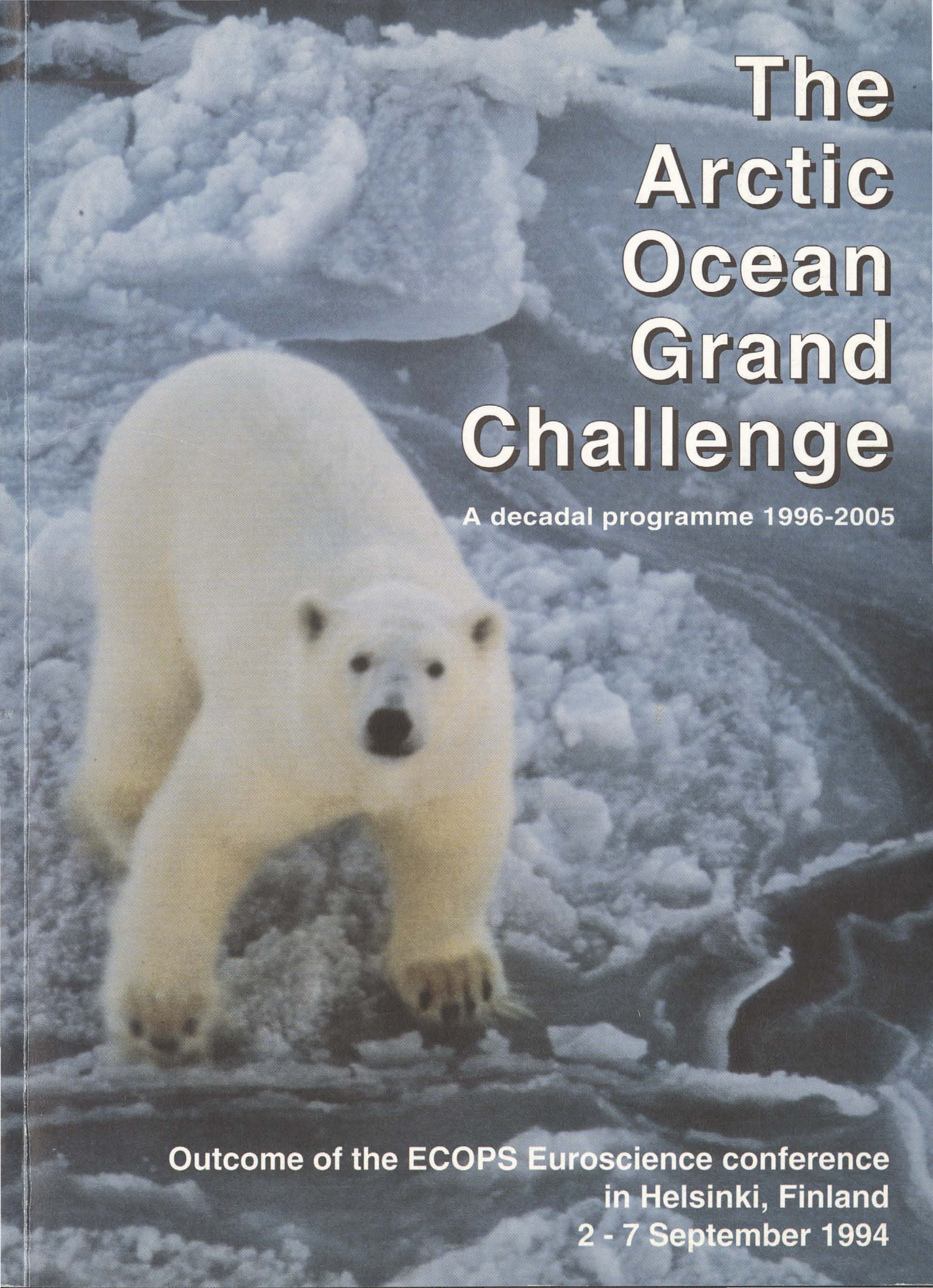

The Arctic Ocean Grand Challenge

A decadal programme 1996-2005

Outcome of the ECOPS Euroscience conference
in Helsinki, Finland
2 - 7 September 1994

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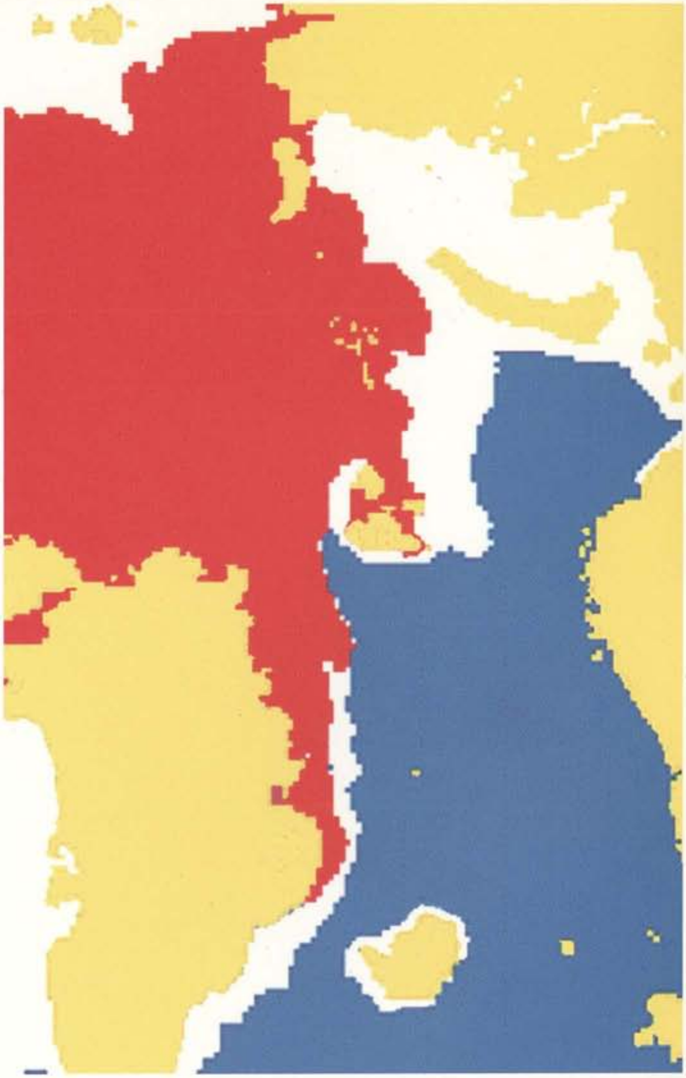

Typical maximum and minimum ice extent in the Arctic for the late winter and late summer. The ice extent is estimated from passive microwave data of the Special Sensor Microwave Imager (SSM/I) on the Defence Meteorological Satellite Program (DMSP). The colour code is: land-yellow, open water-blue, winter ice extent-red and summer ice extent-white.

Cover photo: *Ice structure in the Barents Sea (Courtesy Nansen Center).*

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Organized by
European Committee on Ocean and Polar Sciences (ECOPS)
European Science Foundation (ESF)
in cooperation with Arctic Ocean Sciences Board (AOSB)
International Arctic Science Committee (IASC).

The Arctic Ocean Grand Challenge

The Arctic Ocean is a system of high climatic sensitivity. Predictions of the global climate in the next century using General Circulation Models of atmosphere and ocean indicate an enhanced greenhouse warming in the Arctic relative to lower latitudes by a factor of 2 - 4, which will eventually cause the ice-pack to drastically shrink or even disappear. Therefore the northern seas offer the best opportunity for early detection of the fingerprint of global warming. The ocean circulation itself may be affected, since the Arctic feeds water and ice into the Greenland Sea, where convection provides one component of the thermohaline circulation or "conveyor belt" which affects all oceans. There is evidence from sediment cores that the Arctic Ocean has not always been ice-covered, and ice cores show that it has suffered dramatic and sometimes very rapid changes in its climatic nature. The causes of these rapid changes are not known. The Arctic's climate response concerns us in Europe, since the Arctic Ocean lies so close to us, and Arctic ice and ocean processes directly influence European climate.

One hundred years ago the modern science of physical oceanography began in the Arctic, with Fridtjof Nansen's historic three-year drift across the Arctic Basin in the "Fram" (1893-96). This voyage led directly to the work of Ekman and the Bergen school of meteorologists and oceanographers who created much of the theory of geophysical fluid dynamics. Yet although the Arctic Ocean inspired a new science, she was slow to reveal more of her secrets, and warmer oceans became the focus of oceanographic research efforts. The reason was simply the difficulty of working in the only ocean in the world which is perennially ice-covered. In the Arctic Ocean we still do not understand how water is mixed and transformed on the wide continental shelves which are fed by fresh water from large rivers, how the water enters the deep and intermediate layers, how it circulates within the basin, what governs the variability of ice and water fluxes and ice thickness and extent, how the Arctic ecosystem works or what is the history of the seafloor.

Today, however, new kinds of technology offer us an unprecedented opportunity to overcome these difficulties and radically improve our knowledge of the Arctic Ocean. With satellite sensors, powerful icebreakers, ice camps, aircraft, hovercraft, underwater vehicles, drifting buoys, acoustic techniques and new methods of remote data recording and transmission we can overcome the problems of the harsh climate and the ice cover. Our level of understanding of the Arctic Ocean can rise to match that of other seas. *A major international programme of decadal duration is required, which involves an interdisciplinary approach.*

This will include the study of large scale ice-ocean circulation and climate, meso- and small scale physical processes, biological processes, carbon cycle, and paleoenvironmental evidence of past and present changes on long and short time-scales. This is the Arctic Ocean Grand Challenge.

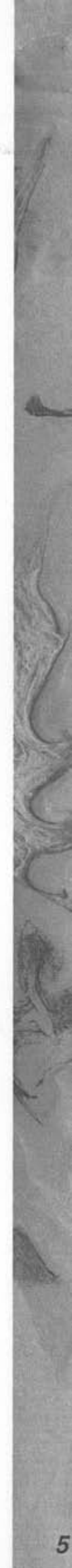
Thanks to global climate modelling and other new approaches such as remote sensing, we have a new view of planet Earth, in which we recognize the interconnection of all aspects of the ocean, atmosphere and terrestrial system, living and non-living, and we have learned something of the complex web of delicate mechanisms and interactions by which energy is exchanged and the system is regulated. We are now ready to face one of the great challenges of environmental science - understanding the cold pole of the world and its role in the global system.

ECOPS "Grand Challenges"

During a preparatory period of 3 years, the European Committee on Ocean and Polar Sciences (ECOPS) has formulated four "Grand Challenges" for the European Research, which have been discussed in several workshops, ESF Euroscience conferences and at the European Conference on Grand Challenges in Ocean and Polar Science in Bremen, September 1994. The four Grand Challenges are:

- Ocean Forecasting - regional and gobal forecasts of weather and climate in the time range from seasons to decades of years depend on a system of ocean observations for which new concepts and technologies are required.
- The Arctic Ocean with its ice cover is the most sensitive part of the globe with regard to greenhouse warming. For natural and political reasons it has been virtually inaccessible to international research. Concentrated efforts are planned for studies of interaction between ocean, ice and atmosphere including biogeochemistry and palaeo-oceanography.
- The Deep Sea Floor covers 60 % of the globe´s surface. Recent studies indicate great spatial and temporal variability in its structure and communities.
- Ice coring in Antarctica shall become one of the great European projects aiming at the understanding of causes and effects of past climate changes.

The European Committee on Ocean and Polar Sciences (ECOPS) is an international advisory group established by the European Commission, Brussels, and the European Science Foundation, Strasbourg. It is chaired by Professor G. Hempel.



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Synthetic Aperture Radar (SAR) image from ERS-1 of the marginal ice zone in the Greenland Sea (75°-79°N) from 13 January 1992. The image covers a stripe which is 500 km long and 30 km wide. The image is processed by NERSC. © ESA/TTS 1992.

Executive Summary

The Arctic Ocean Grand Challenge is an interdisciplinary programme which is tightly integrated both scientifically and logistically. It will address the following issues:

• **Large scale processes and climate**

- pathways and time scales of the Arctic Ocean circulation;
- interactions among atmosphere, ice and ocean, and effects from river input;
- influence of these interactions on the circulation of water and ice including distribution of temperature, salinity, ocean tracers, ice thickness, concentration and velocity.

• **Mesoscale and small scale physical processes**

- water mass transformations on shelves and slopes including river input;
- mechanisms by which water reaches intermediate and deep layers;
- the ice deformation process;
- melt season processes in the ice cover;
- effect of leads and ice type on vertical and horizontal energy exchange processes.

• **Biology and carbon cycle**

- seasonal and interannual variability of key communities and species;
- input of carbon from rivers, atmosphere and by interaction with surrounding seas;
- interactions within, and between, sea ice, the water column and sediments;
- flux of carbon by shelf water - deep basin exchange;
- possible role of methane hydrates in the climate change perspective.

• **Palaeoceanography and climate**

- modern sedimentation processes affecting the Arctic seabed and reflecting circulation patterns;
- palaeoenvironmental variability of the Arctic in terms of extremes, rates of change and gradations;
- assessment of possible future climate change based on geological data;
- impact of Arctic changes on the European climate (historic, modern, future).

The programme will comprise the following elements:

• ***Data analysis and modelling***
- establishment of an effective data and information management system for handling relevant Arctic data;
- analysis of existing Arctic data sets, especially historic data from Russian expeditions;
- improvement of remote sensing techniques and their validation;
- large scale modelling of the Arctic Basin and data assimilation;
- modelling of mesoscale processes in ice and ocean, including biological processes;
- development of coupled physical - biogeochemical models.
- simulation of palaeoclimate scenarios.

• ***Development of new technology for the Arctic***
- new instruments, such as miniaturized sensors to probe brine drainage channels, small low-power sensors for autonomous underwater vehicles (AUVs), advanced floats equipped with upward looking sonar;
- new unmanned platforms;
- the adaptation of submarines for Arctic data gathering;
- development of laboratory techniques such as the EURO ICE TANK for controlled study of small scale sea ice processes.

• ***Field experiments***
- an interdisciplinary drift study, the EURO ICE STATION, to investigate ice and ocean processes through a year;
- shipborne studies over the Eurasian continental shelves and slopes;
- central Arctic sections, carried out by icebreakers;
- synoptic basin-wide ice thickness mapping by submarine, aircraft and moored sonars;
- mapping of the Arctic circulation by buoys, floats and other means;
- seabed mapping of the Arctic Basin, using GLORIA or other techniques;
- acoustic thermometry of the Arctic Ocean.

• ***Laboratory experiments***
- controlled experiments with the EURO ICE TANK;
- biological studies on physiology and adaptation;
- geotechnology studies.

The programme is of decadal length, but will be undertaken in two main phases, as shown in the Implementation Plan. The first phase of data analysis, model development, technology development, field and laboratory experiments, will last from 1996 to 2000. The second phase, from 2001 to 2005, will include more advanced observational work such as detection of greenhouse signal, Arctic Ocean drilling and seabed mapping, as well as the completion of the modelling programme.

1. Large Scale Processes and Climate

1.1 Rationale

The Arctic Ocean (Fig. 1) is one of the least understood of the world oceans, and is in many areas virtually unexplored. Its internal circulation, exchanges with surrounding seas, and details of its ice conditions, in particular ice thickness, have remained largely speculative due to very difficult logistics. Similarly, modelling of the Arctic Ocean poses severe problems to modern computing technology due to the small scales which govern dynamical processes, and the very limited information for validation of the results. Nevertheless, the Arctic Ocean plays an important role in understanding the natural variability of our climate system and its response to human activities. This importance is partly due to its interaction with the adjacent seas and the atmosphere, and partly because antropogenic climatic change is expected to be most pronounced in the Arctic region.

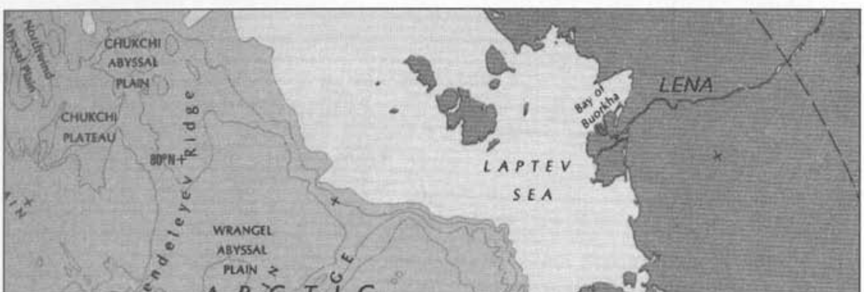

***Fig. 1:** Bathymetric map of the Arctic Basin and the surrounding shallow seas.*

The most important topics to be addressed are:

What is the role of the Arctic Ocean in the climate system, and how does it influence global climate and European climate in particular ?

Investigation of this question requires improved information on the large scale circulation of the Arctic Ocean, on the role of river input and the interaction of large shelf areas with the deep ocean and on the behaviour of the deep layers in the Arctic Basin (Fig. 2).

