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Climate change and effects on the Barents Sea marine living resources

15th Russian-Norwegian Symposium
Longyearbyen, 7-8 September 2011

Edited by
Tore Haug, Andrey Dolgov, Konstantin Drevetnyak,
Ingolf Røttingen, Knut Sunnanå and Oleg Titov

Institute of Marine Research - IMR
Polar Research Institute of Marine Fisheries and Oceanography - PINRO

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December 2011

Preface

The traditional Russian-Norwegian Symposium was held at the UNIS (University Studies at Svalbard) in Longyearbyen, Svalbard (Spitsbergen), during the period 6-9 September 2011. A total of 53 participants attended the symposium which included 3 opening addresses, 4 keynote talks, 31 oral presentations and 13 posters.

The symposium was the 15th in a series of joint Russian-Norwegian symposia which started in 1983. Up to 1999, these symposia were attended mainly by scientists from IMR and PINRO. From 1999 on, a broader scope has encouraged attendance also from fisheries management and fishing industry. At the meeting in Longyearbyen, the prime scope of the symposium was: "*Climate change and effects on the Barents Sea marine living resources*". Contributions were organized under three theme sessions: I) What are the changes?; II) What effects can be expected on the ecosystem?; III) Management implications and challenges.

This gave participating scientists from IMR and PINRO good opportunity to address question related to long and short term variations, and ask what these physical changes really are, and how they may protrude into the future. Furthermore, the question is raised as to how these assumed climate driven physical changes may change the ecosystems, and what implications and future challenges this represents for the management of the resources in the area. Also other institutions in Norway and Russia were invited to give presentations at the meeting.

It was evident that several presentations had a content and quality that would merit more than merely printing in the traditional Proceedings, and 13 of these were selected for potential inclusion in a thematic issue of the journal Marine Biology Research (MBR). Consequently, a special issue of this journal will be published by the end of 2012 or early in 2013.

These proceedings from the 15th Norwegian-Russian Symposium on climate change and effects on the Barents Sea marine living resources, held in Longyearbyen in 2011, contains the written contributions from all participants. Some are comprehensive, others are just extended abstracts (e.g., the 13 presentations selected for publications to Marine Biology Research). The Power Point presentations from all contributors are included as pdf-files on the enclosed CD. Both the proceedings and the PP presentations are available on the IMR website, www.imr.no. As for earlier symposia, the contributions have not been subject to peer reviews. The editors are responsible for a few modest editorial changes for which it has not been possible to obtain the authors' approval. The editors are also indebted to Hugh M. Allen for correcting and improving the English text.

Tromsø/Bergen/Murmansk December 2011
Tore Haug, Andrey Dolgov, Konstantin Drevetnyak, Ingolf Røttingen, Knut Sunnanå, and Oleg Titov

Table of Contents

Opening adress

Ole Arve Misund
Institute of Marine Research, Bergen, Norway

Dear Colleagues, Ladies and Gentlemen
Welcome to the 15th Norwegian – Russian Symposium here at the University Centre, UNIS, in Longyearbyen, Svalbard. This symposium is number 15 in a series of joint Norwegian – Russian symposia on fisheries research with the development of our common living marine resources in the Barents Sea as our common starting point. The scientific and management cooperation for sustainable fisheries and harvest of the living marine resources in the Barents Sea has been there for more than 50 years, and now we have a proper borderline between our nations in the Barents Sea also, and therefore an even better framework for our cooperation.

The topic this time is very relevant; on how climate changes have effects and may have effects on the living marine resources in th Barents Sea. Changes of the climate are evident through many signals, and it is our role as scientists to observe, describe, model, forecast, and not at least to communicate our findings so society has the possibility to decide and take the right measures. Still we see examples that leaders in the society seem to ignore what is going on as the Director of the Norwegian Oil Company who claimed recently that we should concentrate on people's lives today, and not on how the weather might be many years ahead. Our Minister of Environment replied that there is no wonder that young people were difficult to recruit to the oil industry since companies were led by such self-declared idiots!

So, we are definitely focusing on an important subject. I look forward to the many presentations and posters, and in due time to read (or at least to see) the publications which hopefully will come from this event. Good luck!

Thank you!

Photo: Havforskningsinstituttet, Monika Blikaas

Opening adress

Ole Jørgen Lønne
UNIS, Longyearbyen, Norway

Ladies and Gentlemen
It is a pleasure for me, on behalf of your local host, to welcome you all to The 15th Russian-Norwegian Symposium in Longyearbyen, Svalbard. I find it only natural that one of the two most influential scientific institutions working in the high arctic, PINRO from Russia and IMR from Norway, meet on this island where Russians and Norwegians have been working side by side for so many years.

The University Centre in Svalbard, or UNIS for short, is proud to be the host of such an important meeting. UNIS is a limited company, owned by the Ministry of Research and Higher Education and the world's northernmost higher education institution. We were established in 1993 to provide university level education in Arctic studies. The aims of UNIS are to provide a range of studies and engage in research based on the unique geographical location of Svalbard in the High Arctic, exploiting the special advantages that this offers from use of the natural environment as an outdoor laboratory and arena for scientific observations, data acquisition and analytical review. This year we offer 44 high quality courses at the undergraduate, graduate and postgraduate level in Arctic Biology, Arctic Geology, Arctic Geophysics and Arctic Technology. We provide courses complementary to the teaching given at the mainland universities within a structured program on the bachelor, master and doctoral level.

About 350 students from all over the world take one or more courses every year at UNIS. The student body consists of 50 % Norwegian and 50 % international students. This year 5% of our students are from Russia. Faculty are made up by 50 % Norwegians and 50 % international staff, and consist currently of 20 full time professors, 21 adjunct professors and 120 guest lecturers who specialize in arctic issues. With students, staff and families we are about 15 % of the population in Longyearbyen. UNIS researchers work in collaboration with Norwegian and foreign research institutions and are actively involved in a large number of joint research projects.

We moved into this building in 1995. The new part of the building was opened in 2006 to house the Svalbard Science Centre. UNIS is the core of the Svalbard Science Centre, which also is the home of the Svalbard Museum, the Norwegian Polar Institute, Svalbard Science Forum, EISCAT, the Governor's Heritage Magazine and others. The 12 000 square meter science centre is a modern building with optimal conditions for studying and research linked to arctic nature and the greatly expanded volume will facilitate the continuing strong development of education and research at UNIS.

The biology department consists of one marine and one terrestrial research group. The marine research group consists of three faculty members, two Postdocs and three PhDs that work together on joint research programs. In particular we seek to link biodiversity with ecosystem function, aiming to identify the main physio-biochemical factors that determine the ecology of various arctic organisms. We use a combination of molecular and traditional techniques to investigate marine microbes, zooplankton life histories, ice-associated flora and fauna, as well as the ecology of marine organisms during the polar night.

Longyearbyen is the only place in the world where you can find a well-established community, with a well-developed infrastructure and very good possibilities for communication with the rest of the world as far north as 78ºN. We have an international connection through daily departures from the airport, open harbor half the year and telecommunications including high speed internet access through fiber-optic cables. In total we think we have a truly international meeting place for the arctic experts of today and the arctic experts tomorrow.

It is my wish that you find this setting as inspirational as we do, and that this will contribute a successful meeting. Again it is my pleasure to welcome you all to Longyearbyen, to UNIS and that this meeting will be a great success.

Photo: Eva Therese Jensen

Figure 1. The University Centre in Svalbard (UNIS); Venue for the 15. Russian-Norwegian Symposium on Climate change and effects on the Barents Sea marine living resources.

Opening address

Yuri Lepesevich
Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Murmansk,Russia

Dear Colleagues, Ladies and Gentlemen
I am pleased to greet the participants of the 15th Norwegian-Russian Symposium on Spitsbergen. This Symposium represents an example of close international cooperation in general and successful Russian-Norwegian cooperation in particular. In the first place, I would like to express my appreciation to the hosting party for an opportunity to say a few words before the opening of the symposium.

First of all, I cannot but highlight the exoticism of the venue. A special thanks for it to the hosts. It is my first time being here and I hope not the last one. At any rate, a matter of establishing an affiliate of our institute on Spitsbergen is being seriously discussed in Russia on the governmental level. Though I have not seen much of Spitsbergen, I would like to say that severe nature and muted colours of the Arctic can stagger your imagination none the worse than the bright colours in jungles. This Symposium is unique because it is simultaneously being held in three places – international Spitsbergen, Norwegian Svalbard and Russian Grumant.

Now I would like to speak about the event for which we have gathered here. Since the fisheries is a primary matter of interest for us I cannot but remind you once more again about the favourable background for our symposium. The haddock stock in the Barents Sea is at its highest recorded historical peak, abundance and biomass of cod is the highest in over 40 years, Greenland halibut stocks have increased to the level recorded in the beginning of the 1970s and are almost two times higher than the long-term mean. It is expected that total quota amounts for cod, haddock and Greenland halibut will be the highest since the time of introducing quota setting. Capelin and saithe stocks are in stable shape.

I am talking about the current state of fisheries in the Barents Sea because I am sure that not only the warming of the Barents Sea which started at the end of the 1980s contributed to the good status of the stocks but also the fruitful work of scientists from Norway and Russia including the work carried out in the frames of joint symposia.

A history of arranging Russian-Norwegian symposia dates back several decades. Since 1983, the most interesting and burning problems related to fisheries research in the Barents Sea have been traditionally discussed at joint symposia. The considerable warming in the North, including the Barents Sea, has been reported over the recent 10-15 years. The warming resulted in substantial changes in the distribution and abundance of all the components of marine ecosystems, i.e. plankton, benthos, fish species, marine mammals and birds. Thus, climate variations directly affect the interests of fishing industries both in Russia and Norway. Therefore, a decision was made to assess, at the 15th Symposium, the impact of climate variations on some species, interspecific relationships and the Barents Sea ecosystem in general and on how this may affect multi-species fisheries in this area.

I am sure that this symposium will make a considerable contribution to the further development and strengthening of cooperation between Norway and Russia and will offer a possibility to discuss the most challenging problems of the Barents Sea and will allow us to look into the future for a little while. As Russia and Norway conduct the most intense scientific and fisheries research in the Barents Sea, it is the scientists from IMR and PINRO who have greater responsibility for creating favourable conditions for fishermen from both countries and providing a scientific basis for sustainable fisheries in the Barents Sea.

As the previous speakers, I wish all of us fruitful work, scientific discoveries, successful presentations, and interesting reports, as well as practical use to our fishermen. And at off-duty time - interesting meetings with the colleagues, good and interesting pastime, getting to know the severe and beautiful nature of the Arctic.

Photo: Havforskningsinstituttet, Monika Blikaas

Theme session I: What are the changes?

1.1 Arctic surprises: Sea ice loss and increased Arctic/Sub-Arctic linkages

James E. Overland
Pacific Marine Environmental Laboratory, NOAA, Seattle, WA, USA

Recent data over the last decade show an Arctic wide temperature increase consistent with model projections of global warming rather than showing regional warming patterns which would have been caused by natural variability as occurred in previous Arctic warming episodes such as the 1930s.

While a major surprise was the nearly 40% loss of September sea ice extent in 2007, the major change is that in every year since then sea ice has been below 30% and that much old, thick sea ice has disappeared. Extensive forest fires are another major Arctic change. These shifts seem to be rapid and occurring 20-30 years earlier than expected by steady processes in climate forecast models. Perhaps several Arctic feedbacks are kicking in?

Even though Arctic temperatures and the average temperatures of the Northern Hemisphere have increased over the last decade, this does not mean that temperatures smoothly increase in all regions at the same rate. For example, increased north-south (meridional) winds coming out of the Arctic in late autumn and early winter 2005, 2008, 2010, but especially 2009 brought record cold and snow conditions to northern Europe, eastern Asia and eastern North America.

The Arctic is normally dominated a very stable “Polar Vortex” of counter-clockwise circulating winds surrounding the North Pole which traps the cold Arctic air mass at high latitudes. However, during early winter of 2009-2010 the Polar Vortex weakened due to higher geopotential heights over the Arctic, allowing cold air to spill southwards and be replaced by warm air moving poleward, a *warm Arctic –cold continent* climate pattern. One indicator of a weak Polar Vortex is the North Atlantic Oscillation (NAO) index which in December 2009 through February 2010 had its most negative value (weak vortex) in 145 years of record.

Meteorological attribution to these sub-Arctic events is difficult. Certainly random chaos in the development of weather patterns can produce such extreme events. There is a potential impact, however, from Arctic regions where heat stored in the ocean in sea-ice-free and thin ice areas has been released to the lower atmosphere during autumn. One would not expect a sub-Arctic impact in every year or the in the same locations every year. The Barents Sea seems to be part of the Arctic wide warming pattern, while northern Europe is in the sub-Arctic high climate variability zone.

Relevant reference:

Overland, J.E. 2011. Potential Arctic change through climate amplification processes. Oceanography 24(3):176–185, http://dx.doi.org/10.5670/oceanog.2011.70.

Photo: Havforskningsinstituttet, Monika Blikaas

1.2 On drifting ice to the North Pole

Salve Dahle
Akvaplan-niva, Fram Centre, Tromsø, Norway

On 21 May 1937, the world was schocked by the news that a Russian plane had landed on the North Pole and Russia had established a research station on a drifting ice floe. The research team, "The Famous Four" (Papanin, Shirzov, Fjodorov and Krenkl), drifted for almost a year across the Polar Ocean and into the Fram Strait before their camp, and the ice floe it was built upon, inevitably melted into the Greenland Sea. At the last minute, the research team was evacuated during in a dramatic rescue operation by Russian icebreakers. The Severnya Polus (Northern Pole) 1 was the first of 31 research stations on drifting ice during the years 1937 to 1991.

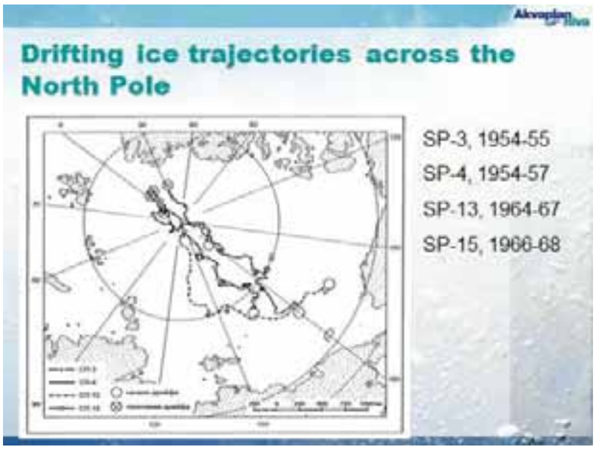
The Russian research programme on drifting ice through the Polar night is one of the most extensive polar explorations ever taken on. At the time, the Polar Ocean was unknown territory: no major research had been carried out since Nansen's famous drift across the Polar Ocean with "Fram" during 1893-96. During the Russian program, the bottom topography was mapped, establishing the fact that the Polar Ocean really was a deep sea with transcontinental subsea mountain ranges. The thickness, origin and drift patterns of sea ice were recorded, making the Russian researchers to be the first to document variations in ice drift across the Polar Ocean due to location of the dominant high pressure centre. These centres tended to change location after a period of years, with the result being periods of strong transpolar drift alternating with periods of weak drift and a strong Beaufort gyre. These observations have later been confirmed by satellite measurements and are important for understanding the distribution of ice in the Polar Ocean in the current period of warming climate. The research teams on the drifting ice also studied the ocean currents, the origin of water masses in the Polar Ocean, as well as their vertical distribution across the Arctic. This information became important for Russian submarines in their cat-and-mouse game with US submarines during the 1960s and later. Meteorological measurements were carried out establishing the first weather forecast including observations from the Polar Ocean, magnetic observations confirmed that there was only one magnetic North Pole, and the biology of the Polar water and the ice itself was studied in depth for the first time

The achievements of the research teams manning the ice floes is hard to evaluate in our modern time with well-developed scientific infrastructure, satellite communication systems and modern rescue teams. Especially during the first years, the challenges were harsh, scientific efforts were hampered by poor equipment, and the cold war interfered with exploration. During these early years the Polar Drift stations were secret, and had to manage totally on their own if accidents should occur. And all the time they had to live in a situation where their camp could break up in the middle of the winter night during stormy weather and minus 40 degrees C. Food and equipment, and even colleagues, could end up in the icy water at any minute during these storms.

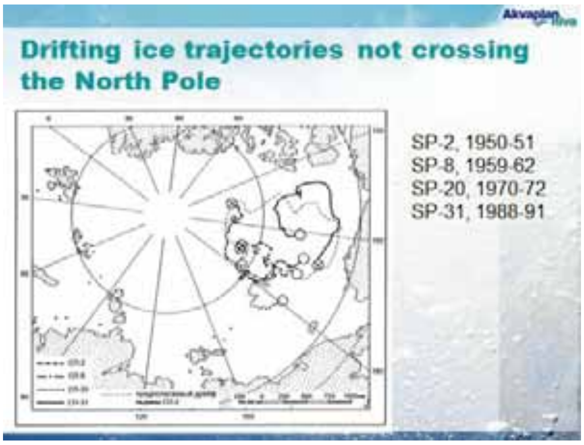
But this was also the period of Soviet Union, which further added to the achievements of these polar pioneers. Politics led to events which today we can find tragic, and others we can find amusing. The wife of Shirzov was a famous artist, and she died in a concentration camp at Kolyma while her husband was celebrated as a hero in Moscow. Krenkl, the telegraphist during the very first ice drift station, had to leave the tent while the three others discussed the messages from Moscow. He was not a member of Communist party while the three others were. When decision was reached, he was called into the tent to send their answer to Moscow. Clearly the true, but largely unknown, pioneers of Polar Research should be celebrated for their immense contribution to science despite the extreme hardships of the natural and human worlds.

Acknowledgment

With courtesy to Alexander Ugryomov and Vladimir Korovin who made the Russian version of this story, and to Arctic and Antarctic Research Institute who opened their archive of pictures and reports from the ice drift stations. Thanks also to Statoil and Fram Foundation that financially supported the project.


Drifting ice trajectories across the North Pole

SP-3, 1954-55
SP-4, 1954-57
SP-13, 1964-67
SP-15, 1966-68


Drifting ice trajectories not crossing the North Pole

SP-2, 1950-51
SP-8, 1959-62
SP-20, 1970-72
SP-31, 1988-91

The main camp, Severnaya Polus 1

The Famous Four: Fjordorov, Papanin, Shirzov and Krenkl

1.3 The Barents Sea – Arctic Ocean gateway: Water mass characteristics and transformations

Vidar S. Lien[1] and Alexander G. Trofimov[2]
[1]*Institute of Marine Research, Bergen, Norway*
[2] *Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Murmansk,Russia*

Dense water masses produced at high latitude shelves play and important role in the world oceans thermohaline circulation. The Barents Sea is the largest shelf sea surrounding the Arctic Ocean and host several dense water formation sites, with the most notable being the Novaya Zemlya Bank. Two processes contribute to form dense water, and both occur within the Barents Sea: *i*) direct atmospheric cooling and *ii*) salinization through ice freezing and subsequent brine rejection.

Inflow of relatively warm and saline Atlantic Water to the Arctic Ocean follows the Norwegian coast northwards, but splits into two main branches at the entrance to the Barents Sea. One branch continues northwards along the western coast of Spitsbergen and enters the Arctic Ocean through the Fram Strait. The other branch flows through the Barents Sea and enters the Arctic Ocean through the St. Anna Trough. North of Spitsbergen, the Fram Strait branch submerges below the cold halocline in the Arctic Ocean, which effectively insulates the heat from the overlying cold atmosphere. In the Barents Sea, however, the oceanic heat is to a large degree lost to the atmosphere. Hence, the two branches have different fates within the Arctic Ocean.

Based on an extensive array of CTD (Conductivity-Temperature-Depth) measurements covering the northeastern Barents Sea and the St. Anna Trough, the hydrographic properties of the Barents Sea branch are investigated. The observations reveal the presence of both branches of Atlantic derived water masses in the St. Anna Trough. However, they show opposite temporal patterns in temperature, despite their common source, which points to the importance of regional processes in determining their characteristics. Furthermore, the measurements show a substantial modification of the Barents Sea branch, and the end product observed downstream in the Arctic Ocean, termed Barents Sea Branch Water, comprises a wide range of densities, and the densest part has the potential to cascade down to at least 2000 m depth in the Arctic Ocean. Hence, the Barents Sea may be an important source of water masses ventilating the deep water masses of the Polar Basin.

Due to the substantial atmospheric cooling, the Barents Sea may not be considered as a source of oceanic heat for the Arctic Ocean, if one uses a common reference temperature of -0.1 degrees Celsius for the water masses leaving the Arctic Ocean through the Fram Strait. A comparison with older data reveals variations between years regarding formation sites of dense water, which impacts the characteristics of the Atlantic Water and the interannual variability therein.

1.4 Barents Sea climate variability during the last decade

Randi Ingvaldsen, Harald Loeng and Sigrid Lind
Institute of Marine Research, Bergen, Norway

Since the 1970s there has been observed a general warming in the Barents Sea, although since 2006 the temperature has decreased (Figure 1-left panel). Strong temperature increase has been observed in the boundary areas where Atlantic Water enters (Figure 1-right panel), and the largest increase (1.5°C) has taken place in the northwestern Barents Sea where Atlantic Water enters from the north. Compared to the 1990s, the strongest increase during the 2000s has occurred in the subsurface water masses connected to the Atlantic Water inflow (Lind and Ingvaldsen, subm).

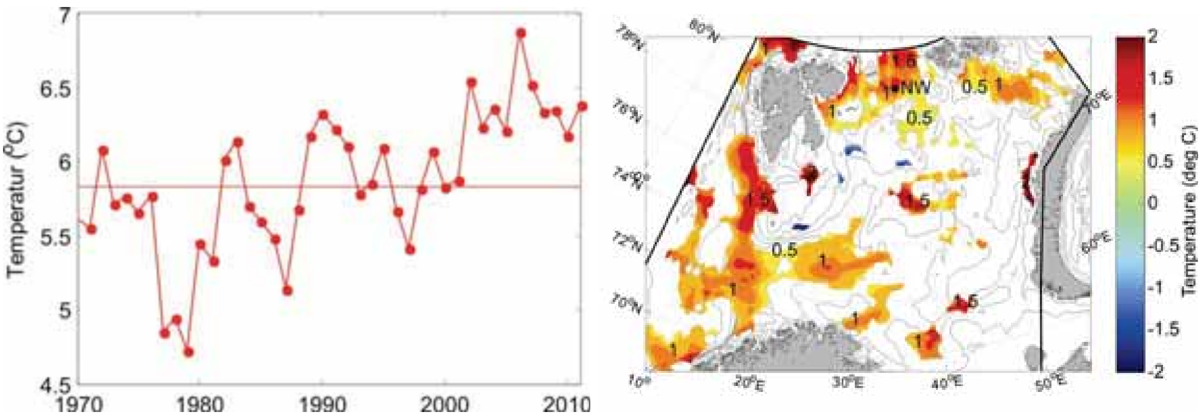


Figure 1. Left panel show mean temperature in the Atlantic Water at the western entrance to the Barents Sea (the Fugløya-Bear Island section). Right panel shows the linear temperature increase over the period 1970-2009 where there is a real (statistical significant) trend. The right figure is taken from Lind and Ingvaldsen (subm).

Associated with the warming in the last decade the area of Atlantic water masses has expanded and the area of Arctic Waters decreased, both making the warm part of the Barents Sea larger and the cold part smaller (Dalpadado et al., subm).

There has also been a large reduction in winter ice cover (Figure 2), although with interruptions of years with close to ”normal” ice conditions like in 2003. In the warmest years, most of the Barents Sea was ice-free also during winter. The years with minimum winter ice was 2007-2008, 1-2 years after the year of maximum temperature (2006). This 1-2 yr lag is well-known and is due to heat storage in the Barents Sea.

This presentation review and document some of the changes that have occurred in the Barents Sea during the last decade. The reason for these changes is high temperatures in the Atlantic Water flowing into the Barents Sea, and changes in the large scale atmospheric fields.

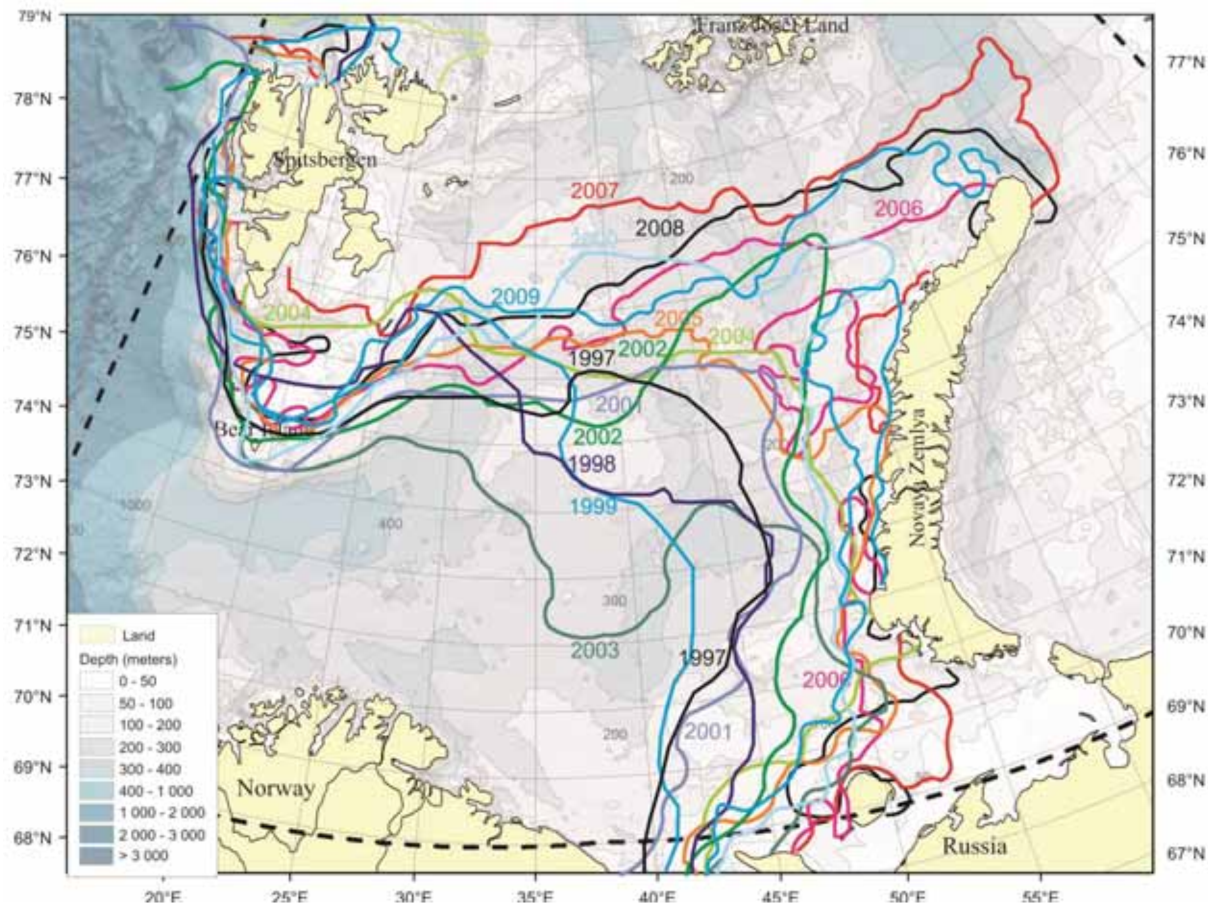


Figure 2. Observed changes in winter ice cover. The colored lines show ice edge (40 % concentration) in late winter, 1997-2009.

References

Dalpadado, P., Ingvaldsen, R.B., Stige, L.C., Bogstad, B., Knutsen, T., Ottersen, G., and Ellertsen, B. Climate effects on the Barents Sea ecosystem dynamics. ICES journal of marine systems, submitted.

Lind, S., and Ingvaldsen, R.B.Variability and impacts of Atlantic Water entering the Barents Sea from the north. Deep-Sea Research, in review.

Photo: T.d.L. Wenneck, Institute of Marine Research

1.5 Climate trend forecast for the Norwegian and Barents Seas in 2012–2025

B.N. Kotenev, A.S. Krovnin, and S.N. Rodionov
Russian Federal Research Institute of Fisheries and Oceanography (VNIRO,Moscow, Russia

Abstract

The shift in the climatic regime in the late 1980s was accompanied by a switch in the leading large-scale modes of the atmosphere-ocean coupling in the Northern Hemisphere, with predominance of the positive NPGO and AMO phases in the North Pacific and North Atlantic, respectively, during the 1990s and 2000s. This resulted in prominent warming in the western North Pacific and Northeast Atlantic, including the Norwegian and Barents Sea. It is difficult to answer the question of how long the current climatic regime will continue. However, analysis of factors that influence climate variability in the global geophysical system (atmosphere, ocean, Earth, Sun, Moon, large planets) indicates a change from a warming trend to a cooling one has taken place during the past 2-3 years. There is a possibility that in the course of the next 10-20 years the climatic regime in the Northeast Atlantic, including the Norwegian and Barents Seas, will be similar to that of the 1950s (1956-1958) and 1960s (1963, 1965-1969).

