01 KORTRAPPORT/BRIEF REPORT SERIES
NORSK POLARINSTITUTT, TROMSØ 2004

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The Marginal Ice Zone of the Barents Sea

Temporal and spatial variability of the ice–ocean system of the ice-edge

Kortrapport/Brief Report Series nr. 1

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The Norwegian Polar Institute is Norway's main institution for research, monitoring and topographic mapping in the Norwegian polar regions. The institute also advises Norwegian authorities on matters concerning polar environmental management.

Norsk Polarinstitutt 2004

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Technical editor:	Gunn Sissel Jaklin
Cover photo:	Hinrich Bäsemann, Gunn Sissel Jaklin and Tor Ivan Karlsen
Cover design:	Jan Roald
Printed:	August 2004
ISBN:	82-7666-211-0
ISSN	1504-3215

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1 Preface

This report describes the activities and results of the project "Temporal and Spatial Variability of the Ice–Ocean System of the Ice–Edge in the Marginal Ice Zone of the Barents Sea". The project investigated three different aspects of the marginal ice zone (MIZ): its physical oceanography, marine mammals and habitats, and ecosystem dynamics. Field data and samples were collected during two month-long cruises to the Barents Sea, in May 1999 and March 2000, and during one cruise to the MIZ north of Svalbard and into the Fram Strait in September – October 1999. The physical oceanographic aspect of the project investigated interactions between the atmosphere, sea ice and the ocean. Currents and water circulation in the area were described, and a model was developed which can be used to simulate the seasonal and interannual variability of ice conditions, thermohaline conditions and water dynamics of the Barents Sea. The marine mammal facet of the project looked at the distribution of polar bears in relation to sea ice conditions. Ecosystem dynamics focused on biodiversity and distribution of plankton in the MIZ, how energy is transferred through the pelago-sympagic food chain, and the role of key species in the MIZ ecosystem. A further phase of the project used a Geographic Information System (GIS) and spatial analyses to develop an analysis and presentation model (the Ice Edge Resource Module) for predicting the distribution of biological resources in time and space in the MIZ. Results of each aspect of the project are here presented, along with a listing of all publications in which material and data were collected from project cruises.

Sincere thanks to the sponsors of the project.

Stig Falk-Petersen
Project leader

2 Introduction

Marginal ice zones (MIZs) are some of the most dynamic areas in the world oceans with large seasonal and inter-annual fluctuations in ice cover and ice transport. For example, in the northern Barents Sea the extent of the ice edge during summer can vary by hundreds of kilometres from year to year. There is a strong relationship between the North Atlantic Oscillation (NAO) index and the ice edge location. These variations reflect directly the inter-annual dynamics of the entering Atlantic water masses.

The MIZ of the northern Barents Sea is an ecologically important area due to its high biological productivity in Arctic water masses and north of the Polar Front. This high productivity is caused by several factors, such as:

1. Seasonally high primary production in close association with the receding ice edge and stratified water column.
2. High annual production of *Calanus glacialis* on the shelf.
3. Advection of *Calanus finmarchicus* from the Norwegian Sea into the Barents Sea and from the area south of Iceland into the Iceland Sea.
4. Transport of ice fauna by the Transpolar Drift from the Arctic Ocean into the Barents Sea and Greenland Sea.
5. Advection of *Calanus hyperboreus* from deep water onto the Spitsbergen shelf.

The seasonal pulse in primary production is transferred as energy through the marine food web. Ice algae and phytoplankton produce lipids from photosynthetic energy, which are rapidly biosynthesised into lipid stores by herbivores. These high-energy lipid compounds are rapidly transferred through the Arctic marine food chains. Lipid levels increase from 10 - 20 % in phytoplankton to 50 - 70 % in herbivorous zooplankton and ice fauna. This increase in lipid levels, combined with high assimilation efficiency in key components of the Arctic marine food chains, is probably one of the most fundamental key specialisations in Arctic bioproduction.

3 Objectives

The project had five main objectives:

To characterise the variation of sea ice distribution in the region as a function of atmospheric forcing, ice-ocean interaction, water mass distribution and topographic influences.

1. To determine the temporal and spatial distribution of chlorophyll-*a*, ice-associated zooplankton and ice fauna in relation to the sea ice and water mass properties.
2. To determine the spatial distribution of polar bears using aerial surveys .
3. To determine trophic relationships and the transfer of energy and lipids through the ecosystem in the MIZ.
4. To integrate the data using a Geographic Information System (GIS) and spatial analyses for possible inclusion in Environmental Impact Assessments or Environmental Risk Assessments.

4 Physical oceanography

The physical component of the project consisted of two parts, one dealing with field data and one dealing with numerical modelling. The activities and results of the two aspects of the project are reported in the following two sections.

Temporal and spatial variability of oceanographic processes at the ice edge: field data

Field data were acquired during two month-long cruises to the Western Barents Sea, in May 1999 and March 2000. The study concentrated on the MIZ, an area characterised by intense interaction between ocean, sea ice and atmosphere. Data were therefore collected from all three media, as listed below.

1. CTD: 243 stations (141 in 1999, 102 in 2000) yielding the temperature and salinity structure across and along the ice edge.
2. Moorings: 4 moorings (2 on each cruise) yielding ocean currents at various depths at the selected sites.
3. ICEX Argos buoys: 4 drift buoys deployed across the MIZ yielding ice drift and lateral mixing patterns.Atmospheric tethersonde (“weather balloon”): 15 launches yielding atmospheric boundary layer temperature, wind speed, humidity and pressure across the ice edge.
5. Weather station: 6 deployments (i.e. on all ice stations) yielding the near-surface boundary layer (wind, temperature) across the ice edge.

Hydrographic data

The position of all CTD stations from the two cruises is plotted in Figure 1. The four moorings and the ARGOS drift buoys were deployed in the same area.

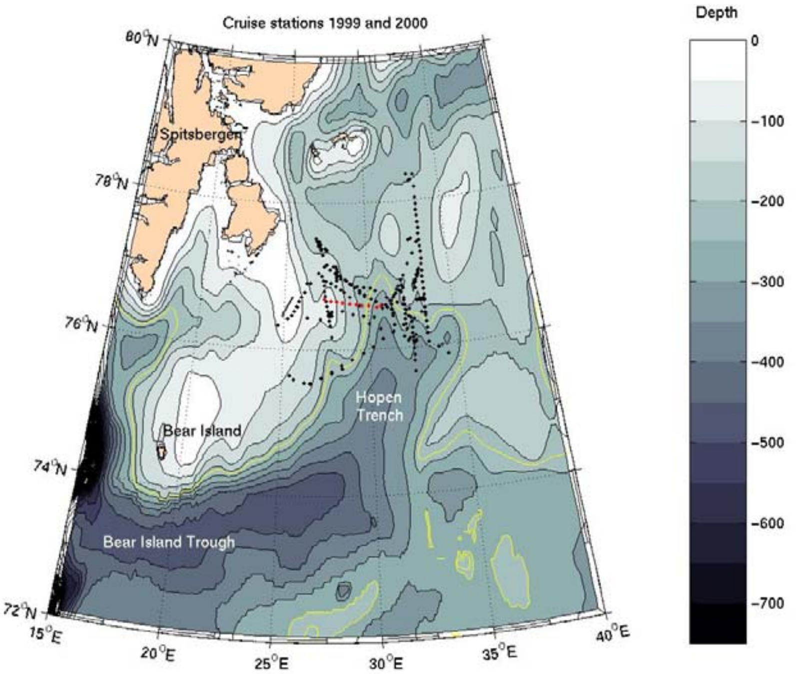

Figure 1
Position of all CTD stations. Transects are seen as straight lines of CTD positions. The red line is section 6 in year 2000. The yellow isobath is the 250 m depth contour.

A purpose of the physical oceanic data was to give the physical background to the biological data sampled during the cruises. The main conclusions for this project are therefore drawn in the sections reporting the biological findings. However, the data are interesting on their own, and the main conclusions of the physical part of the project are reported in the following.The current meters demonstrated a strong, nearly barotropic, tidal signal along the fringes of the Hopen Trench. The tidal signal was also pronounced in the sea ice drift in the area, as measured by the ARGOS drifters. The CTD data revealed two separate fronts in the area. The northward front was a density front separating cold, fresher Arctic water from saltier and warmer water of Atlantic origin. The southward front was located at the 250 m isobath, and exists because of dynamic reasons. An upstream bifurcation of the flow, between Nordkappbanken and Sentralbanken, and conservation of potential vorticity locks the northward flowing branch of the Atlantic water to the 250 m isobath.