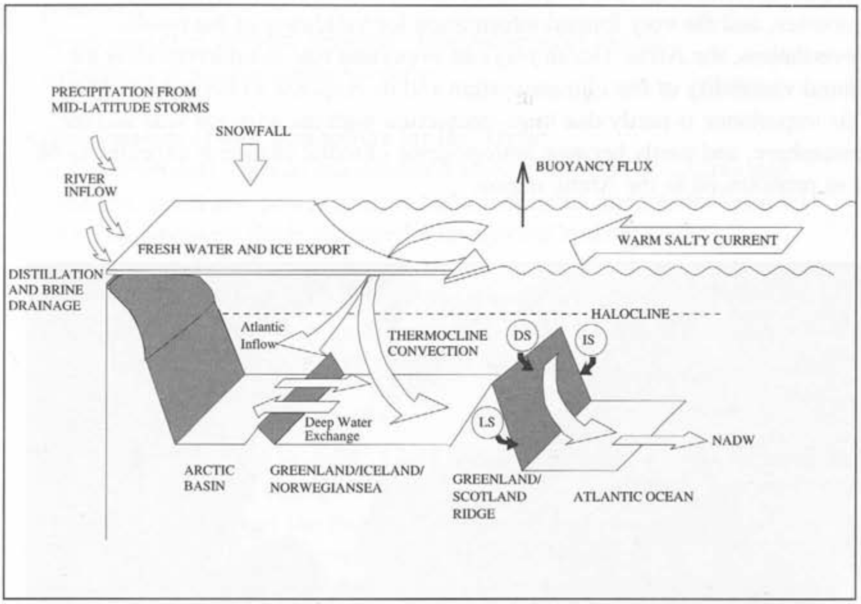

***Fig. 2:** Schematic diagram illustrating the transport of ice and freshwater near the surface of the Arctic Ocean and the termohaline circulation associated with brine transport of the marginal shelves and deep overturning in the Greenland Sea.*
LS - Labrador Sea; DS - Denmark Strait; IS - Iceland - Scotland Ridge;
NADW - North Atlantic Deep Water (From Untersteiner & Carmack).

Furthermore, it has to be clarified how climate changes may be detected, what the most sensitive indices of these changes are, and which are the regions of greatest importance.

Studies are necessary to reveal the magnitude of natural as well as man induced variability of ocean and ice in the Arctic Basin. In particular, the fresh water balance of the Arctic Ocean is of great importance. It is estimated that climate change will alter this budget significantly, resulting in a strong modification of the global oceanic conveyor belt circulation. As a consequence, the climate of a great part of Europe, as well as other adjacent regions will be altered substantially.

Similarly, improved information is required to investigate the role of the Arctic Ocean in the global carbon cycle.

Furthermore, the sensitivity of Arctic Ocean processes to changes in atmospheric forcing (solar radiation, wind, heat exchange) and boundary conditions, such as the inflow from the surrounding seas, is not known.

Information on large scale circulation is required for determining the transport of anthropogenic inputs such as pollutants, radionuclides, etc.

For the management of living and non-renewable resources information is needed on environmental conditions (ice, circulation, climate) in both the shelf regions and the deep ocean.

For other needs, such as marine transport, pollution control etc. large scale processes form a background to understand smaller scale features, and to predict ocean and ice conditions.

1.2 Objectives

The main objectives are to perform observational and modelling studies on the circulation of ice and ocean, and on the associated distribution of salinity, temperature, tracers, sea ice velocity, thickness and concentration. The following themes are of key importance:

Ocean circulation

Present knowledge of ocean circulation is primarly based on analyses of water masses , tracer data and large scale models, which generally have very modest spatial resolution. Very little information is available on the variability on decadal scales. Studies carried out so far reveal that mass transports are most intense in the continental margins and are strongly linked with bottom topography (Fig. 3). There are considerable differences between both water masses and circulation in the two main basins: the Eurasian and Canadian. The objective is to improve the existing basis of information by performing both large scale observations and modelling experiments. To achieve this goal there is a need to optimize existing ocean circulation models through better representation of sub-grid scale processes and to develop improved inverse methods and data assimilation techniques, as well as extended Arctic Ocean data sets. At present, a wide range of Russian data is still not involved in the data assimilation process.

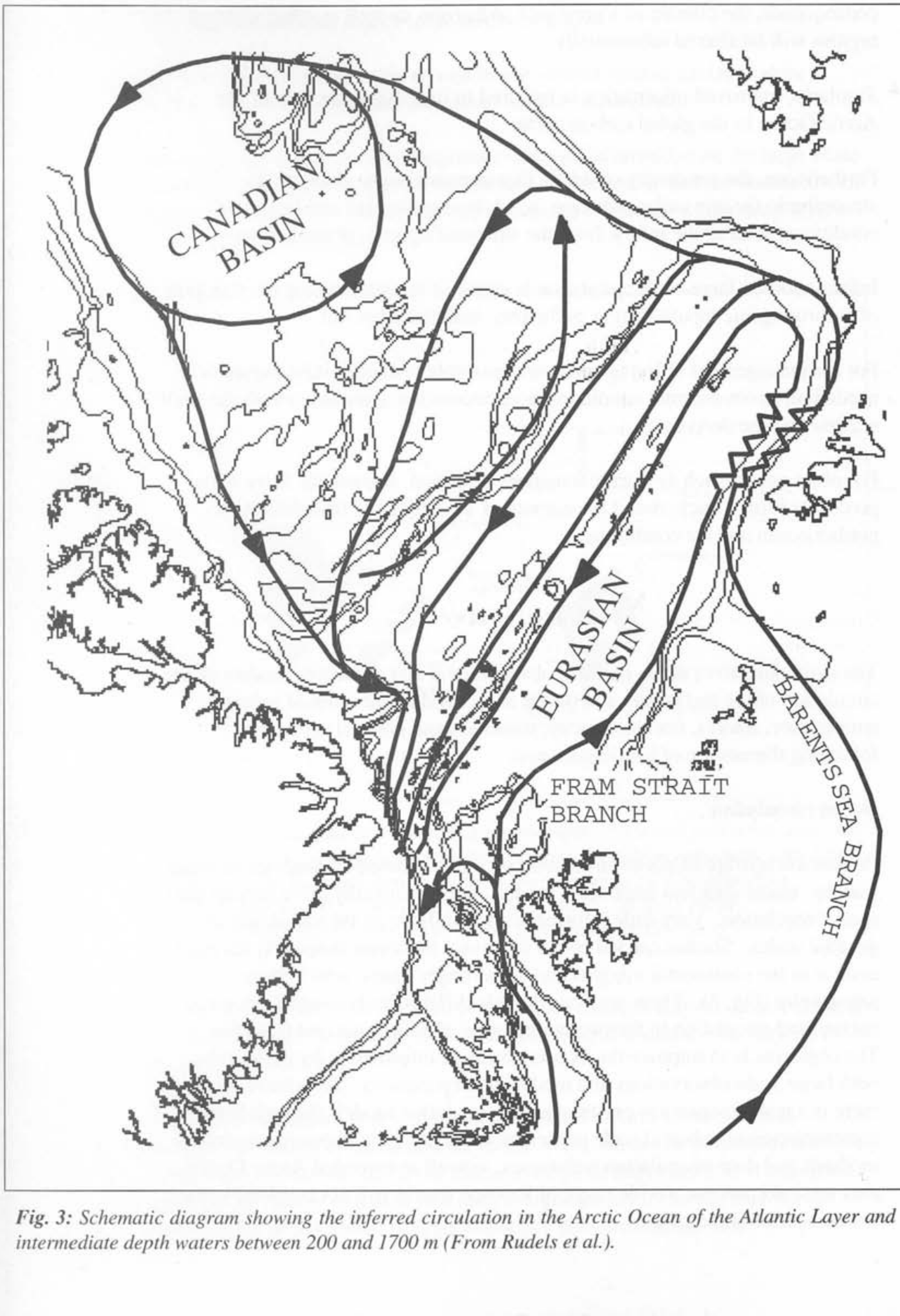

Fig. 3: Schematic diagram showing the inferred circulation in the Arctic Ocean of the Atlantic Layer and intermediate depth waters between 200 and 1700 m (From Rudels et al.).

Mass balances

The use of models in estimating the mass balance of the Arctic Ocean is of great importance. We need improved information on the pathways of heat, salt and other tracers through the Arctic Ocean and the influence of various internal and external factors on their distributions. There is a great need to determine the fresh water balance of the entire region, including inflows from and outflows to the North Atlantic, the freezing and melting balances within the region, and their seasonal as well as interannual variability.

Determination of controlling factors

The large scale phenomena of the Arctic Ocean are controlled by thermohaline processes and by atmospheric forcing, the relative roles of which are not fully understood. Still under discussion is the degree to which topography controls circulation, mixing and consequently also the transport of various substances. The exchanges with surrounding regions are poorly understood and need to be studied in more detail.

Impact of the Arctic Ocean on surrounding regions

The Arctic Ocean has a wide ranging impact on the weather and climate of Europe and other subarctic and boreal regions. Arctic processes determine the formation of North Atlantic Deep Water and can therefore, modify the oceanic conveyor belt circulation, which may imply drastic modifications of European climate. Similarly, the oceanic carbon cycle is considerably influenced by large scale changes in the Arctic Ocean. All these features also have wide ranging consequences for the long-range pollution transport.

Sea ice mass balances

The Arctic sea ice mass balance is essentially unknown. Available data do not provide reliable estimates of the regional distribution of ice thickness and concentration, on the relative magnitudes of local freezing/melting and transport effects (advection and pressure ridge building) and of the export to regions outside the Arctic, although ice extent can be monitored by passive microwave systems (Fig. 4).

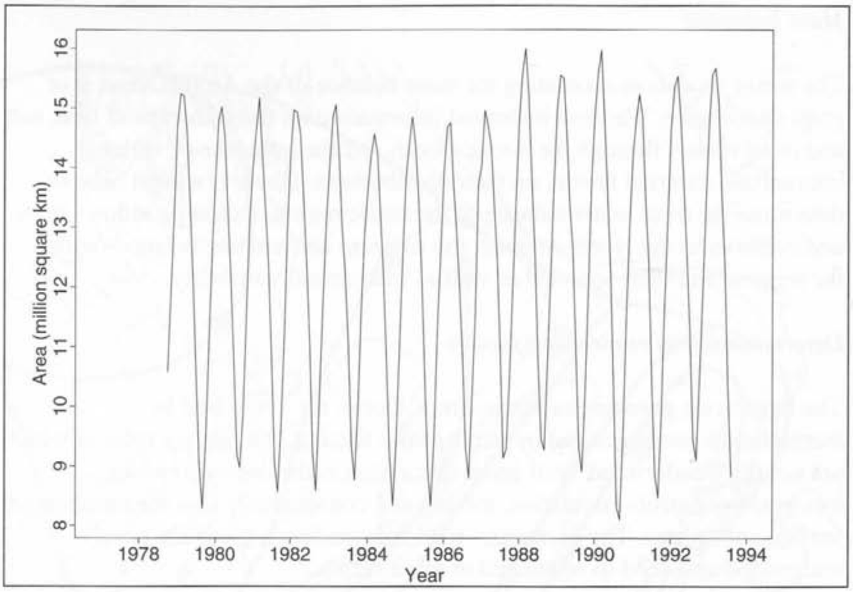

Fig. 4: Time series of Arctic sea ice extent based on passive microwave data from the SMMR and SSM/I instruments (From Johannessen et al.).

Sea ice thickness distributions

The most difficult sea ice variable to observe is the ice thickness distribution (Fig. 5) with its pronounced spatial and temporal variability. To investigate how solar radiation, pressure ridging, new ice formation and interseasonal variability modify the ice thickness distribution requires a wide range of cooperative studies. The ice thickness distribution controls the ocean-atmosphere heat exchange. Its downstream evolution determines the melt rate and, together with the ice velocity, it provides the mass flux.

Open water distribution

In the Arctic, the estimated 10 % open water area may be responsible for as much as 80 % of the total heat exchange with the atmosphere. The accurate magnitudes are not known, nor is the degree of impact of open water on meteorological, hydrological and gas exchange conditions.

Sea ice modelling

Improved sea ice models are required to realistically simulate the Arctic ice cover. Modelling studies should investigate the following questions. How many ice thickness categories have to be resolved by the model ? Which shape

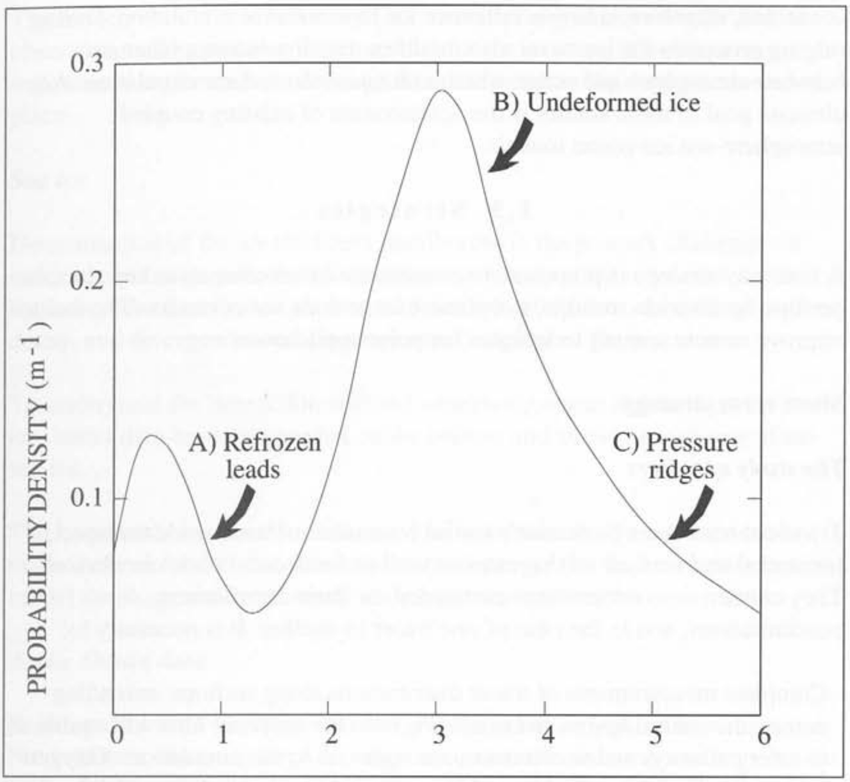

Fig. 5: Ice thickness distribution for the Arctic Ocean. Refrozen leads (A): The majority of polar atmosphere-ocean heat exchange occurs in leads; easily crushed by convergence or shear stresses to form pressure ridges. The peak in the probability density function is represented by undeformed ice of 3 m thickness (B). The thickest ice is represented by the pressure ridges (C) which are transported with the ice in which they are embedded and partake in later melt processes in sub-polar oceans (From Wadhams).

of the yield curve is realistic ? What is the optimal strength parameterization ? Which is the optimal albedo parameterization, including the dependence on melt ponds, ice thickness, snow cover, and snow temperature ? How is the absorbed insolation disposed of including melting of the top, bottom or side surface of the ice, heating of the ice, enlargement of brine pockets, storage in leads and storage in the mixed layer beneath the ice ? The optimal model will be determined by inverse modelling techniques using all Arctic data available on sea ice concentration, thickness and drift.

Interaction of sea ice and ocean

The evolution of the sea ice cover has a pronounced impact on the Arctic Ocean circulation. Freezing and melting change the baroclinic structure of the ocean and, therefore, strongly influence the thermohaline circulation. During ridging processes the ice cover also modifies the momentum exchange between atmosphere and ocean which influences the surface circulation. An ultimate goal of these studies is the optimization of existing coupled atmosphere-sea ice-ocean models.

1.3 Strategies

A four way strategy is proposed: to concentrate on monitoring at key sites, to perform basin-wide sections, to optimize large scale ice-ocean models, and to improve remote sensing techniques for polar applications.

Short term strategy

The study of tracers

Transient tracers are particularly useful for studies of basin-wide transport, horizontal and vertical mixing rates as well as for decadal scale circulation. They contain time information embedded in their distributions, concentrations, and in the ratio of one tracer to another. It is necessary to:

- Complete measurements of tracer distributions along sections extending across the central basins and extending onto the shelves. This will enable us to infer pathways and to estimate time scales of Arctic circulation. Oxygen isotopes will additionally be used to estimate large scale storage and flux estimates associated with the fresh water budget.

- Perform high resolution 3-D surveys of specific tracers in key areas of water mass formation, which provides insight into water mass formation and rates.

- Evaluate tracer data in order to obtain a semi-quantitative interpretation of circulation rates and processes, in particular when these studies are combined with model evaluation and calibration.

Large scale models

Basin scale models require integration with North Atlantic models in order to give estimates of the impacts in both directions. The horizontal resolution, in particular in the Arctic Ocean, has to be improved. A grid resolution of 30 km would be good for many purposes. The inclusion of passive tracers gives additional possibilities for validation and calibration of the models.

The majority of the Arctic Ocean processes occur on sub-grid scales of these models. There is a need to obtain better parameterization from process models, as well as nesting of high resolution submodel into the basin scale models.

The models should also be utilized for identification of key sites for field observations. In particular this is needed for the location of net freezing regions and regions where drainage from shelves into the deep interior takes place.

Sea ice

Determination of the ice thickness distribution is the primary challenge, in order to obtain adequate data for heat exchange, mass balances and climate response. The distribution evolves with time due to thermodynamic growth or decay, and divergences and convergences (ridging) of the ice cover.