Keywords: North Atlantic, Norwegian Sea, Barents Sea, climatic trend, climatic regime, solar activity, Earth's rotation velocity

Introduction

Many studies have confirmed the close connections between climatic regimes and marine bio- and fish productivity. The climatic regime shifts are often accompanied by significant changes in these relationships, whose sign may even change. Therefore, when developing decadal forecasts of the state of fish stocks, it is important to know whether the existing regime with its characteristic trend in climatic parameters will continue in the future.The problem of climatic regime transitions has been widely discussed recently in the literature (Overland et al. 2008; Rodionov 2002, 2004; Kotenev and Rodionov 2009; etc.).

In considering this problem, the position of the researcher regarding the factors that determine the prominent warming trend that we have observed during the past 20 years is a priority. Today, there are three versions of its genesis: (1) the trend is associated with natural multi-decadal variability; (2) it is due to an increase in the level of anthropogenic CO_2 in the atmosphere, and will continue for the next hundred years (IPCC 2007); (3) the trend will continue under the influence of anthropogenic CO_2, but its intensity may vary under the influence of natural decadal and multi-decadal fluctuations (Loeng 2011).

The main purposes of this paper are: (1) to consider the current climatic trend in relation to change in the dominant large-scale atmosphere-ocean patterns in the northern hemisphere since the climatic shift in winter 1988/1989; (2) to review briefly the dependence of decadal climatic variability on the natural factors inherent in the global geophysical system: atmosphere – ocean – the Earth – the Sun – the Moon – large planets, which are indicative of the change.

Data and methods

Monthly mean SST values in the North Atlantic (20-65ºN) and North Pacific (20-55ºN), and geopotential heights on the 500-hPa surface for the 1957-2010 period were used as a basis for the study. The SST data at 5º x 5º grid points were taken from the Russian Hydrometeorological Centre, and those on geopotential heights are available from the National Center for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) Global Reanalysis (Kalnay et al. 1996) at http://www.esrl.noaa.gov. This site also provides monthly means of a number of climatic indices (NAO, AMO, PNA, PDO, etc.), which were also used in the paper.

The empirical orthogonal function (EOF) of the joint mean winter (January-April) sea surface temperature anomaly (SSTA) field in the North Atlantic and North Pacific were computed with the use of software developed by David W. Pierce (Climate Division Scripps Institution of Oceanography) (available online at http://meteora.ucsd.edu/~pierce/eof/eofs.html) and modified by G.P. Moury (VNIRO). The anomalies were calculated relative to the 1971-2000 long-term mean. The principal component analysis of climatic time series was carried out using JACKIE software available online at http://life.bio.sunysb.edu/morph/soft-mult.html.

Results and discussion

Large-scale climatic patterns in the northern hemisphere during 1957-2010

The last 60 years have seen two prominent climate regime shifts in the Northern Hemisphere in the winters of 1976/77 and 1988/89. Several studies have shown that the 1988/89 climatic shift was quite different from that of 1976/77. In particular, there were no prominent changes in indices of the North Pacific climate (PDO, NPI, etc.), while both the Icelandic Low and Azores High intensified in winter 1988/1989 and moved northeastwards in the early 1990s (e.g. Hare and Mantua 2000; Jung et al. 2003; Di Lorenzo 2008; Yeh et al. 2011).We therefore analyzed the dominant large-scale atmosphere-ocean patterns for two periods: prior to the 1988/89 regime shift (1957-1988) and after it (1989-2010).

1957-1988

The EOF1 of the joint mean winter SSTA field in the NA and NP for the 1957-1988 period explains 16.2% of the anomaly variance. In the North Pacific, it corresponds to the well-known Pacific Decadal Oscillation (PDO) pattern with opposite SSTA variations between the central and eastern regions of the Ocean (Figure 1a). Note also the weaker inverse relation of anomaly fluctuations between the northwestern and southwestern North Pacific. In the North Atlantic, the correlation pattern exhibits the AMO-like structure, representative of its negative phase. The EOF1 pattern was associated with the Pacific/North American teleconnection pattern (PNA) in the middle troposphere (Figure 1b), which was also responsible for the high coherence of SSTA fluctuations in the eastern North Pacific and the central eastern North Atlantic, as can be clearly seen in Figure 1a.

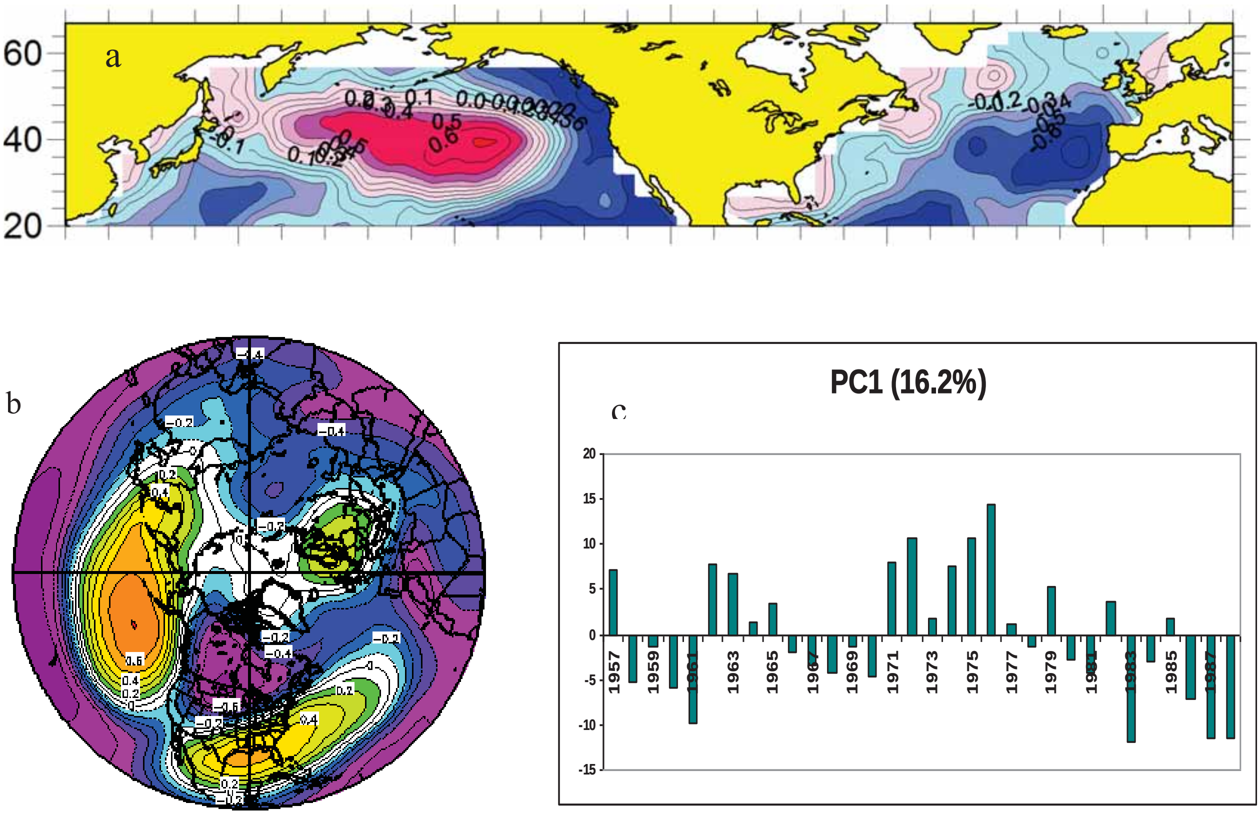


Figure 1. Correlation patterns between EOF1 PC of SSTA in winter and: a) corresponding SSTA field ; b) mean winter H500; c) EOF1 PC time series (1957-1988)

The above is confirmed by the results of cluster analysis carried out separately for each ocean for the period 1957-1991 (Krovnin, 1995) (Figure 2). In that time, there was a high positive relationship ($r=0.74$; $p<0.01$) between the eastern North Pacific and central North Atlantic regions (Regions 1P and 5A, respectively) (Figure 3a) which was realized through the PNA (Figure 3b, c). This teleconnection pattern also affected the NAO through its centers, which were located off the southeastern coast of North America and over eastern Canada as described by Dickson and Namias (1976); namely, by modification of trajectories of cyclones formed along the eastern border of the North American continent.

The time series of PC1 shows pronounced decadal variations in SSTA between 1957 and 1988, with shifts occurring in 1961/62, 1965/1966, 1970/71, and in the late 1970s (Figure 1c).

The EOF2 of the joint SSTA field (13.8%) in the North Pacific is characterized by opposite anomaly fluctuations between its southwestern and northeastern parts (Figure 4a). This pattern is similar to the EOF2 of Bond et al. (2003), also known as “Victoria mode”. Di Lorenzo et al. (2008) showed that this EOF was a component of a large-scale dynamic ocean mode of the North Pacific and reflects changes in the gyre circulation. They termed it the North Pacific Gyre Oscillation (NPGO).

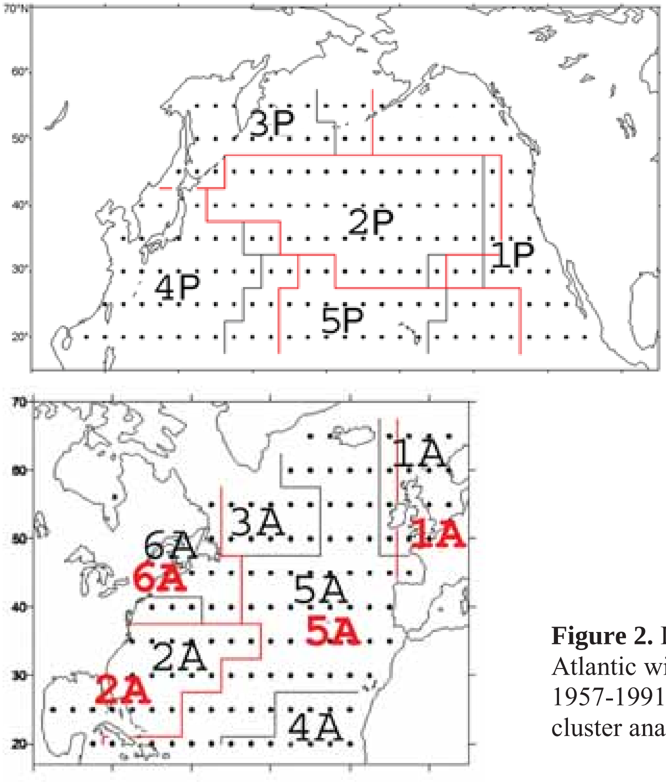


Figure 2. Large-scale regions in the North Pacific and North Atlantic with coherent fluctuations of mean winter SSTA: 1957-1991 (black lines); 1987-2007 (red lines). Results of cluster analysis for the SSTA field (Krovnin 1995).

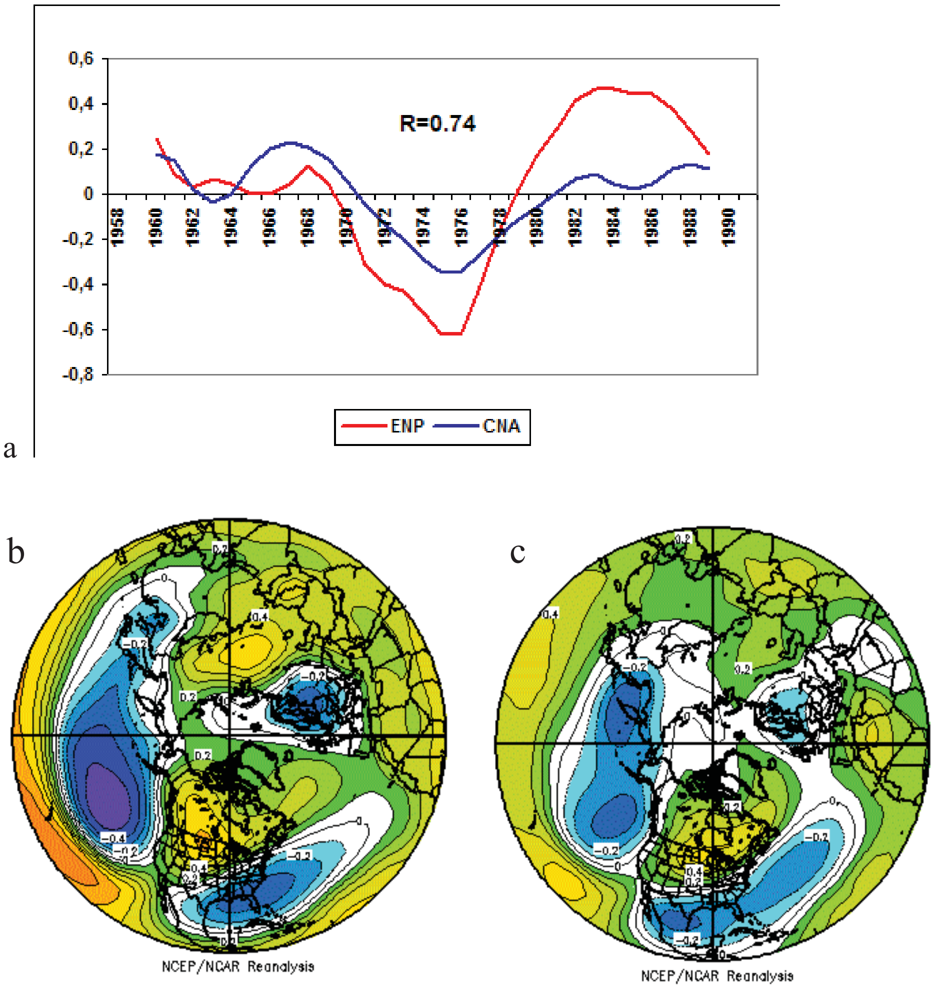


Figure 3. Association between the eastern North Pacific and central North Atlantic (1958-1991)

The pattern of correlations between PC2 and SSTA fields for most of the North Atlantic is characterized by weak positive correlations, except in the northeastern part, where they are higher than 0.60. Moreover, unlike EOF1, the relationship between the SSTA variations in the eastern North Pacific and North Atlantic is mainly negative.

The EOF2 pattern during this period was associated with the meridional dipole in the North Pacific with the extensive high-pressure cell in the subtopical zone centered at the dateline and low-pressure center over the Gulf of Alaska (Figure 4b). This dipole resembles the North Pacific Oscillation pattern described by Rogers (1981).

As Figure 4b shows, in the North Atlantic sector the atmospheric variability was shifted to the east, with a high-pressure center over northern Europe and a low-pressure domain with its axis along 40-45 ºN. Overall, the configuration and signs of the North Pacific and North Atlantic dipoles at the 500 hPa surface explain the significant positive correlation between the variations in SSTA in the southern North Pacific (Region 5P; Figure 2b) and Northeast Atlantic (Region 1A; Figure 2a) with r=0.68 (p<0.01).

The time series of PC2 demonstrates the longer decadal variations in SSTA, compared to PC1, with shifts in 1963/64, 1976/77, and 1987/88 (Figure 4c).

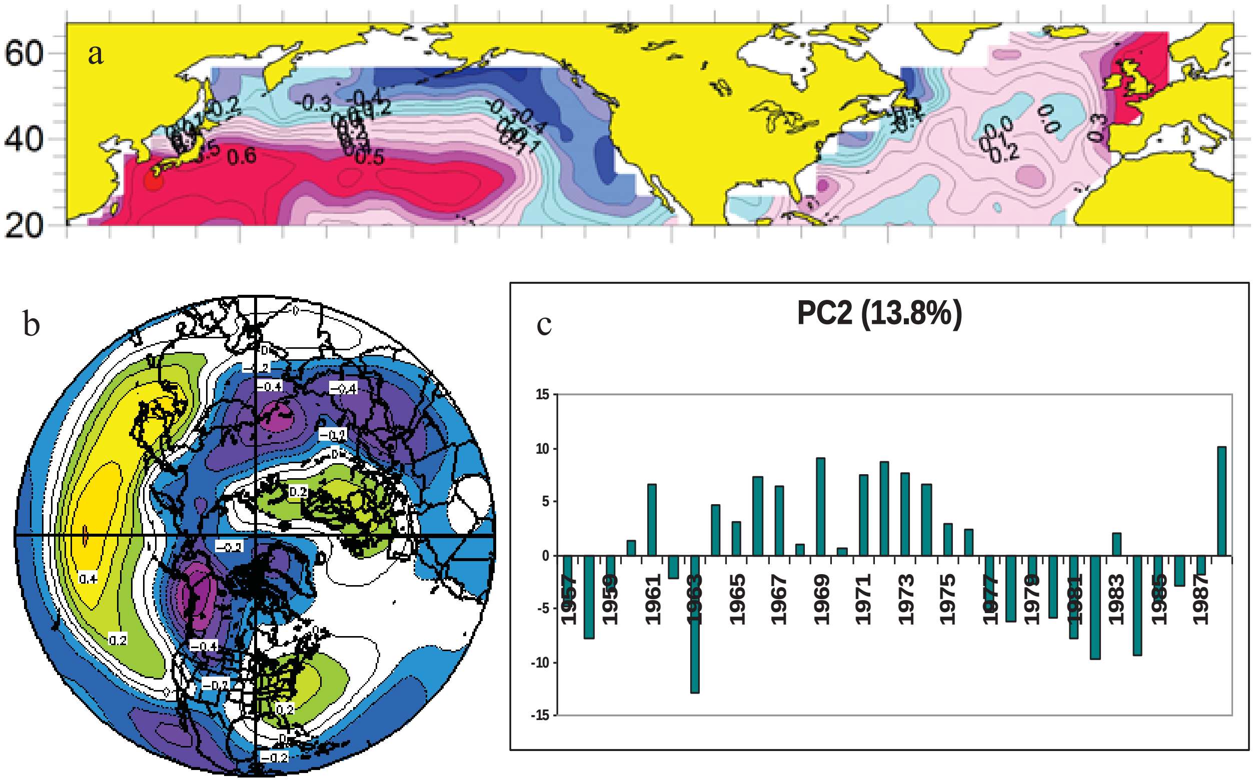


Figure 4. Correlation patterns between EOF2 PC of SSTA in winter and: a) corresponding SSTA field; b) mean winter H500; c) PC2 time series (1957-1988)

Table 1 shows the results of principal component analysis of 36 climatic variables in the northern hemisphere for 1957-1988. Loadings are the correlation coefficients between the time series of the corresponding principal component and time series of each variable. The three first components explained about 56% of total variance.

The first component (26.7%) was associated with the North Atlantic Oscillation ($r=0.78$ $p<0.01$). It is responsible for the four-pole structure of SSTA variations in the North Atlantic, when the fluctuations in the northeastern and southwestern parts of the Ocean are opposite to those in its northwestern and southeastern parts (Figure 5a-d). The correlation coefficient of the time series of this component and time series of PC1 for SSTA in Regions 1A-4A is -0.94 (see Table 1).

Table 1. Loadings on the first three principal components (PC) from a principal component analysis of the 36 mean winter climatic variables for the 1957-1988 period.

Variable	**PC1 26.7%**	**PC2 16.8%**	**PC3 12.2%**	**Variable**	**PC1 26.7%**	**PC2 16.8%**	**PC3 12.2%**
North Atlantic Oscillation	**0.78**	-0.37	-0.19	Tropical North Atlantic	-0.82	-0.29	-0.18
SLPA (Azores)	**0.72**	-0.36	-0.19	SSTA in Region 1A (NE Atlantic)	0.45	0.08	**-0.80**
SLPA (Iceland)	**-0.69**	0.16	0.40	SSTA in Region 2A (SW NA)	**0.76**	-0.21	-0.14
SLPA (Gibraltar)	0.46	-0.41	-0.50	SSTA in Region 3A (NWA)	**-0.80**	0.21	-0.18
Arctic Oscillation	**0.75**	0.16	-0.20	SSTA in Region 4A (SE NA)	**-0.84**	-0.21	-0.19
West Atlantic pattern	**-0.76**	-0.07	-0.09	SSTA in Region 5A (central NA)	-0.42	-0.37	**-0.65**
East Atlatic pattern	-0.10	0.15	0.15	SSTA in Region 6A (NFLND)	0.05	-0.04	-0.13
East Atlatic/West Russia pattern	0.01	0.28	-0.05	SSTA in Region 1P (eastern NP)	-0.27	**-0.75**	0.04
Scandinavia pattern	0.05	0.23	-0.06	SSTA in Region 2P (central NP)	0.07	**0.75**	-0.35
Tropical/NH pattern	0.45	0.29	0.29	SSTA in Region 3P (NW Pacific)	0.44	-0.10	0.31
Polar/Eurasia pattern	-0.13	0.37	0.08	SSTA in Region 4P (SW NP)	-0.18	0.10	**-0.75**
Pacific/North American pattern	0.09	**-0.79**	0.31	SSTA in Region 5P (southern NP)	0.09	0.00	**-0.58**
North Pacific Index	-0.06	**0.88**	-0.25	PC1 (NP and NA SSTA)	0.25	**0.84**	0.27
West Pacific pattern	-0.07	-0.17	-0.38	PC2 (NP and NA SSTA	0.12	0.35	**-0.74**
Southern Oscillation	0.23	**0.59**	0.19	PC3 (NP and NA SSTA	0.80	-0.25	0.28
Atlantic Multidecadal Oscillation	**-0.64**	-0.34	-0.33	Pacific Decadal Oscillation	-0.07	**-0.89**	0.29
Atlantic Tripole	**-0.82**	-0.22	-0.21	North Pacific Gyre Oscillation	0.29	-0.18	0.05
Tw (0-200 m) at Kola Section	0.44	-0.06	-0.40				

The structure shown in Figure 5 (a-d) corresponds to EOF3 of the joint SSTA field (not shown). In our opinion, the discrepancy between the results of EOF analysis and PCA is explained by the fact that the contribution of grid points associated with the four-pole structure is small, compared with that of grid points of PDO and AMO.

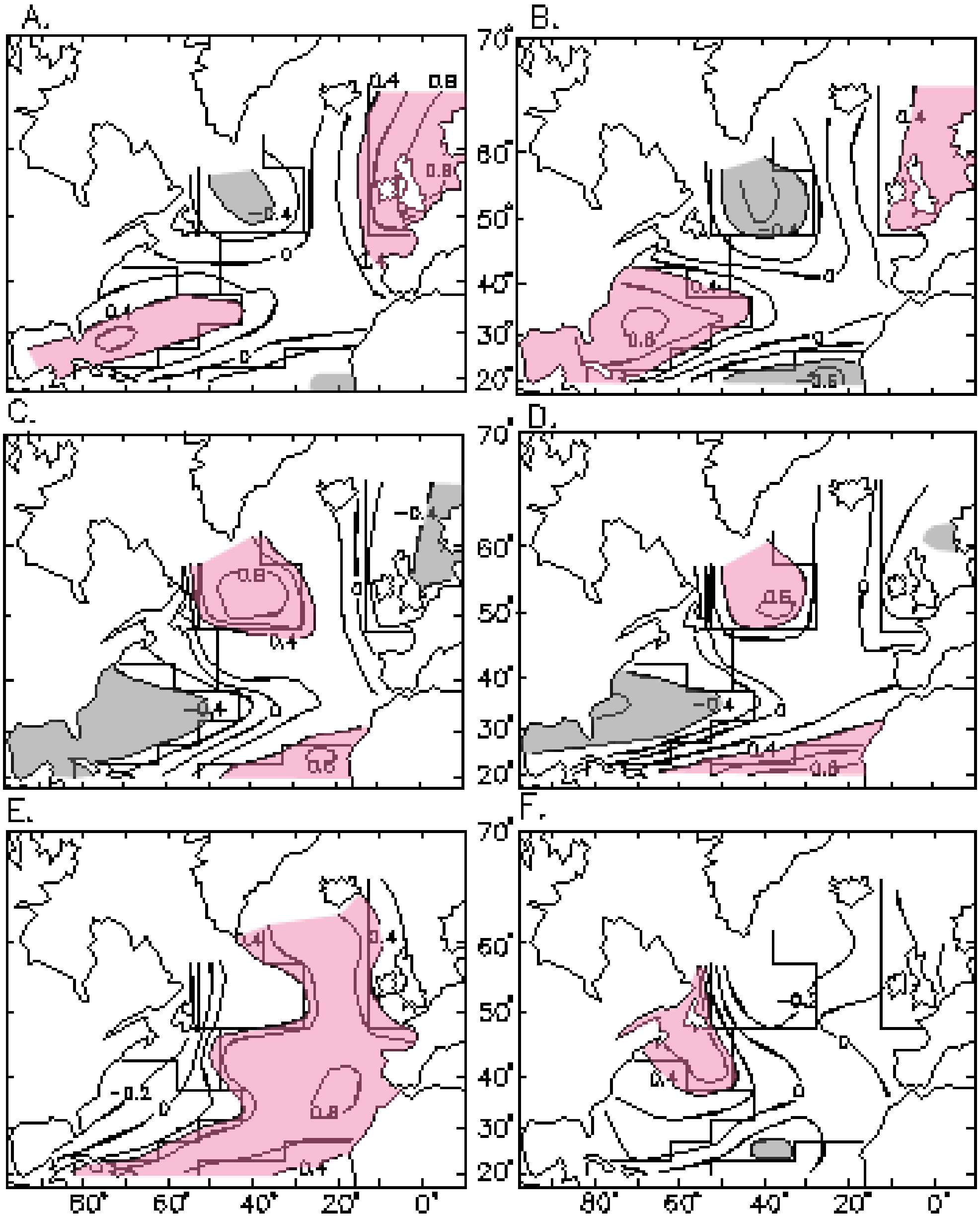


Figure 5. The four-pole structure of SSTA variations in the North Atlantic (1957-1991).

The PC1 of the 36 climatic time series shows the regime shifts in 1957/58, 1970/71, 1977/78, and 1981/82 (Figure 6a).

The PC2 (16.8%) was clearly associated with PDO and PNA, and corresponded to EOF1 PC of the joint SSTA field in the North Pacific and North Atlantic (r=0.84). For this PC the regime shifts were observed in 1962/63 and 1976/77 (Figure 6b).

The PC3 (12.2%) of 36 climatic variables was related to EOF2 PC (r=-0.74) of the SSTA field in both oceans and reflects the coherent sea-surface anomaly variations in the Northeast Atlantic and the southern-southwestern North Pacific. Its time series shows that the transitions occurred in 1975/76 and possibly in 1987/88 (Figure 6c).

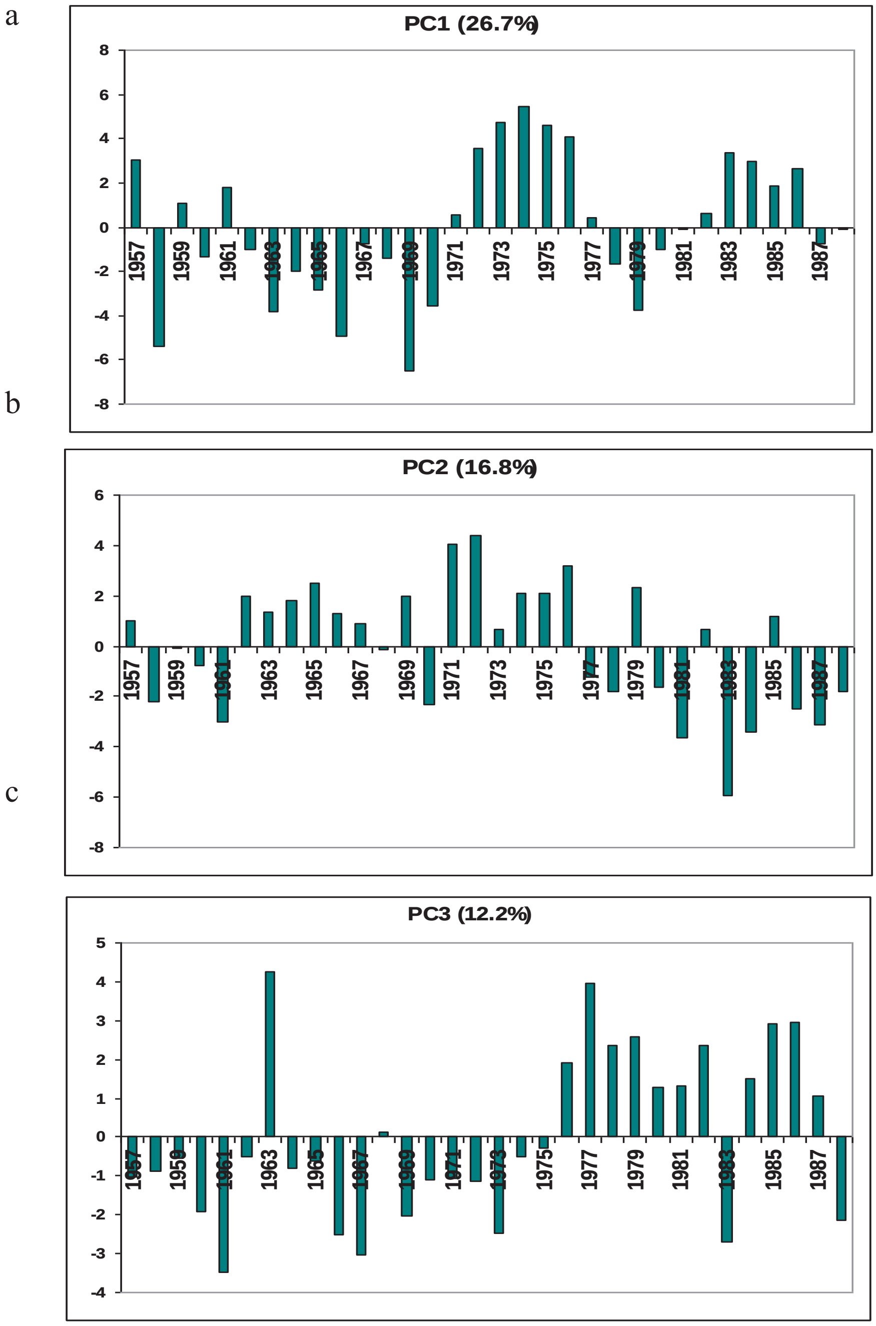


Figure 6. First three principal components (PC) of the 36 mean winter climatic variables for the 1957-1988 period.