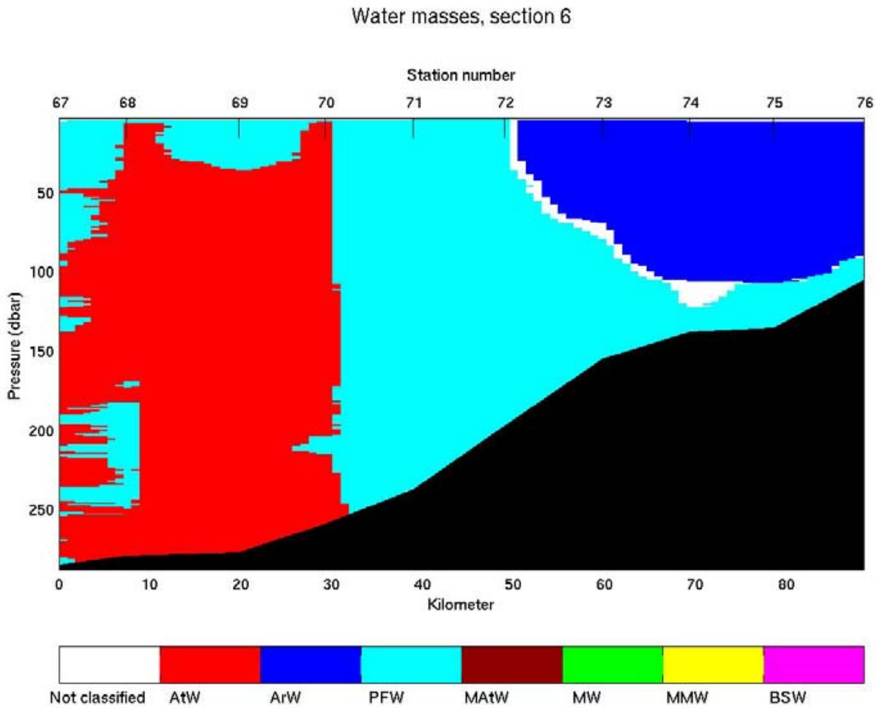

Figure 2
The frontal zone of the western Barents Sea. AtW=Atlantic water; PFW=Polar front water and ArW=Arctic water.

The water between the two fronts is a mixture between the two parent water masses. This frontal zone is demonstrated in Fig. 2, which is based on CTD data from section 6 on the cruise in May 1999 (red transect on Fig. 1). The data supports a recirculation hypothesis put forward by Woods Hole Oceanographic Institution (WHOI) researchers (Gawarkiewicz & Plueddemann 1995), that the northward flowing branch of Atlantic water recirculates back to the Norwegian Sea, following the 250 m isobath (Fig. 3).

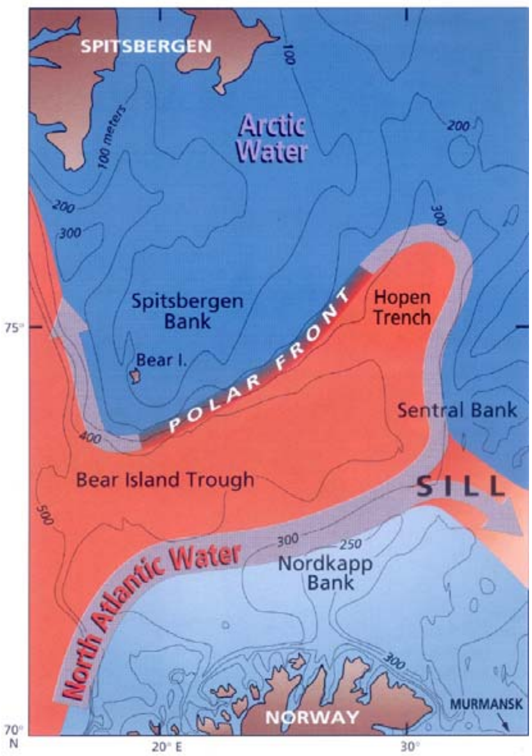

Figure 3
The circulation scheme put forward by Gawarkiewicz and Plueddemann (1995). The hypothesis is supported by data from this project.

Atmospheric data

Tethersonde launches and weather station deployments were performed during selected CTD stations. The data were analysed by Alexei Stuliy, Geophysical Institute, University of Bergen (Stuliy 2001). The NOAA satellite images in Fig. 4 illustrate the sea ice conditions in the study area after a cold air outbreak, on 8 May 1999. The image to the right is a zoom-in of the left one, and illustrates the tethersonde soundings (red circles) and CTD measurements (red squares) used to produce Fig. 5.

A) B)

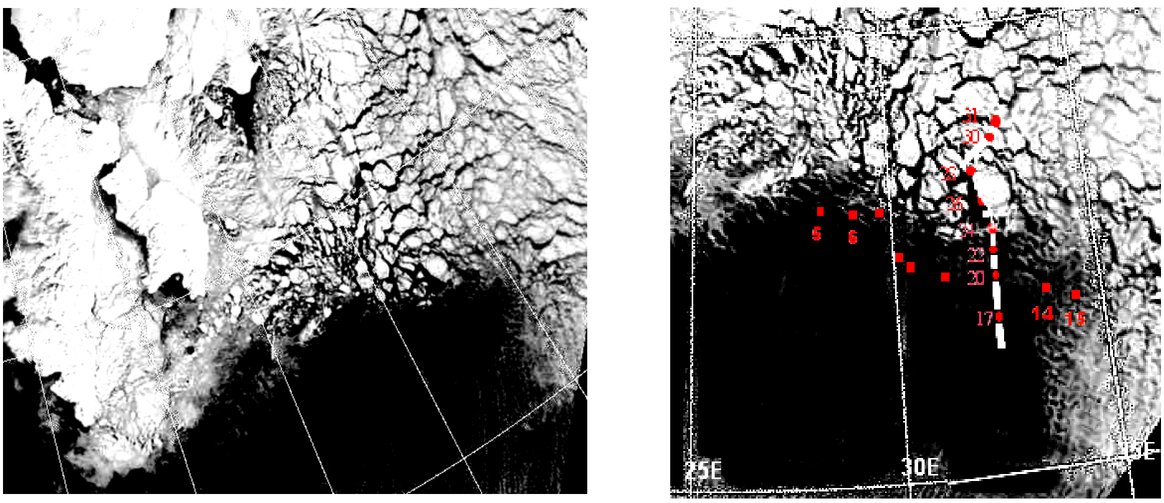

Figure 4
NOAA satellite images of the sea ice conditions during the 1999 cruise (8 May).
A) Full study area B) zoom-in.

All three media must be considered when studying variability along the ice edge due to the strong coupling. The intensity of the colours in Fig. 5 demonstrates the sensible heat flux calculated from the collected data, which may be compared with flux estimates from larger scale numerical reanalysis (NCEP/NCAR, yellow dashed lines). The large-scale product underestimates the heat fluxes by a factor of two, compared to the measurements made during the cruise, and the spatial distribution is very different.

The main conclusions from the atmospheric measurements are:

1. Large scale numerical reanalysis products strongly underestimate heat fluxes at the ice edge during cold air outbreaks.
2. In the MIZ the air-ice drag coefficient is not a constant, but rather increases linearly with increasing wind speed.
3. Atmospheric rolls are likely to be the reason that the MIZ tends to organize itself into ice edge bands.
4. Current parameterisations of sea ice atmospheric heat and momentum transfer are inadequate to model and explain local and meso-scale interactions.

Ice - ocean model

The main goal of modelling work within this project was to develop a coupled thermodynamic ice-ocean model for simulation of seasonal and interannual variability of the meso-scale ice conditions, hydrography and water dynamics in the Barents Sea. For coupling we used the well-known Rutgers University ocean model SCRUM (Hedstrom 1997*)* and the ice statistical model ISMO, developed at the Norwegian Polar Institute (Korsnes *et al.* 2002, Pavlov *et al.* in press). The statistical ice model is now in operative use for research at NPI.

In developing a statistical model we used the approaches suggested in Chen (1999) and Omstedt & Chen (2001). For this purpose, mean monthly wind and vorticity components were used (Korsnes *et al*. 2002, Pavlov *et al.* in press). In addition to these parameters, we used the monthly mean air temperature and seasonal long-term climatology of sea ice thickness. Satellite ice observations in the Arctic Ocean, which have been made over the last two decades, allowed us to obtain statistical parameters of seasonal and interannual variability of the ice condition. Multiple linear regressions for each point of the simulating domain was used to establish the statistical model linking ice concentration and ice drift with air temperature and spatial structure of the sea level atmospheric pressure.

For statistical analysis the following data were used:

1. Mean Monthly Sea Ice Concentration from Nimbus-7 SSMR and DMPS SSM/I Passive Microwave data for the period January 1979 – December 1996. EOSDIS NSIDC Distributed Active Archive Center (NSIDC DAAC). Spatial resolution 25 km. (htttp://www-nsidc.colorado.edu/NSIDC/CATALOG/ENTRIES/nsi-0051.html).

2. Mean Monthly Air Temperature for the period 1946 to present. Spatial resolution 5 degrees. The National Center for Atmospheric Research (NCAR) distributes these data. (http://dss.ucar.edu/datasets/ds085.0).