To understand the interaction with the underlying ocean and transport of the ice, better data bases are needed on the bottom and surface roughness of the sea ice.

The basin scale ice-ocean models need to be improved. The advances to be made in these models are connected to evolution of the thickness distribution, model rheology and in the small scale large scale interaction.

Arctic Ocean data

Existing data from the Arctic have sparse temporal and spatial coverage. Nevertheless, the analysis of existing data in an effective way can improve the understanding of the Arctic Ocean. To achieve this the following will be addressed:

- Assimilation of available data into large scale models. Data assimilation done so far has been based on insufficient or sparse data sets;

- Achieve oceanographical, meteorological and sea ice data from Russian institutions. Special emphasis should be made to incorporate these invaluable historical data into ongoing programmes;

- The comprehensive data bases to be established should also be utilized for studies of variability and long term changes which have taken place in the Arctic Ocean region.

Specific experimental studies

Specific field experiments are needed for the following purposes:

- Large scale experiments for validation of ice thickness distribution models. The current models are based on limited statistics and should be improved with a wider range of surveys of actual ice distributions in different regions;

- Validation experiments of remote sensing results. The basic tools available are both passive and active microwave measurements from satellites. They provide good spatial and temporal coverage, but interpretation of the microwave data can be difficult, particularly during melt season. Special campaigns are required for the validation;

- Monitoring of large scale variability and distribution of temperature and salinity fields;

- The utilization of acoustic tomography/thermometry may prove to be a very useful tool for integrated ice thickness meassurement and for detecting basinwide temperature changes in the Arctic Ocean. Acoustical methods can also be used to study the internal sea ice structure.

Long term strategy

The studies of the Arctic Ocean over many years will reveal information about the variability on decadal time scale. Improved ice-ocean models will be an important tool to study various scenarios of changes in water masses and ice conditions.

Tracer studies

In the tracers studies the following activities are recomended:

- Repeated monitoring of specific sites will give information on the evolution of water masses, mixing and transport in the Arctic Ocean;

- Re-survey of spatial distribution of selected tracers can reveal changes in the entire basin on decadal time scale;

- The variability of freshwater budget can be studied by the use of oxygen isotopes which will be measured in large scale surveys.

Model studies

After the initial improvement of circulation models, simulations are to be carried out with various alternative forcing scenarios. These simulations can be used to determine the role of the Arctic Ocean in global change.

The ultimate objective of modelling is to produce reliable coupled atmosphere-ocean-ice models for the entire Arctic Ocean.

Interconnection of different temporal and spatial time scales are obtained with nested models. These models will become routinely used in global change prediction.

Sea ice

Long term studies of the Arctic sea ice will reveal the sensitivity of the ice to changes caused by external forcing such as solar radiation, changes of the tropospheric circulation and global warming.

1.4 Technology

Requirements for improved data collection in the Arctic Ocean include:

- Sufficient capacity for analyses of tracer data in shore-based laboratories;
- Design and test of small volume water sampling systems for remotely operated vehicles (ROVs), in order to conduct periodic surveys of oxygen isotopes and other tracer substances in upper water masses;
- Submarine sonar profiling for ice distribution functions such as roughness and thickness;
- Moored upward-looking sonars (ULS) for time series of ice thickness in key locations;
- Airborne laser profilometry is needed for surface structure determination of sea ice;
- Airborne electromagnetic techniques, either from helicopters or from fixed wing planes for ice distribution measurements;
- The development and application of acoustic tomography/thermometry in the Arctic Ocean;
- Improvements of microwave satellite remote sensing (e.g. using different frequencies and different polarizations of SAR).

1.5 Logistics

Standard logistics such as icebreakers, aircraft and helicopter will be used. In addition the use of civilian submarines and development of AUVs with a long operating range will be investigated, as well as the adaption of hovercraft to an Arctic Ocean multisensor platform.

2. Mesoscale and Small Scale Physical Processes

2.1 Rationale

Introduction

Mesoscale and small scale processes in the ocean and ice cover play a vital role in the Arctic Ocean system as a whole, since large scale dynamics are often dependent on the smaller scale processes. For example, the rheology for describing ice dynamics on a basin scale is dependent on knowledge of the mechanics of pressure ridge formation on scales of tens of metres. Also the transport of sea ice biota across the Arctic Basin is governed by the habitat offered to algae by brine drainage channels of diameter less than a millimetre. In the Arctic Ocean, mesoscale eddies of diameter tens of km have long lifetimes which enable them to transport anomalous water over distances of order 1000 km and thus influence water mass structure at the location of their decay.

The mesoscale also includes *regional processes*, such as those in Fram Strait (width 400 km) mediating the exchanges of water between the Arctic Basin and Greenland Sea (Fig. 6, colour plate 1, middle page). Regional processes are relevant to global climate and global change via upward scaling links. Regional processes are also important for resource management efforts, such as conserving biological resources, or understanding the nature of the ice environment, including ice strength, for offshore drilling and production or icebreaker transport.

We can define "small scale" from the point of view of ice processes to be from millimetres to tens of metres. "Mesoscale" from the point of view of ice-ocean processes ranges from one to one hundred km. Arctic Ocean water mass transformations involve mixing processes which occur on a small scale vertically (from centimetres to hundreds of metres) but from medium to large scale horizontally (1 - 1000 km).

Why we should study small and mesoscale processes

They are relevant to global scale processes via upward scaling links. That is to say, basin-scale distributions of properties are directly dependent on mechanisms acting at the small and meso-scale. For instance:

- Understanding the small scale mechanics of the ice deformation process which produces pressure ridges allows us to parameterize the thickness redistribution term in basinwide models of ice dynamics-thermodynamics, and to obtain a more realistic ice rheology for use in such models;

- The validation of airborne and other novel techniques of ice thickness measurement against careful local *in situ* measurements allows these techniques to be used across the Arctic to give basinwide ice thickness distributions;

- Small scale measurements of heat exchange in a single lead permit us to understand ocean-atmosphere heat transfer throughout the Arctic, since the bulk of this occurs through open and refrozen leads;

- Local observations of the ice surface through a summer of meltwater pool development allows us to estimate a better area-averaged figure for summer albedo, which is of benefit to ice thermodynamic models;

- Measurement of small scale ice fabric properties allows us to estimate the chemical and biological fluxes associated with ice transport, through understanding the mode by which pollutants, sediments and biological material are carried in the ice cover;

- An understanding of mesoscale eddy structure and life cycle allows us to estimate the characteristics of geostrophic (two-dimensional) turbulence and parameterize the large scale mixing and water mass formation produced by eddies;

- The validation of remote sensing algorithms by *in situ* ice work within a limited region allows us to use satellite remote sensing methods to survey the whole Arctic Ocean synoptically.

There are processes of special regional importance which, although they only take place in a limited region of the Arctic, are essential to the functioning of the Arctic system as a whole. Examples of regions and processes are:

- The St. Anna and Voronin Troughs, and possibly other troughs and canyons along the edge of the Siberian shelves, where Atlantic water and modified shelf water flow down into the Arctic Basin to renew the deep water and to transport sediment. Shelf drainage is central to the energetics of the whole Arctic Ocean. It is therefore essential to locate the regions where these exchanges are taking place, and then seek to measure what may be an intermittent process using long-term monitoring techniques such as moorings and floats;

- Both in these regions, and on continental slopes in general, the large scale currents are constrained by geostrophy to flow along depth contours (themselves not known well and requiring to be mapped as part of the Arctic Ocean Grand Challenge). Mesoscale features like intrusions, filaments and eddies produced by instability of along-slope current and/or topographic effects are ageostrophic and may play a major role in shelf-slope exchange because they relax the geostrophic constraint. Mapping of these features where they occur is therefore very important;

- The Fram Strait, an important region of ice and water exchange between the Arctic and the subpolar oceans;
- The margins of the perennial ice zone (i.e. the ice edge zone in summer), since they mark the limit of the region where first-year ice is being transformed into multi-year ice by summer melt processes.

2.2 Objectives

Small scale ice processes

Sea ice physical behaviour is expressed in ice-ocean models which require knowledge of time-dependent atmospheric forcing (wind, temperature, humidity, cloud cover, precipitation) and need validation data of sea ice concentration, motion and thickness. *The greatest deficiency at present is the lack of sea ice thickness data in both polar regions.* However, sea ice models also need an improved parameterization of small scale processes. This requires observations of processes like ridge building, surface energy balance, effect of melt ponds and the influence of convection. A small scale sea ice process study will also identify the key physical, chemical and biological mechanisms which determine the role of the sea ice system in biogeochemical cycling. It will emphasise the temporal evolution of the system, including ice formation and melting. One end product of such a programme, involving both laboratory and field experimentation, will be an understanding of the environmental control of biological processes at millimetre scales which determine the interaction of the sea ice system with the ocean and atmosphere.

The following topics are of particular importance:

- *The summer melt period.* We need to carefully study the sequence of thermal processes by which meltwater pools form; modify the surface albedo; concentrate sediments and biological material; accelerate the loss of brine; modify the surface and bottom topography to create the characteristic roughness pattern of multi-year ice; vent meltwater into the underlying ocean (with some of it being trapped in under-ice melt ponds); and alter the appearance of the ice on passive and active microwave. These important summer processes in the ice cover have not been studied properly and so will be a special focus of concern. They require a test area of ice cover to be monitored throughout a summer. Although the winter albedo of the ice cover is known to be about 0.8, summer albedos of between 0.4 and 0.55 have been used in models; the uncertainty in summer is significant because of the high radiation flux. Biological processes are also affected by the downflow of fresh water into the near-bottom environment. The flushing of melt water is associated with the release of organisms from one habitat to another.

- *The control of ice structure by thermodynamics.* These are the processes by which the fabric of the sea ice cover - the grain size and orientation, the salinity and bubble content, the distribution of brine drainage channels, the bulk properties such as specific heat and thermal conductivity - evolve through the year under the influence of thermal forcing. Not enough is known about the basic physics of these processes, nor about regional variations in fabric properties over the Arctic.

- *Pressure ridges constitute up to half of the volume of the ice in the Arctic seas.* Physically they determine the ice-water drag coefficient, limit the range of acoustic propagation, determine the ice strength, affect mixing rates and scour the bottom in shallow water. The mechanics of ridge formation are not known well enough to enable the ridging process to be adequately parameterised in ice-ocean models. Ridges are important biologically since they provide a three-dimensional structure one scale up from the brine channel system, offering a substrate for algal growth and a feeding area and protected habitat for larger species. Studies on ridge formation have begun under the mainly US SIMI Program (Sea Ice Mechanics Initiative) of ONR, and our work will build on the results of this programme.

- How ocean-atmosphere heat flux is dependent upon small scale properties of the ice cover, such as melt ponds in summer, and crack and lead distributions in winter.

- The ways in which the properties of the ice cover affect the sea ice ecosystem, relating both to habitat of ice organisms and to light availability.

- The role of sea ice as an environmental archive, revealing the origin of its drift through the distribution of minerals in the sediment that it carries.

Small scale ocean processes

- Processes under a single lead, i.e. the local convective pattern produced by cooling in the lead, and the heat and moisture fluxes through the lead. Work in this area will build on the experience of the recent US-led LEADEX experiment.

- Processes under a newly freezing sea surface, both in calm conditions - the way in which the salt flux is injected into the surface water - and in turbulent conditions, where the formation of frazil and pancake ice permits a high growth rate to continue through maintenance of an open sea surface.

- Processes under a melting ice sheet, relating to stabilisation of the surface water by freshening and the resulting changes in heat flux and bottom melt rate.

- The problem of gas exchange in ice-covered water. It is not known whether gas can be exchanged at all through sea ice or, if so, what is the pathway.

Mesoscale ice-ocean interactions

- Processes of ice-ocean interaction on shelves which mediate the production of dense water through brine production and mixing. These processes include the input of river plumes to the shelf and the associated fronts (Fig. 7, colour plate 2, middle page) which occur at the limits of the plumes; the formation of eddies, jets and upwelling at ice edge fronts and their influence on the front; and the mechanisms of shelf drainage.

- The influence of bottom topography on these processes, in particular the role of canyons in steering shelf drainage plumes; the role of ridges and shallow rises (such as the rise to the south of Yermak Plateau) in guiding fluid flow and in trapping flow by tidal resonance and the creation of eddies; and the effects of rotating tidal currents in general (amplified by certain topographic features) on the ice cover.

- The influence of mesoscale eddies on sea ice properties, especially melt and freeze rates.

- The internal wave field, the role of deep pressure ridges in creating internal waves, and the estimation of the resulting internal wave drag (Fig. 8).

Processes governing water mass transformations in the ocean

Two types of process are involved in water mass modification in the Arctic Ocean, particularly in the evolution of the deep water:

- *Diapycnal processes*, comprising convection (including double-diffusive convection), which releases potential energy, and wind mixing and entrainment into plumes, which require energy. A key process is boundary convection induced by excess brine release on the shelves.

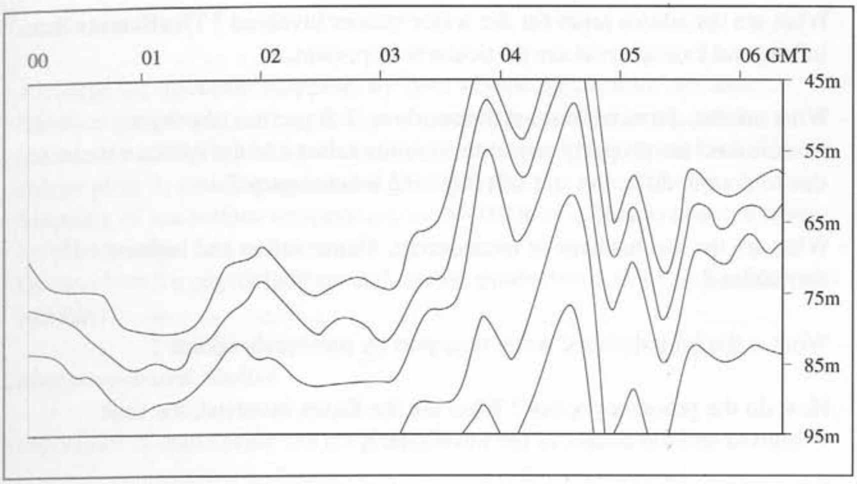

Fig. 8: Internal waves in the thermocline observed by a thermistor chain suspended from ice floes during a 6-hour period. The interval between each contour line is 0.5° C, with warmer water below colder water. The data were obtained in the Fram Strait marginal ice zone in March 1987 (From Sandven and Johannessen).

Unsolved questions which will be investigated are:

- What are the locations and strengths of the sources of diapycnal mixing ? We assume that the edge of the Siberian shelf is the most important place to search. The known source in Storfjorden in Svalbard can be investigated as a case study of the process physics.

- What is the physical nature of the plumes which descend off the shelf break, what is their thickness and velocity, what is the entrainment rate (especially in relation to other outflows in the world, such as Denmark Strait and Mediterranean), and what is the lateral extent of the plumes ?

- What is the importance of boundary plumes for the redistribution of Atlantic heat in the ocean ? What are the relative amounts of heat transferred down by plumes and up by diffusion ? The upward heat transport by mixing and double-diffusive convection would be trapped in the halocline and increase its temperature. Measurements of the change in temperature will give the time scales for these processes.

- Where does the deep water exchange across the Lomonosov Ridge take place, and what is the mechanism ?

• *Isopycnal processes*, such as interleaving and merging of water masses. Problems which should be investigated are:

- What are the source areas for the water masses involved ? The Barents Sea inflow and frontal areas are particularly important.

- What are the characteristics of the resulting T-S profiles, the layer thicknesses, the property steps, the stability ratios and the spatial extension, due to double diffusion and salt fingering mechanisms ?

- What are the mechanisms of meandering, filamentation and isolated eddy formation ?

- What is the long distance water transport by mesoscale eddies ?

- How do the processes occur ? What are the fluxes involved, the time evolution and the details of the interfaces ?

- Can we extend our understanding to larger scales, i.e. the effect on overall water mass characteristics ?

Note that double-diffusive convection is a diapycnal process which may drive isopycnal exchanges and enhance the final mixing of water masses.

2.3 Strategy

Investigations are defined by the space and time scales of the processes to be studied, and will involve the following techniques:

Field studies

- Ice camps - long-term, equipped with hovercraft or helicopters to give extended and directed spatial coverage;
- Ships carrying out sections;
- Drifting ships, performing essentially the same role as an ice camp;
- RAFOS or SOFAR floats to give mid-depth circulation;
- Moorings, for currents, sediment traps and upward-looking sonar;
- Manned or unmanned underwater vehicles, i.e. military submarines on civilian tasks; civilian submarines, AUVs, ROVs;
- Acoustic techniques, both long-range (tomography or thermometry) and short-range (use of acoustics to investigate cracking and ridge building);
- Drilling platforms - these are primarily for geological work, but ice studies can be done from them.

Remote sensing

- Airborne ice thickness mapping, by laser or electromagnetic methods;
- Satellite mapping of ice types, concentration and motion using passive microwave (SSM/I) and Synthetic Aperture Radar (SAR) from ERS (Fig. 9, colour plate 3, middle page) and RADARSAT;
- Mapping of sea surface temperature by AVHRR or ATSR to observe fronts off the ice edge.
- Ocean clour for phytoplankton and marine productivity (CZCS, SeaWifs and MERIS)

Laboratory-based studies

- especially of small scale sea ice processes.