1987-2010

Analysis of the EOFs for the 1987-2011 period reveals that the spatial pattern of SSTA variations was determined by positive phases of the North Pacific Gyre Oscillation mode and AMO (27.9%) (Figure 7a). This pattern is similar to the EOF2 of the previous period but the correlations are much stronger, especially in the northern North Atlantic. In the atmosphere, it is associated with the eastward shift of the NAO variability and amplification of the North Pacific Oscillation (Figure 7b).

The time series of EOF1 PC for this period is evidence of the regime shift between 1997 and 1998 and the decrease in PC scores after 2004 (Figure 7c).

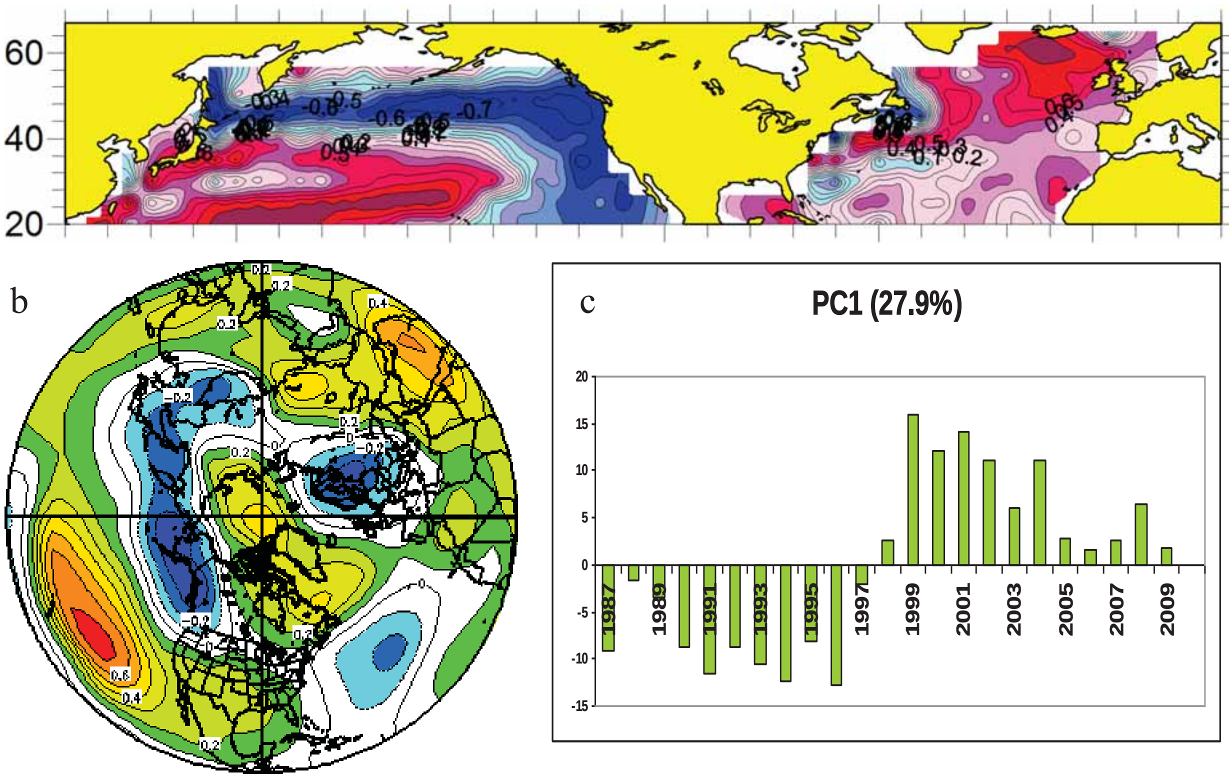


Figure 7. Correlation patterns between EOF1 PC of SSTA in winter and: a) corresponding SSTA field; b) mean winter H500; c) PC1 time series (1987-2010).

The EOF2 (12.4%) for 1987-2010 shows the PDO-like structure in the North Pacific similar to EOF1 for the previous period but with weaker correlations between its eastern and central parts than in 1957-1988 (Figure 8a). The correlation pattern in the North Atlantic corresponds to a certain extent to the well-known Atlantic Tripole, with the SSTA variations of the same sign in its northwestern and southeastern parts and opposite variations in between. This EOF also exhibits the pronounced in-phase SSTA fluctuations in the central parts of both oceans.

The correlation field between EOF2 PC and mean winter geopotential heights at the 500-hPa surface does not reveal the well-expressed PNA pattern (Figure 8b). Rather, it resembles the Arctic Oscillation structure in its negative phase. The time series of EOF2 PC shows the regime shifts in 1988/89 and 1995/96 (Figure 8c).

The results of the principal component analysis of 29 climatic time series for 1987-2010 are shown in Table 2. The first PC, which explains 28.0% of the total variance, is strongly associated with the Arctic Oscillation (r=0.81), PNA (r=-0.87), AMO (r=-0.74), and Tropical North Atlantic (r=-0.82). This component corresponds to EOF2 PC of the joint SSTA field (r=-0.68). The time series of this PC shows the regime shifts in 1989 and 1996 (Figure 9a).

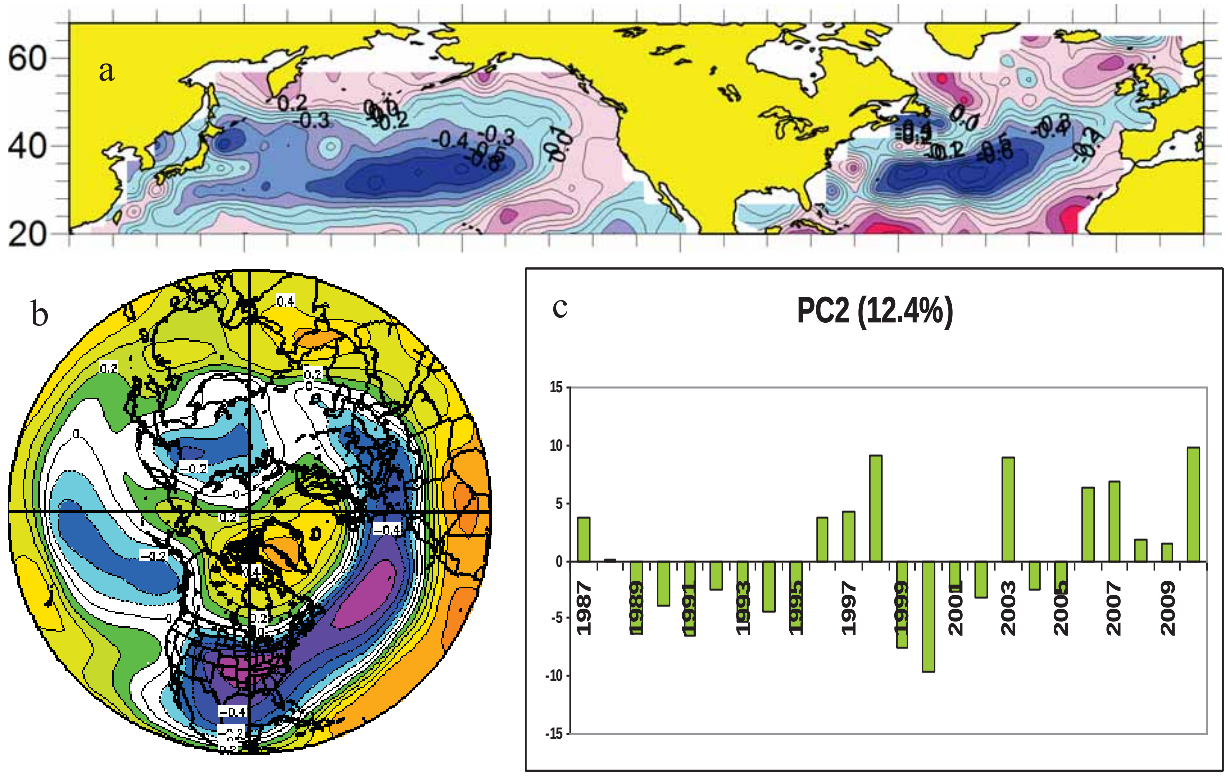


Figure 8. Correlation patterns between EOF2 PC of SSTA in winter and: a) corresponding SSTA field; b) mean winter H500; c) PC2 time series (1987-2010)

Table 2. Loadings on the first three principal components (PC) from a principal component analysis of the 29 mean winter climatic variables for 1987-2010.

Variable	PC1 28.80%	PC2 22.70%	PC3 11.10%
North Atlantic Oscillation	**0.65**	0.07	**0.49**
Arctic Oscillation	**0.83**	0.06	**0.50**
West Atlantic pattern	**-0.81**	-0.06	-0.05
East Atlantic Pattern	-0.15	0.09	0.44
East Atlantic/West Russia pattern	-0.15	0.24	**0.79**
Scandinavia pattern	**-0.61**	0.25	**-0.53**
Tropical/NH pattern	**0.73**	-0.14	-0.37
Polar/Eurasia pattern	0.18	**0.65**	0.36
Pacific/North American pattern	**-0.89**	0.11	0.07
North Pacific pattern	**0.82**	-0.25	-0.26
West Pacific Pattern	-0.19	-0.31	-0.21
Southern Oscillation	**0.51**	**-0.54**	-0.34
Atlantic Multidecadal Oscillation	**-0.70**	-0.51	0.12
Tropical North Atlantic	**-0.80**	-0.20	0.00
SSTA in Region 1A (NE Atlantic)	0.10	**-0.58**	**0.55**
SSTA in Region 2A (SW NA)	0.44	**-0.62**	0.20
SSTA in Region 5A (central NA)	**-0.48**	**-0.71**	0.27

Table 2 cont.

Variable	**PC1** **28.80%**	**PC2** **22.70%**	**PC3** **11.10%**
SSTA in Region 6A (NFLND)	**0.54**	**0.61**	0.06
SSTA in Region 1P (eastern NP)	-0.29	**0.82**	0.17
SSTA in Region 2P (central NP)	**0.66**	-0.08	0.04
SSTA in Region 3P (NW Pacific)	0.10	**0.62**	-0.02
SSTA in Region 4P (SW NP)	-0.10	**-0.78**	0.26
SSTA in Region 5P (southern NP)	-0.13	**-0.58**	**0.43**
Pacific Decadal Oscillation	**-0.72**	0.43	0.21
North Pacific Gyre Oscillation	-0.16	**-0.77**	-0.06

The PC2 (23.6%) corresponds to the EOF1 PC (r=0.93) of the joint SSTA field and is related to NPGO dynamics (r=0.77). The regime shift for this component occurred in 1998/99 (Figure 9b).

The climatic regime shift that occurred in the late 1980s was thus accompanied by a switch between the dominant large-scale modes of the atmosphere-ocean coupling in the Northern Hemisphere. During the 1957-1988 period, the SSTA patterns in the North Atlantic and North Pacific were driven by the Pacific/North American teleconnection pattern and the North Atlantic Oscillation, respectively. The former was responsible for a prominent coherence between the anomaly variations in the eastern North Pacific and central North Atlantic. The PNA state during this period was determined by changes in the tropical Pacific SST, whose effect was transmitted through the atmosphere to the middle latitudes (Trenberth, 1990). Meanwhile, in 1957-1988 the NPGO-like variability in the North Pacific and AMO-like variability in the North Atlantic were of secondary importance.

At the end of the 1980s the situation changed to the opposite. Both the NPGO and AMO modes of SSTA variations (in their positive phases) turned to be predominant. This resulted in the prominent warming in the western North Pacific (especially in the southwest) and Northeast Atlantic, including the Norwegian and Barents Seas. The change in leading large-scale modes of the ocean-atmosphere coupling can be, at least partly, canat least partly be explained by the eastward shift of the NAO variability in the early 1990s (Jung et al. 2003), persistent change in the Arctic Oscillation (Overland et al. 1999), and resulting amplification of the North Pacific Oscillation (Yeh et al. 2011).

It is difficult to answer the question of how long the ongoing climatic regime will continue.It may be modulated under the influence of external factors (e.g. decreased solar activity) as is discussed below.

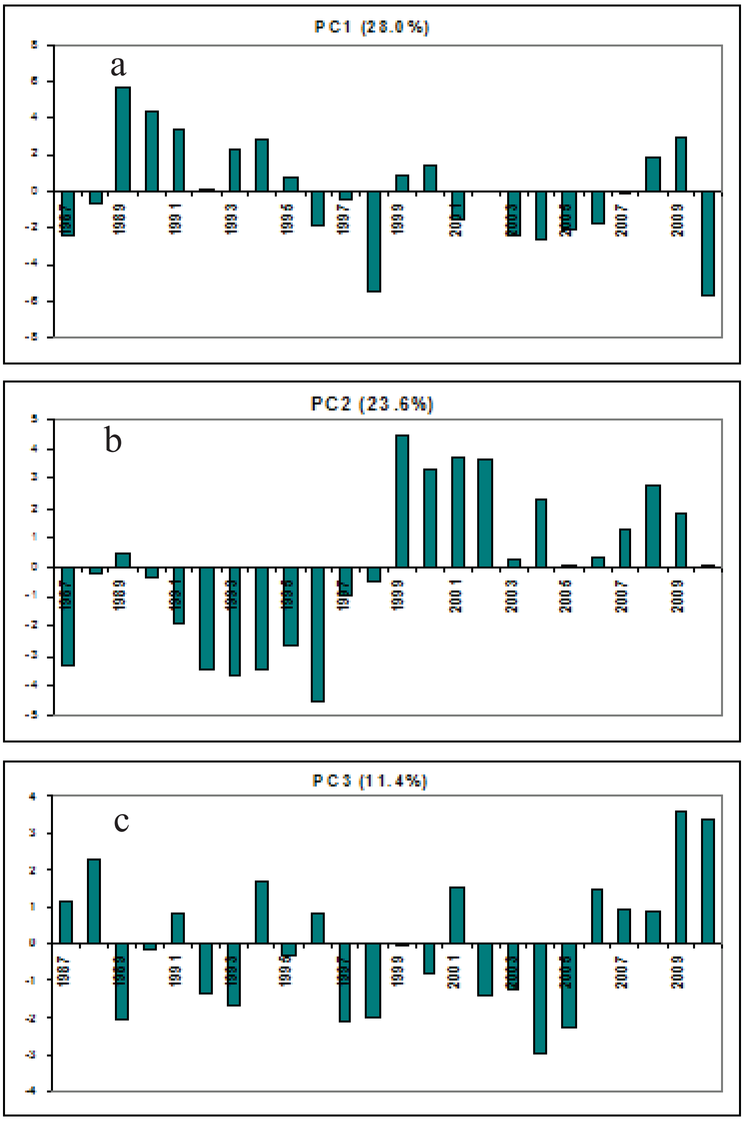


Figure 9. First three principal components (PC) of the 29 mean winter climatic variables for 1987-2010.

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Factors determining the natural temporal variability of atmospheric and oceanic circulation at different time scales

These factors include those that result from the interaction of different components of the global geophysical system (atmosphere, ocean, the Earth, the Sun, the Moon, large planets). They have been discussed in numerous articles and reviews (e.g. Haigh 2009; Klyastorin and Lubshin 2005; Lockwood 2010; Soon 2005).

The Earth's climate – the solar connection

The Sun is the major source of the Earth’s energy. Although solar irradiance changes slightly under solar cycles on different scales, the indirect effects of intensified solar activity such as atmospheric warming can multiple its influence on atmospheric and ocean temperatures and circulation.

Studies of changes in the impact of direct solar radiation on temperature trends have shown that between 1910 and 1960 this was responsible for 52% of temperature change, but for only 31% of the change from 1970 to 1999 (Lockwood et al., 1999). Other authors estimate its influence on temperature change at 69% (Scaffeta and West 2007) and 77% with the account of galactic space rays (Shaviv 2005).

There is a strong relationship between air temperature anomalies in the Arctic regions and total solar irradiance (TSI) averaged over 10-year periods (R^2=0.79) (Soon, 2005). This is almost four times as higher the correlation with the content of greenhouse gases (R^2=0.22). Hence, the warming of the last 20 years is mainly associated mainly with the unusually high solar activity of the 1980s and 1990s, as has been confirmed by observations on the influence of the 23rd sunspot cycle maximum on the climate.

Thus, the winter stratospheric warming in lower and middle latitudes resulting from the absorption of increased ultraviolet radiation by the ozone layer influences the dynamics of geopotential heights in the troposphere (Labitzke 2001). The warming during the period of intensive solar flux from September, 2001 until April, 2002 could be caused by a reduction of the winter stratospheric polar vortex. Also, at that time the summer southern vortex disintegrated into two centers for the first time over the whole observation period.This was proibablt among the causes of the Larsen Ice Shelf collapse in summer, 2002. To explain this event, NASA used the Shindell Ozone Chemistry Climate Model (Shindell et al. 2001).

It should be noted that our study revealed the abrupt changes in sea-surface temperature anomalies in sub-polar latitudes of both the northern and southern hemispheres in the period of double maximum of the 23rd sunspot cycle (1999-2002). In particular, the anomalies have caused a decrease in salmon approaches to the coasts of the far eastern seas in precisely these years.

The Shindell Ozone Chemistry Climate Model showed that the climate during the Maunder Minimum, or the prolonged sunspot minimum, in the second half of the 17th century, was much colder than 100 years later, when sunspot activity increased (Shindell et al. 2001).

Analysis of the relationship between the severity of winters in Central England and the open solar magnetic flux (F_s) showed that for the coldest eight winters (relative to the northern hemisphere trend), which occurred in 1684, 1695, 1716, 1740, 1795, 1814, 1879, and 1963, the mean and median F_s was 45% lower than for all other winters (Lockwood et al. 2010). The winter of 2009/2010 was the 18th coldest. In terms of mean winter air temperature, 2008/2009 and 2009/2010 were among the coldest 43% and 17% of the 350 winters studied. To better understand such a strong relationship of cold winters in England with lower open solar flux (and hence with lower solar irradiance and higher cosmic ray flux), a number of mechanisms were suggested. In particular, the enhanced cooling may be associated with an increase in maritime clouds under the galactic cosmic ray flux increase (Harrison and Stephenson, 2006). On the other hand, as has been demonstrated, the tropospheric jet streams are sensitive to the solar forcing of stratospheric temperatures (Haigh 1996). This can occur through disturbances to the stratospheric polar vortex (Gray et al. 2004) which may propagate downwards and affect the tropospheric jets, or through the influence of tropical stratospheric temperature on the refraction of tropospheric eddies (Simpson et al. 2009). Overall, this leads to the development of winter blocking events over the eastern North Atlantic and Europe during low solar activity (Barriopedro et al., 2008; Woollings et al. 2010). These extensive quasi-stationary anticyclones are characterized by a reversed meridional gradient of geo-potential heights and northeasterly winds.

The mechanism of lower solar flux impact on climate through the stratosphere described above (Barriopedro et al., 2008; Woollings et al. 2010) explains the more frequent development of blocking events and temperature decrease in the Northeast Atlantic between the 1960s and 1990s (Scaife et al. 2005). It should be noted that atmospheric temperature is also affected by the duration of sunspot cycles. Taking into account the long duration of the 23rd cycle, these large negative air temperature anomalies should be expected in sub-polar and middle latitudes of the Northern Hemisphere during 2012-2013.

The gradual decrease in F_s since 1985 suggests that there is an 8% chance that the Sun could return to Maunder Minimum conditions within the next 50 years (Lockwood et al. 2010).
Both geomagnetic activity and ultraviolet radiation result in stratospheric warming, which propagates into the stratosphere and affects the atmospheric circulation and associated climatic patterns. There is thus a strong relationship between the geomagnetic activity and the NAO (Bochnicek and Hejda 2005). In winter, the high geomagnetic activity is associated

more often with the positive NAO phase, and *vice versa*. Fujita and Tanaka (2007) have demonstrated a similar dependence for the Northern Annular Mode (NAM). Analysis of the relationship between the geomagnetic activity index (A_p) and NAO between 1949 and 2000 revealed a high correlation since 1972 (Thejll et al. 2003). The authors have suggested that until that year, the solar forcing of the stratosphere was not transferred downwards to the troposphere.

A stable relationship between variations in the open solar magnetic flux (F_s) and NAM was found by Ruzmaikin and Feynman (2002). According to their results, the index of the NAM was negative (weaker jets) when solar activity was low.

Solar activity also affects the spatial structure of the NAO. Kodera (2002) showed that in years of maximum solar activity the NAO covered the whole northern hemisphere and extended into the stratosphere, similar to the structure of the Arctic Oscillation (AO), except for the North Pacific area. On the contrary, during the periods of its minimum the NAO was limited only by the North Atlantic and did not extend into the stratosphere.

The fluctuations in the NAO index are related to the intensity of electric field of the solar wind and this relationship is evident both in the stratosphere and troposphere. However, it is limited by the North Atlantic area (Boberg and Lundstedt 2002, 2003).

The 22-year sunspot cycle (Hale cycle) also impacts the NAO state. According to Bochkov (1978), on the ascending branch of even cycles the Barents Sea is characterized by the suppressed cyclonic activity, negative air and water temperature anomalies. On the contrary, during the decline of solar activity (2-5 years after its maximum) the Barents Sea tends to be warmer than normal. In periods of the odd cycles, the effects of solar activity on the climatic situation in the sea are less certain.

The negative (positive) phase of the NAO is thus observed more often during the low (high) level of solar activity.

The solar activity is currently on the ascending branch of its 24th cycle, but with respect to the centennial cycle it is on the descending branch. The behavior of the NAO and AO indices is consistent with this variability. Both indices tend to shift from their positive to negative phase. Obviously, the essential weakening of the Icelandic Low should be expected, which might be accompanied by cooling of the Northeast Atlantic, Norwegian and Barents Seas. However, taking into account the high heat content of their waters accumulated in recent years, the formation of significant negative SST anomalies is unlikely.

Relationship between multi-decadal variations in the Earth's rotation velocity and changes in atmospheric circulation

The variability of individual climatic characteristics, such as the air and sea surface temperature, precipitation, clouds, etc., is determined first of all by synoptic processes in the atmosphere. Vangengeim (1952) divided all the varieties of these processes over the Atlantic-

Eurasian sector of the Northern Hemisphere into three types of atmospheric circulation: west (W), east (E), and meridional (C), while Girs (1974) defined similar types for the Pacific-North American sector: Z, M_1, and M_2.

The combination of these types of atmospheric circulation characterizes climatic regime in these sectors of the Northern Hemisphere. Under the zonal processes (W and Z), the negative temperature and pressure anomalies are peculiar to high latitudes, and the positive ones, to middle and subtropical latitudes. Under the meridional types (E, C, M_1, and M_2) the positive anomalies of temperature and pressure are observed in atmospheric ridges, and their negative values, in atmospheric troughs.

Analysis of the recurrence of different circulation types for 116 years has shown that the annual frequency of occurrence of type W decreased from 153 (the 1890s) to 90 days/yr (last years) (Sidorenkov and Orlov, 2008).

In order to define the decadal and multi-decadal variations in atmospheric circulation, the cumulative sums of anomalies of the circulation type occurrence were calculated. The results showed that the recurrence of type W was above normal in 1891-1902 and 1938-1971, and the annual frequency of types W+E in these periods was below normal.

In 1903-1938 and 1972-1988, the recurrence of type C was below normal, whereas that of the combined type W+E, above normal. During the periods of W+E, type W predominated in 1903-1938, and type E in 1972-1988.

The frequencies of occurrence of certain types of circulation correlate with the Earth's rotation velocity. Thus, at the rise of curve of $\sum\Delta C_{\mathrm{freq}}$ the velocity decreases (the length of a day increases). The correlation coefficient between the cumulative sums of anomalies of the day length and frequencies of occurrence of type C is 0.70±0.04, with the trend turning points in 1900, 1935 and 1972.

Therefore, each long-term regime of Earth's rotation is corresponded by the certain predominant type of the atmospheric circulation and thus by the particular weather regime which determines its physical impact on marine ecosystems.

Recently, the relationships of the long-term fluctuations in the Earth's rotation velocity with variations in the global air temperature (Figure 10), precipitation, clouds and fish catches (Klyashtorin and Sidorenkov, 1996), and the Greenland and Antarctic ice sheets (Sidorenkov et al., 2005) have also been established.

The Earth's rotation accelerated from 1973 to 2004 and then started to slow down. This indicates the beginning of new climatic regime with more frequent synoptic processes of meridional type C. The rate of global temperature increase will slacken, and global cloud cover will decrease. This new climatic regime, like the previous three regimes, will continue for about 35 years (Sidorenkov and Orlov, 2008; Sidorenkov, 2009).

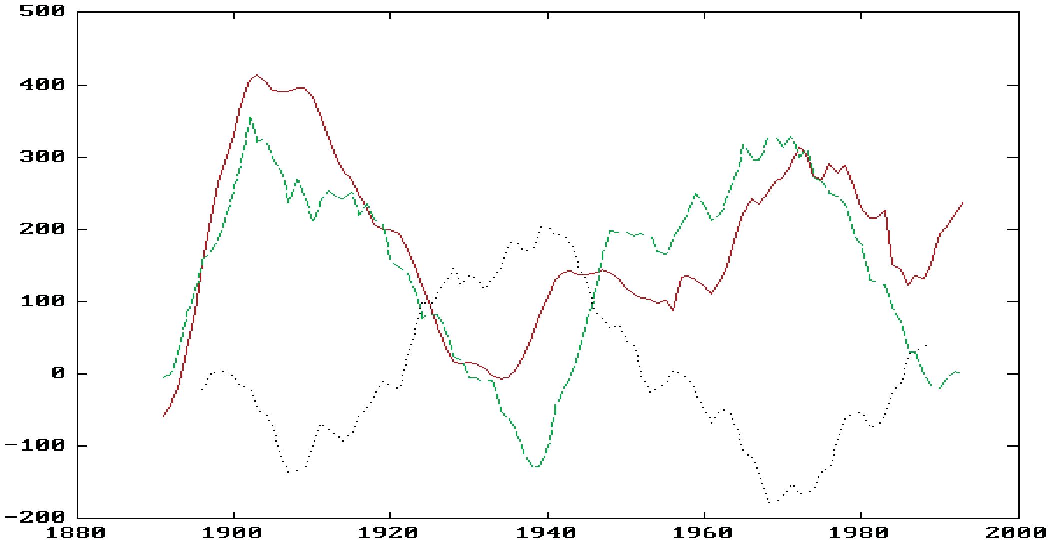

Figure 10. Deviations (δP) in day length (red curve), cumulative sums of frequency anomalies of circulation type C (green curve), and the 10-year moving averages of the Northern Hemisphere air temperature anomalies, Δt (10^3 °C; linear trend is removed) (dotted curve). The Y-axis shows the day length (10^{-5} s), cumulative sums of frequency anomalies (days/year), and temperature anomalies (from Sidorenkov and Orlov, 2008).

It is generally accepted that anomalies of temperature and other climatic characteristics change randomly. However, as has been shown by Sidorenkov and Zhigailo (2011, in press), the impact of the lunar cycle (about 355 days) on the annual (365 days) variations of air temperature or other hydrometeorological characteristics results in the generation of pulses (i.e., periodic change in amplitude of the composite oscillation) with a period of about 35 years. This period has long been known in climatology as Bruckner's cycle (Bruckner, 1890). If the phases of the lunar and solar cycles coincide, the climate tends to shift to its 'continental' type. This occurred around 2010. Thirty five years later, at the phase difference of 180º, the transition to the 'maritime' climate with prevalence of the zonal forms of atmospheric circulation (W and Z) will begin.

Conclusions

The climatic regime shift that occurred in the late 1980s was accompanied by a switch in the leading large-scale modes of the atmosphere-ocean coupling in the Northern Hemisphere, with predominance of the positive NPGO and AMO phases in the North Pacific and North Atlantic, respectively, during the 1990s and 2000s. This resulted in significant warming of the western North Pacific and Northeast Atlantic, including the Norwegian and Barents Sea. At this point in time, it is difficult to answer the question of how long the current climatic regime will continue.

However, analysis of the factors that determine climate variability in the global geophysical system (atmosphere, ocean, Earth, Sun, Moon, large planets) indicates a change of the warming trend to a cooling one during the past two or three years. An increase in salinity and water temperature of Labrador Water and NE Deep Water in the Icelandic Basin since 1995, which occurs simultaneously with the negative trend in the NAO variability, is among the direct signs of this change (Sarafanov et al., 2009). Similar processes were observed in the Northeast Atlantic during 1950s-1960s.

The severe winters in central England (2008/09, 2009/10) are closely related to the decrease in solar activity (Lockwood et al., 2010). A drop in sea temperature at the Kola Section in 2008-2010 may also be evidence of a shift of climatic trend in the Barents Sea.