3. Mean Monthly Sea Level Atmospheric Pressure for the period 1899 – 2001. Spatial resolution 5 degrees. The National Center for Atmospheric Research (NCAR) distributes these data. (http://dss.ucar.edu/datasets/ds010.1).

4. Seasonal long-term climatology of sea ice thickness in the Arctic digitised by Benjamin Felzer using Bourke and Garrett maps from submarine under-ice sonar profiles 1960-1982 (Bourke and Garrett, 1987). Spatial resolution 1 degree. The National Center for Atmospheric Research (NCAR) distributes these data. (http://dss.ucar.edu/datasets/ds233.5).

We used this ice model to simulate the seasonal and interannual variability of ice conditions in the Barents Sea. Implementation of this model allowed us to simulate the ice conditions not only for the period covered by satellite observations but also for the decades before this, when such observations are not available. The simulating domain for the Barents Sea has dimensions of 1470 km x 1845 km. The spatial resolution of the grid is 1/8 degree of latitude (13.875 km). Results of a comparison between simulated and observed ice conditions (ice drift and ice concentration) have shown that the accuracy of the model is good (see Fig. 6). Simulated ice concentration was used for parameterisation of the momentum, heat and salt fluxes at the water surface.

The ice statistical model was coupled with the numerical ocean model SCRUM. The S-Coordinate ocean model SCRUM for the Barents Sea has 10 levels of vertical resolution. For the calculated domain we used bottom topography from the National Geophysical Data Center data set (http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html). Data from the Climatic Atlas of the Barents Sea 1998: Temperature, salinity, oxygen (World Data Center – A for Oceanography International Ocean Atlas series, Volume 1, NOAA Atlas NESDIS 26) were used as a base for constructing the initial conditions in the Barents Sea. The coupled Barents Sea model was run in a prognostic mode for one annual cycle from 1 October 1989 until 30 September 1990.

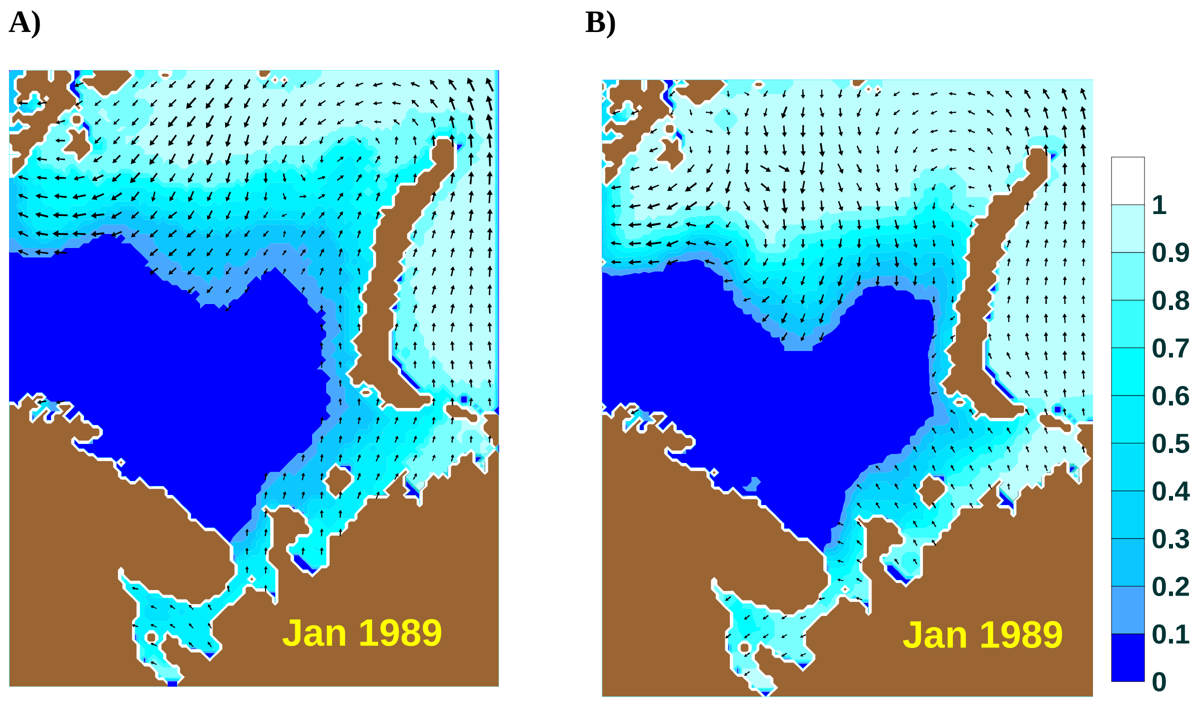

Figure 6
Simulated (A) and observed (B) ice drift and ice concentration in January 1989. The averaged error of the method is less than 15 %.

Surface temperature and salinity in September 1990, after one year of simulation, and observed data for September 1990 are presented (Fig. 7) (there are no observations in the White and Kara seas for September 1990). The general spatial structure and temporal variability of temperature and salinity are well reproduced by the model.

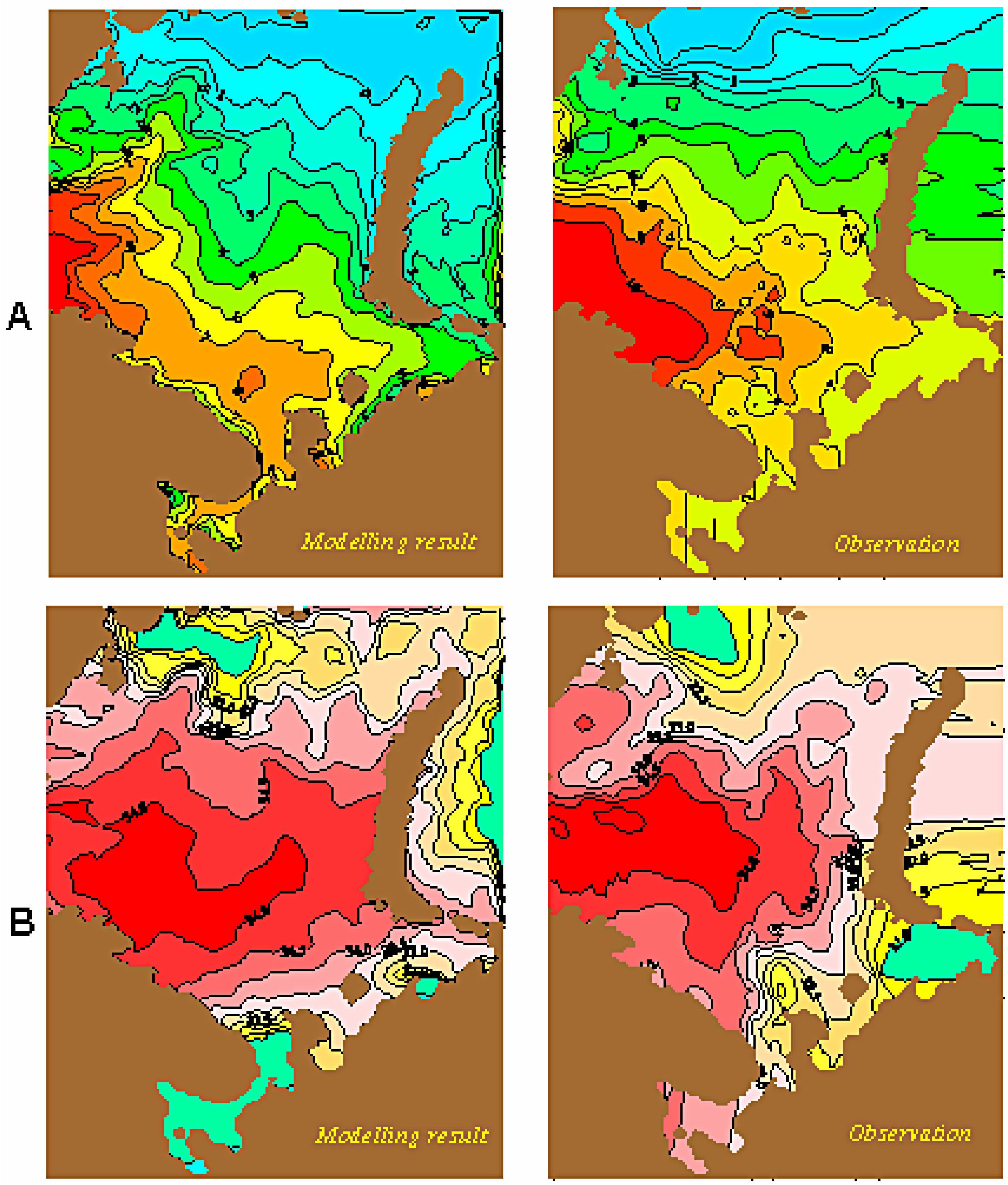

Figure 7
Observed and simulated surface temperature (A) and salinity (B), in January 1990.

