Initiative
- **JOIDES** Joint Oceanographic Institutions for Deep Earth Sampling
- **LIP** Large Igneous Provinces
- **MERIS** Medium Resolution Imaging Spectrometer Instrument (ENVISAT)
- **MIZ** Marginal Ice Zone
- **MOC** Meridional Overturning Circulation
- **MODIS** Moderate Resolution Imaging Spectrometer (NASA)
- **MST** Mesospheric-Stratospheric-Tropospheric
- **NAO** North Atlantic Oscillation
- **NASA** National Aeronautics and Space Administration (US)
- **NCEP** National Centre for Environmental Prediction
- **NOAA** National Oceanic and Atmospheric Administration
- **OC** Organochlorine
- **ODP** Ocean Drilling Program
- **OMEX** Ocean Margin Exchange
- **PCB** Polychlorinated biphenyls
- **POP** Persistent Organic Pollutants
- **RADARSAT** Advanced Earth observation satellite
- **ROV** Remotely Operated Vehicles
- **SAR** Synthetic Aperture Radar
- **SCAR** Scientific committee on Antarctic Research
- **SOFAR** Sound Fixing and Ranging (NOAA ocean explorer)
- **SSM/I** Special Sensor Microwave Imager
- **WOCE** World Ocean Circulation Experiment
- **WR** Wissenschaftsrat (science policy advisory board to the German Government)

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