Finally, recent estimates of the heat content of the ocean (Lyman et al., 2006; Loehle, 2009) indicate that after 2003 the cooling trend is 0.35 x 10^{22} J/yr.

Therefore, the climatic regime in the Northeast Atlantic, including the Norwegian and Barents Seas, will be similar to that in 1950s (1956-1958) and 1960s (1963, 1965-1969). The essential difference is that the heat content of both the North Atlantic and Arctic basins is much higher than in those years. It is important also to take into account how the ongoing ice melting in the Arctic will affect the thermal regime of the area under consideration.

Undoubtedly, the problem needs further study for the quantitative evaluation of possible cooling.

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Appendix: Acronyms used

AO	Arctic Oscillation
AMO	Atlantic Multidecadal Oscillation
EOF	Empirical Orthogonal Function
IPCC	United Nations Intergovernmental Panel on Climate Change North Atlantic Oscillation
NAO	
NPGO	North Pacific Gyre Oscillation
NPI	North Pacific Index
NH	Northern Hemisphere
PC	Principal Component
PDO	Pacific Decadal Oscillation
NA	North Atlantic
NP	North Pacific
PNA	Pacific|North American Teleconnection Pattern
SO	Southern Oscillation
SLPA	Sea Level Air Pressure Anomaly
SSTA	Sea Surface Temperature Anomaly

1.6 Regional climate scenarios for the Barents Sea

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A climate *scenario* (or climate *projection*) is a description of a possible future climate. It is not a prognosis or a forecast. A useful scenario for effect studies on marine ecosystems must be *realistic* (i.e. must not contradict our knowledge of marine climate processes) and *consistent* (meaning that physical variables like wind, circulation, temperature, sea ice etc. go together).

Scenarios can be produced by global climate models, coupling atmosphere, ocean, and sea ice. For IPCC AR4 there was approximately 20 such models. The driving force is release scenarios of greenhouse gases. In the upcoming IPCC AR5 new (and hopefully improved) model runs will be available.

The global climate models can be used regionally as they produce consistent scenarios. These scenarios are however not realistic for shelf seas. This is basically due to low resolution. The bathymetry and coast line are poorly represented. The exchange between deep water and the shelf, in particular the Atlantic inflow to the Barents Sea is underestimated. Details in fresh water runoff like the number and positions of rivers are not sufficient. The circulation is too smooth lacking mesoscale features like eddies. Also important physics is missing from the global models, in particular tidal mixing.

For high-latitudes seas like the Barents Sea there are more shortcomings. First the global models disagree more at high latitudes indicating a larger uncertainty. In particular most global models produce too much sea ice in present climate. This has been examined by Overland and Wang (2007) for the models presented in the 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC AR4). They point to three models with best results in the Barents Sea and central Arctic, namely the GISS AOM model from NASA, the CCSM model from NCAR, and HadCM3 model from the Hadley Centre.

Downscaling is a set of methods to enhance the usefulness of the global scenarios for specific regions like the Barents Sea. Marine dynamic downscaling is done by forcing a regional ocean circulation model with results from a global climate model, using atmospheric fields at the surface and ocean fields at the lateral boundaries. The objective is to obtain consistent scenarios with sufficient realism for marine effect studies. In this study the Regional Ocean Model System (ROMS) (Shchepetkin and McWilliams, 2005). Our version includes sea ice as described by Budgell (2005).

The GISS and NCAR models have been downscaled at IMR. Figure 1 shows the Atlantic-Arctic model domain used for this downscaling. This is a highly stretched grid with resolution of approximately 10 km in the Barents Sea and 40 km in the south Atlantic. For evaluation the years 1986-2000 of the 20th Century in Coupled Climate Models (20C3M) was used, while the future scenario uses A1B, the most commonly analyzed greenhouse gas scenario for the period 2051 to 2065.

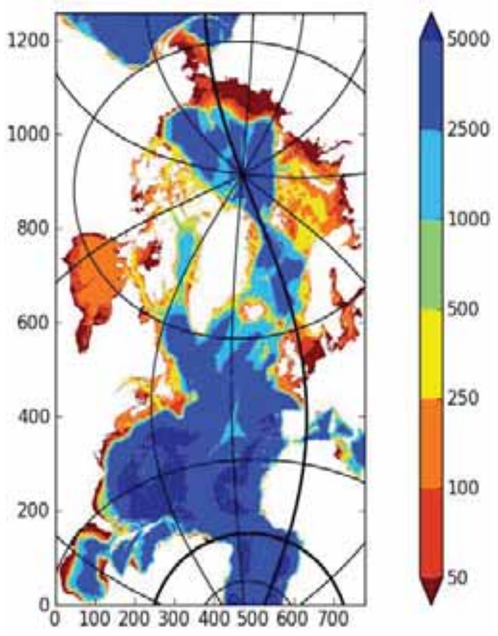

Figure 1. The Atlantic-Arctic model domain with bottom topography in meters. The numbers along the axes are grid cell indices.

Control and validation

As control we downscaled the years 1986-2000 from the 20C3M runs. These runs are "scenarios" for the climate in the last century. They are initialized from long runs with pre-industrial forcing, and are forced by historical concentrations of greenhouse gases, and natural forcing like sun variability and volcanism. These are free runs without any data assimilation. They are therefore uncorrelated with reality, but the climate (mean, trend, variability) should ideally agree with the real climate. The GISS downscaling has been validated in more details by Melsom et al. (2009).

Figure 2 shows the mean ice cover in both models, globally and downscaled. The figure displays the coarse resolution of the GISS model with far too much ice. The global NCAR results have better resolution and more open water. The GISS downscaling is a clear improvement with open water in the Barents Sea. It is forced with an atmosphere that sees ice below. This gives a very strong cooling and the regional model is not able to keep large enough area ice free. The NCAR downscaling has similar extent of the ice cover as the global. In both downscalings we see that the ice cover is improved by following the topography and the circulation.

The climatological temperature for the months Sep-Oct-Nov in the Fugløya-Bjørnøya section is shown in figure 3. Here the downscaled GISS results reproduce the observed temperature structure quite well. Some of the biases are shown in table 1. The global GISS model has a cold bias of 1.59°C in this section. The downscaling improves this, giving a warm bias of 0.24°C. For comparison the downscaled NCAR model has a cold bias of 0.41°C. Going into the Barents Sea at the Vardø-N section, the global GISS results have a huge cold bias of

4.52°C. Here the downscaling gives a strong improvement reducing the bias to 0.73°C. The NCAR downscaling is similar, giving a cold bias of 0.63°C. An explanation of what goes on can be seen in figure 4, the global GISS results have no Atlantic Water in the section. The downscaling, however, has a quite realistic temperature structure. For the NCAR model, both the global and the downscaling give realistic temperatures. It can be argued if the downscaling improves the result in this case.

Using the global models for the Barents Sea is not a good option. The GISS model has too much sea ice and no Atlantic Water inside the Barents Sea. The NCAR model has higher resolution and looks better with a more realistic ice cover and reproduces the hydrography in the Vardø section quite well. The detailed signature from the topography and the circulation is however missing. The downscalings adds value to the global model with increased realism and regional details. In the western Barents Sea both downscalings work well and are deemed useful. The NCAR-based downscaling produces marginally both results. In the eastern Barents Sea, the NCAR model does a better job as the GISS-based clearly is too cold with too much sea ice.

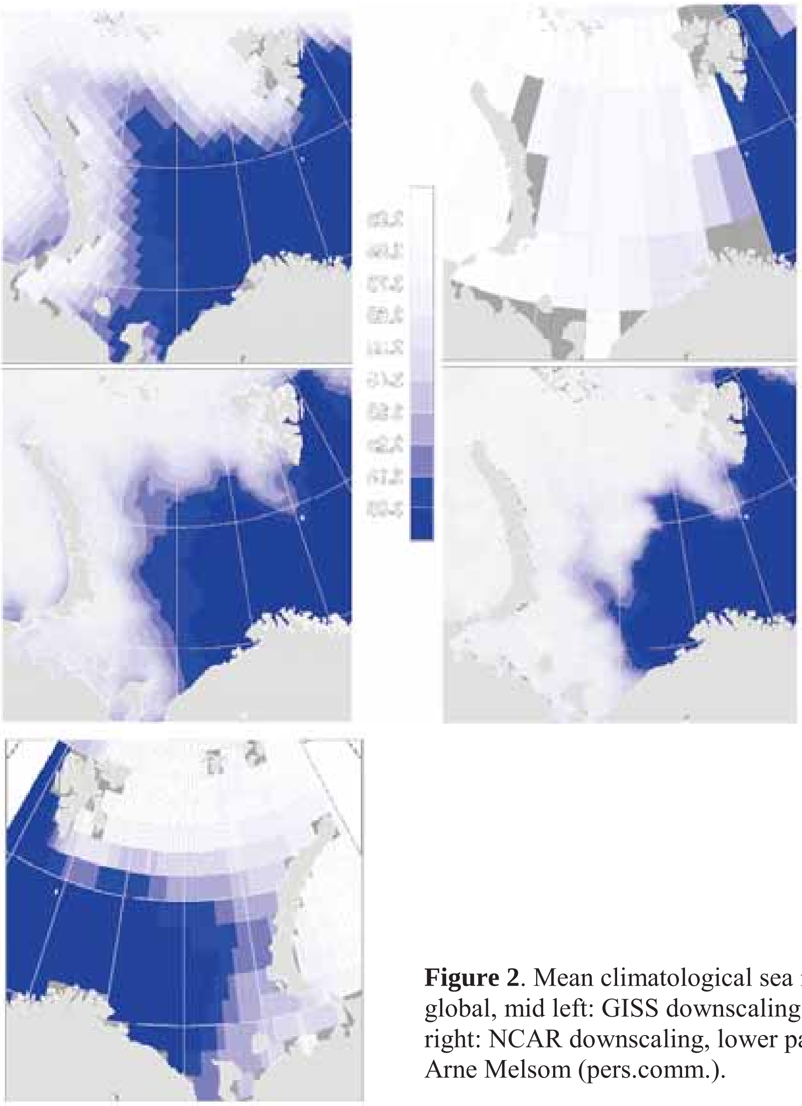

Figure 2. Mean climatological sea ice cover in March. Upper left: GISS global, mid left: GISS downscaling, upper right: NCAR global, lower right: NCAR downscaling, lower panel: NCEP reanalysis. Figure from Arne Melsom (pers.comm.).

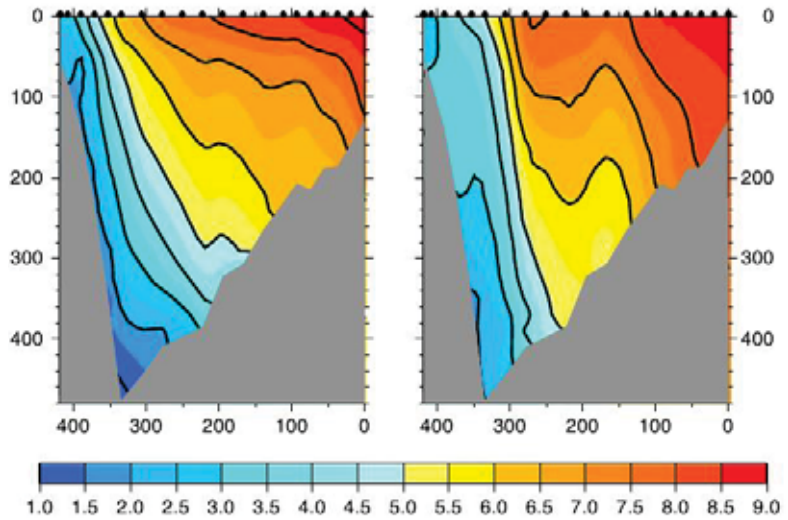

Figure 3. Temperature at the Fugløya Bjørnøya section, left: observations, right: GISS based downscaling. From Melsom et al. (2009).

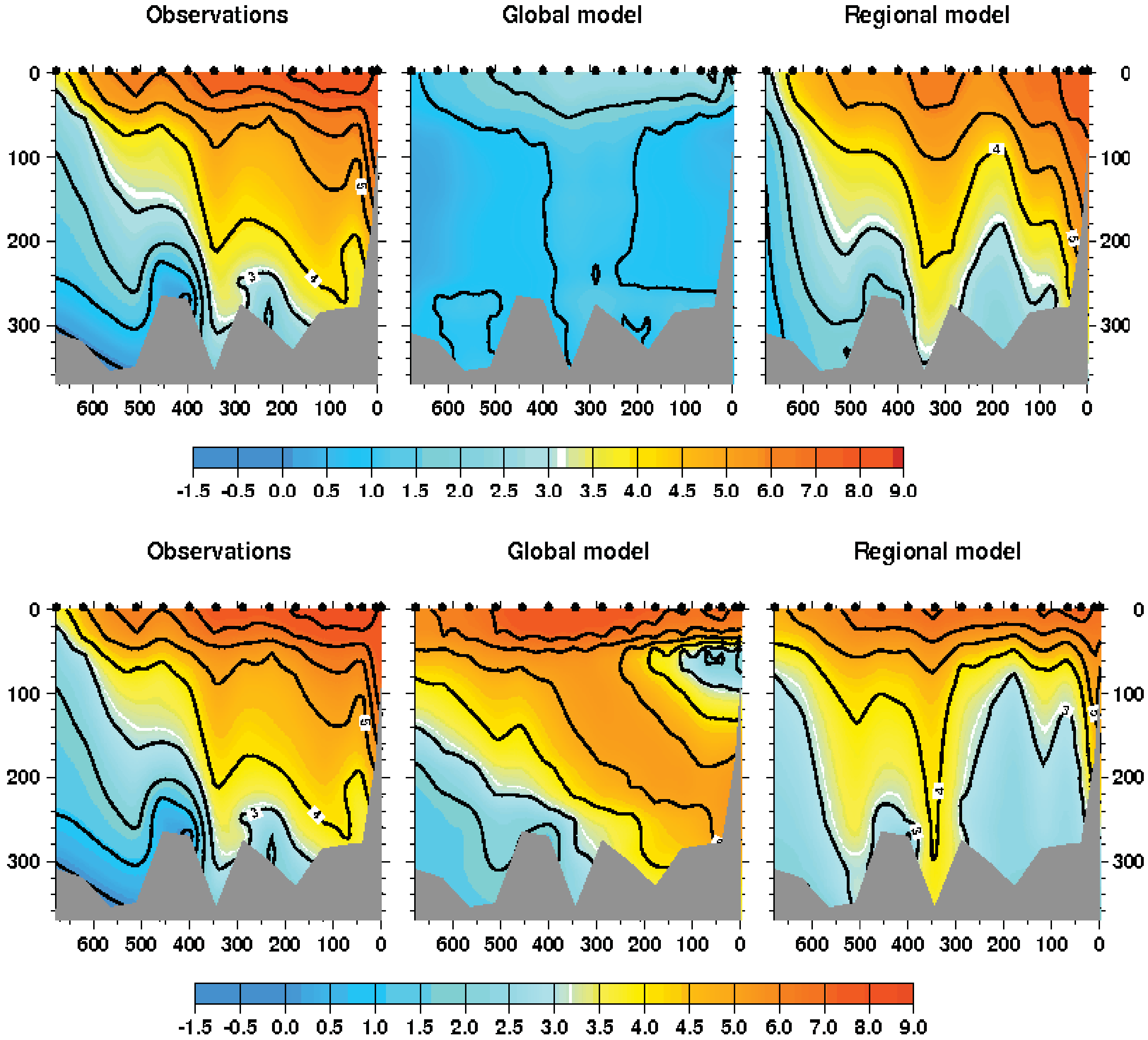

Figure 4. Temperature at the Vardø N section in autumn. Upper left: observations, Upper mid: GISS global, Upper right: GISS downscaled, lower left: observations, lower middle NCAR global, lover right: NCAR downscaled. Figure by A. Melsom (pers.comm.).

Table 1. Quarterly bias (model - observation) of temperature in the Fugløya-Bjørnøya and Vardø-N sections.

	GISS global	GISS downscaled	NCAR global	NCAR downscaled
Fugløya-Bjørnøya	-1.58	0.5		-0.31
	-1.53	0.65		-0.33
	-1.43	-0.15		-0.62
	-1.8	-0.02		-0.35
Vardø-N	-4.32	-0.31		-0.39
	-4.82	-0.4		-0.55
	-4.65	-1.06		-0.78
	-4.3	-1.01		-0.91

Future scenarios

Table 2 gives an integrated overview of the downscaled scenarios for the 20C3M period 1986-2000 and the period 2051-2065 from the future A1B scenario. The Δ-columns show the change. The temperature change in the NCAR-based scenario is roughly double of the GISS-based. Temp and Salt are volume averaged temperature and salinity, while SST is the average surface temperature. The flux values are through the Barents Sea Opening resp. the Novaya Zemlya – Franz Josef Land section. The NCAR-based volume averaged warming is 1.4°C and the average surface warming is slightly stronger with 1.6°C. For volume integrated salinity there is little change with GISS, while NCAR shows a strong decrease in practical salinity of 0.6. This is not limited to the Barents Sea as the NCAR scenario, both without and with downscaling, show a salinity drop in the whole North-Atlantic region. For the volume fluxes, the GISS-based scenario shows only small changes while the NCAR-based show a strong increase in the future scenario.

Table 2. Integrated values from the downscalings.

	NASA GISS			NCAR CCSM		
	20C3M	A1B	Δ	20C3M	A1B	Δ
Temp	1.7	2.3	0.6	2.1	3.5	1.4
SST	1.5	2.3	0.8	2.1	3.8	1.6
Salt	34.5	34.6	0.1	34.6	34.0	-0.6
Flux BSO	2.2	2.1	-0.1	2.2	2.8	0.6
Flux NZ-FJL	1.9	2.1	0.2	1.7	2.7	1.0

More geographical details are presented in figure 5, showing the climatological mean April temperatures and the warming at 100 m in both scenarios. For the GISS-based scenario, the main warming is found in the southern Barents Sea. The NCAR-based downscalings has colder Atlantic water in the Norwegian Sea and Barents Sea Opening. In the future scenario most of the cold Arctic water is replaced with Atlantic water giving a strong warming in the south and eastern parts of the Barents Sea. A different view of the results is given in figure 6. This gives the volume in the Barents Sea at different temperatures throughout the year. In the

GISS based control has some very cold water in winter. Most of this has vanished in the A1B scenario. The scenario also shows more of the Atlantic water with 3-4 degrees. The NCAR based control has a peek around 0°C and a weaker peek around 4°C. In the future scenario, the cold water has almost disappeared, leaving a strong maximum with Atlantic water around 4°C.

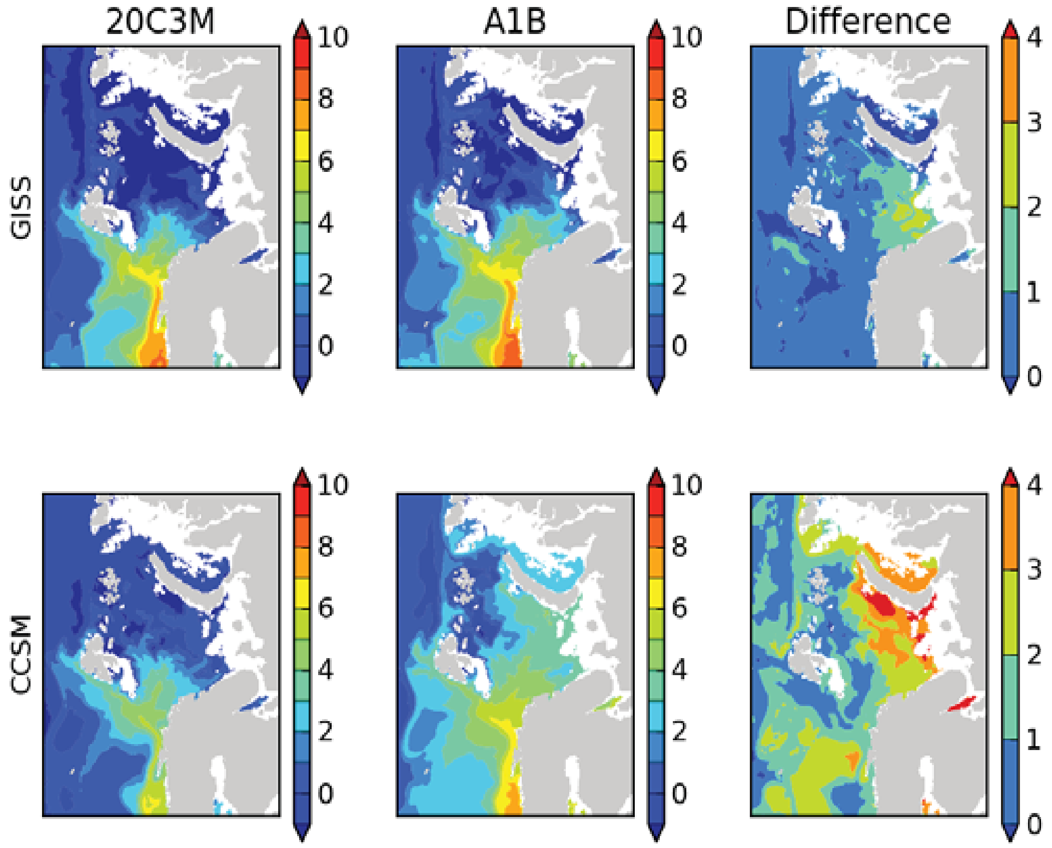

Figure 5. Temperature climatology and differences for April at 100 m depth. Upper panels: GISS based scenario, Lower panels: NCAR based scenario.

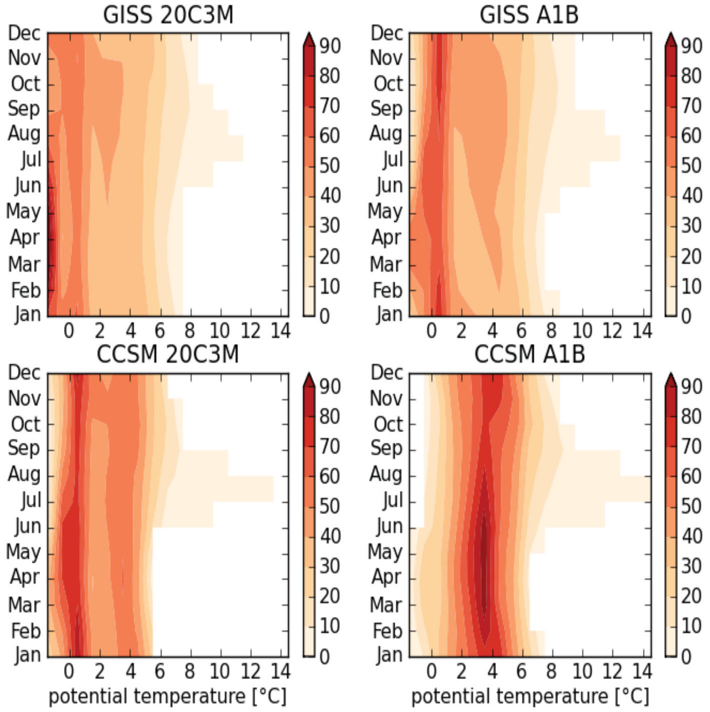

Figure 6. Volume of different temperatures in the Barents Sea

Concluding remarks

Dynamical downscaling of global climate model results provides added value. There is however problems in particular due to sea ice in the global scenarios.

The downscaled scenarios shows a warming in the Barents Sea of approximately one degree during 65 years, a little more with the NCAR based model and a little less with GISS. Strongest warming is found in south and east.

With only two downscalings it is hard to estimate the uncertainty in the projections. For this purpose and the identification of robust features a larger ensemble of downscalings is needed.

The ROMS ocean model has been coupled regionally with the WRF atmospheric model, (Warner et al, 2010). Work is underway to extend this coupling to include sea ice. We hope that this new tool that includes feedback between the climate components will do a better job with downscaling of the Barents Sea climate.

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Photo: Institute of Marine Research

1.7 Observations and fine-resolution large-eddy simulations of the katabatic wind over Kongsvegen glacier, Kongsfjorden and Ny Ålesund

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Meteorological gravity currents (also called the katabatic winds) are air flows developing on cooled slopes where the dense, colder air moves downhill with acceleration under the action of gravity force. The katabatic winds are channeled by the relief and collected in open valleys. Thus, the offshore winds out of the open valley can reach a hazardous speed, often more than 30 m/s, in narrow strips of the sea. Such high wind speed, long-distance (up to 100 km from the shore) impact and low air temperature, which favor the sea ice formation, determine the particular interest to the katabatic winds in the offshore areas around Svalbard. The classical theory of the katabatic winds (Prandtl, 1949; Ball, 1956; Gutman, 1983) attributed the surface friction and cooling as the major control factors for the wind speed and temperature of the katabatic wind. This theoretical model has been recently challenged by some authors (e.g. Davis and McNider, 1997; Renfrew, 2004; Ingel, 2011) who established a solution invariant to the surface turbulent exchange parameters. The matter is made even more complicated by the fact that the relief as such causes the wind channeling, which is easy to mistake with the katabatic wind in observations. The aim of the present contribution is to compare the simulated and observed properties of the wind in the area of Kongsvegen glacier, Kongsfjorden and Ny Ålesund (Figure 1).

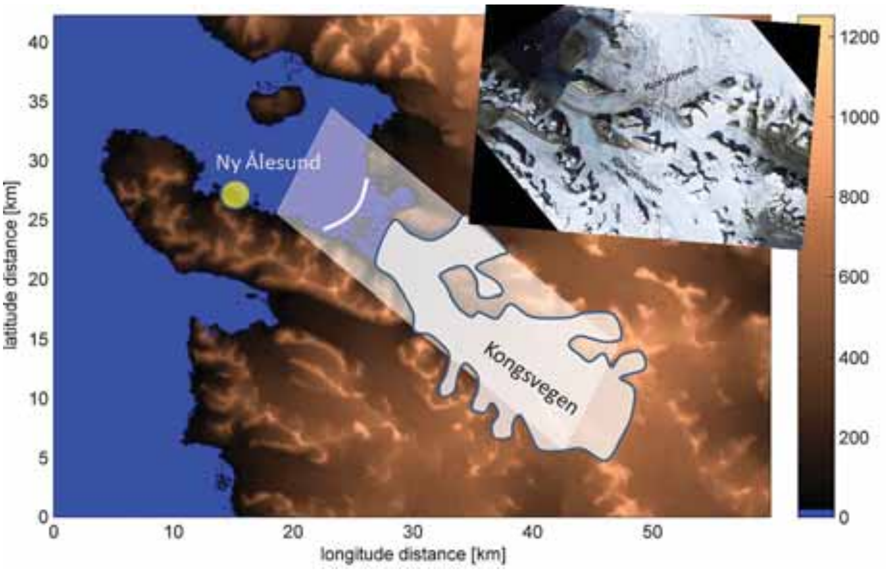

Figure 1. The area of Kongsvegen glacier, Kongsfjorden and Ny Ålesund. Elevations (color bar in meters) are shown from the digital elevation model ASTER. The simulated area is shown with semitransparent rectangle. The inserted satellite image shows the glaciers.

The wind field in the area of Kongsvegen glacier, Kongsfjorden and Ny Ålesund has been already studied in several papers and dissertations based on in situ observations (Krismer, 2009), special observational campaigns (Beine et al., 2001) and single-column (Erath, 2005) and regional scale modeling (Sandvik and Furevik, 2002; Kilpeläinen et al., 2011). However, there are still no publications reporting either longer time climatological analysis or fine resolution numerical simulations. Here, we contribute both to close this gap in knowledge.

Wind climatology

In order to establish the wind climatology in the area, we analyzed observations from Ny Ålesund station collected in the archive of radiosounding data IGRA. This archive is described in details in Sorokina and Esau (2011). Figure 2 shows the median climatology of the wind speed (colors) and direction (wind roses) in Ny Ålesund for the period 1992 – 2008. It is obvious that the channeled winds exert a considerable drive on the local weather and occur frequently in this geographical area in all seasons of the year. The general structure of the wind profiles indicates persistent easterly surface winds that change to persistent westerlies at 2 – 3 km altitude. The level of the standard isobaric surface of 850 hPa (or about 1.5 km height – just above the mountain summits) does not have any preferable wind direction. This systematic change in the wind direction clearly characterizes the local winds as overwhelming in the lower 1 km of the atmosphere. The layer of 1 km depth is however far too deep to be attributed to the impact of the katabatic winds. Indeed, the theoretical prediction suggests the depth of the katabatic wind layer in an equilibrium steady-state flow of just 250 m (Ingel, 2011). The known direct observations in Antarctica (the Halley station) give the depth of 100 m to 150 m (Renfrew, 2004). In situ data for Ny Ålesund by Beine et al. (2001) give the depth of 300 m to 400 m. Equally, our SODAR measurements (Figure 3) in the middle part of the Konsvegen glacier give the depth of 200 m. Thus, the climatologically significant deep surface counter-flow observed in Ny Ålesund is inconsistent with both theoretical and in situ estimates provided for the katabatic winds.