One goal of this work was the investigation of processes in the MIZ. The results of simulations show that in June, when the heat and fresh water flux at the surface is largest, the water dynamics in the MIZ has very specific features. Under these conditions the horizontal salinity gradients and stratification of the water column have maximum values. The velocity of currents in MIZ increases sharply (Fig. 8). The calculated sea level has a local maximum in the area of ice concentration of about 20 - 30 % (Fig. 9), whereas the current in the zone of the maximum sea level gradient is directed along the front. Its speed is greater than 10 cm s^{-1} and it extends from the surface to the bottom without changing significantly. Such a horizontal circulation also induces intense vertical circulation (Fig. 9). The upward flows transport more saline deep water to the surface and increase the stratification in the MIZ.

The results obtained from the model allow us to conclude that the coupled statistical-numerical ice-ocean model developed within the framework of the project gives realistic results. It can be used for simulations of the seasonal and interannual variability of ice conditions, thermohaline conditions and water dynamics of the Barents Sea.

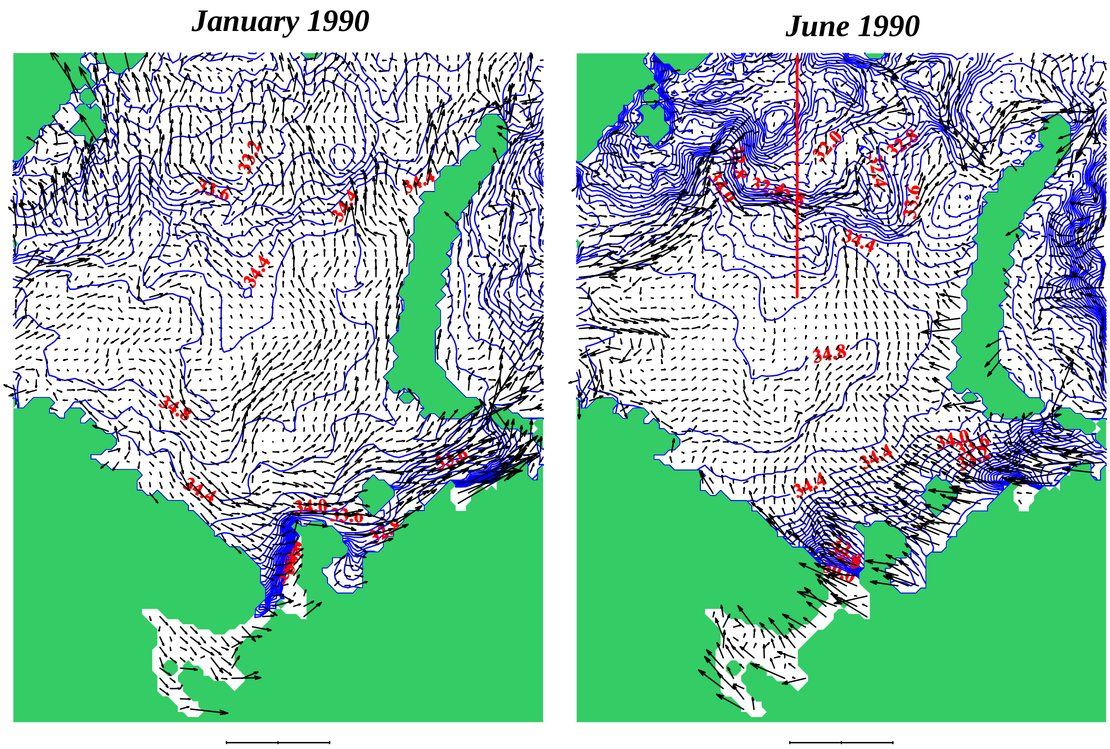

Figure 8
Simulated salinity and current velocity at the surface of the Barents Sea. The red line indicates the section referred to in Figure 9.

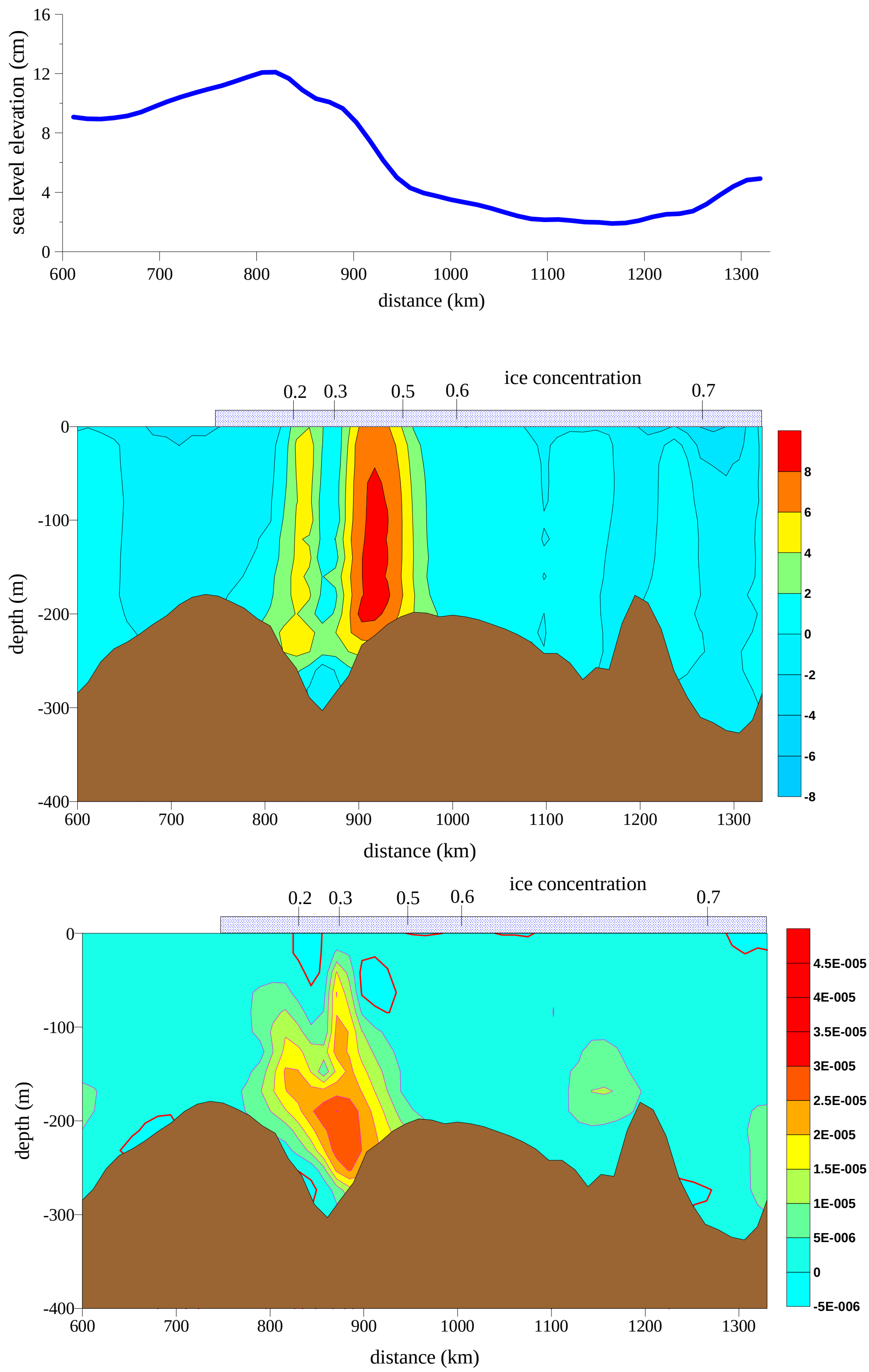

Figure 9
Results of the simulation of dynamic parameters along a section in June 1990 (for section location see Fig. 8). Sea level elevation (upper panel), horizontal velocity (cm s^{-1}) normal to the section (middle panel) and vertical component (cm s^{-1}) of the current (lower panel).

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5 Marine mammals and habitats

Distribution of polar bears in the Barents Sea in relation to sea ice characteristics

Introduction

Polar bears (*Ursus maritimus*) are totally reliant on sea ice as their habitat for almost all components of their life cycle (DeMaster & Stirling 1981). Polar bears in the Barents Sea inhabit the very dynamic shifting pack ice, and have evolved to exploit the sea ice niche as a predator on seals in a dynamic habitat. Sea ice provides a platform from which to hunt, to seek mates and breed, for movements and migrations, and as a vehicle to terrestrial maternity denning areas. Polar bears rely on ringed seals (*Phoca hispida*) as their primary prey and secondarily on bearded seals (*Erignathus barbatus*) (Lønø 1970, Smith 1980, Stirling & Archibald 1977).