Modelling

- of key processes using analytical and numerical models.

Historical data analysis

- in particular a large effort to make use of the very extensive Russian data sets collected from the "North Pole" drifting stations and High Latitude Research Expeditions.

Field studies

Studies from a drifting ice camp

The process studies described above, including in situ remote sensing studies, require the use of a drifting ice station, the EURO ICE STATION (Fig. 17), for a period of one year. The station may be physically a ship or a small camp, and is designed to enable a fixed region of ice a few hundred metres square, to be followed as it evolves and interacts with the underlying ocean and atmosphere through an annual cycle. The programme is thus aimed at understanding sea ice and ocean processes which occur on scales of metres to hundreds of metres, i.e. it is concerned not with the microstructure of an ice sheet but rather with physical, geochemical and biological couplings associated with sea ice features such as ridges, meltwater pools and leads.

Work done from the EURO ICE STATION will include, firstly, a multidisciplinary study of individual pressure ridges, selecting a limited number of first-year and multi-year ridges, and focusing on the structure and morphology of the ridges rather than their strength or the stresses involved in their formation.

Measurements will comprise:

- *the three-dimensional structure of ridges,* including top and bottom shapes, block sizes, arrangement of voids, salinity and temperature profiles. Techniques include in-ice acoustic tomography (yet to be developed for such an application) or borehole video to map the three-dimensional structure, and the use of divers;

- *gradients of velocity, turbulence and oceanographic properties* very close to the ridge surface, using small scale chains of probes deployed by divers;

- *biological and geochemical studies of the cavities*, to determine the significance of the cavities for primary and secondary production, and the utilisation of ridges by higher trophic levels;

- *sedimentation rates under the ridge.*

A parallel study of melt season processes will be carried out from the beginning of snow melt to the time of autumn freeze-up (July-October). The study will cover the initiation, development and draining of meltwater pools, their effect in flushing salt out of the ice as well as biological material and sediments, their effect in changing the surface and bottom topography of first-year ice in the transition towards multi-year, their role in defining the summer albedo, their absorption of radiation, and the fate of the meltwater as it is injected into the water column.

Visits will be made to nearby leads for a biological survey of the lead community and productivity in relation to the thicker ice nearby, and for a physical study of heat and moisture exchange through the lead and small scale convection under the lead, aiming at an energy balance for the lead from formation to refreezing and through to its final crushing to form a ridge. The final module of this integrated study is the field component of small scale ice properties studies. The concentration upon sea ice structural studies at all scales and with a physical-biological emphasis sets this type of drifting ice study apart from all previous drifting stations.

Sections

Just as the ice station is essential for studying small scale and mesoscale ice and ice-ocean processes, so are shipborne sections necessary to observe the water mass transformation processes. Cruises should cover the St Anna and Voronin Troughs, and the shelf, slope and margin regions of the Kara, Laptev and East Siberian Seas, with coverage in winter and summer, and an emphasis on early winter.

Floats

RAFOS floats will be used to map the movement of water into the Arctic Basin through Fram Strait and off the Siberian shelves. They will require read-out stations to be installed through the ice on a dense grid which will require regular updating as the ice drifts out of the Basin.

Moorings

A limited number of moorings will be used to measure current flows through critical parts of the Arctic, including Fram Strait, the Siberian shelves and slopes, and gaps in the Lomonosov Ridge. Each mooring will include an upward looking sonar as well as current meters and sediment traps.

AUVs and submarines

The prime use of submarines will be for the large scale mapping of ice thickness over the Arctic Basin, requiring either the conversion of a military submarine to civilian use or dedicated use of a military submarine for a number of cruises. During the large scale mapping cruises, submarines can operate in the shelf break regions, collecting in situ data on the upper parts of plumes using along-track oceanographic sensors, or XCTDs launched from the boat. Ar alternative technique is to use AUVs. Under present technology where ranges are limited to some 300 km, the AUV must be deployed outside the ice edge by a ship so it can only be used to investigate a limited region near the ice edge, but during the Arctic Ocean Grand Challenge we expect AUV technology to advance rapidly to the point where they can carry out many of the tasks for which a submarine is presently required.

Remote sensing

Remote sensing is primarily a tool for large scale studies - mapping the distribution of ice types and thickness over the whole Arctic Ocean. It is also of value to smaller-scale studies, however. For instance, remote sensing is the only tool for mapping the overall distribution of leads in the Arctic and Antarctic, extending from systems of wide leads (AVHRR) to narrow leads of 25 m width or less (SAR). The primary biological significance of leads is to permit the existence of air-breathing animals within the pack, and to provide a feeding area for seabirds. Of importance also is how efficiently shade-adapted phytoplankton can utilise the enhanced light in the lead. Physically, narrow leads may be specially important in summer because of the additional perimeter they offer for lateral melt. It is not known for sure whether it is the large lead systems or the smaller leads which control sea ice deformation processes, although SAR mapping of Arctic ice velocities suggests that the ice

moves as large rigid sheets with the stresses relieved by shear across systems of large leads.

In connection with the EURO ICE STATION, an ensemble of passive and active insitu remote sensing instruments will be deployed for seasonal validation of different space born sensors in order to improve algorithms for the ice cevered seas. Mesoscale remote sensing will be carried out by aircraft to map ice types and roughness in the experimental region. Possible instruments include the airborne electromagnetic mapping system mounted in a Twin Otter of the Finnish Geological Survey, which uses an eddy current technique to map ice thickness; airborne laser profilometers; airborne microwave radiometers; and cameras.

Laboratory-based studies

The understanding of biological-physical interactions starts at the level of individual organisms. Nearly all techniques applied to sea ice biota at present involve destruction or radical alteration of the habitat prior to the experiment. This implies that the conditions under which rates are measured are very different from the natural situation. Similarly, physical investigations of ice fabric in the field do not allow structural changes to be initiated and followed under conditions which can be varied at the experimenter's discretion.

A key facility to overcome these problems will be the use of a large ice tank (the EURO ICE TANK) in which ice can be formed under controlled conditions. The tank will be used to study the evolution of the small scale physical structure of features with sea ice biological communities. By producing ice under strictly regulated conditions, the role of external factors on the ice fabric, and hence its properties as a biological habitat, will be quantified.

The optimum requirements include large size (up to about 10 m long, a few metres wide, over 2 m deep), with facilities for wave and wind generation (for the simulation of frazil and pancake ice), simulated solar radiation, temperature control, replacement of under-ice water, and facilities for the installation of experimental equipment from the underside of the ice cover.

Understanding the small scale physical-biological interactions in the system will involve making measurements at millimetre scales in a spatially complex environment. It will be necessary to develop *microsensors* for light, temperature, salinity, chemical nutrients, pH, oxygen, chlorophyll and biomass. These can monitor the conditions actually experienced by algae within brine drainage channels, as well as the physical environment which governs the development of the channel and the internal ice fabric.

Modelling

The key mesoscale processes which require modelling are associated with the river input, shelves and shelf-slope regions. These processes include brine rejection and the associated shelf drainage, upwelling, lead formation, river fronts and hydrodynamic instabilities, and they are important for water mass formation and modification for the whole Arctic Ocean. Heat exchange with the atmosphere takes place on these scales through ventilation processes. The dominant sub-surface circulation patterns in the Arctic Basin are associated with intense, localised (< 50 km wide) bands of along-isobath flow, and this is also the scale for the primary signals in the carbon cycle and biological activity, and for the physical processes which control chemical variability.

It has already been found by numerical experiments that local topographic features (canyons, ridges, depressions, banks) can assume an importance in affecting water circulation out of all proportion to their size or frequency. Canyons, for instance, are particularly effective for generating upwelling or creating leads and polynyas. The canyon not only induces upwelling of water to the surface, but ensures that upwelled water is ventilated to the atmosphere by causing open water formation through divergence in the ice cover.

It is reasonable to believe from these unpublished experiments that the dominant physical processes of ice edge - shelf break dynamics can be properly treated with currently available models provided adequate horizontal resolution is achieved. This entails resolving the topographic length scale and the first internal Rossby deformation radius, requiring a grid size of no more than 1 km. This is a daunting requirement, but can be achieved through the use of massively parallel computing technology at present under development. Processes on the shelf and slope spin up over 2-3 years, while the interior basin requires about 100-200 years to equilibrate water masses. Thus a high-resolution, 2-3 year time scale model will be used over the whole Arctic to determine the shelf-basin exchanges, then suitable averaged values will be fed to more coarsely resolved models which can determine the much more slowly evolving processes in the interior.

The development of a realistic shelf / shelf break modelling capability for the Arctic Ocean through transfer of massively-parallel computing technology constitutes a fitting technological contribution to the Arctic Ocean Grand Challenge.

Small scale coupled biological-physical models will also be developed on the basis of laboratory experiments, equivalent to mesocosm studies in pelagic systems. Enhanced models could then be tested in field experiments, and would then form a component of coupled regional-scale biogeochemical models for polar oceans.

Historical data analysis

There are very large dataset available of relevant ice, ocean and meteorological data obtained by the Arctic and Antarctic Research Institute and other Russian agencies through the series of "North Pole" drifting ice stations and High Latitude airborne expeditions. It will be highly cost-effective to process and collate these data, since they are drawn heavily from the part of the Arctic upon which the Arctic Ocean Grand Challenge will focus its attention for process studies.

2.4 Technology

To accomplish the above strategy, it is necessary to make use of new technology which in its nature, or in its particular application to the Arctic, goes beyond the present state-of-the-art. Some of the innovative technological challenges that we have identified are:

- Building the EURO ICE TANK with its associated measurement and control equipment, the first facility for completely simulating the physical and biological environment within a sea ice sheet;

- Designing the *microsensors* required to make measurements inside brine drainage channels in the ice tank;

- Developing *in-ice acoustics tomography* or other techniques usable on metre scales to map the three-dimensional structure of voids and blocks in a pressure ridge;

- Development of a realistic shelf/shelf-break modelling capability for the Arctic Ocean through transfer of *massively-parallel computing technology;*

- Development of unmanned data recording and transmission techniques for polar use that will enable the EURO ICE STATION (Fig. 17) to operate more effectively with smaller physical and personnel facilities than ice stations to date.

- Application of a *submarine* for civilian under-ice use, and development of longer-range technology for autonomous underwater vehicles (AUV).

- Validation and use of a reliable *airborne ice thickness mapping system* for mesoscale applications, with eddy current systems as the first candidates.

2.5 Logistics

The EURO ICE STATION is a major logistical need, requiring manning throughout a year by groups of researchers carrying out specific tasks on the ice and water column. It will be the base for operations by a hovercraft and a helicopter to extend the range of the observations, with light aircraft flying over or refuelling at the ice station when they carry out mapping missions.

Ice-strengthened ships or icebreakers will be required for the sections work.

A lesser but vital logistic need will be to hold *workshops* at an early stage of the Arcic Ocean GrandChallenge, on specific aspects of technology. These will bring together groups of specialists capable of advancing these fields of technology by combining their skills - e.g. microsurgical specialists for the development of sea ice microsensors.

3. Biology and Carbon Cycle

3.1 Rationale

It is only poorly known how life (either individual species or communities) is maintained in the harsh environment and how this is connected with fluxes of organic matter and sedimentation, especially to what degree the marginal seas feed the system by advection (Fig. 10). Moreover, there are limited data on the relative contribution of the in-situ production of ice algae and phytoplankton to the food chain and their contribution to the benthos. There is also meagre knowledge of how these processes have changed during the past and how they will develop in the future. *We are more or less unaware of most aspects of the carbon cycled through the Arctic system.* We would like to understand the driving forces and their sensitivity to environmental and climatic changes.

The Arctic Ocean is a unique environment due to the extreme seasonality and to its permanent ice cover persisting over a large area. In contrast to the Southern Ocean it extends up to the Pole, has large shelf areas, large inputs of freshwater from river runoff, and different sea ice dynamics. In the Arctic Ocean primary production can be characterized by a single pulse during the short summer season. Therefore polar organisms must have evolved life cycle strategies to overcome the dark season. However, observations on a seasonal basis are very scarce up to now. Studies of the interactions within and between the different compartments, sea ice, water column, and sea floor are of major importance to understanding the functions in this environment (Fig. 11). Information on all of these aspects is needed to address the question of the sensitivity of the Arctic ecosystem to a changing environment. There is little knowledge of how these processes have changed during the geological past and how they will develop in the future.

In addition the special processes involved in the production of high salinity bottom waters over the shelves make it possible to export remineralized carbon out into the waters of the deep basins. Hence, an understanding of these physical processes is essential. It is of special interest to study production during varying annual sea ice cover in order to estimate effects of likely results of climate changes. The Arctic Ocean and especially her shelf seas are regarded as most sensitive to climate changes since the North Atlantic water circulation is believed to be a sensitive preconditioning mechanism. Taking the supply of nutrient by today's circulation into account, there is a potential for a significant increase of carbon by new production.

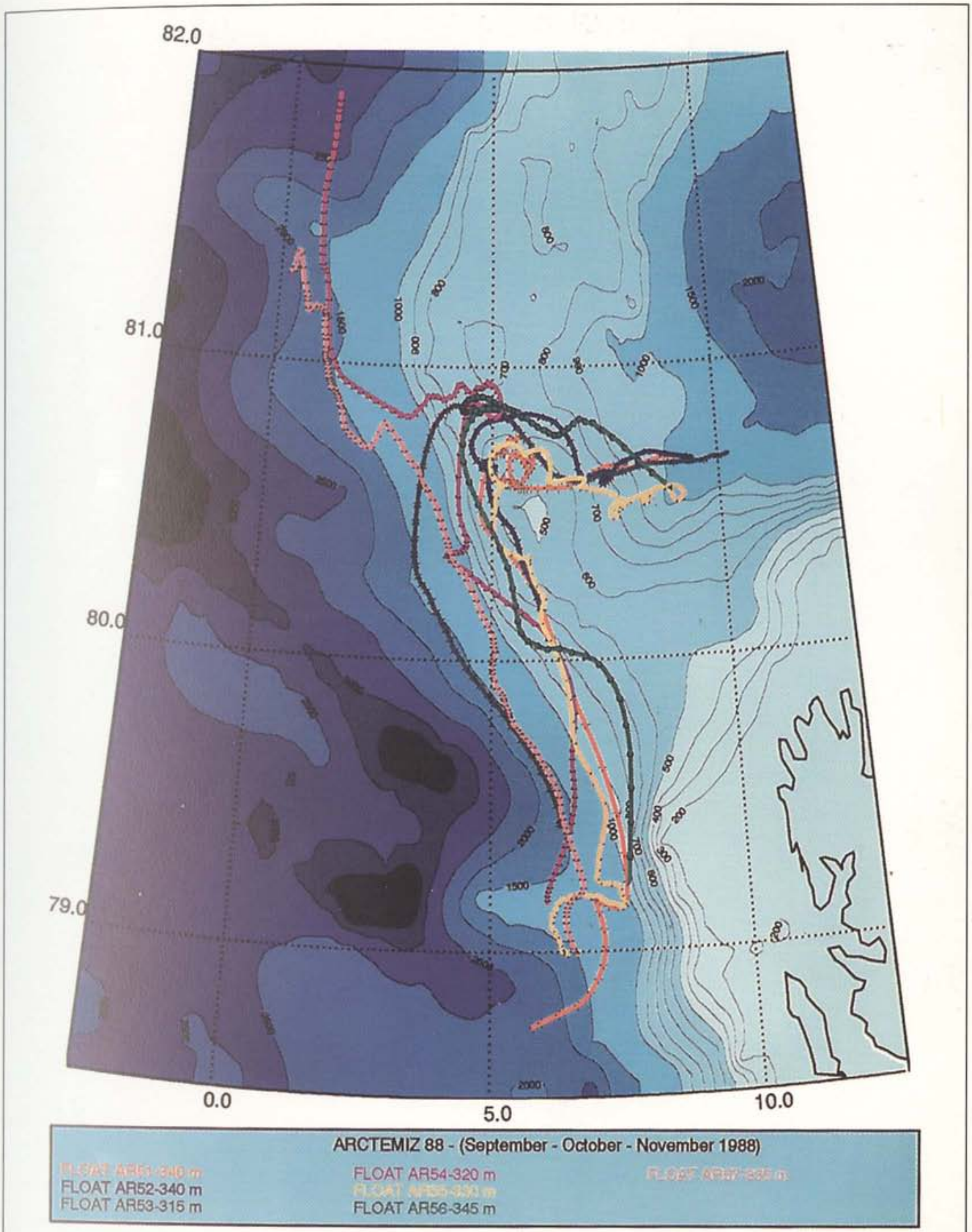

Fig. 6: Float trajectories in the Fram Strait and Yermak Plateau during the ARCTEMIZ 88 experiment (From Gascard et al.).