Wind simulations

The regional scale model simulations (Sandvik and Furevik, 2002; Kilpeläinen et al., 2011) demonstrate strong wind outbreaks in the areas of Svalbard fjords and sounds. The model resolution (10 km to 50 km) is however too coarse to simulate the wind field in valleys. The vertical model resolution and turbulence closure are also unable to simulate the katabatic wind effect as such while signature of the gravity currents on larger scales could be resolved. Thus, the wind outbreaks found in the modeling results are unlikely to be caused by the katabatic wind effect. Another plausible explanation is an orographic wind effect, which is purely mechanical – without surface cooling and gravity acceleration – effect on the flow in a narrowing channel. In a stratified flow, which is always the case in the atmosphere, it may become energetically more efficient for the flow to move along the surface in counter current than to overflow the surrounding mountains. As expected, such a flow should have a vertical scale comparable with that of the mountains. This explanation would be in good agreement with the IGRA wind climatology. However, the effect of much more shallow katabatic flow is also seen in the in situ and remote sensing data.

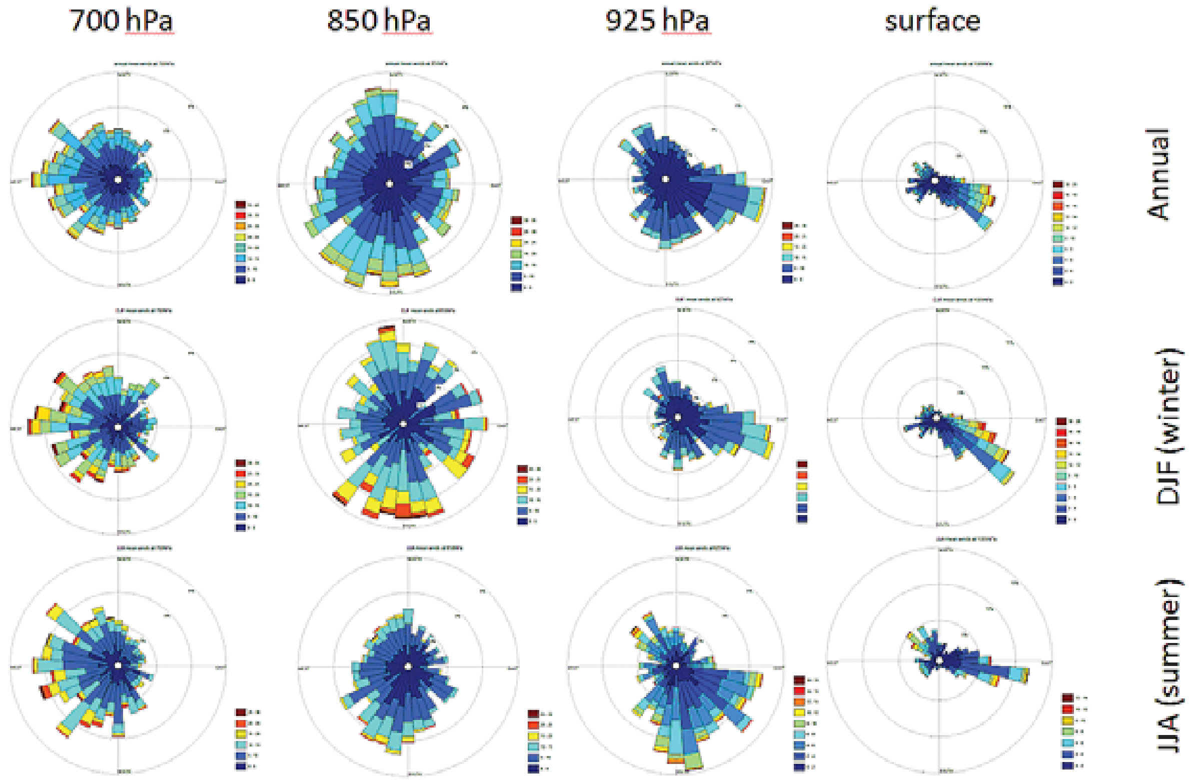

Figure 2. The median wind climatology compiled on the basis of the archive of radiosounding data (IGRA) for the period 1992 – 2008. The data only for the Ny Ålesund station were used (contribution by S. Sorokina). The wind speed climatology is shown with color; wind direction – with the orientation of the bars; probability – with the size of the bars.

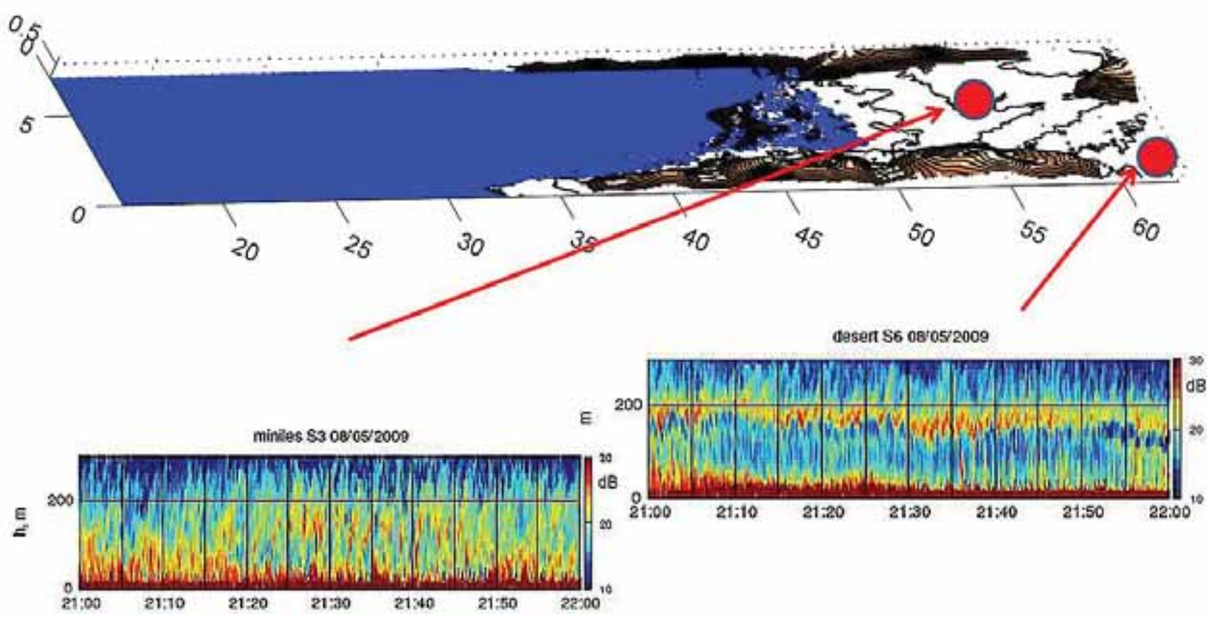

Figure 3. Two simultaneous records from SODAR at the automatic weather station (AWS) S6 near the Kongsvegen glacier's summit (right) and at the AWS S3 at the middle of the glacier (left). The turbulent layer of the katabatic wind is seen in a high level of the sound echo (red signal). The data provided by R. Kuznetsov.

Fine resolution turbulence resolving simulations could clarify the interplay of different mechanisms driving the wind in the area. Although the katabatic winds have been studied for many years, it is still a challenge to simulate them in any type of models (Axelsen and van Dop, 2006). We utilized the turbulence-resolving model PALM (Raasch and Schroeter, 2001; Castillo et al., 2009). The model was run in a selected rectangular area (Figures 1 and 2) with periodic boundary conditions. In order to minimize the effect of the boundary conditions, the model domain was mirrored relative the glacier summit and an equally large section of the flat surface was added. The constant surface kinematic heat flux of 0.1 K m/s was chosen for the flat (ocean) surface thus representing a strong surface heating from the open water areas. The constant surface cooling of -0.02 K m/s was chosen for the elevated (land and glacier) surface thus representing a strong surface cooling from the land areas. The model resolution was 60 m for horizontal dimensions and 10 to 20 m in the vertical direction. The experiments were run for 12 hours out of which the last 6 hours were used for analysis. One should note that the analysis of the hours 3 to 6 of the experiments gives almost the same results. It was observed that after about 3 hours the flow wind speed and statistics saturate and further fluctuate around the same state. In order to exclude the mechanical effects associated with the mean wind channeling in a narrowing canyon, the mean wind has been set to zero. Thus, in the simulations, the air flow is solely caused by the horizontal temperature gradient created by the differential cooling/heating at the surface.

Figure 4 shows the vertical slices of the mean wind and temperature field averaged across the valley. The tong of cold (blue) air near the surface is clearly recognizable on the plots. The dotted line shows the wind inversion layer where the wind direction changes. Its elevation is about 600 m and remains fairly stable over the 23 hours of simulations. The wind speed e-folding height (i.e. the height of the layer where the wind speed decreases e-times as compared to its maximum value) is about 300 m. These numbers are in good agreement with in situ data presented above but disagree with the IGRA climatological analysis. Moreover, it is clearly seen that the cold temperature tong hardly reaches the distance 30 km – 25 km (on the plot), which is comparable to the distance between the glacier and the Ny Ålesund station. Thus, Ny Ålesund should have some impact from the katabatic wind as it is described in Beine et al. (2001) but this effect is comprised in a shallow layer and relatively weak. It seems reasonable to conclude that the orographic wind effect has stronger influence (in average) on the local wind climatology in the area. Comparison between panels (a) and (b) of Figure 4 suggests that even the relatively weak effect observed on the panel (a) should be attributed mostly to the horizontal temperature difference (the breeze circulation) than to the gravity drainage flow, i.e. the contribution of the katabatic effect as such to the total wind field could be rather modest. The PALM run on the panel (b) is exactly the same as on the panel (a) except for the fact that the surface is flat and therefore the flow cannot gain the energy due to the downslope acceleration.

Another simulation of the surface layer wind field in a larger area is shown in Figure 5. This PALM run has finer horizontal resolution of 15 m. The color shading approximate the age of the surface air, i.e. how long the air is in contact with the surface. As one can observe, the flow in this simulations is channeled not only in the Kongsvegen valley but in other valleys as well. There is also a regular effect of the shallow flow drainage with the maximum concentration of the old air near the edge of the glaciers. The numerical experiment in Figure 5 is the finest resolution and the largest domain simulations completed for this area up to date. The experiment shows that the winds from glaciers are of rather local nature. Already in Ny Ålesund their influence is weak.

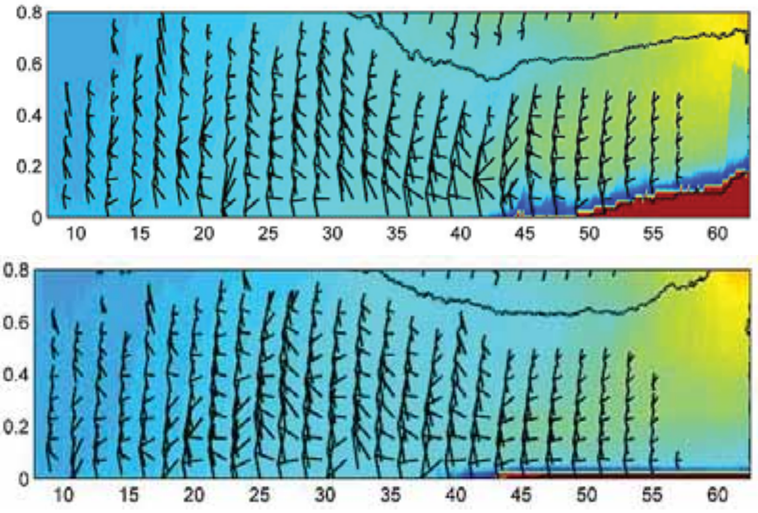

Figure 4. The simulated mean wind (given by arrows) and temperature (color) fields along the valley with (a) and without (b) underlying topography (shown by red shading). See details in text.

Conclusions

The study of the wind climatology in the area of Kongsvegen glacier, Kongsfjorden and Ny Ålesund revealed that there is a persistent outward (eartherly) flow aligned with the valley axis at the surface. In situ observations of the wind with SODAR instrument and with stations on higher elevations show the uniform wind direction from the surface to the height of about 300 m. The IGRA radiosounding data however show much deeper layer of the aligned flow in the layer up to 1.5 km height.

We studied mechanisms responsible for the structure of the wind field in the area with the help of turbulence-resolving model PALM run at the resolution of 60 m to 15 m. The model results are in good agreement with the in situ data collected by the authors and by earlier studies. But the results do not confirm the slope wind flow as the main mechanism responsible for the local wind field structure. Comparison of two identical numerical experiments with and without the slope revealed that the flow gravitational acceleration due to the difference in the air density resulting from the surface cooling is not one of the major effects shaping the wind field. The horizontal temperature difference creates almost the same wind field in the breeze circulation.

We conclude that the local wind channeling is the climatologically important process, which is able to modify the temperature, humidity and surface fluxes. At the same time the results suggest that the katabatic wind effect does not play a significant role in structuring of the wind field.

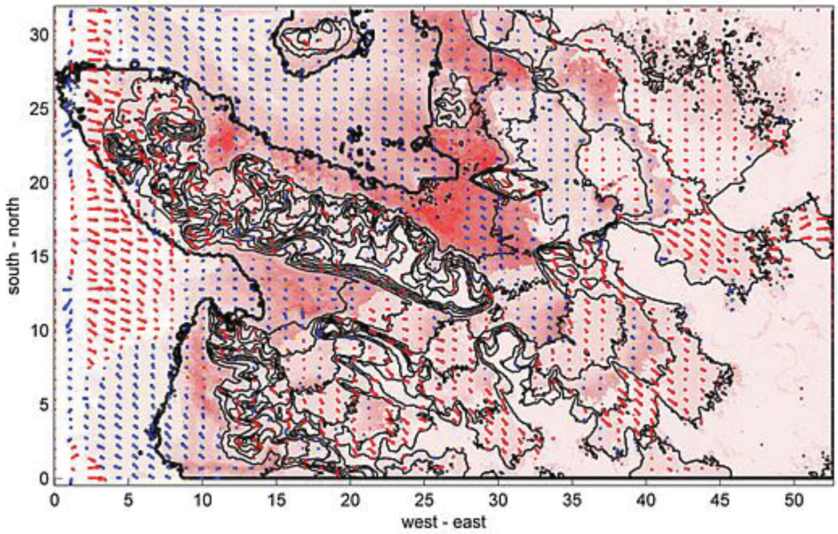

Figure 5. The near surface wind in the PALM simulations using 2048 by 1024 by 96 grid points, vertical resolution at the surface is 13 m. The shading corresponds to the concentration of the passive scalar emitted from the surface. Blue arrows correspond to the katabatic wind. The simulations were run for 6 model hours.

Acknowledgements

We thank for support the Norwegian Research Council bilateral collaboration projects: NERSC-IAP 196174/S30: “The atmospheric boundary layer structure and surface-atmosphere exchange in the Svalbard area”; PAACSIZ 178908/S30: “Planetary Boundary Layer Feedbacks Affecting the Polar Amplification of Arctic Climate Change in Seasonal Ice Zone”; NERSC-IARC 196178/S30: “Detailed studies of the Bjerknes compensation mechanism”.

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Photo: Institute of Marine Research

1.8 Variability of hydrochemical structure at the inner and outer boundaries of Eurasian Arctic estuaries.

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River discharges are the most important constituent of the hydrological and hydrochemical regime of seas and of productivity in coastal areas. It also serves as a sensible indicator of climate changes in catchment areas that are of particular importance in high-latitude seas. Reliable assessment of present conditions of the coastal and marine ecosystems in the Arctic region are also important in helping to avoid potential ecological problems caused by the planned exploitation of oil and gas deposits in the region.

This study aimed to identify the role of changes in water chemistry in the downsteams of Arctic rivers just before their estuaries. This investigation of the lower reaches of the Ob, Yenisei, Pechora, Severnaia Dvina has shown that river runoff undergoes significant changes before it reaches the inner boundary of estuaries. These changes are comparable to changes in the chemical composition of river water at the geochemical barrier or in the framework of a marginal filter. Changes in individual parameters range from 53 to 97%. The main reasons for spatial irregularities in nutrient discharge in the lower reaches of a river are changes in the dynamic characteristics of the flow (at the widening of a channel the flow velocity falls sharply, leading to the mass settling of certain substances and to changes in the chemical composition of the waters connected with them); the influence of the orography of river deposits (at the bottom there is a natural accumulation of organic substances); photosynthetic processes; anthropogenic impact.

The chemical composition of river discharges is individual to each river and is generated by the character of a catchment area. The results of scientific expeditions have revealed irregular levels of hydrochemicals along the course of the rivers and over their cross-sections. In spite of essential mixing waters entering from other parts of a catchment retain their hydrochemical features in the main channel for some distance. This feature can be observed at both inner and at outer of estuary boundaries. High concentrations of nutrients tend to be localized at deeper channel line stations in warm seasons. The highest concentrations of nutrients are often deposited on river-banks during cold seasons.

On the basis of the data obtained in the course of several seasons (1993 – 2005 – 2007 – 2010) we can conclude that a zone of river-sea interaction drifted considerably to the North.

Theme session II: What effects can be expected on the ecosystem?

2.1 Fishery and oceanographic aspects of performance of the Barents Sea ecosystem and the experience with their application by the ICES AFWG

Oleg Titov (Keynote)
Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Murmansk,Russia

One of the most important practical and theoretical problems related to studies of marine ecosystems is prediction of recruitment levels in commercial fish populations. An experiment on application of the ecosystem approach for prediction of Northeast Arctic cod recruitment abundance was modeling with the use of data on physical and chemical status of the environment (Titov, 1999, 2001). The models (Titov *et al*., 2005), as well as several other statistical models (e.g. Borisov and Bulgakova, 2002; Svendsen *et al*., 2007), have been compared by the ICES Arctic Fisheries Working Group (AFWG) and adopted for practical use. Thus at present, natural processes, influencing the dynamics of the marine ecosystem, are taken into consideration when predicting levels of cod recruitment. This leads to increased prediction accuracy of recruitment abundances of cod and, correspondingly, to decrease in error at prognostication of total allowable catch (TAC). Based on the experience gained during the development of prediction models the physical and chemical processes in the Barents Sea ecosystem, which reflect the impact of climate change on the cod population, are discussed.

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2.2 From the Barents Sea to the Arctic Ocean

Harald Loeng
Institute of Marine Research, Bergen, Norway

Physical factors that make arctic marine ecosystems unique are a very high proportion of shallow continental shelves, dramatic seasonal change, low temperature, extensive permanent and seasonal ice-cover, and a large supply of freshwater from rivers and melting ice. Because of these conditions, many of which are challenging for marine biota, arctic marine ecosystems have a large number of specialists, many of which are not found elsewhere. These organisms have through time been able to adapt to the environment, they are still challenged by extreme inter-annual variations.

The possible pathways by which climate variability may affect ecological processes are many and vary across a broad range of temporal and spatial scales. Climate variability affects fish both directly through physiology, including metabolic and reproductive processes, as well as through affecting their biological environment (predators, prey, species interactions) and abiotic environment (habitat type and structure). Furthermore, ecological responses to climatic variation may be immediate or lagged, linear or nonlinear, and may result from interactions between climate and other sources of variability.

The presentation will focus on physical and biological characteristics of Arctic Ocean and the Barents Sea, and how ecosystems interact. There is ample evidence of the effects of climate variability on the marine ecosystems, e.g. the response of the abundance and distribution of fish species associated with long-term temperature changes. These occur as direct physiological responses as well as indirectly through effects on the prey, predators or competitors. However, many aspects of the interaction between the atmosphere and the ocean, and between climate and the marine ecosystem require a better understanding before the high levels of uncertainty associated with present predicted responses to climate change can be significantly reduced. This understanding can only be achieved through monitoring and research. The later should include comparisons between and among other sub-Arctic and Arctic regions.

Photo: Institute of Marine Research

2.3 The Polar Front and its influence on the Barents Sea's ecology

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The International Polar Year (IPY) consortium Ecosystem Studies of Subarctic and Arctic Regions (ESSAR) focused upon the biology of the Arctic and was lead by Norway under the then GLOBEC (now IMBER) regional program Ecosystem Studies of Sub-Arctic Seas (ESSAS). This consortium studied various effects of the physical forcing on sub-arctic and arctic marine ecosystems and consisted of 10 separate projects from 7 countries. The Norwegian component of ESSAR, called NESSAR, was to quantify the impact of climate variability on the structure and function of Arctic marine ecosystems of the Nordic and Barents seas in order to predict the ecosystem response to possible future climate change, with particular focus on the fronts separating warm and salty Atlantic waters from the cold and less saline Arctic waters. Of special interest was how and why fish use the fronts to feed, in the case of the Barents Sea, the fish species of interest was capelin. As part of this interdisciplinary program, NESSAR mounted intensive field studies from the RV Jan Mayen of the physical and biological processes at the Arctic Front in the Barents Sea using state-of-the-art instrumentation and methods during August of 2007 and in April-May of 2008. Instrumentation included CTDs, bottle samples, autonomous gliders, turbulence profilers, Fast Repetition Rate Fluorometer (FRRF), spectrophotometer, a towed body (ScanFish) equipped with a fluorometer, CTD and Optical Plankton Counter (OPC), phytoplankton net, benthic graps and tows, various zooplankton nets, and mid-water trawls for fishing.

The Polar Front in the western Barents Sea is topographically steered, hugging the southern slope of Spitzbergen Bank located south of Spitzbergen and the western slopes of Great Bank (Storbanken) and Central Bankto the northeast and east of Spitzbergen Bank, respectively. During the NESSAR Project in August of 2007, sampling began in the vicinity of Hopen on Spitzbergen Bank but latter moved over to Great Bank where we obtained our most complete dataset. In 2008, we decided to sample earlier in the production cycle, which would allow us to compare spring with the summer conditions observed in 2007, as well as possibly observe the effects of the ice edge on the Polar Front. Unfortunately, the sea ice prevented us from sampling the front on Great Bank in 2008 and therefore most of the measurements were taken on Spitzbergen Bank.

The Polar Front was observed on the slopes of the two banks as anticipated. The front is density compensating, i.e. there is a strong horizontal gradient in both temperature and salinity, but not in density. This is because of density compensation of the hydrographic properties of the two adjacent water masses. Strong interleaving of the water masses along isopycnals was observed. There was a slight increase in the turbulence levels in the vicinity of the front but these were still relatively weak. The lack of strong mixing at the front meant that nutrient levels were not elevated there during the summer. Consequently, there was no indication of elevated primary production at the Polar Front on an annual basis. We concluded that the front is no more or less important from a primary production perspective than other regions in the Barents Sea. This conclusion was supported by several other pieces of evidence. First, measurements using the FRRF, which provides an index of primary production, showed no increase in the vicinity of the Front. Second, satellite imagery showed no increase of chlorophyll-a or primary production at the front over the year. Third, there was no increase in the light absorption spectra by colored dissolved organic matter (cDOM) as is usually found in high production fronts. Finally, benthic samples showed no increased production below the front, indeed if anything it was slightly lower than observed on either side of the front.

During the summer sampling in 2007, the highest phytoplankton biomass was observed in the surface layers of the Atlantic waters where a bloom of *Emiliana huxleyi* was found. On both Great Bank and Spitzbergen Bank the fluorescence data across the front showed the vertical distribution of phytoplankton biomass gradually descending as one moved from the Atlantic into the Arctic waters. In the latter, the highest concentrations were located subsurface near the pycnocline. There was no increase in chlorophyll-a as we crossed the front. In April-May of 2008, high phytoplankton biomass was found in the low salinity waters on the Spitzbergen Bank formed from melting sea ice and very low biomass in the Atlantic waters. Again there was no increased phytoplankton biomass at the front. Modelling studies of the region suggested that in addition to blooms being initiated by increased stratification through melt water, they may also be initiated by stratification caused by rapid increases in the density of near bottom waters. These dense bottom waters are formed through brine rejection from sea ice and appear in the spring through horizontal advection. Confirmation of this hypothesis is not yet established, however.

If the Polar Front is not a region of high primary production, what effect does it have on the marine ecosystem? The front forms an important boundary in terms of community structure with generally different species assemblages in the Atlantic and Arctic waters. Many species typically are confined to one or other of the water masses, but for some species the front is “leaky” in that they can be found on both sides to the front. There are also some species that appear to inhabit both Atlantic and Arctic water masses, species such as capelin. In addition to the Polar Front being an ecological boundary, our sampling during 2007 on Great Bank suggests that the front may further structure the biology. OPC data from ScanFish transects across the Polar Front indicated that the size structure of the zooplankton samples varied horizontally. The smallest size zooplankton were located in the vicinity of the front, with the size of the zooplankton increasing with distance from the front towards the Arctic Water and the top of Great Bank. In addition to this, capelin samples collected from mid-water trawls indicated that the smallest capelin were located in the front and the larger capelin in the Arctic Water on the bank. Cause of similar trends in the size of the zooplankton and capelin with distance along the across front transect is unclear at this stage but may be related to the capelin having to be in an area with the correct size of prey. This is being explored through diet analysis from stomach samples taken from fish caught in the mid-water trawls.

Many of the results of the NESSAR project will appear in a special issue in the Journal of Marine Systems in 2012.

R/V "Jan Mayen" photo: Institute of Marine Research

2.4 Baseline mapping: a necessity for an assessmentof effects on climate changes on benthic communities

Lene Buhl-Mortensen, Pål Buhl-Mortensen, Arne Hassel, Børge Holte, Lis Lindal Jørgensen, Anne Helene Tandberg
Institute of Marine Research, Norway

The MAREANO mapping programme collects and describes the benthic biodiversity, the physical environment and the nature types in Norwegian waters. Since 2006, seabed areas (25 - 2700 m depth) in the Barents Sea and the northern parts of the Norwegian Sea have been documented using video, beamtrawl, epibenthic sled and grab. This has produced a comprehensive dataset with a total of 607 video-mapped and 125 benthos-sampled stations.

The data produced by the MAREANO program is to be used in the Norwegian governmental management of the Norwegian marine areas. The main task of the MAREANO program is to provide new knowledge about the bottom habitat through gaining geological and biological information, and also environmentally-related data. The results have supported the implementation of the Norwegian Barents Sea management plan and its revision in 2010. MAREANO is as well included in an EU project that focuses on management of marine areas (MESMA). The information provides a baseline for management of the environment and biodiversity.

Using the extensive data of MAREANO as a baseline for future comparisons will enhance the possibilities of detecting environmental-related biodiversity-changes. Comparison with historical records may provide an early indication of climate related biological effects within benthic ecosystems. In order to prepare such use of MAREANO data, the results have been compared with the compilation of historical records of coastal samples registrered by Brattegard and Holthe (2001).

We see a tendency of a north-shift of the boundary for boreal species compared with Brattegard and Holthe (2001). This is confirmed by Brattegard (2011), and is in compliance with other reports of north-shifts of species-distributions. (Ching-Chen *et al*, 2011). But because MAREANO covers a larger area and deeper range of depth than Brattegard and Holthe (2001), our result needs to be further evaluated and made more comparable. We acknowledge that the lack of taxonomists, both earlier and today, might have influenced the understanding of both historical and present distribution of taxa.

In order to bring this work beyond the presence/absence data, which were produced for this study for comparison with Brattegard and Holthe (2001), the next step will be to include data on depth- and spatial distribution, together with more thorough studies of historical records.

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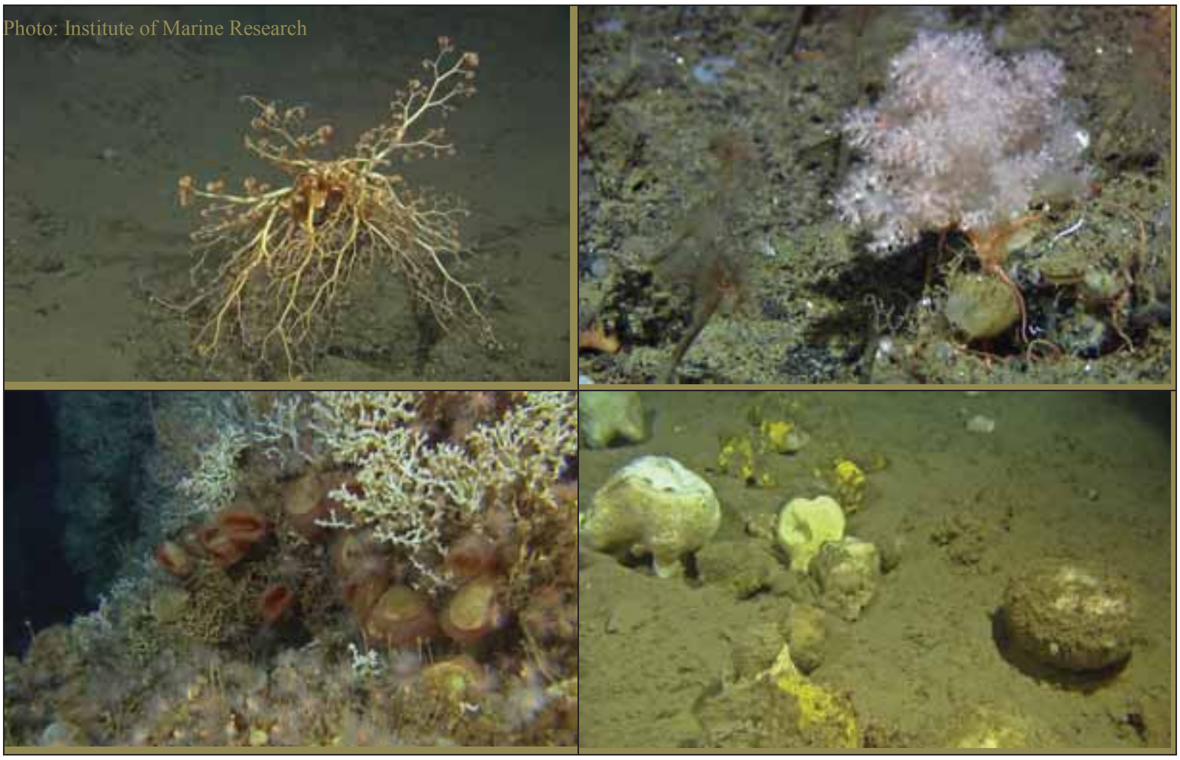

Photo: Institute of Marine Research

2.5 Long-term changes of macrozoobenthos in the southeastern Barents Sea

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The Barents Sea is one of the most extensively studied marine arctic areas. The archives of the Polar Research Institute of Marine Fisheries and Oceanography (PINRO) in Russia contain vast amount of information on quantitative and qualitative benthos research in the area. The large scale benthos surveys carried out in the Barents Sea in 1920s, 1960s and 2000s allow us to observe the long-term changes in bottom communities due to various factors.