Polar bears in the Barents Sea use the Marginal Ice Zone but also rely on the heavier annual ice found further north. The heavier annual ice provides breeding habitat for ringed seals. The more dynamic annual ice along the Marginal Ice Zone provides good habitat for bearded seals and Greenland seals (*Phoca groenlandica*) but the relative importance of the two areas remains uncertain. Polar bears have very large home ranges. In the Svalbard area, home ranges are between 1 044 km^2 and 249 046 km^2 (Wiig 1995). The reasons for the highly variable home range sizes for polar bears is unclear but may relate to differential selection of sea ice habitats, prey availability and ice dynamics. Variation in sea ice may impact polar bears by affecting seal populations, hunting success and access to denning areas. It is important to consider that habitat selection by polar bears is markedly different than that of terrestrial species because habitat availability can change much faster than terrestrial habitats, which are largely governed by predictable seasonal climates (Arthur *et al.* 1996). In contrast, the sea ice habitat of polar bears is highly diverse and varies greatly within a year, with major climatic events and between years. We have very limited understanding of the relationships between polar bears and the shifting sea ice habitats.

Seasonal distribution of sea ice, percentage ice cover, pressure ridging, snow cover, ice thickness and ice type all vary greatly in the Barents Sea (Vinje 1985). Sea ice directly and indirectly affects the ecology of polar bears. The most important feeding period for polar bears is likely from early April, when ringed and bearded seal pups are born, to ice retreat in July. The timing of sea ice arrival and departure around Hopen Island is likely to impact reproduction by controlling access to, and departure from, the denning area.

Polar bears have a long life-span and high adult survival, and their reproductive rates are among the lowest known for terrestrial mammals (Bunnell & Tait 1981, Taylor *et al.* 1987, Ramsay & Stirling 1988). Population trend is largely determined by the survival rate of adult females (Taylor *et al.* 1987). The life history of polar bears is such that any given attempt at reproduction can be abandoned if conditions for rearing young are poor and continuing to rear young reduces the lifetime reproductive potential of the mother. Therefore, any event that reduces the survival of adult female polar bears (e.g., an oil spill) will have a major effect on population trend.

Methods and Results

Standard capture techniques were used to collar 125 female polar bears with satellite transmitters (Stirling *et al.* 1989). The majority of bears were captured in Storfjorden and around Hopen (Fig. 10).

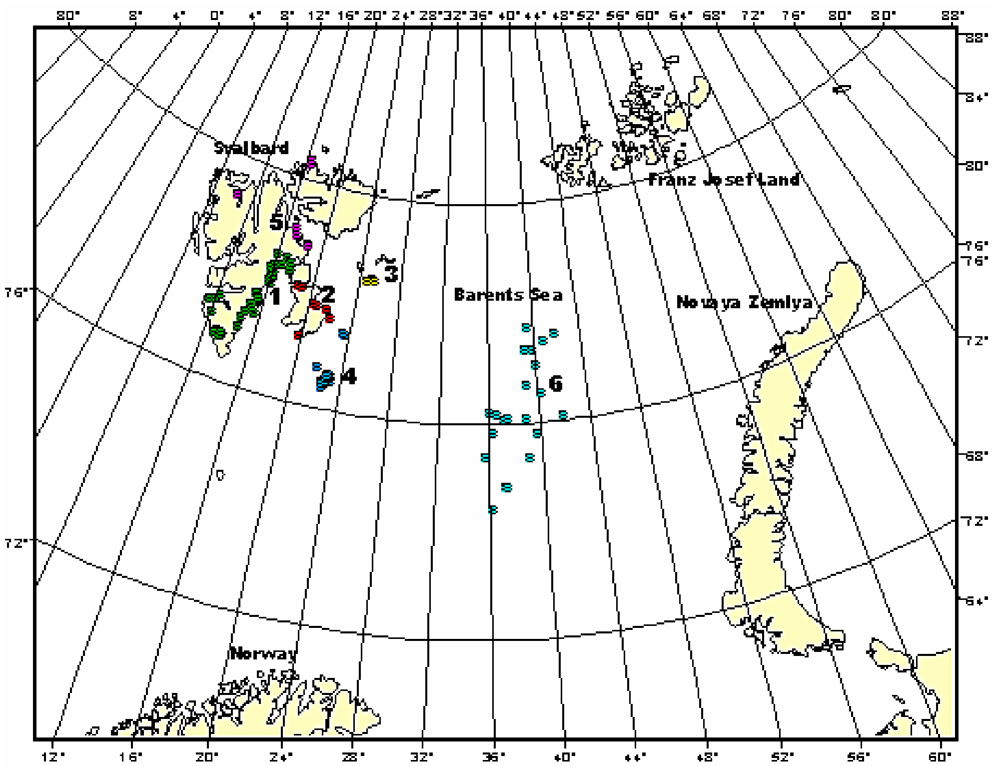

Figure 10

Capture locations of the 125 female polar bears and division into the six populations used in the estimation of probability polygons (Derocher *et al.* 2000).

From 1988 to 2000, 5054 locations of accepted quality were used to estimate polygons, which define the probability of polar bears being within a certain area. Full details of the methods used and the results obtained are presented in Derocher *et al*. (2000).

The synthesised satellite telemetry data reflects the seasonal distribution of adult female polar bears in the Norwegian area of the Barents Sea. Given that only adult female polar bears were monitored, the data cannot fully assess the use of the area by subadults and adult males. However, because the population processes are largely driven by adult females, the identified areas should be considered as the most critical habitats. Polar bears of all age and sex classes can be found throughout the drifting and landfast sea ice areas in the Barents Sea and adjacent waters, but the core of the Norwegian population is centred SE of Svalbard. Inclusion of data from Russia would likely alter this distribution and could shift the core activity areas further eastward, although without additional data, this cannot be assessed.

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6 Ecosystem studies

The MIZ of the northern Barents Sea represents a biologically highly productive area and supports a diverse community, consisting of small phytoplankton organisms, zooplankton and a specific ice-associated faunal complex up to higher trophic level organisms such as fish, seabirds, seals and polar bears. This community is strongly dependent on the dynamics and structure of the covering sea ice as well as on the underlying water masses. Changes in the environmental conditions due to natural variations in, for instance temperature, as well as human impacts may severely influence the community structure and trophic relationships among the organisms.

The aims of the current study were:

1) To understand how the physical and oceanographic properties affect the biodiversity and distribution of plankton in the MIZ.
2) To understand the energy transfer through the pelago-sympagic food chain and the role of key species in the ecosystem of the MIZ.

The ecosystem of the MIZ is strongly influenced by different physical and oceanographic factors such as ice coverage, ice movement, temperature, and water currents. However, the effect of these factors on the development and distribution of plankton communities, as the basic components of Arctic marine food chains, is not well understood. The present study focused on establishing the links between biological and physical phenomena in order to understand the mechanisms responsible for the dynamics and biodiversity of the area. The analysis of the energy transfer from lower to higher trophic levels within the pelago-sympagic food chain will enable us to identify key components and determine their importance for the entire food web of the MIZ.

Temporal and spatial variability of biological diversity in the Marginal Ice Zone of the northern Barents Sea

During the spring cruise with RV ‘Lance’ in May 1999, zooplankton samples were taken along one west-east transect following the ice edge and along two across-ice transects near Hopen and close to 35 °E. In total, 65 zooplankaton taxa were found in the net samples, showing the high diversity in this area. The number of taxa per station ranged between 29 - 46 along the west-east transect and between 28 - 33 and 36 - 38 along the western and eastern across-ice transects, respectively. Dominant taxa in terms of percent occurrence were copepods (different developmental stages) of the genera *Calanus*, *Pseudocalanus*, *Metridia*, *Oithona*, *Oncaea*, and *Microcalanus* as well as harpacticoid copepods, pteropods, polychaetes, ctenophores, appendicularians and chaetognaths. The numerically most abundant species in the area was *Oithona similis*, which constituted up to 50 % of the samples. *Microcalanus* spp. were dominant in the open water along the ice edge, whereas copepod nauplii, *Pseudocalanus* spp., *Calanus glacialis* and *Fritillaria borealis* were more abundant along the across-ice transects. The very high number of copepod nauplii along all transects indicates that reproduction had occurred prior to sampling.

The total abundance of all taxa found along the ice edge increased from west to east, ranging between 14 600 and 61 800 ind. m^{-2}. The highest abundance was found in the middle of the Hopen trench. On the eastern across-ice transect the total abundance was higher at stations with ice coverage (86 400 – 111 000 ind. m^{-2}) than at the open water station (49 100 ind. m^{-2}). On the western across-ice transect the situation was reversed, with lower zooplankton abundance at stations in the ice covered sea (79 300 – 97 400 ind. m^{-2}) than at the open water station (109 000 ind. m^{-2}).*Oithona similis* was the dominant species in both shallow and deep water (Fig. 11). *Microcalanus* sp. and copepod nauplii were abundant in deeper water, whereas *Pseudocalanus* sp. and *Fritillaria borealis* were numerous in shallow water. The total zooplankton abundance was approx. two times higher in deep water (43 700 ind. m^{-2}) compared to shallow waters (20 200 ind. m^{-2}).