Colour plate 1

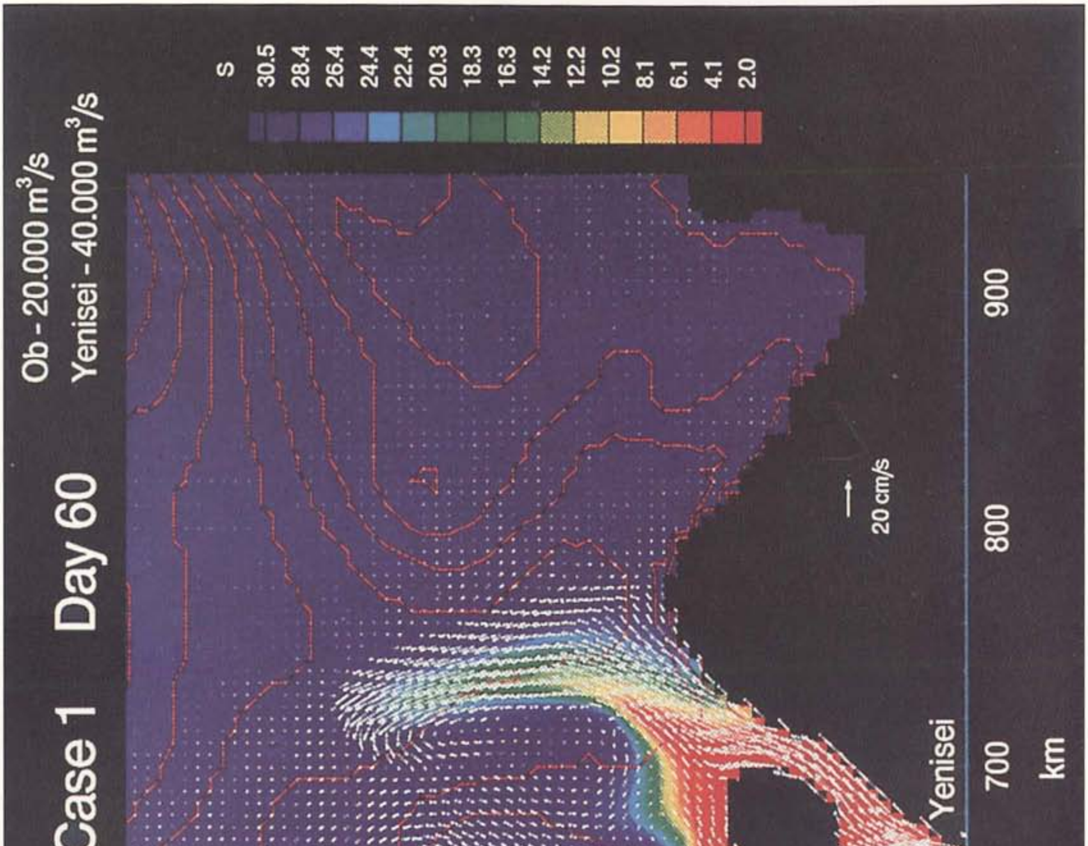

Fig. 7: Mesoscale model of the Kara Sea showing outflow of fresh water from the Ob and Yenisei rivers. The figure shows the depth contours at 10 m interval and upper layer currents (arrows) and salinity (colour code). It is expected that dissolved radionuclides and suspended radioactive sediments would spread into the Kara Sea in a similar manner as the low salinity water (From Budgell).

Colour plate 2

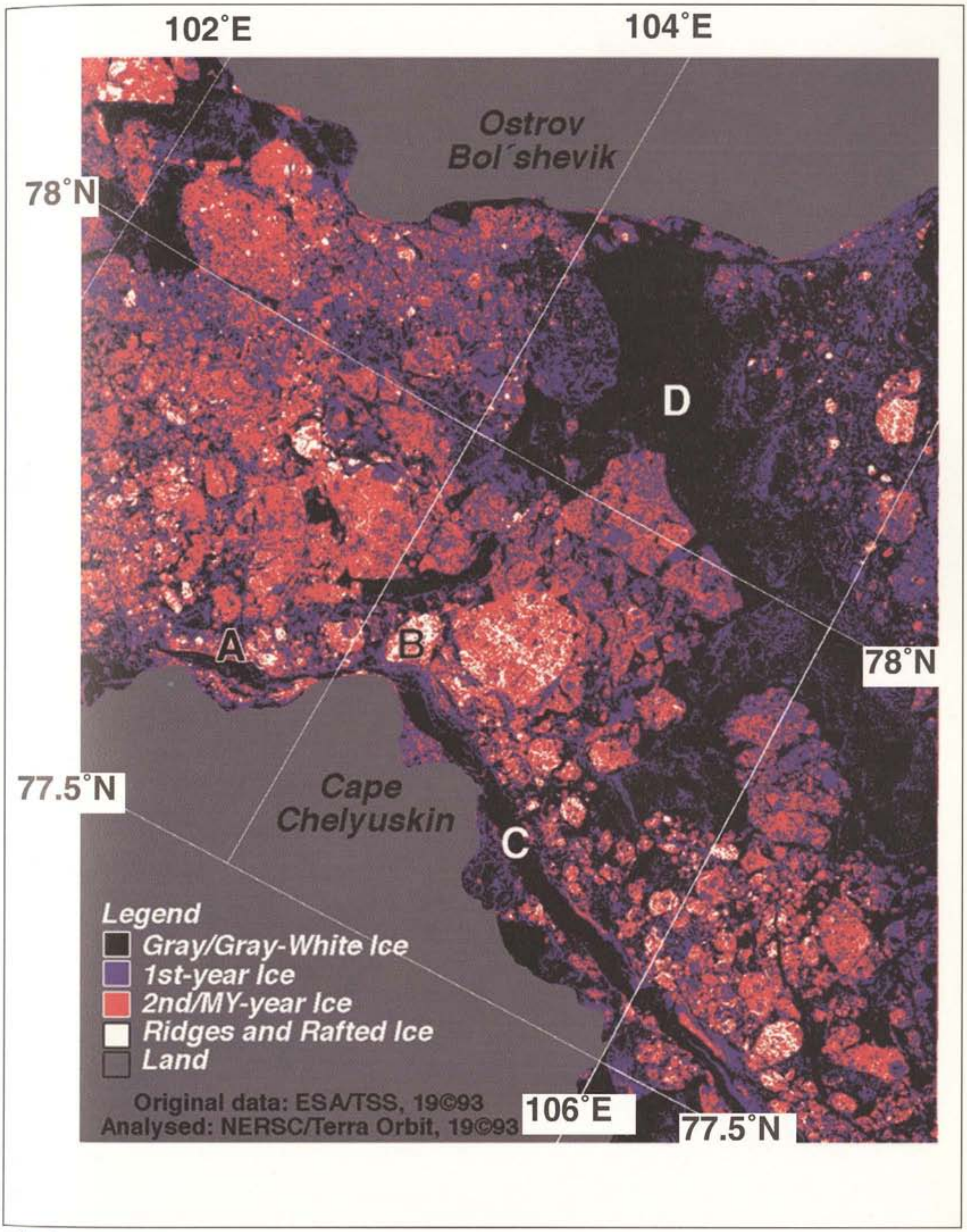

Fig. 9: A classified ERS-1 SAR image from the Vilkitskogo Strait on the Siberian Coast. The image was obtained on 4 November 1993, and was used to assist I/B "Sovetsky Soyuz" in ice navigation. The classification is derived introducing 3 threshold levels of the radar backscatter values and tuning of the magnitude of each level with in situ observations (From Johannessen et al.).

Colour plate 3

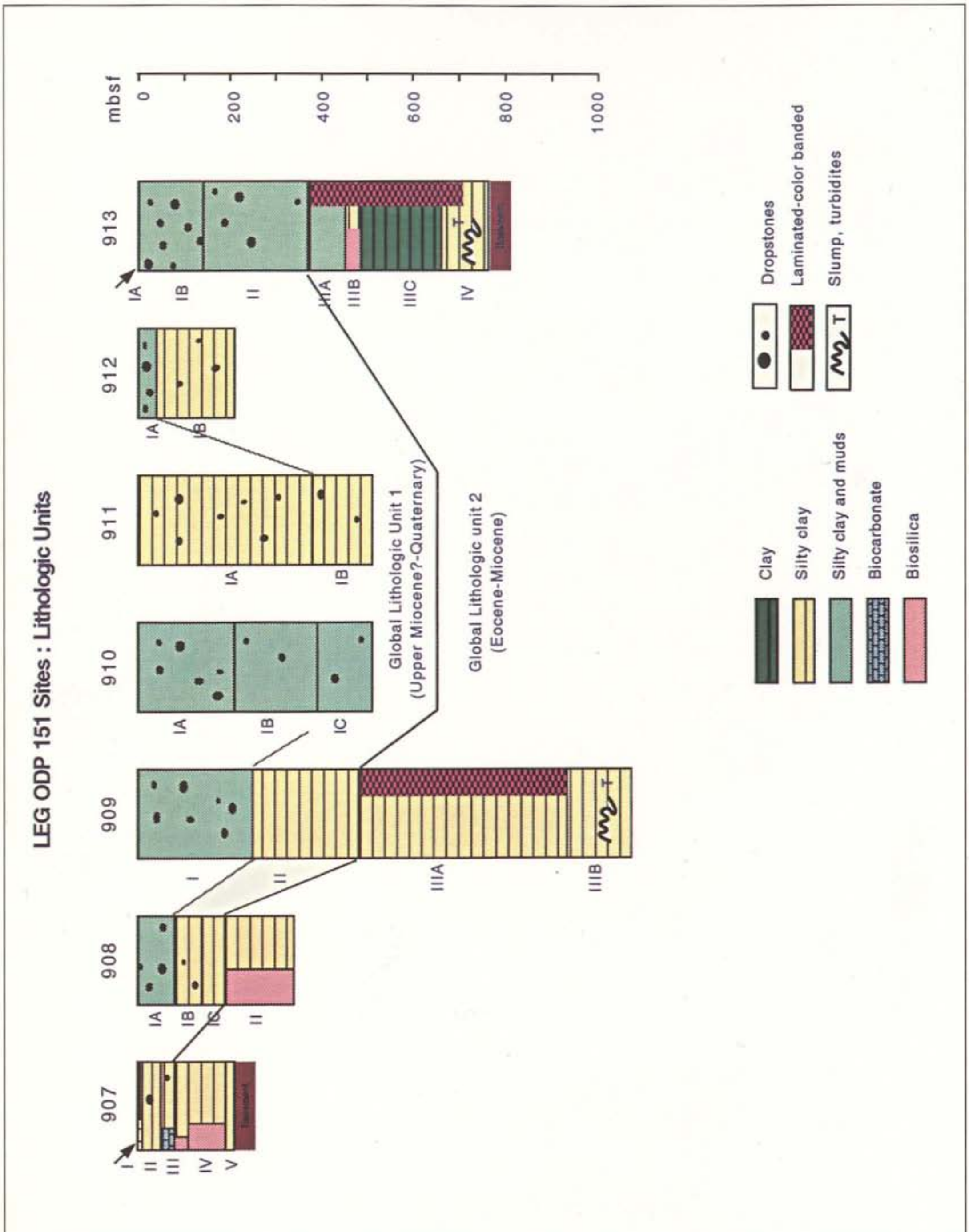

Fig. 14: Simplified lithological units in sediment cores obtained during Ocean Drilling Project Leg 151 (1993) from the Fram Strait, the Yermak Plateau, and the Greenland Sea (From Thiede and Myhre).

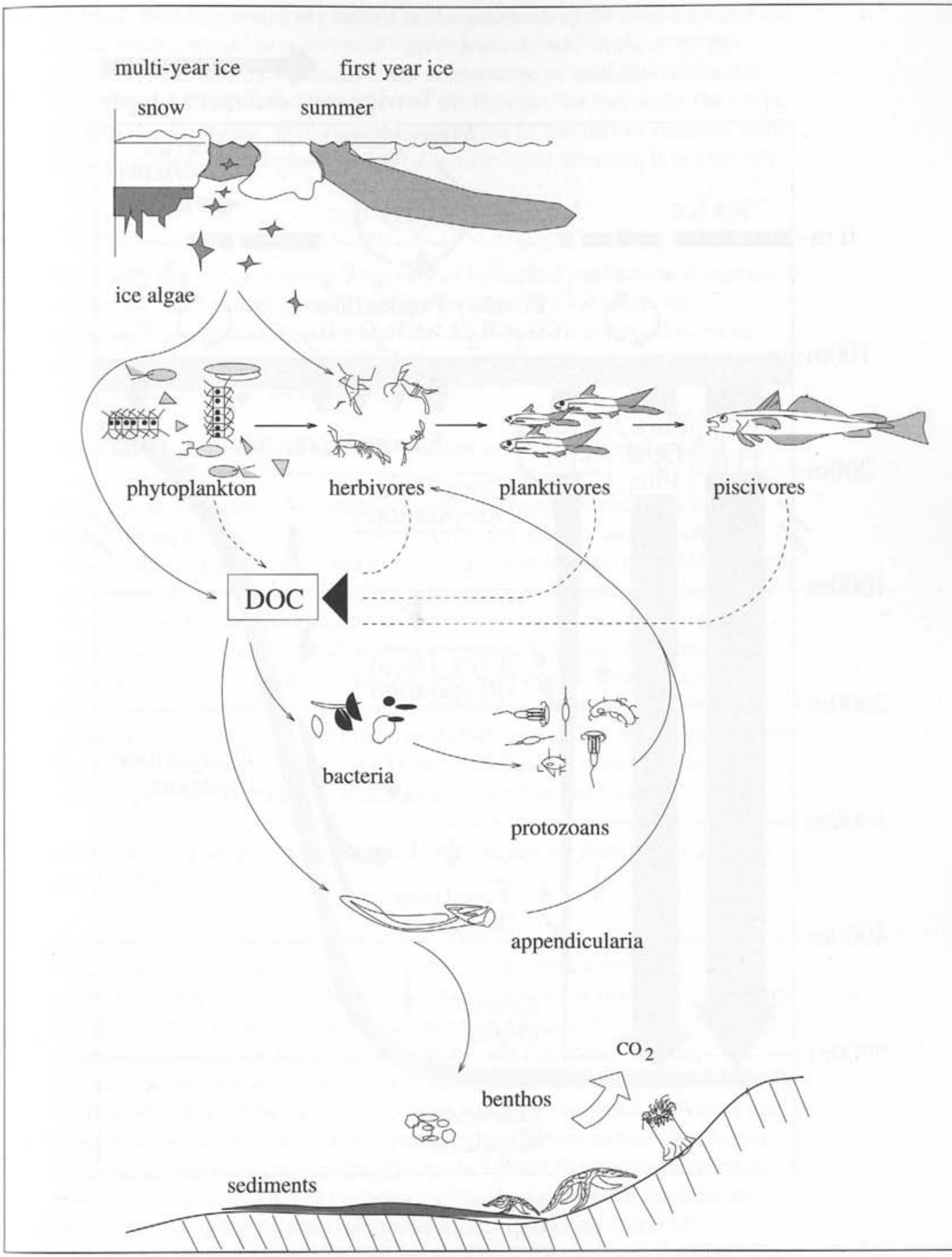

Fig. 10: Schematic of Dissolved Organic Carbon cycles (From Tande).

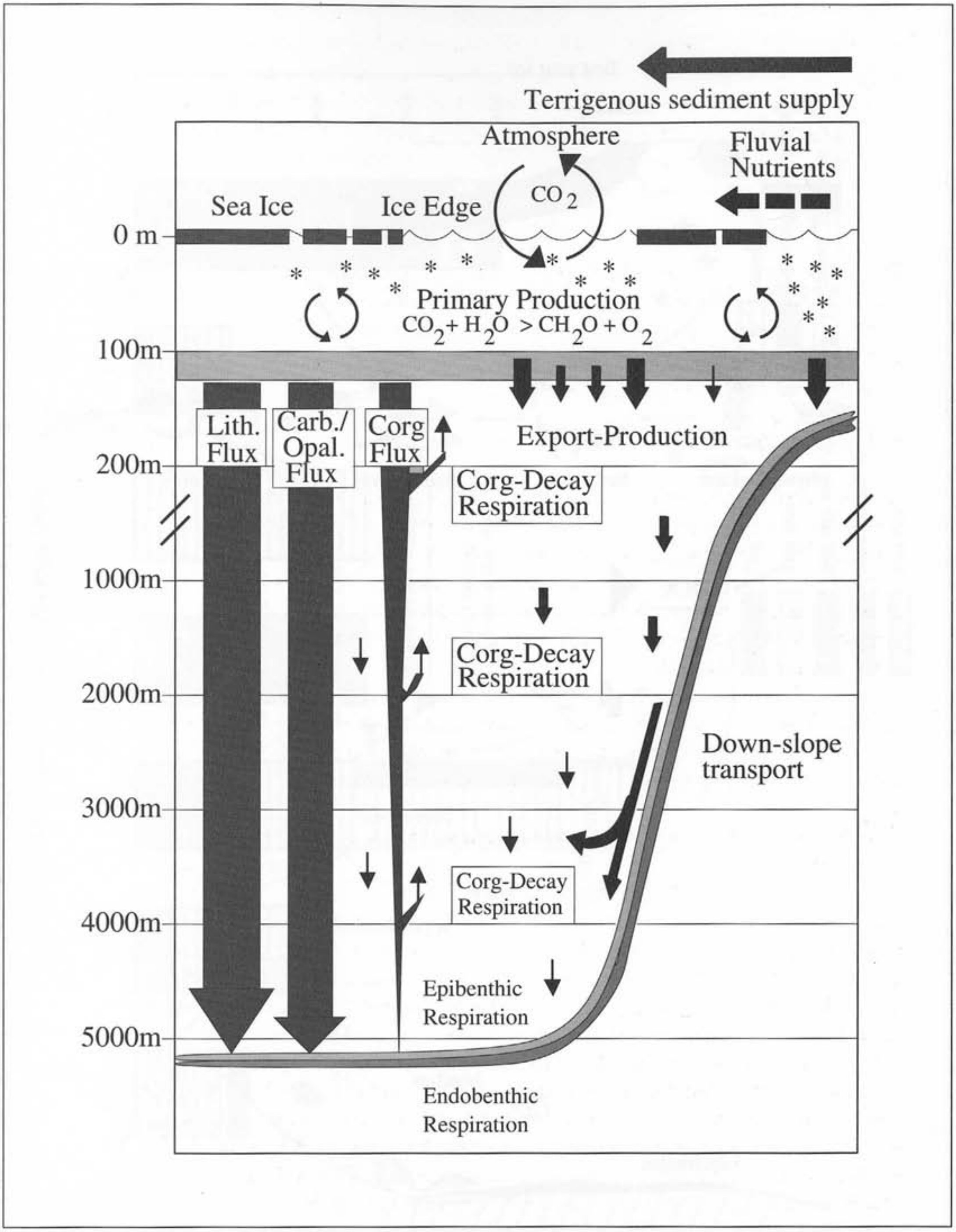

***Fig. 11:** Present and past biogenic, chemical, and terrigenous fluxes in the Arctic Ocean (From Spindler).*

Methane hydrates, which are buried in the sediments of the shelf seas and the Arctic tundra, would be a potential "greenhouse bomb" in the event of significant warming . Even today there is an escape of methane, which has been observed both in the open water of the Barents Sea and under the ice in the Siberian shelf seas. However, the magnitude of this flux of methane from the sediments to the atmosphere and its sensitivity to warming is not known.