We examined effect of temperature on structure and production characteristics of benthic communities in the southeastern Barents Sea located at the border of the arctic and boreal biogeographic regions. This area is of particular interest due to its minimal exposure to apparent anthropogenic factors and invasive species.

Figure 1 illustrates changes in total biomass of benthic communities in the Southeastern Barents Sea during the cold (the 1920s), intermediate (the 1960s) and warm (the 2000s) temporal periods. During the cold and the warm periods the temperature remained consistent, where as during the intermediate period the cooling time followed the long warming. The cold period was characterized by high biomass of benthos with the highest proportion of arctic species as compared to other climatic periods. The intermediate period stand out by reduced benthic biomass with the increased proportion of cosmopolitan species. The warm period was characterized by high total biomass of benthos. However, in contrast to benthic biomass of the cold period the high benthic biomass of the warm period was attributed to increase in proportion of boreal-arctic species.

Figure 1. Total biomass of benthos in the south-eastern Barents Sea in 1924-1928, 1968-1970 and 2004-2006.

We also observed changes in ecological and trophic structures of benthic communities during each period. The increase in proportion of epifauna and decrease in proportion of infauna during study period may be explained by increased speed of currents and, consequently, elevated substrate hardness. Perhaps speed of currents increase may be explained by suggestion that currents in the Barents Sea demonstrate higher speed in warm years than in cold ones. The increase portion of sestonophagous species biomass also may corroborate the influence of the currents speed increase on the benthic community. The value of subsurface deposit feeders was the highest during the intermediate temporal period, which may reflect negative changes in benthic community structure during that period.

Our results suggest that the stability of temperature has more importance on structure and abundance of benthic communities of the Southeastern Barents Sea than the actual temperature values. The other factors, such as current speed, should also be considered.


Photo: Institute of Marine Research

2.6 Pan-Svalbard growth rate variability and environmental regulation in the Arctic bivalve Serripes groenlandicus

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Growth histories contained in the shells of bivalves provide continuous records of environmental and biological information over lifetimes spanning decades to centuries, thereby linking ecosystem responses to both natural and anthropogenic climatic variations over a range of scales. The goal of our study is to advance the understanding of the mechanisms by which climatic and environmental conditions regulate bivalve growth in Svalbard by simultaneously applying sclerochronological analyses of shell ring patterns to several sites over a common time period.

We examined growth rates and temporal growth patterns of 260 individuals of the circumpolar Greenland Smooth Cockle (*Serripes groenlandicus*) collected between 1997 and 2009 from 11 sites around the Svalbard Archipelago. These sites encompass a range of oceanographic and environmental conditions, from strongly Atlantic-influenced conditions on the west coast to high-Arctic conditions in northeast Svalbard. This breadth of samples provides the opportunity to study temporal and spatial variation in bivalve growth in a regional context and identify environmental drivers that are site-specific and/or are regionally consistent. Our specific goals were: (1) to assess growth rates and temporal growth patterns among sites of contrasting habitats and environmental conditions, specifically testing the null hypothesis of no differences among sites, and (2) to identify the proximal factors regulating growth at single sites and across the region.

Individual clams ranged in age from 3 years to 30 years old. The average site chronology length was 23 years, with individual chronologies ranging from 34 years in Kongsfjorden to 17 years in Storfjorden. The overall growth rate was highly variable among the 11 sites; the fastest growing population (Smeerenburgfjorden) had three to four times faster growth rates than the slowest growing population (Storfjorden). Comparison of growth performance among stations revealed a significant difference in growth rate among stations (ANOVA, $P<0.001$). Pairwise comparisons revealed 5 different site groupings that corresponded positively with proximity to water masses, with those populations in Atlantic water masses or closest to the West Spitsbergen Current exhibiting the highest growth rates.

We also developed, using a standardized growth index (SGI), growth chronologies up to 34 years in length extending back to 1974. SGI patterns exhibited substantial inter-site variability, with pairwise site correlations (R) spanning +0.60 to -0.77. Rijpfjorden SGI was significantly, and positively, correlated to 5 other sites. The temporal growth pattern at Rijpfjorden was also broadly representative (R=0.81) of the entire dataset. Despite inter-site variability, there were also some common temporal features. Most sites show increasing SGI from the mid-1980's through the early 1990's followed by declining values after 1995 or 1996. This multi-annual temporal pattern is more evident in the aggregated SGI from all stations, which follows a cyclic pattern. Growth increased from a minimum in 1981 and then steadily from 1986 to a peak in 1994. Subsequently, SGI began a general decline lasting until 2005, with an interim maximum in 2001.

This temporal SGI pattern was consistent with phase-shifts in large-scale climatic drivers, and interannual variability in SGI was also related to local manifestations of the large-scale drivers, including sea temperature and sea ice extent. Using multiple regression models, we were able to account for up to 84% of interannual variability in SGI time series patterns with known environmental variables. While there were site-related differences in the specific relationships between growth and environmental parameters, the aggregated dataset indicated an overriding regional driver of bivalve growth: the Arctic Climate Regime Index (ACRI).

In summary, our regional comparison of growth rates and patterns established a 34 year chronology encompassing warmer and cooler phases of large-scale climate oscillations, and a large range of environmental conditions across the Svalbard Archipelago. There was substantial site-to-site variability in growth rates, indicating that bivalve growth, in this case of the Greenland Cockle, is sensitive to environmental variability and is therefore a valuable proxy of ecosystem variation. Proximity to Atlantic water was the primary determinant of growth rate, with a strong influence on juveniles, while the large scale climatic oscillation (ACRI) was the primary determinant of temporal growth patterns. Both of these factors control growth through their influence on food supply to the benthos. Rijpfjorden seems to represent the range of growth responses across Svalbard, while the temporal trends toward decreased SGI in the past decade suggest that climate change in Svalbard will not be associated with increased growth rates of this species. Even though our results provide a temporally and spatially extended view of benthic ecosystem structure over several climatic cycles, further studies are needed to understand the specific responses of populations and communities to climate variability in the Arctic. These results demonstrate that sclerochronological proxies can be useful retrospective analytical tools for establishing baselines of ecosystem variability and for identifying key ecosystem drivers across spatial and temporal scales.

For more detailed analyses and presentation of results, please see two refereed publications:

Ambrose, W.G., Carroll, M.L, Greenacre, M., Thorrold, S., McMahon, K. 2006. Variation in Serripes groenlandicus (Bivalvia) growth in a Norwegian high-Arctic fjord: Evidence for local- and large-scale climatic forcing. Global Change Biology 12:1595-1607.

Carroll, M.L., Ambrose, W.G., Levin, B.S., Locke, W.E., Henkes, G.A., Hop, H., Renaud, P.E. 2011. Pan-Svalbard growth rate variability and environmental regulation in the Arctic bivalve Serripes groenlandicus. Journal of Marine Systems 88:239-251. doi: 10.1016/j.jmarsys.2011.04.010

2.7 Climate induced changes in primary production and pelagic-benthic coupling in the northern Barents Sea

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Despite of the rapid changes in Arctic Ocean physical forcing and ecosystem function, quantitative ecological knowledge is limited and physically-biologically couple models are few. This is also true for the Barents Sea, the best-known Arctic ecosystem. As a first step an evaluation of future development of biogeochemical cycling has thus to be explored through examination of conceptual models that address climate warming and ecosystem development. Here we present three conceptual models of biogeochemical cycling and climate warming in the seasonal ice zone (SIZ) of the Arctic Ocean, based upon experience from the Barents Sea. They aim at to understand, in a conceptual and semi-quantitative manner, the future develop of productivity and the fate of carbon in the future Arctic Ocean, in particular the pelagic-benthic coupling. The SINMOD model will then be applied to provide quantitative estimates on the time variation and spatial distribution of primary and secondary production. We speculate that the largest changes will take place in a) the northern sections of today's seasonal ice zone, which will expand to cover the entire Arctic Ocean (increase in productivity) and b) the southern section that will get exposed to more thermal stratification (decrease in productivity). Due to the thinning of the ice, the significance of ice algae for the total primary production may increase in the central Arctic Ocean, but decrease in the outer SIZ. The blooms of ice and plankton algae will stretch over longer periods of time, supporting increased pelagic retention processes. The weakening of today's highly episodic primary production and algae blooms in the SIZ will result in lower food concentrations for heterotrophic organisms and more recycling of available energy, changes in life cycle strategies and less variable vertical export. Freshening of the Arctic Ocean, nutrient limitation and a prolonged growing season will shift the community composition towards smaller phyto- and zooplankton forms, more retention and decrease seasonality in pelagic-benthic coupling.


Photo: Institute of Marine Research

2.8 Trophic structure and carbon flow in Arctic and Atlantic regimes around Svalbard revealed by stable isotopes and fatty acid tracers

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Carbon flow and trophic structure of zooplankton and benthos in different marine climatic regimes around Svalbard were assessed by stable isotopes and fatty acid trophic markers. Our findings were related to differences in ice cover and proportions of ice algae vs. phytoplankton carbon sources as well as to differences in pelagic and benthic community composition and biomass.

Ice algal carbon sources were particularly important for benthic soft-bottom communities, in addition to phytoplankton carbon sources, the latter being most important for zooplankton. The proportion of ice algal vs. phytoplankton food sources increased from Atlantic- to Arctic-dominated waters and with duration of ice cover. Areas dominated by consolidated pack ice had particularly low zooplankton and benthic biomass, reflecting overall low algal production. However, seasonally ice covered areas until June/July, had on average 2-3 times higher benthic biomass than Atlantic-dominated open waters. Zooplankton biomass differed little among areas, but was positively correlated to benthic biomass. This suggests that both pelagic and benthic components benefit from increased production period and biomass of ice algae as long as the time of ice break-up is not delayed beyond July/August. Areas of particularly high pelagic and benthic biomasses were dominated by Arctic organisms with opportunistic feeding strategies.

Photo: Institute of Marine Research

2.9 Double menu for *Calanus* in the Arctic: what are the life history consequences in a changing climate?

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Many animals feed on different food sources at different times of the year. Temporally separated food may constrain growth and reproduction, but may also offer opportunities that are worth exploiting compared to a single seasonal food source. The bimodal primary production in the Arctic, with ice algae production taking place on the underside of sea ice and a pelagic primary production occurring after the sea ice has melted, is one case of temporally separated food sources. Herbivores, such as calanoid copepods, feed on both these phytoplankton blooms. In the arctic copepod *Calanus glacialis* the adult generation produces eggs while feeding on ice algae in spring while the offspring generation feeds on the later pelagic bloom. Matching the occurrence of life cycle stages with the two food sources is among the challenges of this way of life. Here we model the life cycle of a calanoid copepod, presented with a spring and summer food source, the ice algae and the pelagic phytoplankton bloom, respectively. We predict optimal annual routines found by dynamic programming, including the timing of growth, reproduction and seasonal migrations, and compare with previous models where a single pelagic phytoplankton bloom was modelled. With declining sea ice distributions in the Arctic, the ice algae bloom may become insignificant and adaptations to this food source maladaptive. We discuss potential changes caused by a move from a twofold to a single food source, or by a mismatch with either of the two food sources.

The modeling approach and much of the ecological and evolutionary reasoning built on for this work in progress are extensions of our previous work, most notably the work reported by Varpe et al. (2007, 2009). Parameterization of metabolic rates, mortality, feeding rates and so forth are kept as for *Calanoides acutus*, as in this earlier work. This Southern Ocean species is similar to *Calanus glacialis* in size as well as overall life history.

References

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2.10 Plasticity in timing of reproductive events in *Calanus glacialis*: a Pan-Arctic perspective

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The Arctic herbivore, *Calanus glacialis*, is a key species in Arctic marine ecosystems converting low energy carbohydrates and proteins from ice algae and phytoplankton into high energy lipids, which makes it an extremely lipid-rich food item for higher trophic levels. With a circumpolar distribution, *C. glacialis* experience a large range of environmental conditions. Since much of the distributional area of *C. glacialis* is seasonally ice covered *C. glacialis* can feed on on two primary production events: the ice algae bloom and the open water phytoplankton bloom that occurs after the ice break up. Since occurrence of these blooms is coupled to ice conditions duration and intensity of ice algae and phytoplankton bloom differ widely between regions of different ice regimes. Reproductive events, growth, lipid accumulation, seasonal and diel vertical migration, and spatial aggregations are timed with the Arctic ice algal and phytoplankton bloom and we can expect to find differences in life history traits between populations of the same species of areas that differ with regard to ice cover and occurrence, duration and intensity of both ice algae and phytoplankton.

Based on data collected within the IPY projects PanAME, CLEOPATRA and CFL we have investigated how variability in these two food sources influences the life history strategy of *C. glacialis* in the ice-covered seas of the Canadian Arctic (Amundsen Gulf) and European Arctic (Svalbard), two regions that differ with regard to ice conditions, hydrography and light regime and consequently primary production regimes.We focused on plasticity shown in life-history traits closely interrelated to food availability such as timing of reproduction (spawning, occurrence of young life stages), timing of seasonal vertical migration, overwintering stage and generation time.

In Amundsen Gulf and a high Arctic fjord in Svalbard *C. glacialis* utilizes the ice algae bloom to fuel spawning in spring while growth and development of the new generation is supported by phytoplankton blooms in spring and summer. Differences in onset of spawning, vernal ascent and autumn descent and overwintering stage between populations can be related to variability in ice conditions and hydrography and consequently onset of ice algae and spring bloom in the these regions. Data from an ice free high Arctic location (Kongsfjorden, Svalbard) indicate that *C. glacialis* can sustain successful development despite the lack of an ice algae bloom by adapting the strategy of capital breeding. Plasticity in life history traits observed in our data is compared with previously published data on population dynamics of *C. glacialis* from Greenland and the White Sea to presents a more a pan-Arctic perspective of the life cycle strategy of *Calanus glacialis* in ice covered waters.

2.11 Studies of early development of Barents Sea capelin in different temperature conditions

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Abstract

Capelin is an ecologically and commercially important fish species and a general increase of temperature in the Barents Sea, especially on the spawning grounds, may influence capelin recruitment. However, studies of temperature effects on capelin egg development and embryo malformations are very scarce. In the present study, the embryonic development of about 4000 artificially fertilized eggs from 77 capelin pairs were recorded individually. Eggs were kept at two constant temperatures (5°C and 8°C) during the incubation period and until yolk sac resorption. Malformations were described and analysed with regard to temperature conditions. Most of the observed malformations were incompatible with larval survival beyond hatching and yolk sac resorption. Our results showed that the occurrence of malformations varied from ca. 6.6% to 20% among the various groups of spawners and temperature conditions. Smaller fish seemed to produce more eggs with malformations with higher mortality. A significant increase of mortality from 7.4 to 13.6% was observed at higher temperature. The ecological implications of reduce incubation time are unknown, but could be substantial with increasing of temperature at the spawning grounds.

Keywords: capelin, egg, embryonic development, temperature and malformation

Introduction

The largest stock of capelin in the world is found in the Barents Sea, where it plays a key role in the ecosystem and is also an important commercial fish species. During the last 40 years the capelin stock underwent huge fluctuations in size: from below 100 thousand tonnes to above 8 million tonnes.

Capelin is a short lived species and mature fish of age 3-4 years, more seldom 2 and 5 years, migrate from the feeding areas in the northern parts of the Barents Sea, to the spawning areas near the Norwegian and Murman coasts during winter (Collet 1903; Rass 1933; Pozdnyakov 1959; Sætre and Gjøsæter, 1975; Gjøsæter 1998). The majority of capelin spawns during February-April, while some capelin spawn along the eastern Finnmark and Murman coast during summer. The significance of summer spawning is poorly known. Temperature conditions along the migrations paths and on the spawning grounds are generally presumed to be an important factor influencing spawning migration and spawning time (Rass 1933; Pozdnyakov 1960; Sætre and Gjøsæter, 1975; Gjøsæter 1998). During cold years a western spawning migration of capelin was often observed, while during warmer years an eastern spawning migration was more common (Rass 1933; Pozdnyakov 1959; Gjøsæter 1998). However, in the recent, very warm period, a western distribution of spawning areas has been observed, for instance in 2008 (Eriksen at al. 2009). Several studies describe temperature condition on capelin spawning beds: spawning occurred at temperature ca 2 °C near the Finnmark coast in 1931 (Rass 1933), 1.7-2.7°C along the Finnmark and Murman coasts in 1953-1955 (Pozdnyakov 1959), 1.5 - 6.5° along the Finnmark in 1971-1974 (Sætre and Gjøsæter, 1975), 4.1 – 7.4 °C in 2008 and 4 – 6 °C in 2009 north of Finnmark coast (Eriksen et al. 2009).

Both high and low temperature can have a negative impact on egg development, depending on the species (Bobe and Labbé 2010). However, studies of temperature effects on capelin egg development are very scarce. Gjøsæter and Gjøsæter (1986) constructed hatching curves for artificially fertilized egg kept at various temperatures (2°C, 4°C and 7°C), and found that average incubation time was twice as long at the lowest temperature (59 days) compared to the highest temperature (25 days). Friðgeirsson (1976) studied egg development of capelin from the Icelandic stock kept at 7.2°C, which hatched after 21-23 days. It has been shown for various salmonid species that temperature play a vital role for the quality of eggs (Bobe and Labbé 2009). In brook trout (*Salvelinus fontinalis*) temperatures of 12 °C and above significantly reduced hatching rate and significantly increased the incidence of embryonic deformities (Hokanson et al., 1973).

Capelin may have two modes of spawning; beach spawning and deep water spawning. A local fjordic stock found in Balsfjorden, Norway, spawn at beaches. Præbel et al. (2009) studied the temperature and salinity conditions in the intertidal spawning habitat of that stock, and suggested that beach-spawned capelin eggs have evolved an array of biological adaptations to survive the unpredictable physical conditions of an intertidal habitat. Several studies on embryology of several teleost fishes showed spontaneously occurrence of malformations (Nicholas 1942; Oppenheimer 1947; Svetlov 1960; Vladimirov 1975; Longwell 1977; Laal 1981). Unfortunately, possible temperature effects on malformations during capelin embryo and larval stages are poorly understood. Different malformations of eggs and larvae were described based on experimental and field work (Longwell and Hughes 1980; Kjørsvik et al. 1984; Stene 1987; Solemdal et al. 1998; Makhotin et al. 2001). Wallin and Nissling (1988) and de Braak (1994) studied artificially fertilized eggs with asymmetric cleavage, using NUNC-trays. Since then, this methodology was used in several studies of cod egg development (Solemdal et al., 1998; Makhotin et al. 2001). Makhotin et al. (2001) studied the pelagic cod eggs from different spawners, and concluded that the mortality was significantly higher among eggs from first-time spawners. Capelin spawns only once (Christiansen et al. 2008), seldom two times during its lifetime, and therefore the quality of spawners is an important factor influencing the quality of eggs and larvae.

The aim of this work is to study the dynamics including death rates of embryos and larval stages of capelin, as well as occurrence of malformations. In the present paper we describe an experiment where we observed the development of 3850 eggs from 77 capelin pairs; studied the temperature effect on mortality and abnormal development of embryo, and compared results with earlier findings.

Materials and methods

Choice of temperatures for the experiment

Observations during the last 100 years have shown that temperature on capelin spawning beds have varied from 1.5°C (1931) to 7.4°C (2009). We chose two temperatures for our investigation: 5°C, which is probably associated with normal temperature condition during recent years, and second 8°C, higher than ever observed, but probably realistic if the temperatures in the Barents Sea will continue to rise in the future as a result of global warming, and if the capelin will continue to utilize the same spawning areas as has been used up to now. This high temperature may point out possible effects of increased temperature on spawning success by survival of eggs. Additionally, our experiment will supplement Gjøsæter and Gjøsæter (1986) experiment with three temperature conditions (2°C, 4°C and 7°C).

Collection of biological data

Ripe pre-spawning capelin were collected during capelin fishery on board the Norwegian purse seiner MS "Libas" during the period 16–21 March 2009. Catches were taken by purse seine north of Nordkapp (72°08N, 26°15E). After the capelin were pumped on board, individual fish were inspected, and those found sufficiently mature were collected immediately and separated by sex based on outer sex characters. Spawners consisted of 3 and 4 years old fish, and, as expected, females (13.0-18.0 cm) were smaller than males (16.0-19.5 cm) and 3-years old fish were smaller than 4 years old fish (Table 1).

Table 1. Biological parameters of females by age and length groups (below and above average fish length, respectively).

Age of females	Size group and fish length cm	Mean weight gram	Mean length cm	Number of fish
Age 3	Small (13.0-16.0)	13	15.1	28
	Large (16.5-18.0)	18	16.6	26
Age 4	Small (15.5-16.5)	16	16.1	8
	Large (17.0-19.5)	21	17.4	15

Females and males were kept in different tanks (1m*1m), and sea water was pumped into the tanks continuously with speed ca 100 litres per minute. The tanks were fitted with aeration systems, where oxygen was constantly infused. Between 10 and 15 females and males were taken at a time from the tanks into the on-board lab for artificial fertilization. The fish was cleaned and dried with paper towels. Eggs, followed by sperm from one single pair of capelin were stripped onto a glass slide. Some sea water was added and the glass slides were allowed to rest for 10–15 minutes to allow fertilisation. The glass slides were rinsed, first with fresh sea water, followed by sterilized sea water. Each egg was separately placed in depressions in a NUNC plate (25 eggs from a capelin pair in each NUNC plate). It took ca 1.5 days to place all collected and fertilized eggs. Totally, 154 NUNC plates (two plates from each capelin pair) were taken, resulting in a total of 3850 eggs from 77 capelin pairs. The development of each specimen was checked individually. The length and weight of each parent fish were measured, the maturation stage (Forberg 1983) was determined, and the otoliths were extracted for age determination. Unfortunately, the data on fish weight could not be used in the analysis because not all sex products were removed from the fish before weight measurement took place.

Treatment of biological materials

The NUNC plates were placed in a refrigerator (Termax KB8182) at 5 °C and 8 °C (varying by 0.1 °C in both). The eggs used for analysis of temperature effects were placed in sterilized sea water, where one plate from each pair, (1925 eggs from 77 pairs) were kept at 5 °C and a similar number of eggs were kept at 8 °C. After the fertilization experiment was finished on board the fishery vessel the NUNCs plates were transferred to the Institute of Marine Research in Bergen, and placed in cold-storage chambers, at temperature 5 °C and 8 °C varying by 0.1-0.3°C) respectively. At intervals of 2 days the sterilized water was changed in the NUNC plates.

Each egg was inspected at regular intervals (approximately 10 times) during the incubation period. Records were kept on special forms where general information like female number, NUNC plate number, and date of fertilization, was noted. In addition, individual information for each egg (embryonic stage, presence and type of malformation, egg diameter) was also noted. These paper records were put into electronic form and summarized in various tables. In addition to the written description of the larval abnormalities, some of them were photographed.

The data sets used for the analyses consisted of data of i) experiments (start and end) ii) biological parameters of parents (sex, length, weight, maturity stage) and iii) notes of embryologic stages, malformation, date of hatching and death). There are reasons to believe that the maternal effects on egg quality are stronger than paternal (Pavlov et al. 2009), since the males only supply genetic material to the egg; practically all the biomass of the egg comes from the female. In the analysis we therefore grouped data by female age and length to study if and how the physiologic condition of females influenced egg quality.

Data treatment

We divided data with regards to:

- *Temperature condition,* where 5 °C, is probable associated with normal temperature condition during recent years (see above) and 8° C, higher than ever observed, but probably realistic within a few years if the temperatures in the Barents Sea will rise according to the prognoses made by IPPC (IPCC, 2007). Hereafter we called temperature of 5°C as lower temperature, and temperature of 8°C as higher temperature.
- *Biological parameters of spawners.* All spawners (females, see above) were divided in to length and age groups 1) small and 2) large (Table 1) with regards to average length. Analysis of variance was used to evaluate differences in the sum of malformations among different size, age and temperature groups.
- *Type of malformations* was recorded. The specific malformations were analysed with regards to temperature condition, and T-test was used to evaluate differences between the different temperatures.

- We also calculated followed
- *The proportion of specific malformations* of total malformation, and the percentage of egg with malformation of total 3850 eggs.
- *Mortality* presented in number and percentage, corresponding to the embryos, which died during the experiment (from cleavage to right after spawning). We used T-test to evaluate differences between the different temperatures.

Results

During the laboratory experiment the embryonic development was recorded, and the following malformations were observed:

- Abnormal cleavage or a total absence of cleavage
- Abnormal blastula formation or a development stop after blastodisk formation
- Abnormal gastrulation, when hypoblast cells formed small disordered aggregates in the germ ring, forming two or more centres of convergence of hypoblast cells.
- A stop of epiboly process. Malformation of axial convergence of the cellular material, leading to undeveloped axial rudiment and doubling and asymmetry of various sites of axial structures of the germ.
- Necroses were found in different parts of the central nervous system. These led to many malformations, including microcephaly (embryo with underdeveloped head), microps (embryo of very small size), body curvatures, and so on. Normally, the observed necroses did not lead to rapid death of embryo, although almost all embryos with necrosis died at a later stage
- Hatching of abnormal pre-larvae. In the majority of cases various parts of the body showed curvatures, some of these larvae are shown at Photo 1 B.
- Death at later stages of embryogenesis without obvious morphological deviations. Very often a strong reduction of tempo of development was observed at the earlier stages.
- Death during, or right after hatching. Embryos fully or partly left the egg membrane (Photo 1, A).
- Inability of embryos to release from the egg, and embryos were alive inside the egg until yolk sac absorption.

Malformations were strongly related to the stage of early development. Most of the observed malformations during embryonic stages were incompatible with larval survival, and led to death immediately (1-4) or at later embryo or pre-larval stages (1-9). Almost all embryos with malformations during early ontogenesis died before the end of the experiment.

The incubation time ranged from 30 to 36 days at 5°C and from 22 to 24 days at 8°C ($t=58.26$, $p\leq 0.000$).. The individuals kept at lower temperature had significantly lower mortality rate than the individuals kept at higher temperature ($t=-3.19$, $p\leq 0.000$), and cumulative mortality was 7.4 and 13.6 %, respectively (Figure 1 and Table 2).

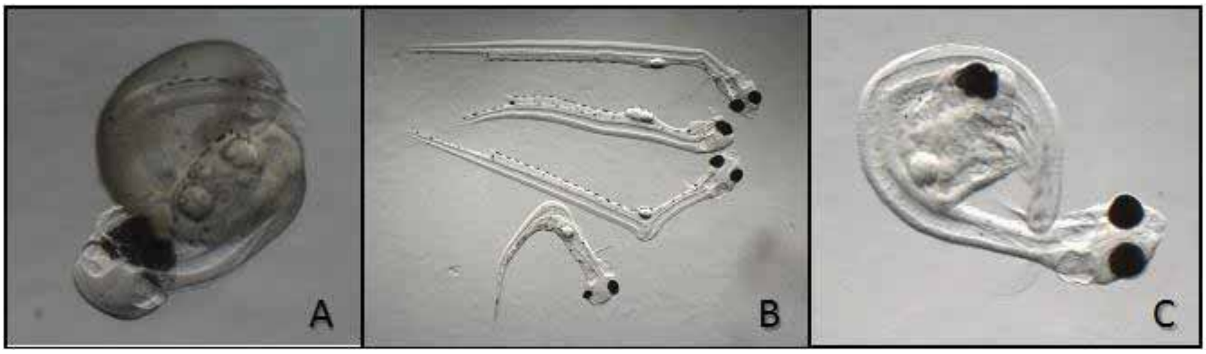

Photo 1. Some of observed malformations during capelin embryos and larval stages: A - Cyclops, B- abnormal developed larvae and C – two-headed larva, and one of heads has a single Cyclops eye.

Table 2. Occurrence of malformations of different size and age groups during different lower (5°) and higher (8°C) temperatures, and significant variation between groups shown in bold ($p \leq 0.05$).

Age of females	**Size group and fish length cm**	**Occurrence of malformation %**		**Mean length cm**	
		5 °C	**8 °C**	**5 °C**	**8 °C**
Age 3	Small (13.0-15.5)	6.6	20.0	5.6	16.9
	Large (16.0-18.0)	12.5	12.9	9.2	11.8
Age 4	Small (15.5-16.5)	15.0	15.5	10.0	14.5
	Large (17.0-19.5)	11.7	9.1	6.1	9.9
Mean		10.4	15.0	7.4	13.6

The dynamics of formation of malformations and mortality rates during incubation at different temperature conditions seems to be of general character. The peaks of malformations were observed during the first stages (cleavage and blastulation) and before and after hatching, and varied between temperatures. However, a significant increase of mortality with temperature was only found for those embryos, which died before hatching ($t= -1.67$, $p \leq 0.00$).