A comparison of the abundance of dominant zooplankton species in ice covered and open waters showed distinct differences: *Oithona similis* was the most numerous species in ice covered areas followed by copepod nauplii, *Pseudocalanus* sp. and *Calanus glacialis* (Fig. 12). In open water, the shares of *Oithona similis*, *Microcalanus* spp. and copepod nauplii were nearly the same, and were complemented by a high number of the appendicularian *Fritillaria borealis*. Mean abundance in ice covered water (91 400 ind. m^{-2}) was two times higher than in open water (43 000 ind. m^{-2}). However, these results should be interpreted in view of the changing ice extent during the sampling period. Previously ice covered areas suddenly opened up, and vice versa.

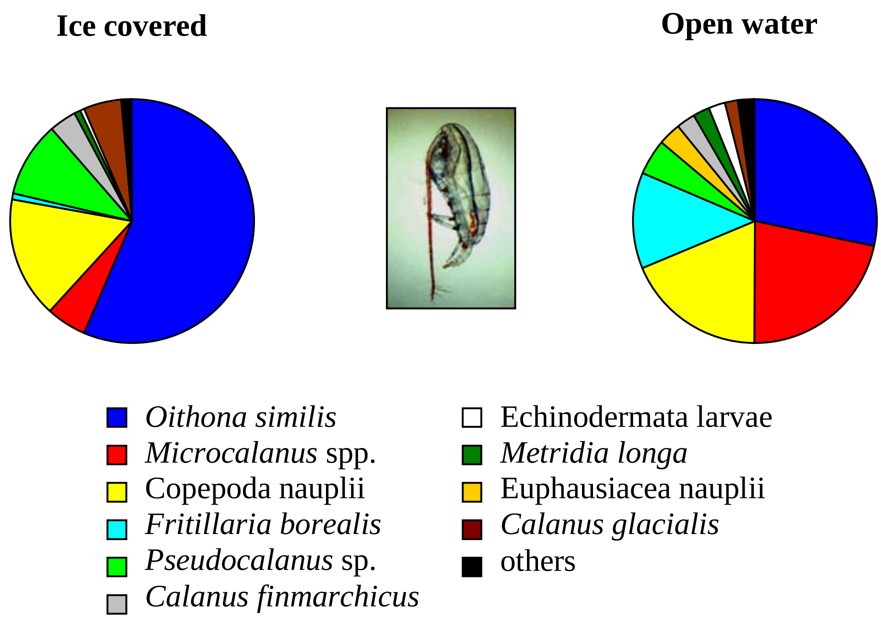

Figure 12
Shares of dominant zooplankton taxa in ice covered vs. open water areas in the MIZ of the northern Barents Sea. The picture shows a female *Calanus glacialis*. Photo Werner J. Hannappel.

The correlation between the different water masses and the zooplankton abundance (per m^3) in the MIZ showed that most of the animals were located in Melt water and Arctic water masses, i.e. under the sea ice, where these water masses were present (Fig. 13). The most abundant species in these water masses were *Oithona similis*, *Pseudocalanus* sp., *Calanus glacialis* and copepod nauplii. Interestingly, the number of *Calanus finmarchicus*, a typical Atlantic species, was also highest in Melt water layers. This finding indicates that strong mixing processes take place in this area and that *C. finmarchicus* had been advected into water masses where it is usually not found. In open water, predominately in the warmer Polar Front and in Atlantic water, the total zooplankton abundance was low and the only abundant species was *Microcalanus* sp.

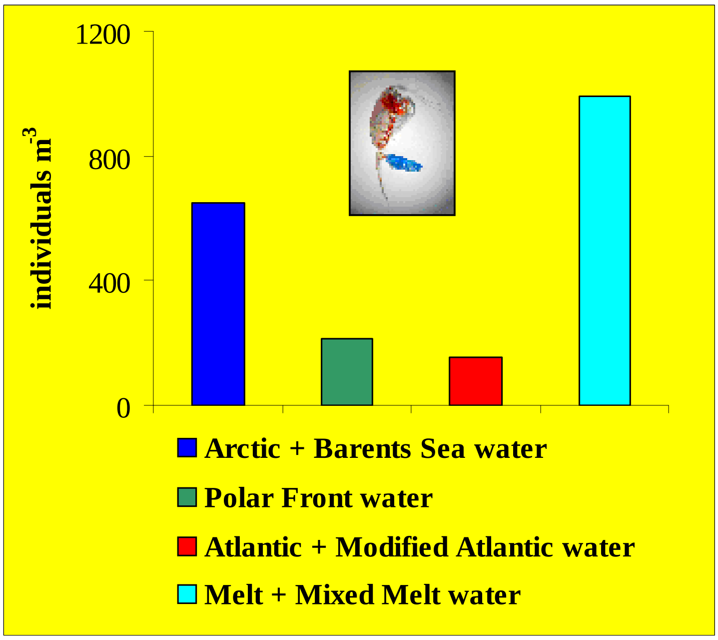

Figure 13
Total zooplankton abundance in relation to different water masses. The picture shows a female *Paraeuchaeta norvegica* with eggs.

In summary the MIZ of the northern Barents Sea is an area of high biological diversity and production in the springtime. The highest total zooplankton abundance can be found in the deepest part of the area, the Hopen Trench. The zooplankton abundance in ice covered areas, dominated by surface melt water and underlying Arctic water masses, is much higher compared to that of ice free areas, dominated by Atlantic and Polar Front water masses. The dominant taxa are small copepod species such as *Oithona similis*, *Microcalanus* sp. as well as copepod nauplii. These small zooplankton species are of major importance to small predators such as fish larvae (polar cod, capelin), arrow worms, amphipods (*Themisto libellula*) and ctenophores. Some of these are, in turn, important food for predators at higher trophic levels, such as seabirds, whales and seals. Of the three *Calanus* species only *Calanus glacialis* is numerically important, especially under the sea ice. Collections of species in water masses where they are usually not found (e.g. *Calanus finmarchicus*) indicate that strong mixing processes take place in the MIZ at this time of the year.

Energy transfer and lipids

Polar pelagic systems are notoriously unstable and herbivorous zooplankton exposed to marked variations in food availability have adapted by storing lipids as energy reserves. The oils accumulated in large amounts by calanoid copepods are exploited as an energy source by large stocks of fishes, such as polar cod (*Boreogadus saida*), herring (*Clupea harengus*) and capelin (*Mallotus villosus*), which themselves can store large quantities of oil derived from zooplankton. These oil rich fish stocks constitute, together with the oil rich *Calanus* species, krill and amphipods, large energy-packed food items for seabirds and marine mammals, which enable them to maintain over-wintering populations. In this project we studied the importance of herbivores and their role in energy transfer to higher food chain levels.

The size spectrum and energy content of the major zooplankton species in Arctic ecosystems determine their value as food sources for the upper trophic levels. Both vary substantially among the three *Calanus* species: *Calanus finmarchicus, Calanus glacialis* and *Calanus hyperboreus*. For example, stage V copepodites of *C. glacialis* and *C. hyperboreus* contain 10 and 25 times as much energy, respectively, than *C. finmarchicus*. What further amplifies the energy value of these three species is the very high amounts of *de novo* synthesised 22:1 and 20:1 fatty alcohols and acids in their wax esters. A longer chain fatty alcohol (or fatty acid) is more chemically reduced and has a higher energy content per unit mass than a shorter chain fatty alcohol (or fatty acid). Therefore, the energy content of wax esters (or triacylglycerols) is maximised by increasing the chain lengths of their constituents. The amounts of 22:1 and 20:1 fatty alcohols / acids correlate with energy content in the three species, with *C. hyperboreus* having the highest ratio of 22:1 to 20:1 fatty acids, followed by *C. glacialis* and *C. finmarchicus.* The equation below shows how a large amount of energy (ATP) is generated from the catabolisation of one mole (338 g) of 22:1 fatty acid:

$$C_{22}H_{42}O_2 + 31.5\ O_2 = 22\ CO_2 + 21\ H_2O + 176\ ATP$$

The important characteristics of the individual *Calanus* species are summarised in Table 1. In the Arctic basin, *C. hyperboreus* is the most highly adapted of the three species when it comes to accumulating large, energy-rich lipid reserves. The second most adapted is the Arctic shelf species *C. glacialis* and, finally, the north Atlantic *C. finmarchicus.*

Table 1. The *Calanus* complex – species differences, stage V copepodites.