3.2 Objectives

We would like to study recent processes of biological production of organic matter, its transformation on its passage through the food chain, its sedimentation and final burial within the sediments. This may allow us to understand also past processes which formed the sediments we find today. We plan to concentrate on the following topics:

Seasonal and interannual variability of key communities and species

We have only limited information on seasonal changes since most data are derived from the summer season. This is true for species and important communities for all habitats: sea ice, water column and sea floor. Only proper knowledge on interannual variability will enable us to detect changes due to climatic change. The contribution to biomass by higher trophic levels (vertebrates) is relatively small. Thus the focus will be put on invertebrates. Also of interest is the pollutant transfer by lower trophic levels to top predators such as birds and seals. Pollutants are taken up by organisms associated with sea ice on the Eurasian shelves and will be transported to the Fram Strait area by the Transpolar Drift. After melting of the ice they are preyed upon by top predators which accumulate these pollutants.

Interactions of organisms within and between sea ice floes, water column and benthos

The following key questions concerning life cycles and behaviour can be raised: Are there special adaptations to the polar environment (e.g. hibernation, energy storage, seasonal and ontogenetic migrations) ? What are the mechanisms for the timing of reproduction and growth ? In regard to the food web structure we need to know: Where and when does primary production take place (sea ice, shelves, open ocean river mouths, polynyas) ? what are the controlling factors (e.g. light, ice cover, nutrients) ? What is the relative contribution of sea ice and pelagic algae ? How and to what extent is the production used by higher trophic levels ? What fraction of the primary production and what kind of particles are finally reaching the sea floor and how is it used by the benthos (phytoplankton, aggregates, faeces) ? Preliminary results indicate the existence of hydrothermal activity with associated typical vent organisms in the Laptev Sea. After verification, investigations on these phenomena may shed more light on e.g. larval dispersion, or temperature tolerance.

Sedimentation

It is incompletely understood how much of the biological production finally is buried within the sediment and thus lost for the organisms (Fig. 12). On the other hand there may be considerable advection from surrounding seas to support some of the Arctic biota. We need to know the amounts and the nature of the material sedimented and finally buried in the sediments. The geological interpretation of sediment parameters from different depositional environments may provide us with estimations on past changes in productivity, circulation patterns and climate.

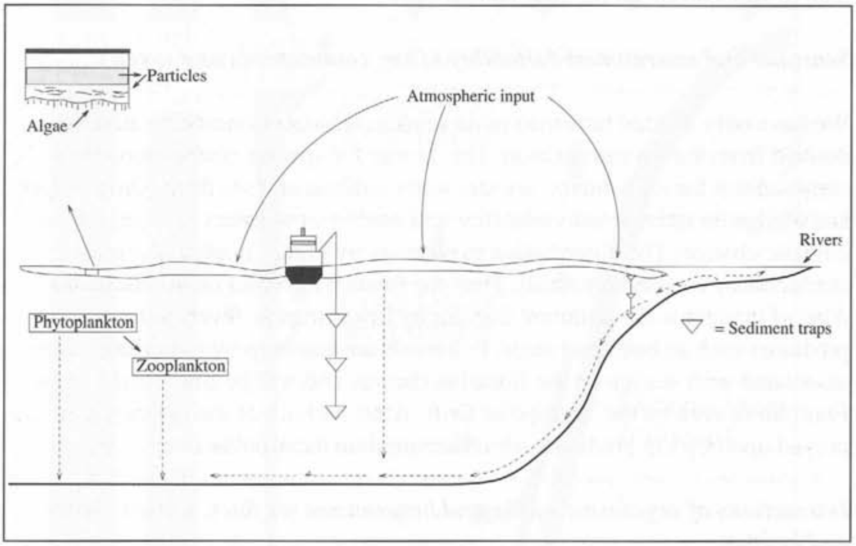

Fig. 12: Schematic illustration of the sediment sources to the Arctic Ocean (From Spindler).

Investigation of input by rivers

The input of the organic, inorganic and particulate carbon concentration by rivers and how much of this is used by organisms from the different habitats needs to be better understood. There is information available on the concentration of inorganic carbon from a few rivers entering the European sector of the Arctic Ocean. The knowledge of the organic content and its quality is very limited. Measurements of the discharge have been carried out in most of the major rivers, but it has been estimated that about half of the discharge from the American continent to the Arctic Ocean is through creeks and small rivers, and this may also hold true for the Eurasian Arctic.

Advection - interaction with surrounding seas

Seawater has a high concentration of dissolved inorganic carbon and a smaller but not insignificant concentration of dissolved organic carbon. Thereby large amounts of dissolved carbon are transported with the oceanic currents which need to be known in order to calculate accurate carbon budgets. For an enclosed sea, like the Arctic Ocean, the volume of water entering and exiting must balance, making the sensitivity smaller. The majority of water exchange occurs through Fram Strait and any effort to get better estimates of this exchange is encouraged. There is also strong evidence that food is advected from the surrounding seas which partly help to sustain populations even underneath permanent ice cover in the central Arctic.

Shelf water - deep basin exchange

The dissolved inorganic carbon, which is released from the sediment surface during decay of organic matter will to a significant degree be transported by bottom currents out into the deep basins. These currents are believed to be concentrated at a few locations along the shelf slope, where the topographic conditions are favourable. The water masses of these currents are often salinity-enriched by addition of brine from sea ice formation.
Hence, the density of these water masses are generally higher than those at the continental break. Accordingly, plumes of bottom water will sink down the continental slope while entraining surrounding water. In this process the plume will interleave and mix with the surrounding water. Depending on the density of the bottom water and the entrainment rate, the plumes will interleave at different depths. It is obvious from the chemical signatures in the deep Arctic Ocean that plumes originating on the shelves are important in transporting different chemical constituents, including dissolved carbon species, out into the deep basins. Modelling quantities and transport pathways of the chemical constitutes will be coordinated with the modelling of the mesoscale physical process.

Air-sea gas exchange during presence and absence of sea ice cover

A question of general interest is how the exchange of carbon dioxide between atmosphere and ocean varies in different parts of the world oceans. Specific for Arctic research is the sea ice cover and its role in the gas exchange. Experiments to study this gas exchange will therefore be carried out in the Arctic Ocean Grand Challenge programme.

Methane hydrates

Under high pressure and/or low temperature methane hydrates are stable. Seismic investigations in Arctic shelf seas have shown significant deposits of methane hydrates within the sediment. The existence of these deposits is supported by the occurrence of high concentrations of methane in the water just below the ice cover in the Siberian shelf seas. Climatic records show a substantial temperature increase over the last 30 years in local regions along the coast of the Laptev and East Siberian Seas. The question is whether a steady state leakage of methane from the sediments occur or whether the observed high concentrations under the ice are due to this local temperature increase. Today's knowledge of the future fate of these methane hydrates is very limited and need to be seriously addressed, especially as methane is a much more efficient greenhouse gas than carbon dioxide.

3.3 Strategy

Our large scale strategy is to perform seasonal, interdisciplinary investigations of the "European Arctic shelf seas" (including sea ice, pelagic realm and benthos), the interaction with the deep basins, and the biological system in the multiyear ice cover over the basins. The investigations will include the studies of:

Life cycles of Arctic organisms

The studies will include animals and plants from the different habitats such as the sea ice, water column and benthos.

Physiology and behaviour, sensitivity to temperature changes

There is need to study adaptations to the environmental parameters specified to the different habitats such as sea ice parameters, ocean parameters and light conditions.

Production within the different compartments

There are only vague estimates on how much is produced by the organisms in the different systems sea ice, plankton, benthos.

Exchange of organisms and pathways of carbon between adjacent media

There exists a strong coupling between adjacent media. Some of the organisms have seasonal and/or ontogenetic migrations or life styles (e.g. meroplanktic larvae, which settle from the water column to the seafloor after reaching a certain maturity). Also carbon is channelled from the sea ice through the water column to the sediments.

Input and quality of different carbon compounds by rivers

The average input of fresh water by the 8 largest Eurasian rivers is in the range of 2000 km^3 annually. This amount of water spills into the Arctic Ocean only during a few months after the onset of ice melt. In addition to biotic and abiotic carbon pollutants find their way into the marine environment.

Seasonal and interannual biogeochemical transformation of carbon

Activities of most organisms are restricted to certain seasons. To gain a complete picture, most aspects have to be observed on at least a year´s cycle.

Fluxes associated with shelf water - deep ocean interaction

Large amounts of the organic carbon are transported with ocean currents within the water column. However, to some degree bottom currents may contribute material from the slopes into the deep basins. Therefore, most carbon data will be collected jointly with oceanographical and geological data.

Methane flux from the sediments, through the water column and into the atmosphere

Methane is stored in large quantities in the permafrost which extends far into the marine environment on the shallow shelf areas. Methane is a potent greenhouse gas which can amplify climatic changes if released in large quantities from the sediments.

Gas exchange between sea and atmosphere in ice-covered waters

It is not known whether gases can penetrate a closed sea ice cover. If there is gas exchange through the ice, the areas of open water within the pack ice zone determine the gas exchange.

Investigations will include time series studies and put emphasis on questions concerning geographical distribution as well as patchiness. On a regional scale shelf areas and adjacent slopes will have priority. However, sea ice studies should also be performed on multiyear ice floes during their drift through central parts of the Arctic Ocean.

The short-term goal is to understand the processes of importance for the flux of carbon in selected areas (e.g. Barents, Kara and Laptev Seas). As a long-term goal we wish to expand the investigated areas and to quantify the flux of carbon on a large scale basis. This will include the evaluation of interannual variability of key processes. The final goal is to gain enough knowledge and data to construct a realistic integrated model for the carbon cycle within the Arctic Ocean.

3.4 Technology

In adddition to adjust standard equipment to the special environment in the Arctic, there is a need to develop new instruments and techniques to investigate different parameters, such as acoustic analyzing equipment for rapid determination of biomass and special water sampling devices for collecting water from under the sea ice (without leakage of gas to the atmosphere). Technology to recover moored equipment from under the ice will be important. Use of ROV's equipped with different "biological" sensors will be tested, for example Chl.a-sensor for mapping algal distribution. Satellite data such as ocean colour sensor and temperature will be used whenever there are cloudfree conditions.

3.5. Logistics

The logistical requirements are crucial in order to achieve the goals of this programme. In the summer season, much of the work can be done by regular, multidisciplinary cruises on ice-strengthened research vessels. However, it is also required to use an icebreaker with high ice class which can operate over larger areas and in different seasons. During the icebreaker cruises the areal coverage should be extended by helicopter or hoovercraft observations. It would also be feasible to set up week-long camps in the vicinity of the ship for process-oriented studies. For some of the investigations it is essential to cover extended periods of the year, which would need the EURO ICE STATION for the summer as well as other seasons. In addition some processes will be studied from moorings, equipped with sediment traps, upward looking sonars (ULS), current meters, and other oceanographic sensors. All the biological and carbon cycle data collection will be coordinated with the field work in the other sub-programmes.

4. Palaeoceanography and Climate

4.1. Rationale

The study of the palaeoenvironmental record of the Arctic will contribute to a scientifically based assessment of past and future climatic change. Geological and palaeontological-palaeoceanographic data have proven that the Arctic Ocean represents one of the most sensitive elements of the global climate system which has responded frequently at dramatic rates and with extreme values to past climate change. The Arctic Ocean may therefore offer good opportunities for real-time monitoring of global change, a detailed documentation of the historic development of factors controlling the European climate and for an assessment of scientifically well founded attempts to forecast mid- and long-term environmental change and the impact of such changes on ecosystems of the Arctic Ocean as well as surrounding shelves and continents.

To assess past and future climatic changes, modern geological processes in the ice-covered Arctic Ocean and its marginal seas have to be understood. This includes monitoring of transport processes of dissolved and particulate matter and of fluxes through the water column as well as the investigation of their reflection in sea floor sediments. Long and large-volume high-resolution sediment cores from the Arctic Ocean (Fig. 13) will allow a detailed reconstruction of Cenozoic palaeoenvironmental changes, with particular emphasis on the Quaternary glacial-interglacial cycles and on the Holocene climatic variability. Investigations will focus on the high-resolution analysis of high-frequency (orbital-scale or shorter) variations of the climate system. This will include time-scales from decades and millennia to millions of years.

4.2 Objectives

Challenging objectives of Arctic environment studies and their palaeo-records include:

- *Contemporary processes shaping the Arctic environment*
- *The establishment of a Neogene and Quaternary lithostratigraphy and chronology*
- *Evolution of Arctic palaeoenvironments*
- *Modelling of Arctic palaeoenvironments*

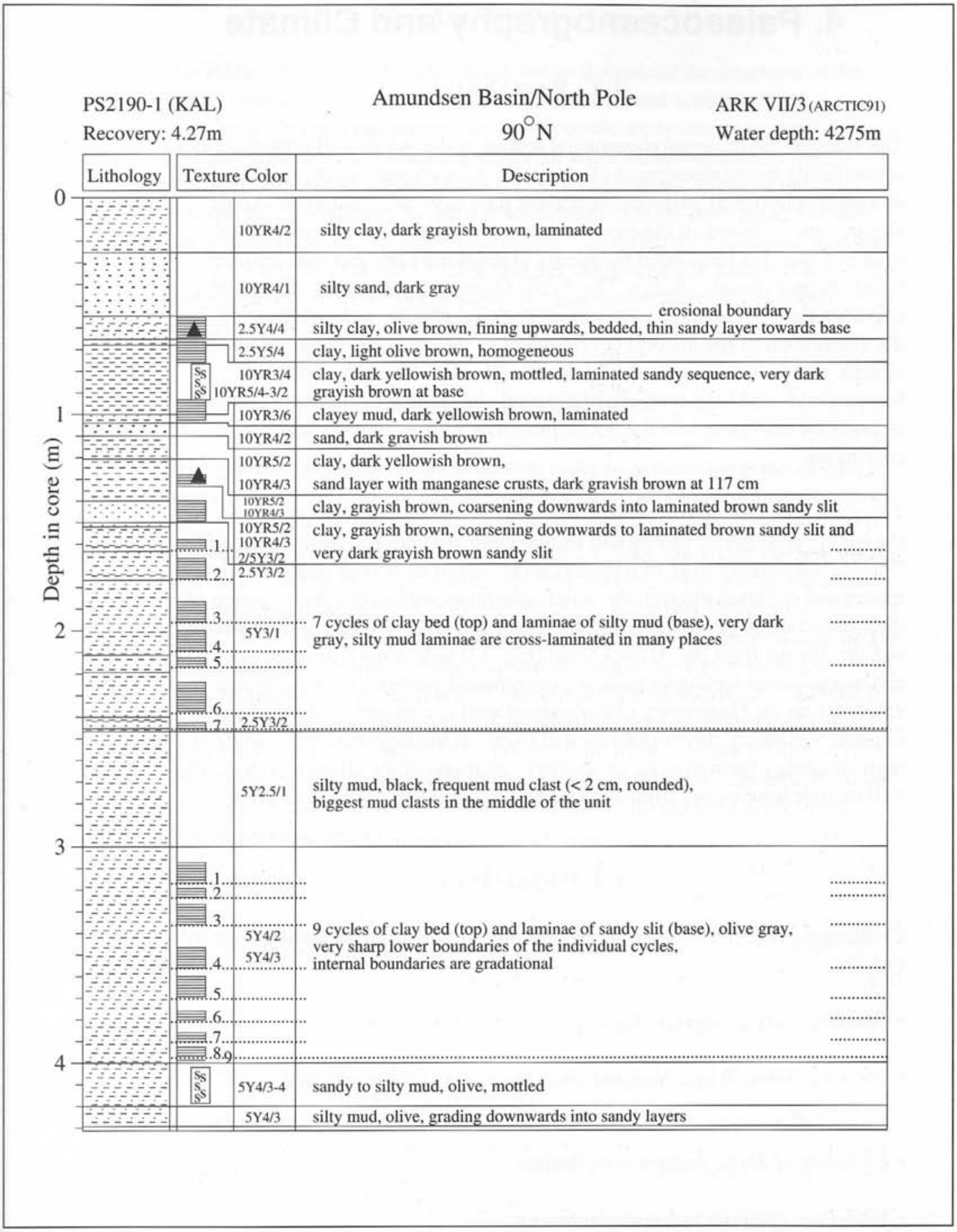

Fig. 13: *Lithology of large-volume sediment core 2190-1 from the North Pole (Amundsen Basin). Dark trianges indicate graded bedding (turbidites), which is typical for many sediment cores from the deep Arctic basins (From Thiede).*

Contemporary Processes Shaping the Arctic Environment. Their Reflection in Sea Floor Deposits and Morphology

Topics of major interest are:

- Freshwater output from Arctic rivers and its chemical and isotopic signature whose record in the water column is also studied by the mesoscale processes;
- Quantification and characterization of the supply of dissolved and particulate material;
- Accumulation and redeposition on the shelves;
- Uptake and transport by ice, currents or gravitational processes to the open-ocean and deep sea environment;
- Final deposition and diagenetic alteration;
- The isotopic and geochemical signature of different Arctic water masses as investigated by large- and mesoscale studies and their reflection in planktonic and benthic biota as well as sediment properties;
- Detailed morphology of the Arctic sea floor, with a particular focus on deep-sea areas and continental margins (canyons and troughs).