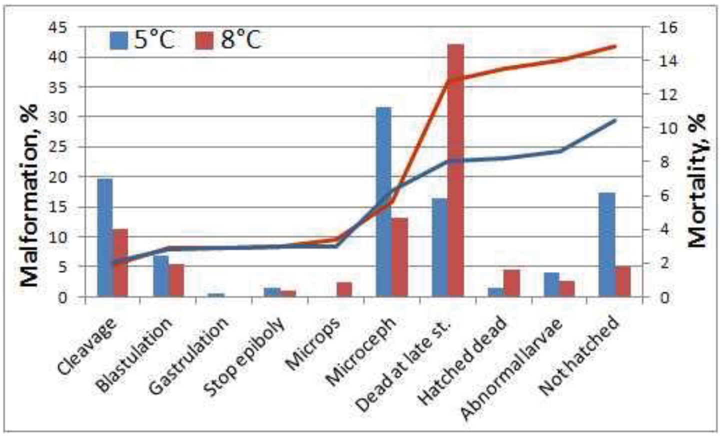

Figure 1. Proportion of specific malformation of total malformations (bars) and cumulative mortality (lines) during early ontogenesis of eggs kept at different temperatures (5°C and 8°C).

Analysis of variance indicated no significant differences in occurrence of malformation among the different size, age and temperature groups, except smaller 3 years old capelin produced almost 3 times more malformations at higher temperature (Table 2). Eggs from smaller fish of age 3 and 4 produced significantly higher number of malformations (ANOVA, $F=2.3$, $p \leq 0.05$).

Some few capelin pairs produced egg with ca. 30% of abnormal embryos, considerably more than other pairs. Malformations were recorded in form of necrosis at earlier stage, and later these embryos developed microcephaly, Cyclops or two heads (Photo 1C) , although the parents from these pairs visually seemed to be of normal condition.

Discussion

The capelin is a key fish species in the Barents Sea with regards to its ecological and commercial importance. Capelin is short lived and spawn only once, very seldom twice (Collett 1903; Rass 1933; Pozdnyakov 1960, 1962; Sætre and Gjøsæter, 1975; Gjøsæter 1998, Christiansen et al. 2008). Therefore, quality of spawners and their sex products (sperm and eggs) is crucial for survival of egg and larvae, and hence recruitment to the population (Neifakh, 1969; Ponomarenko 1973; Kimmel, 1989, Marshall et al. 1998; Hylen et al. 2008).

During the experiment we observed several malformations, which were strongly related to the specific stage of early development. The malformation recorded first was absence of cleavage or abnormal cleavage. These abnormalities represented the first peak of mortality and constituted about 15% of total malformations. Such anomalies are common for unfertilized eggs or eggs with chromosomal aberration, or egg with a genome with lack of ability for further development (Neifakh 1969; Neifakh and Timoveeva 1977, 1978; Kafiani and Timoveeva, 1964; Kimmel, 1989). In our study, the mortality of embryos during these stages was perhaps mostly influenced by lower quality of sexual products, and therefore, temperature did not have any significant effect on the dynamics of formation of malformations (Figure 1 and Table 2).

Abnormal gastrulating was recorded, and in general, the formation of anomalies was influences by errors in morphogenetic movements of various combinations of the hypoblast and the epiblast cell populations. The proportion of such malformations composed less than 1% of total malformations. Malformations characterized by stop of epiboly processes were also seldom, and composed only ca. 1 % of total malformations.

Necrotic processes were observed during the active tissue differentiation in the formation of axial structures, the increasing complexity of the morphological structure of the embryo. In this study, necroses were found in different parts of the central nervous system. Makhotin et al. (2001) suggested that the necrosis at earlier embryonic stage may lead to the formation of malformations, like microcephaly, microps and body curvatures. In this study, the formation of microcephaly, microps, cyclops, two-headed embryo/larvae, and larvae with crooked body (Photo 1) was observed. Occurrence of microcephaly was twice as high at lower temperature and was probable due to unobserved damages in the head region at earlier stages. Instances of microps were observed only at the higher temperature condition, but constituted only ca. 2% of total malformations. During the experiment we observed an increase of mortality just before or right after hatching, inability of embryos to release from the egg, or embryos wich remained inside the egg much longer than the majority of observed individuals. Occurrence of these abnormalities can be influenced by many factors, among them may be: hatching gland dysfunction and lower activity of the hatching enzyme (chorionase), reduced general motor activity due to curvature of the body or low muscle activity. However, the difference in mortality at different temperatures became prominent in the second half of embryogenesis, and increased by the end of the incubation period (Figure 1). The proportion of dead embryos before hatching was significantly higher at higher temperature. This indicated that negative effects of temperature became prominent during the mid and late embryogenesis (Figure 1).

Hatching of abnormal pre-larvae were observed, and the majority of these pre-larvae were characterized by different curvatures of the body. The formation of these deviations was a result from necrosis not possible to detect visually during earlier embryonic stages. During the experiments three of 77 capelin pairs produced sexual products of low quality, resulting in higher mortality of embryo due to malformations. This was most likely caused by genetic disorders of spawners, and did not a result from negative influence of environmental factors.

Most of the observed malformations that occurred during the embryonic stages were incompatible with larval survival. Makhotin et al. (2001), studying malformations in cod embryos, suggested that most of the lethal malformations were identified after hatching, and some of the malformations of embryo and larvae were compatible with larval survival. It seems that capelin, with low fecundity (6 000-18 000 egg) in comparison to cod, with high fecundity (5-7 millions eggs), has a different strategy, where abnormal or weak individuals are removed at the embryonic stage, thus keeping only normally developed fish.

Incubation time lasted for about 30 days at normal temperature conditions and about 20 days at warm temperature conditions. Our results supplement the experiment carried out by Gjøsæter and Gjøsæter (1986) with three temperature conditions (2°C, 4°C and 7°C), and the new data (5 °C and 8 °C) fit very well with previous data (Figure 2).

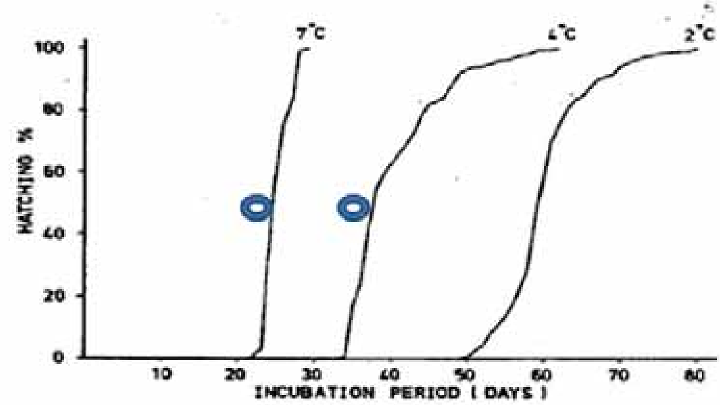

Figure 2. Hatching curves found in an earlier study (Gjøsæter and Gjøsæter (1986)) for temperatures 2, 4 and 7 degrees C, with the results (mean hatching date, blue circles) from the present study added.

If the temperatures at the spawning beds of capelin should increase to 8°C, the incubation time will decrease to little more than three weeks. The ecological implications are unknown, but could be substantial, since the timing of spawning relative to the timing of appearance of suitable food for the newly hatched larvae is of crucial importance for larval survival after yolk sac absorption.

Although firm conclusions cannot be drawn from the present experiment, our study indicate that a further increase of temperatures at the spawning grounds may negatively influence embryo development, especially in eggs from smaller spawners, and may lead to higher mortality during embryo/pre-larvae stages and hence, less recruitment. However, we cannot conclude that temperatures of 8°C are critical for Barents Sea capelin, since this species shows great flexibility in adaption to variable environmental condition.

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2.12 Impact of marine climate variability and stock size on the distribution area of Barents Sea capelin

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The spatial distribution of capelin at the end of the feeding season shows large inter-annual variations (Figure 1). Using data for the period 1972-2010 we investigate if observed changes in the capelin distribution can be explained using stock size, the individual ambient temperatures preferred by capelin, ocean temperatures in the outer boundaries of the capelin distribution, and summer ice cover. The results show a strong relation between stock size and distribution area/center of mass (Figure 2a-b). This is likely caused by a large stock extending the feeding area to meet the increasing food demand.

Assuming stock size and climate will affect the distribution independently, we adjust for the stock size effect before analyzing the effects of climate (Figure 2c). During the last decade there has been a general expansion of the capelin distribution area and a northward shift of the high-concentration areas (Figure 2c and 3). Capelin has distributed widely but in lower concentrations. This shift/ expansion seem to be related to the high temperatures and extremely low ice cover observed in the northern Barents Sea during the last decade (Figure 3). The study shows that climatic conditions set the large-scale terms for the distribution of capelin, while stock size determine how the capelin population will occupy the available area.

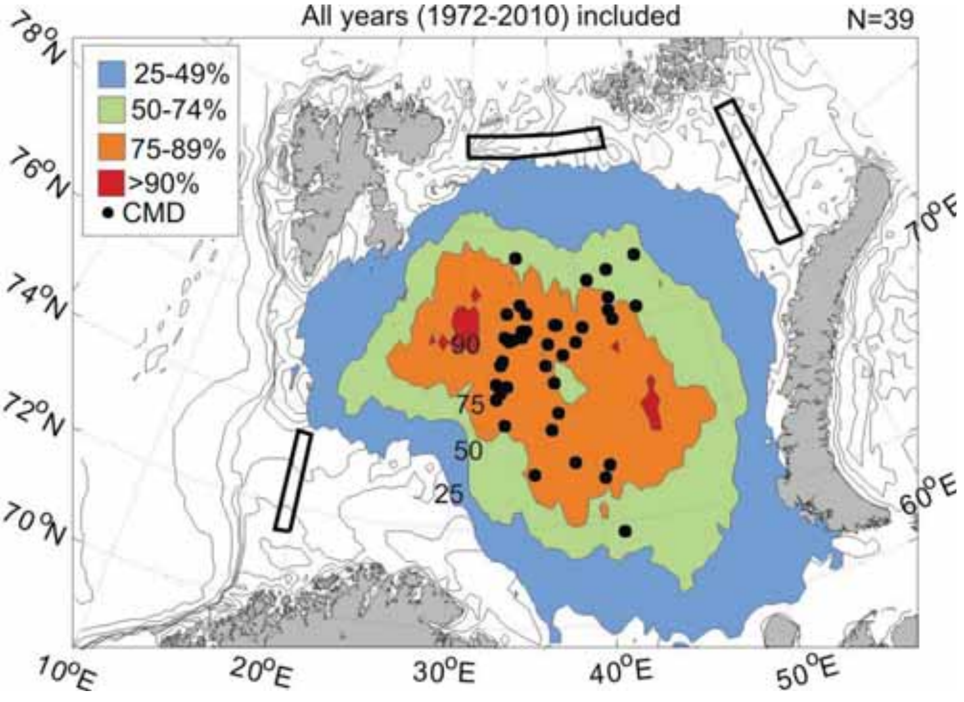

Figure 1. Core area of the capelin distribution in September-October. Contoured values are the number of years (in % of total) when capelin is found. Black dots show center of mass of the distribution.

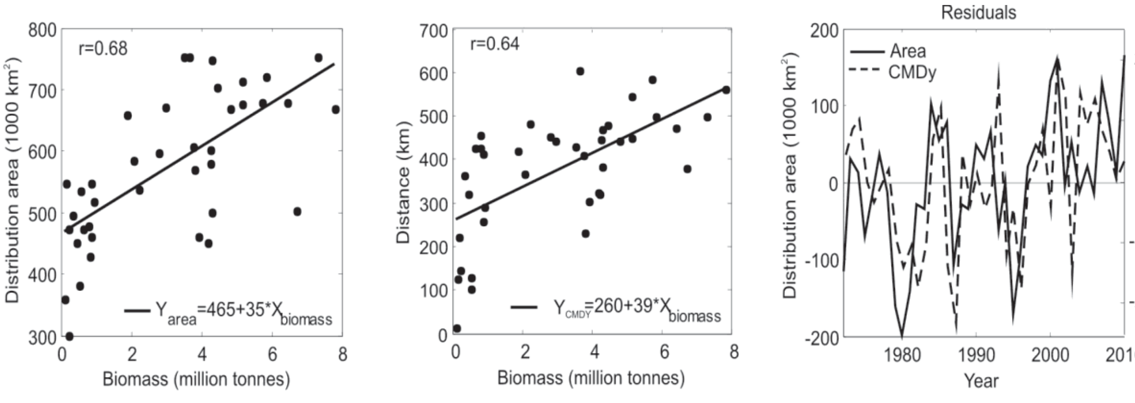

Figure 2. Relation between distribution area (a), center of mass (b) and stock size. Time series of residuals (c) which are compared to temperature series.

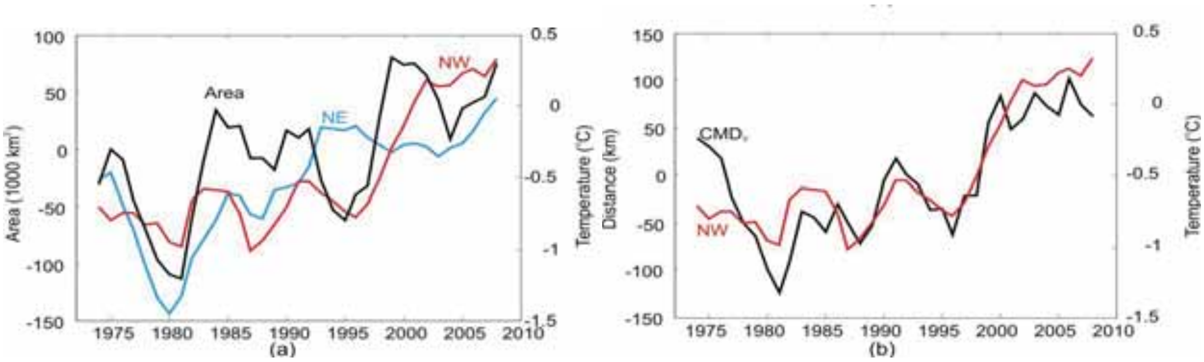

Figure 3. Five year moving average of temperature and distribution area residuals (a) and CMD_Y residuals (b).

The extent of capelin geographical distribution at the end of the feeding season varies between 300.000 and 750.000 km^2. The main drivers causing the variability are changes in stock biomass and ocean temperature. Our results show that an increase in stock size of 4 million tonnes and an increase in temperature of 1 °C give comparable impact on the distribution; both cause a northward expansion increasing the distribution area by 125.000-140.000 km^2 and shifting the high-concentration areas ~150 km northwards. Thus, to give reliable projections of climate-induced changes in the capelin distribution, the factors influencing the stock size (prey, predators, trophic interactions) must be included.

2.13 Polar cod and capelin in relation to water masses and sea ice conditions

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Polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) are key species in Arctic and sub-Arctic marine food webs, respectively (Welch et al. 1992; Sakshaug et al. 1994; Orlova et al. 2009). Polar cod has an Arctic distribution, whereas capelin is distributed in the marginal seas of the sub-Arctic (Svetividov 1948; Andriyashev et al. 1980; Rose 2005). Both species are pelagic with similar characteristics, such as: maximum size (20-30 cm), maximum age (5-7 y), sexual maturity (2-5 y), fecundity (10-30,000 eggs), and energy content (4-5 kJ g^{-1} wet weight). However, there are also notable differences, since the polar cod is iteroparous and spawns below Arctic sea ice in November-March, whereas the capelin is semelparous and spawns demersally on sand or gravel during March, e.g. on coasts of Northern Norway and the Kola peninsula of Russia.

The two species occur sympatrically in the Barents Sea, with large standing biomasses (0.5-1.5×10^6 t polar cod *vs* 2-8×10^6 t capelin). The biomass of polar cod has been relatively stable at high levels during the last 20 years, whereas that of capelin fluctuates grandly with periods of about 10 years. The distribution of these species is largely dependent on water masses, with polar cod being associated with cold, sub-zero Arctic water, whereas capelin is distributed further south into Atlantic water masses (Figure 1and 2). The distribution of polar cod seems to be more static than that of capelin, which distribution tends to extend further north in warm years and fluctuate based on predator-prey relations, e.g. with herring (*Clupea harengus*). The species overlap in distribution near the polar front and in the north-eastern Barents Sea, as well as in the marginal ice zone and in fjords in Svalbard. However, polar cod is more associated with the ice than is capelin, and juvenile polar cod are often found in water wedges and cracks in drifting sea ice (Lønne and Gulliksen 1989; Gradinger and Bluhm 2004). Thus, polar cod is adapted to cold water (< 0 °C) and has antifreeze components in its blood to prevent freezing when in contact with ice (Osuga and Feeney 1978).

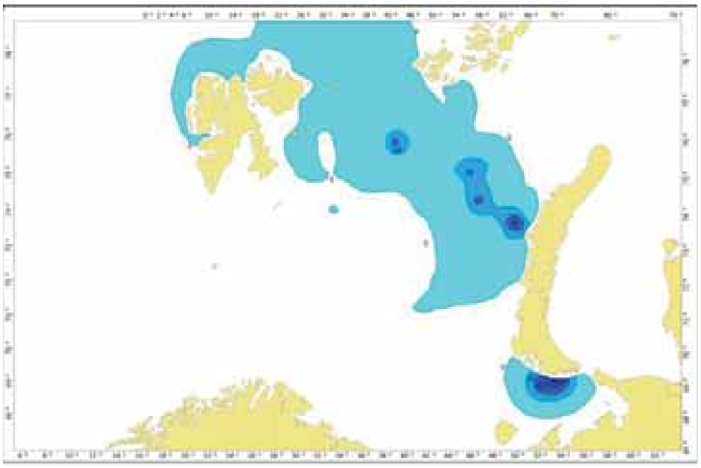

Figure 1. Geographical distribution of polar cod during autumn 2007 (Anon. 2007).

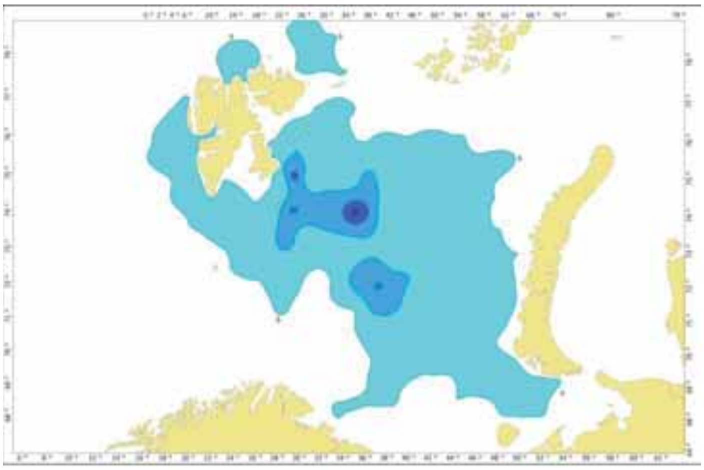

Figure 2. Geographical distribution of capelin during autumn 2007 (Anon. 2007).

Both species aggregate in large schools (Gjøsæter 1998; Hop et al. 1997) and utilize zooplankton food sources, such as calanoid copepods, although with some niche segregation since polar cod feed to a larger extent on pelagic and sympagic amphipods, whereas capelin feed predominately on krill (Lønne and Gulliksen 1989; Orlova et al. 2010). There is potential for competition for food sources in the north-eastern Barents Sea, where both species feed on *Calanus* copepods to a large extent (Orlova et al. 2009).

Because of their high abundance, small size and high energy content, polar cod and capelin are both prey for many predatory fishes, diving seabirds and fish eating marine mammals (Welch et al. 1992; Barrett and Krasnov 1994; Brekke and Gabrielsen 1994). The lipid content (mainly triacylglycerol) of both fish species is high, but distributed differently. The polar cod contains lipids (up to 60% of wet weight) in its large liver, whereas the capelin contains lipids (up to 20% ww) in its muscle tissue. The total energy content in their bodies during summer is similar, although polar cod may attain higher energy (6-7 KJ g^{-1} ww) content during late autumn and winter prior to spawning (Brekke and Gabrielsen 1994; Hop et al. 1997).

Global warming with reductions in sea ice thickness and extent, as well as increase in sea temperature, is expected to affect these two species differently. Polar cod will likely become less ice-associated and more pelagic due to reductions in ice extent, with more restricted distribution to cold Arctic water of fjords and in the Arctic Ocean. The future distribution of capelin is expected to involve an expansion to the north and east. This species may partly replace polar cod as a key forage species in the Arctic marine food web as it moves in a sub-Arctic direction due to climate warming (Figure 3). This, however, may not grandly influence the energy flow through the ecosystem, given that the two species have similar size and energy content. It has been shown that predators, e.g. seabirds, can shift prey species based on their availability (Gaston et al., 2009). Because of the similar feeding ecology of polar cod and capelin, top-down effects would likely not result in major changes in zooplankton abundance. However, lower ecosystem resilience is expected due to grandly fluctuating population numbers in capelin, with potential bottom-up effects on predators dependent on capelin (Erikstad 1990). Unless the capelin should shift their spawning areas northwards, this species may also be less available during spring, when birds are nesting and are dependent on finding food in the local area.

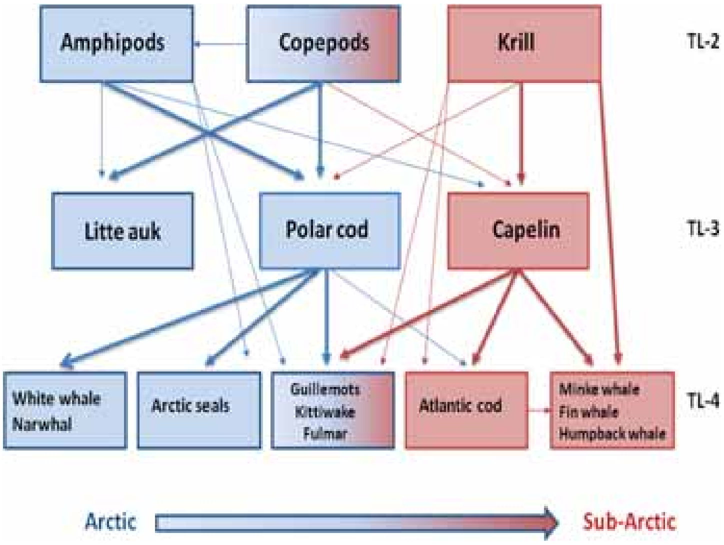

Figure 3. Polar cod and capelin in Arctic to sub-Arctic marine food webs, with indicated links and trophic levels (TL 2 to 4). Thickness of arrows indicates relative importance of energy flow based on known stomach content of predators. The system is expected to shift from Arctic (blue) to sub-Arctic (red) as polar cod is being replaced by capelin as a key forage species.

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Photo: Tor Ivar Halland, Institute of Marine Research

2.14 The link between temperature, fish size, spawning time and reproductive success of Atlantic cod

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Factors affecting spawning and larval survival in marine fish are of fundamental importance in understanding population demography. Physiological processes associated with reproduction and early larval growths are regulated, in part, by water temperature (Otterlei et al. 1999), which also affects the phytoplankton bloom (Kristiansen et al. 2011) and thereby the zooplankton peak (Ellertsen et al. 1995). In the northern hemisphere temperatures are predicted to increase by 3-6º C by the year 2100 due to global warming (Drinkwater et al. 2010). These temperature changes may have dramatic effects on the reproductive success of marine fish, but to predict effects at the population level it is necessary to understand how climate change will affect physiology and maturation at the individual level. We specifically chose to examine this question for the Northeast Artic cod (*Gadus morhua*) evaluating the effect of increasing sea temperatures on recruitment success through the complex interplay with spawning time, fish size, overlap with zooplankton abundance and larval survival in a theoretical conceptual model.

Vitellogenesis for the Northeast Arctic cod generally starts around autumnal equinox, and oocyte growth is positively associated with ambient water temperature (Kjesbu et al. 2010), and consequently spawning will occur earlier at higher temperatures. The same generally also holds true for the time of peak zooplankton production (Ellertsen et al. 1989), the prime cod larval food, although there is a limit to how far the zooplankton bloom can be advanced given that zooplankton will increase in abundance as a response to the phytoplankton bloom, which again will be limited by the available light. Preliminary investigations also indicates that for the main spawning grounds of Northeast Arctic cod, earlier zooplankton peak will predominantly be caused by an accelerated developmental time of the copepodite stages, not by a shift in the timing of the phytoplankton bloom itself.

Interestingly, cod will show a temporal separation in spawning time according to size at temperatures above 5º C, with large cod spawning earlier than smaller fish (Kjesbu et al. 2010, Figure 1). Earlier spawning in larger females may reflect avoidance of an earlier oxygen limitation experienced at lower temperatures (cf. Pörtner et al. 2008).

This physiological effect leading to length-dependent spawning time may have profound consequences for reproductive success for the Northeast Arctic cod. At slightly heightened temperatures preliminary results indicates that this temporal separation of spawning time will lead to increased overlap with the zooplankton peak of larvae produced by the more fecund larger females. This provides a functional explanation for the commonly observed increased chances of improved recruitment of Northeast Arctic cod in warm years (Solemdal 1997). However, under a climate change scenario temperature might increase to a point where the largest females spawn too early, missing peak zooplankton production with an overall negative effect on the recruitment potential as a result. Also, warmer temperatures may lead to selection for earlier spawning, but the current fishing practice in Norwegian waters generally targets the earlier spawners more, thereby negating such an effect. We are currently incorporating such effects in our model to further be able to understand and predict the effect of global warming on spawning time and reproductive success of the Northeast Arctic cod.

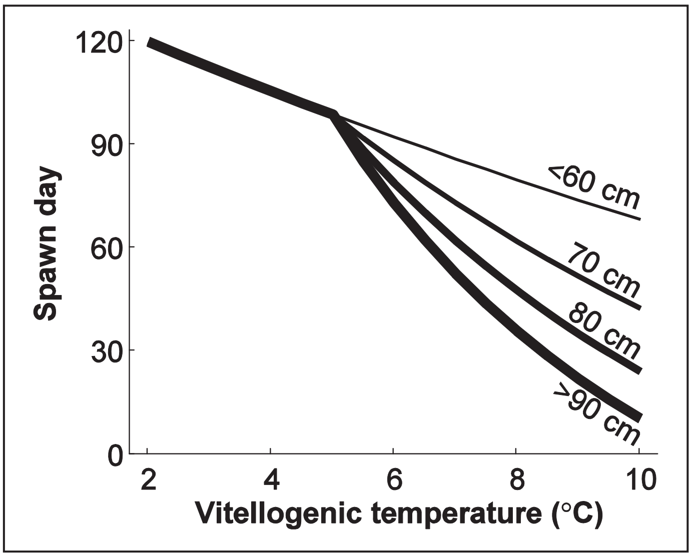

Figure 1. Influence of temperature on start of spawning in Atlantic cod females. At higher temperatures oocytes mature faster, and this effect is more pronounced in larger females. See Kjesbu et al. 2010 for details.

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2.15 Changes in the relations between oceanographic conditions and recruitment of cod, haddock and herring in the Barents Sea

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Extended abstract

Cod, haddock and herring in the Barents Sea all have strongly variable recruitment. Earlier studies have suggested a positive relationship between high temperatures and recruitment of cod, haddock and herring in the Barents Sea as well as a correlation between the recruitment of these three species. These hypotheses were revisited using stock assessment and survey data for the period 1950-present, as well as temperature data. We found that recruitment variability declined towards the end of the period 1950-present for all species, in particular for cod. Recruitment correlation between the species is positive, but significant only during shorter periods. In accordance with previous studies, recruitment is low at low temperatures and variable at medium/high temperatures in the spawning year for all three species. The temperature during the first winter of life correlates positively with residuals from a stock-recruitment relationship for haddock and cod. This correlation is weakened towards the end of the period for cod, but stays for haddock. Haddock survival to age 1 is also related to winter temperature. No significant relationships between recruitment and inflow were found.

2.16 Size and age dependent geographic distribution of Northeast Arctic cod in the Barents Sea - effects of physical conditions and abundance

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Survey area coverage is a large source of error in fish surveys, and the ocean warming experienced the latest 30 years may have exaggerated the influence of this error on the survey abundance indices. A well known influence of ocean warming is the shift of geographic distribution of temperate fish species towards higher latitudes. Climatic effects on geographic distribution of cod with consequences for catchability in surveys and abundance index estimation is experienced in several marine ecosystems. Here we study the variation in geographic distribution of Northeast Arctic (NEA) cod, and the questions addressed are: How does the geographic distribution of the year classes (YC) 2003, 2004, and 2005 vary seasonally? What is the relationship between the survey coverage and the age dependent geographic distribution? Can this relationship explain the unexpected high occurrence of the 2004 and 2005 YC at older ages in the winter survey abundance indices?