Species	**Length (mm)**	**Wet weight (mg)**	**Lipid (mg ind $^{-1}$)**	**20:1 + 22:1 % of total lipids**
Calanus finmarchicus	2.0 - 3.0	0.56	0.04	75 %
Calanus glacialis	3.0 - 4.0	2.38	0.38	77 %
Calanus hyperboreus	4.5 - 6.0	6.44	1.03	83 %

The geographical distribution of Arctic zooplankton is susceptible to climatic variations and to climate change, with consequences for the large stocks of fish, seabirds and mammals in the Arctic ecosystem. We postulate that a warmer climate with reduced ice cover will shift zooplankton community structure towards a smaller size spectrum, with lower energy content per individual. Consequently, this will lower the potential for seasonal accumulation of lipid stores in their predators. The changes in zooplankton communities will be reflected in the diet composition and affect the general ecology of specialised seabirds. The little auk (*Alle alle*) requires access to large numbers of energy-rich zooplankton (preferably *C. glacialis*) to successfully raise their chicks (Fig. 14a). On Iceland, colonies of this high-Arctic seabird were heavily reduced during the first half of the last century. The cause of the decline strongly pointed shift in the zooplankton distribution, favouring *C. finmarchicus* instead of *C. glacialis*, a situation having fatal impact on the little auk. This example demonstrates the vulnerability of specialised species to climatic changes. A possible effect of a warmer climate on fish stocks will be that a *C. finmarchicus* prey base will favour capelin and herring stocks (Fig. 14b). These may therefore expand northwards to the northern Barents Sea and into the Arctic Ocean north of Svalbard.

Our main idea is that the high-energy lipid compounds biosynthesised by herbivorous zooplankton and the resulting lipid-driven energy flux are likely to be key determinants of biodiversity towards a rapid change in the Icelandic climate during the same period. The rise in temperature probably triggered a and productivity within Arctic systems. We conclude that climate change can affect biology, from the level of cellular physiology and biochemistry up to food webs and habitats.

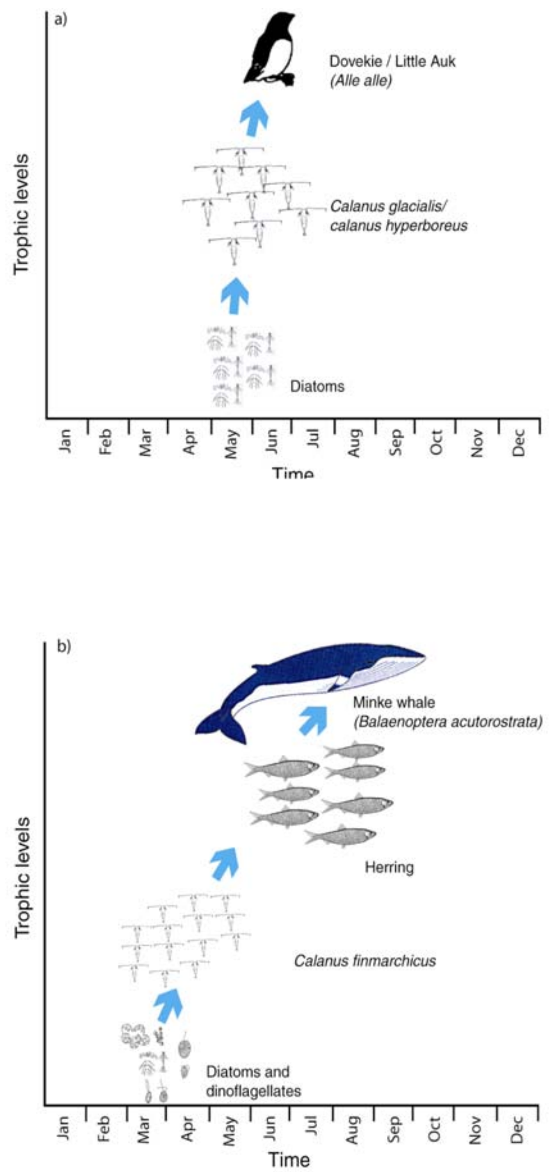

Figure 14

Calanus-based food webs in the Nordic Seas. a) *C. glacialis / C. hyperboreus* based food web b) *C. finmarchicus* based food web.

7 The Ice Edge Resource Module

In order to increase the use and usefulness of the data collected, Akvaplan-niva was subcontracted to develop an analysis- and presentation module for predicting the distribution of biological resources in space and time in the MIZ. This module is named the Ice Edge Resource Module (IERM).

The IERM project identified and quantified correlations between abiotic factors, primarily ice conditions and water temperature, and biological resources in the Barents Sea MIZ. Together with a correlation model for zooplankton, an associated GIS presentation model was developed (Pedersen *et al.* 2001). The resulting module can be used as a tool to improve Environmental Impact Assessments, Environmental Risk Analyses and other contingency plans with respect to the distribution of biological resources. Full details of the IERM are found in the report listed below.

Reference

Pedersen, G., Larsen, L.-H., Årsand, E. & Olsen, L. R. 2001: Ice Edge Resource Module (IERM): A tool for prediction and presentation of biological resources in marginal ice zones. In: *Akvaplan-niva rapport nr APN-421.1544.1*.

8 Data assimilation and databases

Zooplankton/Lipid database

Biological data from this project are organised in a database. The database is based on MS Windows Explorer, MS Excel and MS Word. In general, data are sorted by year and according to expeditions/cruises. The folders contain the following information: abundance, biomass, lipids, stable isotopes, and background data. The ecological or taxonomic groups sampled during the different expeditions are given in the next levels. The background folder contains mostly cruise logs, cruise reports and additional relevant information. The type of data given in the files is explained by the file name. Most of the files contain a sheet "Abbreviations" to explain short names used in the tables.

9 Project activities

Cruises

- 30.04 - 26.05 1999: RV ‘Lance’, Marginal Ice Zone, northern Barents Sea.
- 23.09 - 12.10 1999: RV ‘Jan Mayen’, Marginal Ice Zone, north of Svalbard, Fram Strait, Greenland Sea.
- 08.03 - 24.03, 1999: RV ‘Lance’, Marginal Ice Zone, northern Barents Sea.

Symposium presentations

- AMAP International Symposium on Environmental Pollution in the Arctic. Tromsø, Norway, June 1-5, 1997.
- The Gordon Research Conference on Sea Ice Ecology. Ventura, California. March 2-7, 1997.
- 30th International Liège Colloquium on Ocean Hydrodynamics. Liège, Belgium, May 4-8, 1998.

- 18th Symposium on Halogenated Environmental Organic Pollutants. Stockholm, Sweden, Aug 17-21, 1998.
- International Symposium on Polar Aspects of Global Change. Tromsø, Norway, Aug 24-28, 1998.
- Second International Symposium on Krill, UCSC, Santa Cruz, Aug 1999.
- 50th Anniversary Meeting of the Norwegian Society of Ocean Researchers (Norske Havforskeres Forening), Geilo, Nov 3-5, 1999.
- International conference on Long-term changes of the Arctic. Marine ecosystems, climate, marine periglacial, bioproductivity. Murmansk, May 2000.
- American Society of Limnology and Oceanography Symposium, Copenhagen, June 5-9, 2000.
- “Oceans from Space”, Venice 2000 Symposium, Venice, Oct 9-13, 2000.
- Arctic Science Summit Week (ASSW), Iqaluit, Canada, April 22-27, 2001.
- International Polynya Symposium 2001, Quebec, Canada, Sept 9-13, 2001.
- Carbon flux and climate change: The Nordic contribution to a panarctic perspective. International Symposium funded by Nordic Arctic Research Programme (NARP). Sigulda, Latvia, Nov 1-7, 2002.
- 52nd Annual meeting of the Norwegian Society of Ocean Researchers (Norske Havforskeres Forening), Bodø, Nov 23-25, 2001.
- 37th European Marine Biology Symposium, Reykjavik, Aug 5-7, 2002.
- The bioproduction and energy transfer in the Nordic Seas, the role of key zooplankters in a system with rapid climate change. Nordic Arctic Research (NARP) Symposium. Sangerdi, Iceland, Aug 1-3, 2002.

10 Publications, reports and presentations

This list contains all known publications where material and data were collected on cruises arranged by the two programs "ICE-BAR" and "Temporal and spatial variability of the Ice-Ocean system of the Ice-Edge in the Marginal Ice Zone of the Barents Sea".

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2. Bluhm, B. A., Pipenburg, D. & von Juterzenka, K. 1998: Distribution, standing stock, growth, mortality and production of *Strongylocentrotus pallidus* (Echinodermata: Echinoidea) in the northern Barents Sea. *Polar Biology 20*, 325-334.

3. Borgå, K. 1997: *Bioaccumulation of organochlorines (OCs) in an Arctic marine food chain.* Candidata Scientarium Thesis, Norwegian College of Fishery Science, University of Tromsø.

4. Borgå, K., Gabrielsen, G. W., Hop, H. & Skaare, J. U. 1998: Organochlorines and trophic positions in a marine pelagic food chain leading to seabirds in the Norwegian Arctic. *Organohalogen Compounds 39*, 431-434.