Interaction across continental margins

The history of the shelf seas and continental margins and their shaping by past and present geological processes will be studied from mapping of small- and large scale morphologic features and from the analysis of sedimentary records. This will include the land-to-ocean transport of freshwater and dissolved and particulate terrigenic and biogenic matter and the impact of sea-level changes.

Sediment budgets and sediment fluxes

Arctic sedimentary sequences are characterized by strong lithological changes, which reflect changes in the supply of biogenic and terrigenic materials as well as different transport modes (ice-rafting, currents, turbidites). For the determination of changes of sediment fluxes (Fig. 11) with respect to changes in palaeoenvironmental parameters, sediment budgets have to be calculated from physical properties and sedimentological measurements as well as sub-bottom seismic profiling.

Arctic permafrost: a "greenhouse bomb"?

Occurrence of gas-hydrates on the floor of the shelf seas and in the tundra must be mapped by geophysical methods. Arctic permafrost is assumed to represent an enormous reservoir of potential greenhouse gases, which cannot be quantified yet but is expected to contribute significantly to global change.

Establishment of a Neogene and Quaternary lithostratigraphy and chronology

A high-resolution stratigraphy is essential for all palaeoenvironmental reconstructions. The difficulties in establishing a reliable stratigraphy require the application of various recently developed and improved methods (e.g. AMS-C^{14} dating, ^{10}Be, ^{230}Th, ESR dating, palaeomagnetics, oxygen and carbon isotopes, biostratigraphy). The combination of these methods has proven to give a reasonable time frame for high-resolution studies of other parameters.

Evolution of Arctic Palaeoenvironments

Arctic ice cover

Changes in the areal extent and nature of the ice cover will be reconstructed from the sediment composition (ice-rafted debris, planktonic microfossils, bulk and clay mineralogy). Particular emphasis will be laid on deglaciation events.

Upper layers of the water column

Changes in the physical and chemical properties in the upper layer of the Arctic Ocean and formation and dstribution of water masses are to be reconstructed from palaeontological, geochemical and isotopic studies of microfossils and sediment composition. There will be particular emphasis on studies of the strength and direction of currents, the history of Atlantic and Pacific water inflow, the freshwater input from Siberian rivers, the meltwater events from decaying ice-sheets, and the history of bioproductivity.

Deep-water evolution

Changes in the evolution and stratification of Arctic Ocean deep waters and their exchange with the Atlantic Ocean through the Fram Strait will be reconstructed from benthic microfossils (foraminifera, ostracodes) and their isotopic and geochemical composition. Such changes will have a strong impact on the temporal variability of the North Atlantic Deep Water renewal.

Arctic biota

Presently, the planktonic microfossils community contains only few species adapted to the cold ice-covered environment, while the benthic community is much more diverse. The Pliocene and Quaternary history of faunal changes correlated to oceanographic and palaeoclimatic changes is poorly known and still lacks a good stratigraphic framework.

Circum-Arctic ice sheets

In many areas the extent of Late Quaternary circum-Arctic ice sheets is still under debate. Apart from the impact of ice sheets on the shelf morphology, they leave an imprint in Arctic sediments through iceberg-rafting of coarse sediment particles, which can be traced back to their place of origin. The decay of ice sheets and the release of glacial meltwater will be studied from isotopic records of planktonic foraminifera.

Modelling of Arctic palaeoenvironments

To achieve a better representation of the Arctic Ocean in global climate and palaeoclimate models, the Arctic palaeoenvironmental system will be modelled using the input of proxy data for geological oceanographic, atmospheric and ice cover parameters.

4.3 Strategy

A Scientific programme to study the Eurasian Arctic Margins (EURAMAR): Late Cenozoic and modern environmental change

Since the important role of the Eurasian shelves for the formation of Arctic water masses is now widely accepted, it is suggested that the common efforts of several bilateral projects in this area be coordinated under the auspices of a scientific programme or network. To achieve an optimum exchange of samples, data and results, it is proposed to establish a network tentatively named "EURAMAR". Key areas for EURAMAR studies are and will be: Svalbard/Franz-Josef-Land/New Siberian Islands; Barents, Kara, Laptev Sea; fjord-shelf transects; land-coast-shelf transects; Arctic Ocean continental slopes and deep sea.

Present and past biogenic, chemical and terrigenous fluxes in the Arctic Ocean and climate change

To continue and to complement already existing research activities in the extreme Arctic Ocean environment, international cooperation and multidisciplinary programmes need to be intensified. To understand the modern processes in this ocean and their reflection in the sediments, a close cooperation among geologists, biologists, chemists and oceanographers is necessary. Thus, the marine geology programme should be supported by major contributions by these disciplines, e.g. studies on surface and deep-water circulation (oceanography), pore-water diagenesis (chemistry), and faunal and floral assemblages (biology).

There are three major areas where the variability of the sediment fluxes at various time scales will be studied: the Kara Sea area with the St. Anna Trough, the Laptev Sea, and the Alpha Ridge/Mendeleyev Ridge area. Expeditions to these regions are planned for 1995, 1996 and subsequent years. The main interest is to carry out transects (geological, biological, oceanographic) from the shelf areas into the deep ocean in order to reconstruct the interaction of processes between these two ocean environments. Two-ship operations will be most fruitful to reach an optimal sampling and data programme along these transects during the relatively short time which is available during the summer months.

Long Arctic sediment cores

Only the study of long sediment cores (25-50 m) from the Arctic Ocean will allow investigations resulting in a detailed reconstruction of Neogene and Quaternary palaeoenvironmental changes. Such cores will allow us to focus on the high-resolution analysis of high-frequency variations of the climate system. There are different objectives including the Neogene/Quaternary stratigraphy, evolution of water masses, sea ice cover, and deep water, history of ice sheets, Arctic biota and sediment fluxes.

Four key areas have been selected:
- the Yermak Plateau and the Fram Strait
- the eastern Lomonosov Ridge
- the Chukchi Plateau
- the Alpha-Mendeleyev Ridge

Laptev Sea drilling: a key to Arctic Ocean history

Deep drilling sites have been proposed to sample most major basement units of the Arctic Ocean and to describe the Late Mesozoic and Cenozoic depositional environment, selecting high and low sedimentation rate areas. A stepwise approach over several years to combine heavy coring with light and heavy drilling is proposed to obtain an undisturbed record of basement rocks and of the history of the Arctic Ocean depositional environment. It is therefore envisioned that initial efforts will be on obtaining long cores from shallow continental margins, because these seas are more susceptible to environmental changes.

The research will focus on site survey for offshore drilling of complete Upper Cenozoic sequences in order to understand the onset of glacial conditions as well as tectonic evolution of the Laptev Shelf-Gakkel Ridge intersection. Seismic reflection data already collected by several Russian institutions will be used to determine actual drill sites.

The main objectives of the Laptev Sea Drilling Project is to obtain as complete as possible records of the Cenozoic sediments of Upper Miocene to Holocene sequences. The proposed drill sites are located within the eastern part of the Laptev Sea from where a detailed seismic stratigraphy is available.

Central Arctic drilling: a new effort of geoscientific research in the Arctic

The Arctic Drilling Programme will conduct investigations in the ice-covered Central Arctic Ocean to resolve the Late Mesozoic and Cenozoic palaeoceanographic, climatic, and tectonic history with the particular aim of obtaining sediment records of a pre-glacial polar ocean. This activity is closely linked to ongoing international efforts of deep-sea drilling in the ice-free subpolar to tropical ocean basins (ODP-Program).

4.4 Technology

To quantify fluxes of dissolved and particulate matter and compare them with surface sediments, sediment traps in key areas (ice margins, polynyas, deep basins and ridges) are important tools for describing the modern sedimentary environment (Fig. 12). However, the recovery of moorings from permanently ice-covered regions not only requires new sophisticated technology, but also the permanent observation of these systems. Here, autonomous underwater vehicles (AUV) and/or remotely operated vehicles (ROV) will provide new possibilities to operate moored systems in the Central Arctic Ocean.

To select suitable sampling sites and for a large scale mapping of the sea floor and the subsurface structure, swath mapping systems, sediment echosounders and side-scan sonar technology will be used. Submarines offer unequalled opportunities for subsurface surveys. They can conduct whole-basin studies of sea-floor imagery and sediment distribution as well as site surveys for deep-sea drilling.

While the uppermost 0-10 m sediment sequence can be sampled with standard coring equipment, to obtain long sediment cores from the Arctic Ocean it is necessary to use a long piston coring system on a well equipped ice-protected vessel. It is intended to use the "giant" piston corer designed by the Institut Francais pour la Recherche et la Technologie Polaire (IFRTP), which is able to obtain cores of 26 to 30 m length. For thick ice, the support of research vessels by icebreakers will be necessary.

Due to the permanent ice cover, drilling of deep cores (several hundred metres to km long core) from ships or platforms has until now only been possible in the marginal areas of the Arctic Ocean such as the Yermak Plateau (Fig. 14, colour plate 4), the Barents Sea and the Bering Sea. Design of new ships or platforms for the operation in the central Arctic Ocean are now being considered. This may include the use of submarines and hovercraft.

For drilling in marginal areas it is proposal to use the new "Baikal" drilling module, a cost-effective technology for drilling deep water wells from the ice in lakes and marine shelves frozen in winter. This drilling module was developed by GNPP "Nedra" (Yaroslavl, Russia). The ice-based drilling is limited by the seasonal conditions. An ice cover exists approximately from the beginning of November to the middle of June within the Laptev Sea. However the ice sheet is unstable during the autumn and winter periods when strong wind condition prevail. Therefore, the spring time is the most favourable for drilling. A truck-mounted drill with mobile laboratory is suggested to conduct the initial expedition on the extensive fast ice regions of the Laptev Sea. Long core drilling will be carried out from floating ice platforms. The drilling module can also drill deep water wells with a depth from 100 m to 1500 m at a water depth up to 800 m.

4.5 Logistics

The understanding of modern processes shaping the depositional environment and their comparison to past environmental changes allows the identification of key areas for marine-geological investigations. At least two to three trans-Arctic expeditions during the next few years are suggested to allow exemplified studies of present and past environmental changes.

Complementary expeditions on land and in nearshore areas will complete the proposed transects: land/nearshore-shelf-deep sea and river-fjord-shelf-oceanic ridges-deep sea. A prerequisite for multidisciplinary research in high northern latitudes will be multi-ship expeditions. Icebreaker support is necessary to make ice-covered areas accessible to research vessels. Joint expeditions with Russian icebreakers are strongly suggested. The use of submarines is recommended for scientific mapping and site surveys to cover large areas of the Arctic Ocean with minimum efforts of time. Compared to ordinary icebreakers and icebreaking research vessels, the use of submarines will be more efficient for certain purposes, despite the relatively high expected costs.

Long sediment cores can be obtained through the technique of ice-based drilling or from specifically designed drilling platforms. These could also provide logistic base-camps for numerous other disciplines of polar research.

5. Technology

The Arctic Ocean Grand Challenge programme requires state-of-art technology adapted to Arctic use as well as new development of sensors, instruments and platforms.

Vehicles/Stations

Due to the vast area to be investigate and the wide range of approaches many vehicle systems are required. Based on long Arctic and Antarctic experience most of them already exist and some of them need minor adaptations.

- Devoted ships such as research vessels with highest ice class (available)
- Ships of opportunity fitted with automatic sensors (available)
- Hovercraft (available, to be adapted)
- Submarines (available, to be adapted)
- Aircraft (available)
- Helicopters (available)
- Satellites (available)
- Ice camps (available, see schematic of the EURO ICE STATION Fig. 17)

Data collecting platforms

Considerable technological efforts have to be made to improve the quality and methods of the data collection including better temporal and spatial coverage.

- Stationary long term buoys (under development)
- Drifting buoys (available)
- Teleoperated unmanned stations (under development)
- Moorings (available, recovery techniques must be improved)
- Neutrally buoyant RAFOS floats with upward-looking sonar (to be developed)
- ROVs (available/under development, to be adapted to scientific payload and to special functions)
- AUVs (under development, power supply limits the range and the functions and require special sensors)

Instruments and sensors

The development of new sensors and instruments, including modifaction of the existing ones to be suited to new platforms is crucial.

- Miniaturized water sampler (to be developed)
- Miniaturized water analyzer (to be developed)
- Miniaturized sensors for the investigation of the structure of the sea ice and for use onboard AUVs to measure light, temperature, salinity, chemical nutrients, pH, oxygen, chlorophyll, biomass, etc. (partly to be developed)
- Ice sampler/corer (available)
- Sea bottom sampler/corer/driller (available)
- Sediment traps (under development)
- Acoustic underwater tomography/thermometry (under development, see fig. 15 and 16)
- Acoustic upward looking sonar for the measurements of sea ice draft and velocity (under development)
- Acoustic in-ice tomography for structural measurements (under development)
- Airborne laser profiler (available)
- Airborne electromagnetic techniques (under development)
- Satellite microwave sensors such as multifrequency and multipolarization SAR (to be developed)

Shore based facilities

The most important shore-based facilities concern the data analysis and management, and the modelling and simulation activities. The following components will be an essential part of the Arctic Ocean Grand Challence programme:

- EURO ICE TANK (to be developed)
- Massive parallel computing architecture for modelling (under development)
- Laboratory techniques for chemical/physical/biological analysis compatible to miniaturized samplers/analyzers (to be developed)
- Common data exchange network system for the Arctic (to be developed)

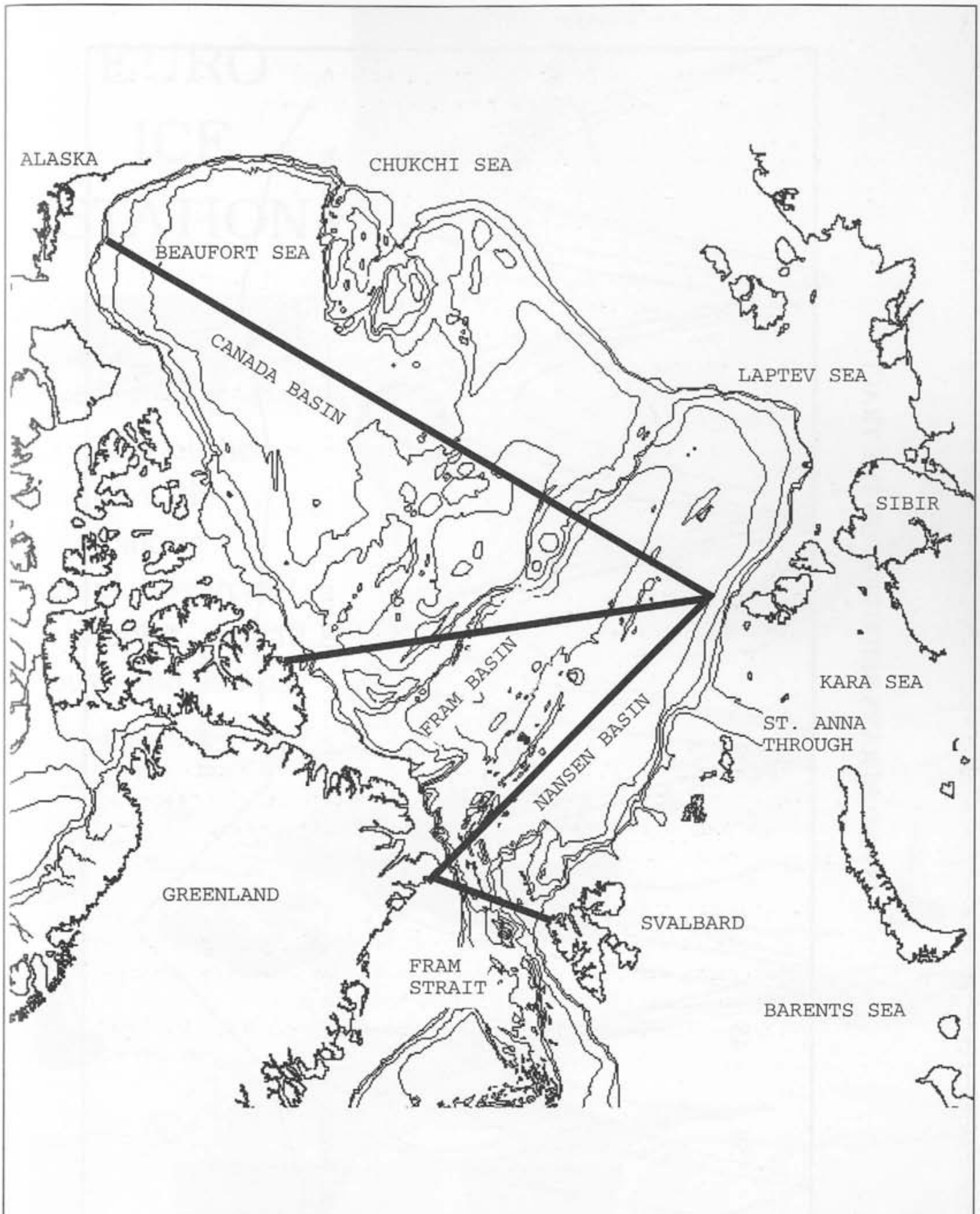

Fig. 15: Acoustical transmission lines for an acoustic thermometry experiments in the Arctic Ocean (From Johannessen).