5. Borgå, K., Gabrielsen, G. W. & Skaare, J. U. 2001: Biomagnification of organochlorines along a Barents Sea food chain. *Environmental Pollution 113*, 187-198.

6. Borgå, K., Gabrielsen, G. W. & Skaare, J. U. 2002: Differences in contamination load between pelagic and sympagic invertebrates in the Arctic marginal ice zone: influence of habitat, diet and geography. *Marine Ecology Progress Series 235*, 157-169.

7. Borgå, K., Gulliksen, B., Gabrielsen, G. W. & Skaare, J. U. 2002: Size-related bioaccumulation and between-year variation of organochlorines in ice-associated amphipods from the Arctic Ocean. *Chemosphere 46,* 1383-1392.

8. Borgå, K., Poltermann, M., Polder, A., Pavlova, O., Gulliksen, B., Gabrielsen, G. W. & Skaare, J. U. 2002: Influence of diet and sea ice drift on orgaochlorine bioaccumulation in Arctic ice-associated amphipods. *Environmental Pollution 117*, 47-60.

9. Dahl, T.M., Falk-Petersen, S., Gabrielsen, G. W., Sargent, J. R., Hop, H. & Millar, R. -M. 2003. Lipids, fatty acids and stable isotopes contained in fat, muscle and liver of common eider (*Somateria mollisima*), black-legged kittiwake (*Rissa tridactyla*) and northern fulmar (*Fulmarus glacialis*) - A trophic study from an Arctic fjord. *Marine Ecology Progress Series 256,* 257-269.

10. Engelsen, O., Hegseth, E. N., Hop, H., Hansen, E. & Falk-Petersen, S. 2002: Spatial variability of chlorophyll-*a* in the Marginal Ice Zone of the Barents Sea, with relations to sea ice and oceanographic conditions. *Journal of Marine Systems 35*, 79-97.

11. Engelsen, O., Hop, H., Hegseth E. N., Hansen E. & Falk-Petersen S. 2004. Deriving phytoplankton biomass in the Marginal Ice Zone from satellite observable parameters. *International Journal of Remote Sensing 25,* 1453 - 1457.

12. Falk-Petersen, S. & Hop, H. 1996: Ecological processes in the marginal ice-zone of the northern Barents Sea. In: *ICE-BAR 1995 Cruise Report. Norsk Polarinstitutt Rapportserie 93*. 240 pp.

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14. Falk-Petersen, S., Sargent, J. R., Henderson, J., Hegseth, E. N., Hop, H. & Okolodkov, Y. B. 1998: Lipids and fatty acids in ice algae and phytoplankton from the Marginal Ice Zone in the Barents Sea. *Polar Biology 20,* 41-47.

15. Falk-Petersen, S., Pedersen, G., Kwasniewski, S., Hegseth, E. N. & Hop, H. 1999: Spatial distribution and life cycle timing of zooplankton in the marginal ice zone of the Barents Sea during the summer melt season in 1995. *Journal of Plankton Research 21,* 1249-1264.

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18. Falk-Petersen, S., Sargent, J. R., Kwasniewski, S., Gulliksen, B. & Millar, R. -M. 2001: Lipids and fatty acids in *Clione limacina* and *Limacina helicina* in Svalbard waters and the Arctic Ocean: trophic implications. *Polar Biology 24,* 163-170.

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27. Mauritzen, M., Derocher, A. E. & Wiig, Ø. 2001: Space use strategies of female polar bears in a dynamic sea ice habitat. *Canadian Journal of Zoology 79,* 1704-1713.

28. Mauritzen, M., Derocher, A. E., Wiig, Ø., Belikov, S. E., Boltunov, A., Hansen, E. & Garner, G. W. 2002: Using satellite telemetry to define spatial population structure in polar bears in the Norwegian and western Russian Arctic. *Journal of Applied Ecology 39,* 79-90.

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37. Scott, C. L., Kwasniewski, S., Falk-Petersen, S. & Sargent, J. R. 2000: Lipids and life strategies of *Calanus finmarchicus, Calanus glacialis* and *Calanus hyperboreus* in late autumn, Kongsfjorden, Svalbard. *Polar Biology 23,* 510-516.

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Hansen, E. H. & Nøst, O. A. The Western Barents Sea polar front zone.

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Okolodkov, Y. B. 1997: Biodiversity of algae in the sub-ice and marginal ice zone (MIZ) assemblages in the Siberian seas and the Barents Sea. *The Gordon Research Conference on Sea Ice Ecology*. Ventura, California, USA, March 2-7 (Poster).

Pavlov, V. K. & Pavlova, O. 1998: Modeling of the thermohaline water circulation and trajectories of transport of long-life pollutants from possible sources in the Barents Sea. *Proceedings of the 1st International Workshop on the Barents Sea Impact Study (BASIS)*. AARI, St. Petersburg, Russia, Feb 22-25 1998 (Oral presentation).

Søreide, J.E., Hop, H., Falk-Petersen, S., Gulliksen, B. & Hansen, E. 2002: Macro-zooplankton - indicators of water masses in the northern Barents Sea. *Carbon Flux and Climate Change: The Nordic contribution to a panarctic perspective (NARP)*. Sigulda, Latvia, Nov 1-7 (Poster / presentation).

Public relations

Interviews

- Interview with Nordlys and Tromsø after naming of *Protoperidinium falk-petersenii.*
- Interview in Finnmark Dagblad (03.08.00).

TV and radio programmes

- Interview on NRK-P1 (04.07.95).
- Interview on NRK-P2 "Verdt å vite" (23.08.00 and 05.09.00).
- Bäsemann, H. 1995. Gift in der Arktis. TV-film, 9 min. Nordeutscher Rundfunk.
- TV- programme NRK-1 "Schrødingers Katt" (12.10.00), also sent on TV in Denmark.
- Interview on NRK-P1 "Naturens verden" (June 2001).
- Interview on NRK-P2 (25.09.02).

Exhibitions / photographer

- Professional photographers on cruises: Hinrich Bäsemann 1995 'Lance', 1999 'Jan Mayen'; Werner Hannappel 2000 'Lance'.
- Photo exhibition at UNIS (Sept 2000) " The ice edge - about the marine biological investigation in the marginal ice zone" by Hinrich Bäsemann.
- Photo exhibition at "Galerie Michele Chomette", Paris, "Arctic sealevel" by Werner Hannappel (2000).
- Slides show at "Science days" at UNIS about "The ice edge" (Sept 2000).
- The rich forests and fauna of icy seas – new perspectives from diving in the Arctic. Svalbard seminar, with slides and underwater video, for the people of Longyearbyen (Feb 2002).

Journals

New information about life at the ice edge. Article (2 pp.) about the project in Braathens´ Inflight Magazine "På Norske Vinger", 1, 2000.

- Polar bear eating ringed seal. Cover photo by H. Hop for Natur & Miljø Bulletin 1-2, 2000.
- Hop, H. 2003. Productive but short. Non-fish food chains in the Marginal Ice Zone of the Barents Sea. Polar Research in Tromsø 2003.

11 Institutes, participants and students

Institutes

Arctic and Antarctic Research Institute, St. Petersburg (AARI)

Norwegian Polar Institute, Tromsø (NPI)

Norwegian College of Fishery Science, Tromsø (NFH)

Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland (IOPAS)

University of Stirling, United Kingdom (UoS)

University of Tromsø (UoT)

Akvaplan-niva, Tromsø (APN)

Participants

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Dmoch, Katarzyna (IOPAS)

Engelsen, Ola (NPI)

Engen, Frode (NPI)

Falk-Petersen, Stig (NPI)

Fossan, Kristen (NPI)

Gabrielsen, Geir Wing (NPI)

Goodwin, Harvey (NPI)

Hansen, Edmond (NPI)

Hauser, Adrian (NPI)

Hop, Haakon (NPI)

Ivanov, Boris (AARI)

Jacobsen, Torbjørn (NPI)

Løyning, Terje Brinck (NPI/UiO)

Karlsen, Tor Ivan (NPI)

Kwasniewski, Slawek (IOPAS)

Kulakov, Mikahel (AARI)

Nøst, Ole-Anders (NPI)

Pavlov, Vladimir (NPI)

Pavlova, Olga (NPI)

Poltermann, Michael (NPI)

Sargent, John (UoS)

Seim, Bjørnar (NPI)

Støen, Ole Gunnar (NPI)

Vollen, Tone (NFH)

Wiktor, Jozwa (IOPAS)

Økland, Janne (NPI)

Students

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Dahl, Trine (NPI/UoT)

Dale, Kjersti (NPI/UoT)

Mauritzen, Mette (NPI/UiO)

Scott, Catherine (NPI/UoS)

Stuily, Alexei (UiB)

Søreide, Janne (NPI/UoT)

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NORSK POLARINSTITUTT, TROMSØ 2004