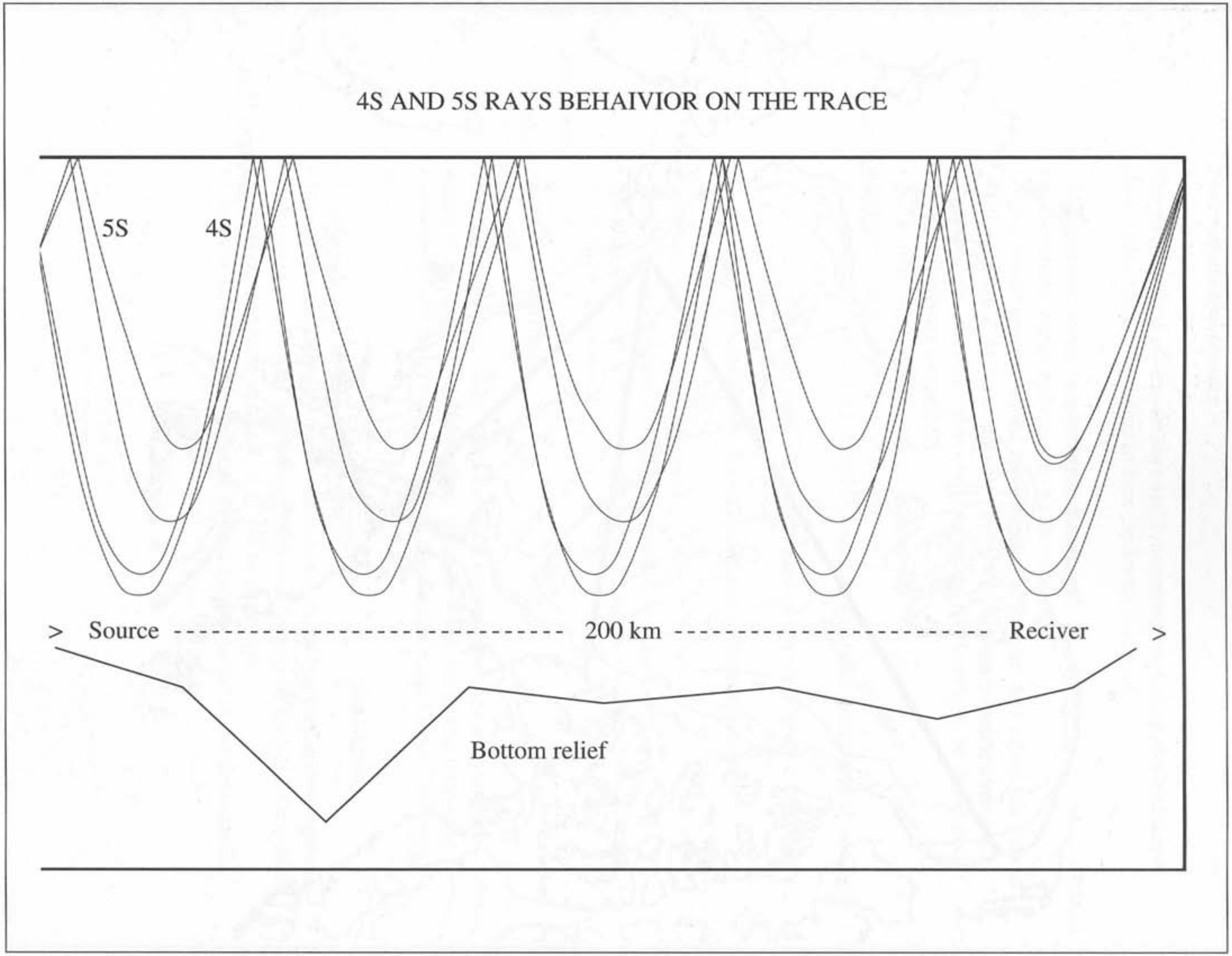

Fig. 16: *Acoustic propagation across the Fram Strait (From Naugolnykh & Johannessen).*

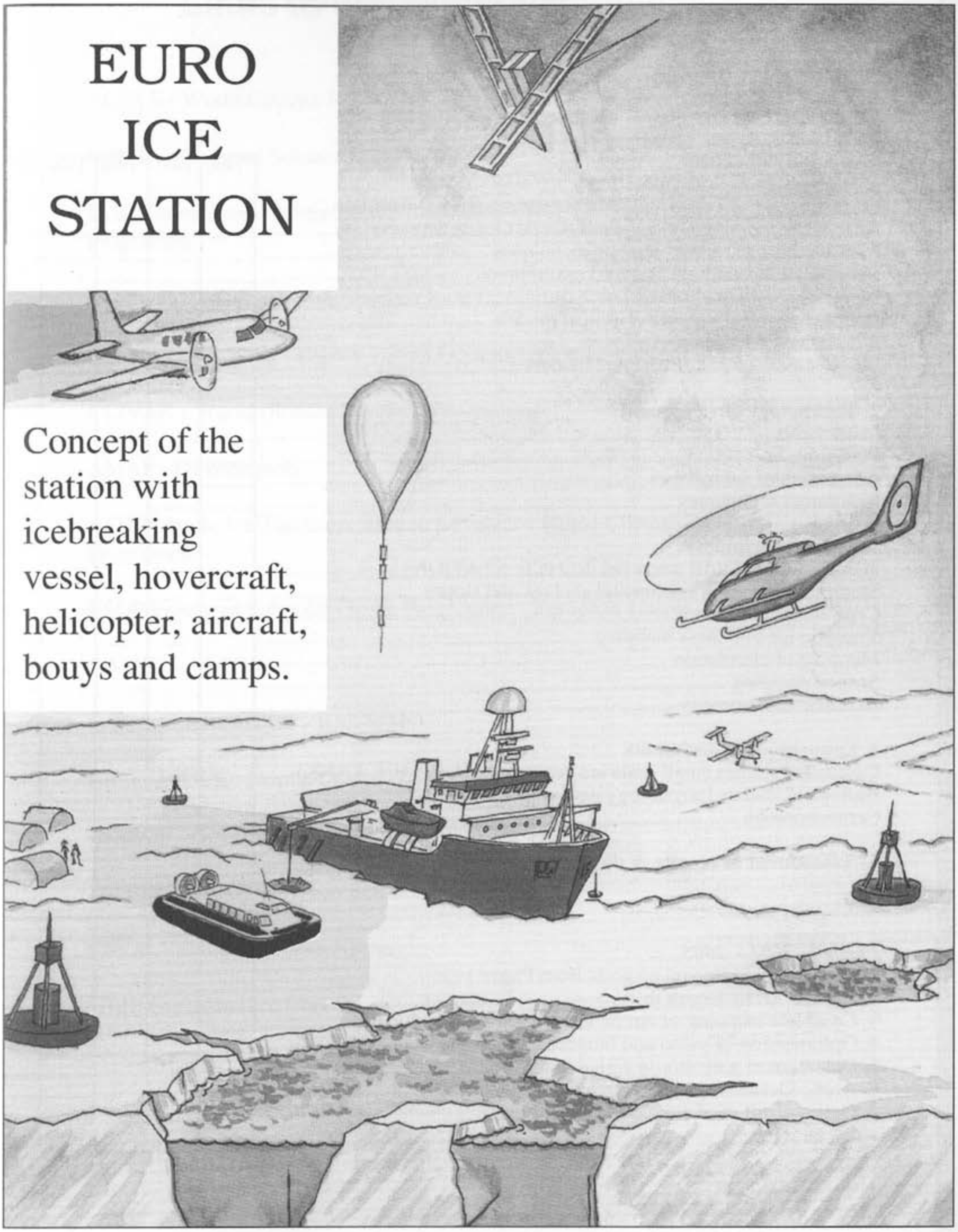

Fig. 17: EURO ICE STATION.

Implementation

Phase 1: 1996 - 2000

	1996	1997	1998	1999	2000
1. Data analysis and modelling					
Establishment of a data and information management system	------	---			
Analysis of existing and acquired Arctic Ocean data sets	------	------	------	------	------
Improvement of remote sensing techniques	------	------	------	------	
Large scale modelling and data assimilation	------	------	------		
Modelling studies of processes	------	------			
Coupled physical - biogeochemical models	------	------	------		
Simulation of palaeo scenarios	------	------	------		
Improvement of Arctic coupled models	------	------	------	------	------
2. Technology development					
Instruments	------	---			
Platforms	------	---			
Adaptation of submarines	------	------			
Laboratory techniques	------	------			
3. Field experiments					
Interdisciplinary drift study (EURO ICE STATION)		-----			
Studies on Eurasian continental shelves and slopes	----	---	---		
Central Arctic sections	----	---	---		
Synoptic ice thickness mapping		---	---		
Mapping of circulation	----	------	------		
Seabed mapping			---		--
Acoustic thermometry	------		---	------	
4. Laboratory experiments					
Controlled studies small scale ice processes (EURO ICE TANK)	------	------			
Biological studies (physiology and adaptation)	------	------			
Geotechnology	------				
5. Assessment of results & design of Phase 2 activities				------	------

Phase 2: 2001 - 2005

	2001	2002	2003	2004	2005
1. Extension of selected projects from Phase 1	------	------	------	------	------
2. Central Arctic Ocean drilling	------	------	------	------	------
3. Complete mapping of Arctic Ocean seabed by submarine	--	--	--	--	------
4. Optimization of paleo and biogeochemical models of the Arctic	------	------	------	------	------
5. Detection of greenhouse signal in the Arctic				------	------
6. Arctic Ocean response to greenhouse warming				------	------
7. Optimalization of coupled models for global change prediction				------	------

Links to other programmes

ACSYS - World Climate Research Programme

SHEBA - National Science Foundation

IABP International Arctic Buoy Programme - World Climate Research Programme

NDP Nansen Drilling Programme - Joint Oceanographic Institution

ODP Ocean Drilling Program - Joint Oceanographic Institution

CLIVAR - World Climate Research Programme

AMAP - Governments

AITRP Arctic Ice Thickness Research Project - World Climate Research Programme

ESOP European Subpolar Ocean Programme - European Union

IMAGES - SCOR

GOOS / EUROGOOS - IOC/WMO

Nordic WOCE - Nordic Council of Ministers

INSROP - Government

IAPP/NEW - Arctic Ocean Science Board

PIPOR - European Space Agency

GRIP Greenland Ice Core Project - European Science Foundation /EU

PONAM - European Science Foundation

Programme of the Euroscience conference

Friday, 2 September

17.00	Registration
21.00	*Fridtjof Nansen as a Scientist, a Diplomat and a Humanist* by O. M. Johannessen

Saturday, 3 September

Session: Large Scale Ice-Ocean Circulation and Climate

Chairman: P. Malkki, Helsinki

08.30	Opening Remarks, H Kock, ESF
09.00	D. WALLACE, Brookhaven. *Large Scale Arctic Ocean Modelling*
09.40	Discussion
10.00	R. GERDES, Bremerhaven. *Large Scale circulation and water mass formation in the Arctic from models and observations*
10.40	Discussion
11.30	I. POLIAKOV, St. Petersburg. *Large Scale Arctic Ocean circulation*
12.10	Discussion
12.30	Session poster presentations by Chairman

Chairman: G. V. Alexeyev, St. Petersburg

14.00	M. LEPPÄRANTA, Helsinki. *Ice modelling*
14.40	Discussion
15.00	G. BJØRK, Gotenburg. *The relation between ice deformation and the equilibrium ice thickness in the Arctic Ocean*
15.40	Discussion
16.30	P. WADHAMS, Cambridge. *Ice thickness distribution in the Arctic*
17.10	Discussion
17.30 - 19.30	Session Workshop with recommendation for topics to be dealt with under the Arctic Ocean Grand Challenge programme
21.00	Poster session (displayed from the morning)

Sunday, 4 September

Session: Meso and Small scale Physical Processes

Chairman: S. Sandven, Bergen

09.00	H. EICKEN, Bremerhaven. *Small Scale processes in the Arctic Ocean's sea ice cover: Reflections on the work of Nansen, Malmgren and the drifting ice camps*
09.40	Discussion
10.00	W. P. BUDGELL, Bergen. *Mesoscale ice-ocean modelling*
10.40	Discussion
11.30	B. RUDELS, Hamburg. *Mesoscale oceanography of the Arctic Ocean*
12.10	Discussion
12.30	Session poster presentations by Chairman

Chairman: P. Wadhams, Cambridge

14.00	C. RICHEZ and J. C. GASCARD, Paris. *Circulation in the Fram Strait.*
14.40	Discussion
15.00	Posters (displayed from the morning)
16.30 - 18.30	Session Workshop with recommendation for topics to be dealt with under the Arctic Ocean Grand Challenge programme

Monday, 5 September

Session: Biology and Carbon Cycle

Chairman: L. Anderson, Gotenburg

09.00	I. SMIRNOV, St. Petersburg. *The Fauna of the Arctic Seas*
09.40	Discussion
10.00	K. TANDE, Tromsø. *Pelagic Productivity, Zooplankton and Ecology*
10.40	Discussion
11.30	R. GRADINGER, Kiel. *Arctic Biology*
12.10	Discussion
12.30	Session poster presentation by Chairman

Chairman: M. Spindler, Kiel

14.00	L. ANDERSON, Gotenburg. *The carbon cycle of the Arctic Seas*
14.40	Discussion
15.00	H. DRANGE, Bergen. *Carbon Modelling*
15.40	Discussion
16.30 - 18.30	Session Workshop with recommendation for topics to be dealt with under the Arctic Ocean Grand Challenge Programme
21.00	Poster session (displayed from the morning)

Tuesday, 6 September

Session: Palaeo Environment and Climate

Chairman: S. Drachev, Moscow

09.00	J. THIEDE, Kiel and D. FÜTTERER, Bremerhaven. *Arctic Ocean Palaeocanography and Palaeoclimate*
09.40	Discussion
10.00	D. NÜRNBERG / W. WASHNER, Bremerhaven. *Sediment transport in the Arctic Ocean*
10.40	Discussion
11.30	A. ELVERHØJ, Oslo. *PONAM- Geological history of Polar North Atlantic margins*
11.50	T.O. VORREN, Tromsø. *Late quaternary depositional environments in and around the Barents Sea*
12.10	Discussion
12.30	Session poster presentation by Chairman

Chairman: J. Thiede, Kiel

14.00	N. NØRGAARD-PEDERSEN/R. SPIELHAGEN, Kiel. *Quaternary Arctic Ocean environment*
14.40	Discussion
15.00	S. DRACHEV and L. SAVOSIN, Moscow. *Laptev Sea Drilling plans: Steps to the detailed investigation of East Arctic environmental changes*
15.40	Discussion
16.30 - 19.00	Session Workshop with recommendation for topics to be dealt with under the Arctic Ocean Grand Challenge programme
21.00	Poster session (displayed from the morning)

Wednesday, 7 September

Co-chairmen P. Lemke and O. M. Johannessen

09.00	Reports from the session co-chairmen with recommendation for topics which could be dealt with under the Arctic Ocean Grand Challenge programme
11.30	Discussion, recommendation and outline for a first phase, 1996-2000, of the Arctic Ocean Grand Challenge programme

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Participants at the Helsinki Euroscience conference.

Back cover photo: *A characteristic ice field in the Arctic. The ship is the ice strengthened vessel Polarbjørn which has participated in many research expeditions in the the Arctic.*