Climate and abundance indices of Northeast Arctic cod in the Barents Sea

The time series of climate in the Barents Sea demonstrates a steady warming trend from the 1980's, with a particularly warm period from 2000 with 2007 as the warmest recorded. During the same period, a retreat of the ice cover has also been observed. The abundance index of Northeast Arctic (NEA) cod from the winter (January/February) bottom trawl survey for demersal fish in the Barents Sea have showed some unexpected patterns the last years. Particularly the 2004 and 2005 year class of NEA cod haven't followed the development with age typical for other year classes. They went from being of medium strength at young ages, to suddenly stick out from the rest of the year classes as all time high as 7 and 6 years old, respectively, in the 2011 winter survey. These high indices were unexpected compared to their occurrence earlier and compared to for instance the 2003 year class (Figure 1).

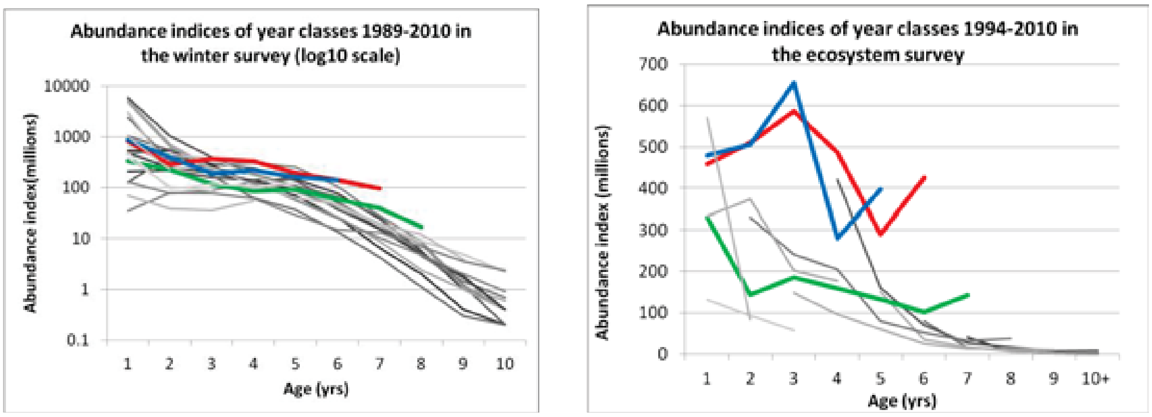


Figure 1. Development of the year classes of NEA cod in the abundance indices from the bottom trawl catches at the winter bottom trawl survey (left panel) and the ecosystem survey (right panel) in the Barents Sea. Green line represents the 2003 year class, red line the 2004 and blue line the 2005 year class. Other year classes in grey tones. Based on data from ICES AFWG 2011.

The unexpected patterns found in the winter survey data, was not evident in the abundance index of NEA cod based on bottom trawl catches at the ecosystem survey (August/September) in the Barents Sea (Figure 1). In contrast to the winter survey, the 2004 and 2005 YC are high throughout the series from the ecosystem survey, while the 2003 YC seems to follow the other YCs (Figure 2). Note that the ecosystem survey has wider area coverage than the winter survey.

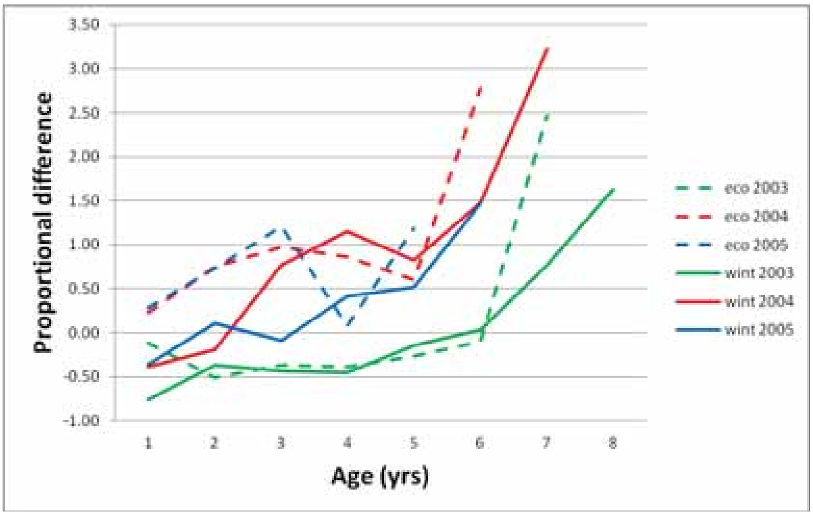
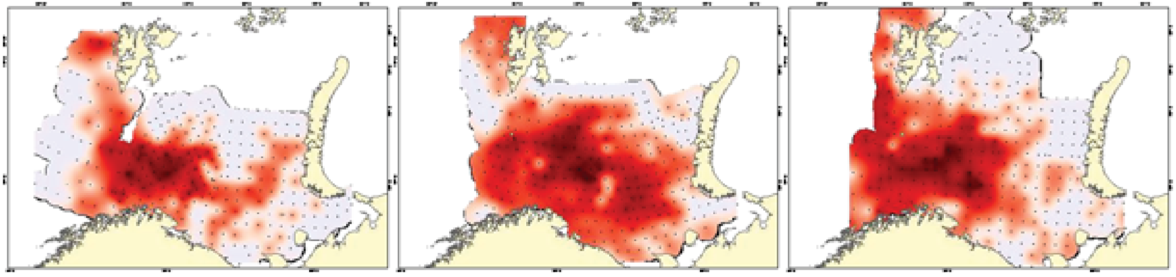


Figure 2. Proportional difference between bottom trawl index for each YC 2003 (green), 2004 (red) and 2005 (blue) and the average index for each age class in the surveys.

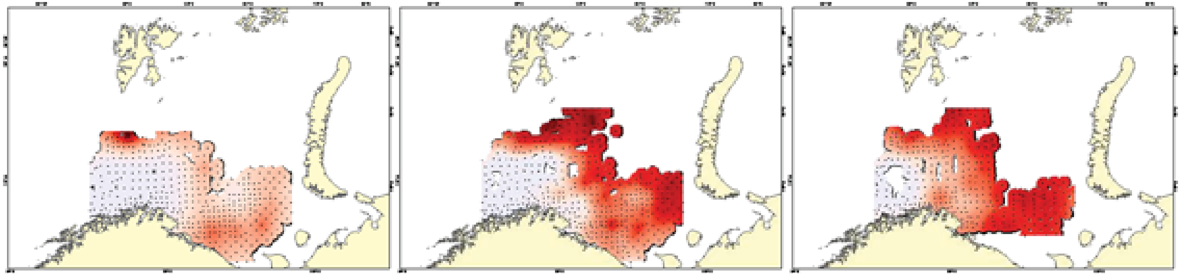
Seasonal variation in the geographic distribution of the YCs 2003, 2004, and 2005

The maps representing the seasonal variation in geographic distribution of the 2003, 2004 and 2005 YCs at different ages are given in Figure 3. They are based on data from the winter surveys 2004–2010, the 0-group surveys 2003–2004 and the ecosystem surveys 2004–2010. The distribution of 0-group of 2003 YC was more restricted than that for the 2004 and 2005 YCs. There seems to have been a systematic under-coverage of the young age groups (1-3 yrs) by the winter survey. At age 2 years the difference between the 2003 YC and 2004/2005 YCs started to emerge. Compared to the 2003 YC in the winter survey, the 2004 and 2005 YCs had larger parts of the distribution near or at the northern and eastern limit of the area covered. For age 3 this pattern became more visible and parts of the 2004/2005 YCs were in the ecosystem survey distributed in northern and eastern areas, far outside the area covered by the winter survey. Also for ages 4 and 5 the under coverage of these two YCs in the winter survey is evident and large parts of the2004/2005 YCs was in the ecosystem survey distributed in northern and eastern areas, outside the area covered by the winter survey. As 6 and 7 years old the 2004/2005 YCs had returned to the area covered by the winter survey. These age groups start spawning migrations and this leads to a westward shift in the geographical distribution, and reappearance in the winter survey area. Note the larger difference in distribution between winter and autumn when the cod grows older. This is both caused by extended seasonal feeding migration at increased age and caused by the fact that a considerable fraction of age 6 and 7 is maturing and takes part in the spawning migration.

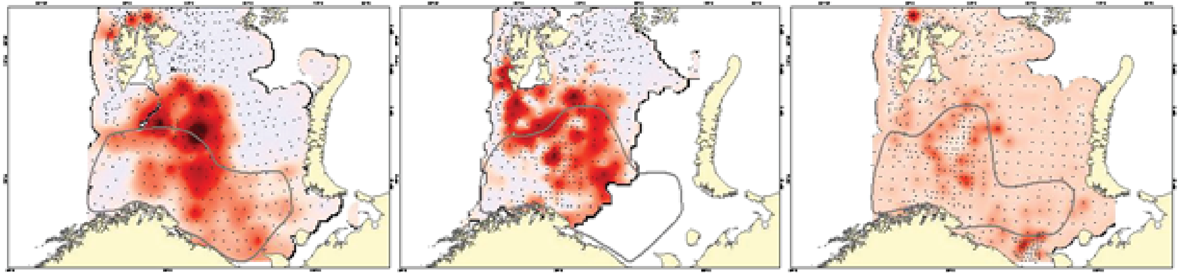
Age 0, 0-group survey



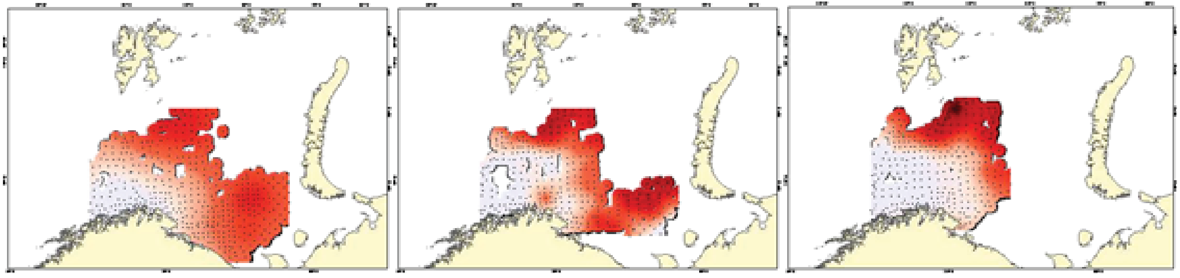
Age 1, Winter survey



Age 1, Ecosystem survey



Age 2, Winter survey



Age 2, Ecosystem survey

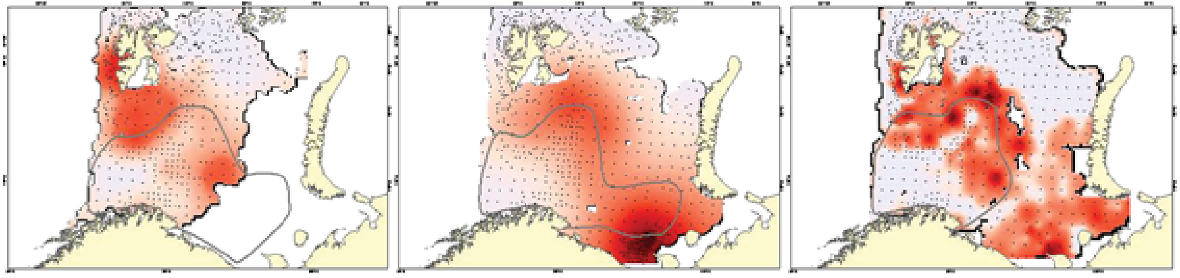
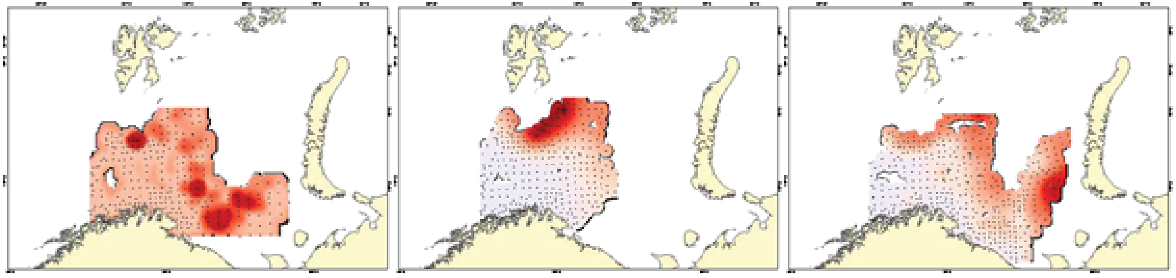
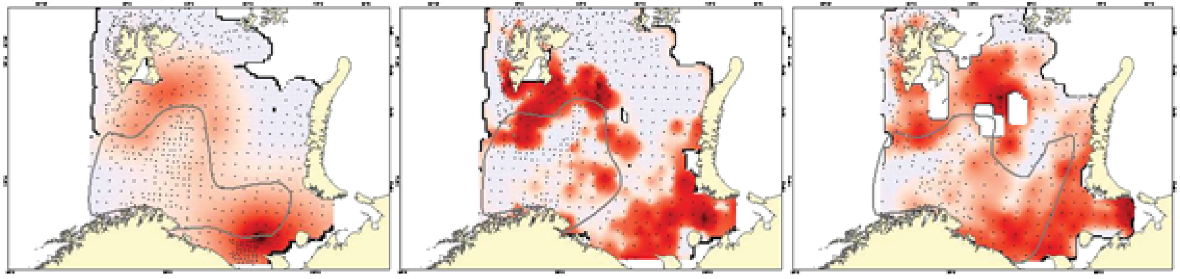


Figure 3. Interpolated abundance fields for the 2003, 2004, and 2005 (left to right) year classes of NEA cod at different ages from the 0-group, winter and ecosystem surveys in the Barents Sea. Interpolation by ordinary Kriging for visual purposes only, and the maps show relative distribution pattern within the years. Winter survey areas are shown as a thin line, to enhance comparison between the two surveys.

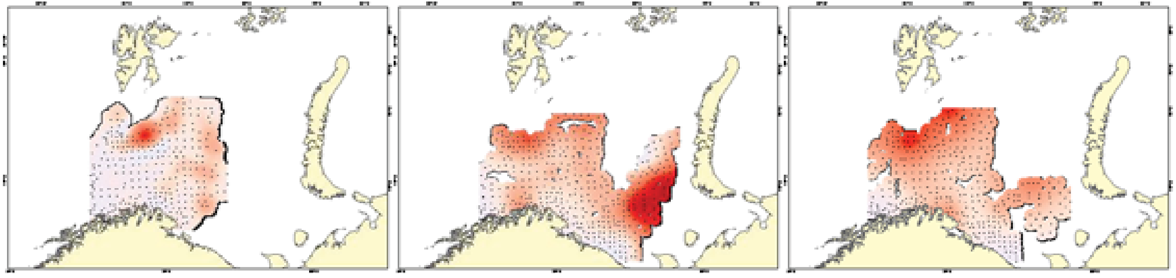
Age 3, Winter survey



Age 3, Ecosystem survey



Age 4, Winter survey



Age 4, Ecosystem survey

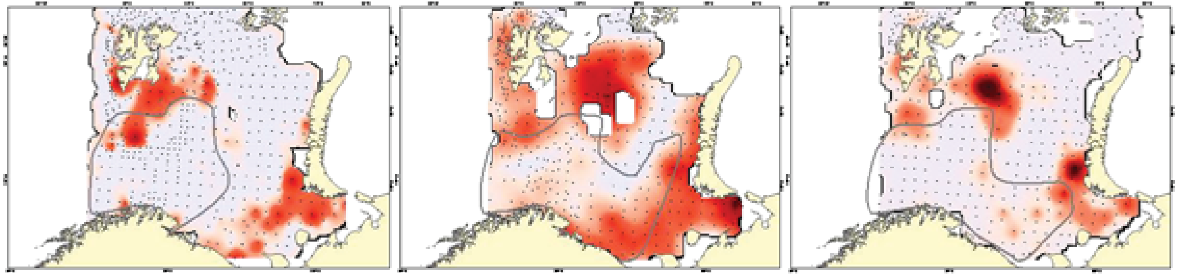
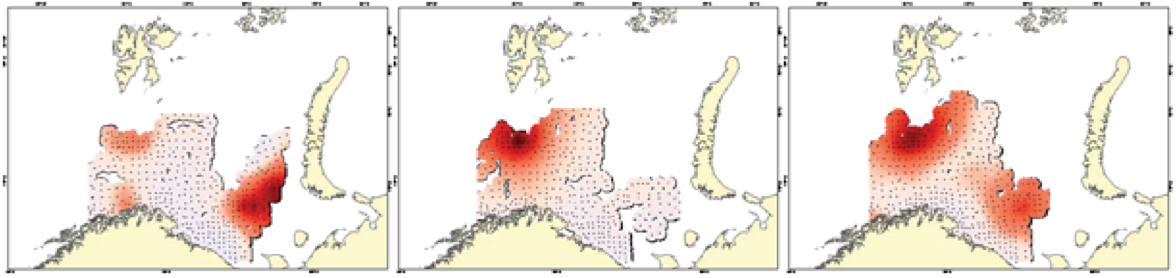
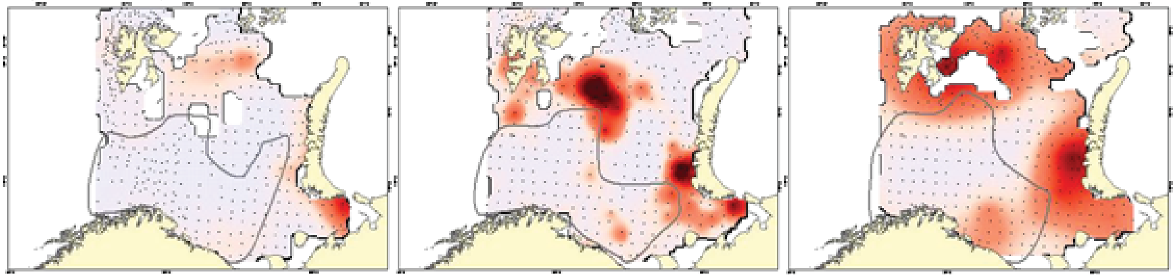


Figure 3 continued. Interpolated abundance fields for the 2003, 2004, and 2005 (left to right) year classes of NEA cod at different ages from the winter and ecosystem surveys in the Barents Sea. Interpolation by ordinary Kriging for visual purposes only, and the maps show relative distribution pattern within the years. Winter survey areas are shown as a thin line, to enhance comparison between the two surveys.

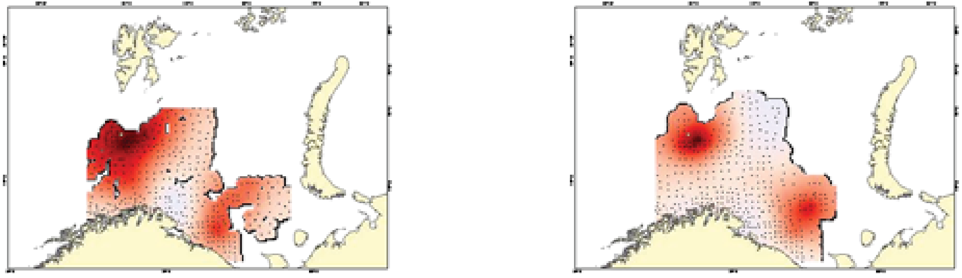
Age 5, Winter survey



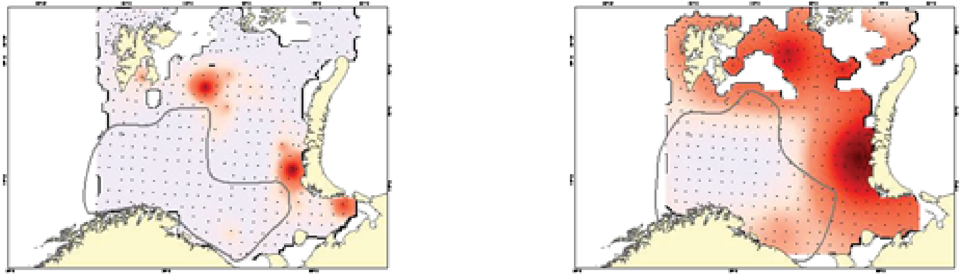
Age 5, Ecosystem survey



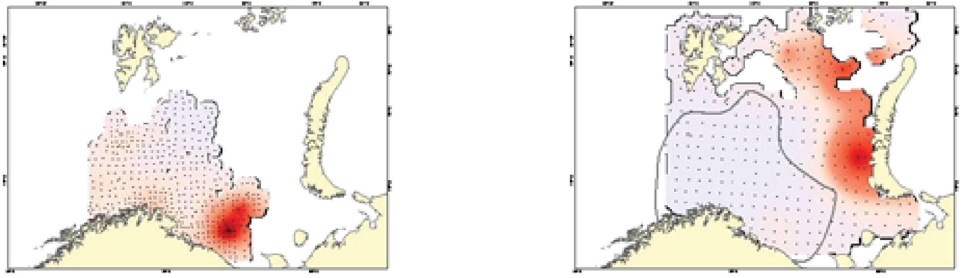
Age 6, Winter survey (2003 and 2004 YCs)



Age 6, Ecosystem survey (2003 and 2004 YCs)



Age 7, Winter survey (2003 YC)



Age 7, Ecosystem survey (2003 YC)

Figure 3 continued. Interpolated abundance fields for the 2003, 2004, and 2005 (left to right) year classes of NEA cod at different ages from the winter and ecosystem surveys in the Barents Sea. Interpolation by ordinary Kriging for visual purposes only, and the maps show relative distribution pattern within the years. Winter survey areas are shown as a thin line, to enhance comparison between the two surveys.

Summary and conclusions

The age dependent seasonal variation in geographic distribution of NEA cod in the Barents Sea in the 2000s was characterised by a wide distribution of cod up to age 3 and distinct seasonal redistribution of older cod between the periods Jan/Feb to Aug/Sep (the two periods covered by the winter and ecosystem surveys, respectively). The fraction of the cod stock distributed in the northeast areas varied between year classes. These characteristics are probably most pronounced when the climate in the Barents Sea is warm.

The relationship between these characteristics of the seasonal, age and year class dependent geographic distribution of cod and the survey coverage of the winter survey is important for this surveys ability to follow the dynamics of different year classes. The winter survey coverage of NEA cod varies with age and between year classes. In the 2000s, 1-3 years old fish were consistently under covered. The moderately large 2003 YC was covered quit well contrary to the large 2004/2005 YCs which fell out of the winter survey as 3, 4 and 5 years old. The ecosystem surveys more or less covered the total distribution range of all year classes.

The relationship between geographic distribution and survey coverage seems to explain the sudden occurrence of 6 and 7 year old cod in the winter survey 2011. The combination of high temperatures and abundant year classes in the 2000s may have increased this effect. These findings may have implications for the winter survey as an input source for abundance indices to the stock assessment of NEA cod in the Barents Sea. A way forward is to explore the potential of tuning the abundance indices from the winter survey by information from the ecosystem survey.

Acknowledgements

We wish to thank Asgeir Aglen and Åge Fotland at IMR for their contributions. We are also grateful to the IMR project “Expected Change in Fisheries in the Barents Sea” (FishExChange), funded by the NORKLIMA research program under the Norwegian Research Council (NFR contract number 178338/S30) for making distribution data available.

Photo: Institute of Marine Research

2.17 Species-specific habitat conditions and possible changes in the distribution of fish in the Barents Sea during climate change

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Abstract

Habitat conditions for a number of fish species in the Barents Sea (preferred depth, water temperature and salinity) have been examined and the species characterised according to these characteristics on the basis of data from the Russian autumn-winter bottom fish surveys for 1998-2010. The dependence on a given habitat and the limits of distribution of the most important and typical fish species on oceanographic characteristics at different standard sections were analyzed. We also examined the impact of climate change for all the groups of fish species selected by habitat conditions, on their distribution in the Barents Sea and potential changes in their distribution.

Introduction

Climate change affects various components of marine ecosystems, including fishes. Many new fish species, mainly warm-water, have appeared in the Barents Sea since the beginning of the 2000s (Dolgov and Igashov, 2001; Rusyaev and Shatsky, 2001; Byrkjedal and Lemvig, 2002; Dolgov, 2006; Rusyaev et al., 2007). However, the recent period of warming in the Barents Sea is not unusual. Despite a lack of ecosystem studies of the Barents Sea during the whole of the last century, many notes on the appearance of warm-water fish were published as early as the 1930s (e.g. Berg, 1939; Boldovsky, 1939). Just as changes in fish distribution are related to their habitat preferences, so changes in water temperature will result in changes in the distribution of many fish species.

The main goals of this paper were the following; to consider species-specific habitat conditions for fish species in the Barents Sea (depth, temperature and salinity), to study the relationships between habitat conditions and distribution parameters for species from different ecological and zoogeographical groups, and to evaluate possible changes in fish distribution under warming in the Barents Sea.

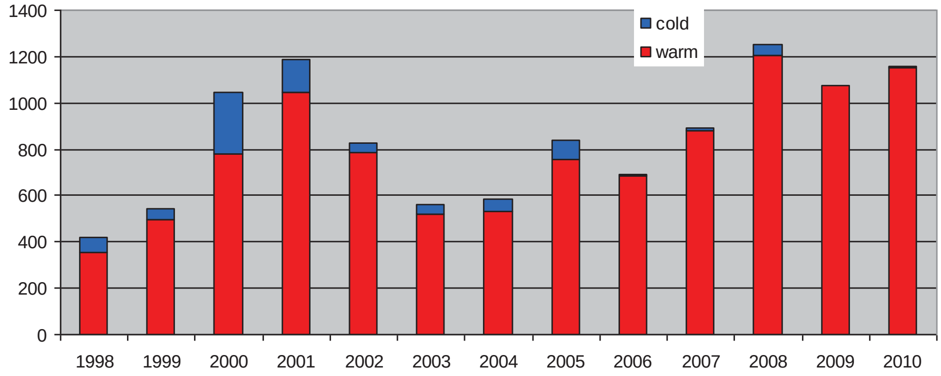
Material and methods

Data were collected during the Russian autumn-winter trawl-acoustic surveys of demersal fish which were performed in October-December 1998-2010. Data on species abundance were obtained from each tow.

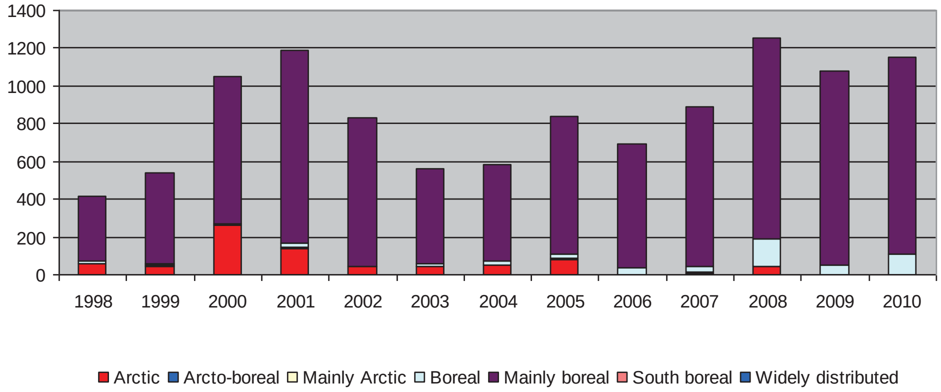
As characteristics of habitat conditions, we utilised data on depth in each tow as well data on sea-bed water temperature and salinity collected from CTD stations. Data from standard oceanographic sections were also used to analyse relationships between fish distribution and water temperature.

Results and discussion

The fish community of the Barents Sea is a mix of cold- and warm-water species. Cold-water species made up only 26% of the total fish abundance, while the proportion of warm-water species is much higher at 74% (Figure 1A). Among the warm water species, mainly boreal species were totally dominant (Figure 1B).



A



B

Figure 1. Total mean catches of cold- and warm-water fish species (A) and species from various zoogeographic groups in the Barents Sea in 1998-2010 based on data from the Russian October-December survey (y-axis: ind./1 hour tow).

Habitat conditions

Distinct differences in the depth, bottom water temperature and salinity characteristics of various fish species were observed.

In spite of a rather wide range of these habitat characteristics in most species obvious groups of fishes can be distinguished in terms of depth, temperature and salinity (Figures 2-4).

Shallow-water species like the Arctic staghorn sculpin *Gymnacanthus tricuspis* and bullrout *Myoxocephalus scorpius* occurred mainly at depths of less than100 m, while deepwater species like the roughhead grenadier *Macrourus berglax* and Arctic rockling *Gaidropsarus argentatus* preferred depths below 600 m. The preferred depth for other species ranged from 100 to 600 m.

Warm-water species like the Norway haddock *Sebastes viviparous*, greater argentine *Argentina silus* and lemon sole *Microstomus kitt* occurred at temperature >6ºC. The cold-water species Atlantic spiny lumpsucker *Eumicrotremus spinosus* and gelatinous snailfish *Liparis fabricii* preferred bottom temperatures below 0 ºC. The preferred bottom temperature for other species ranged from 1 to 6 ºC.

In terms of water salinity differences between various species were not so pronounced (Figure 4). Only three species, including the dab *Limanda limanda*, plaice *Pleuronectes platessa* and whiting *Merlangius merlangus* occurred in low-salinity waters (<34.5). The preferred salinity range for other species was not so wide – from 34.5 to 35.1, suggesting that salinity is not as important a characteristicas depth and water temperature.

It is obvious that a wider range of habitat characteristics will extend the species distribution area, as is reflected in the frequency of occurrence of individual species. The two most abundant and widely distributed species in the Barents Sea are long rough dab and Atlantic cod (Figure 5), which were found in 94-95% of the tows in the Russian survey.

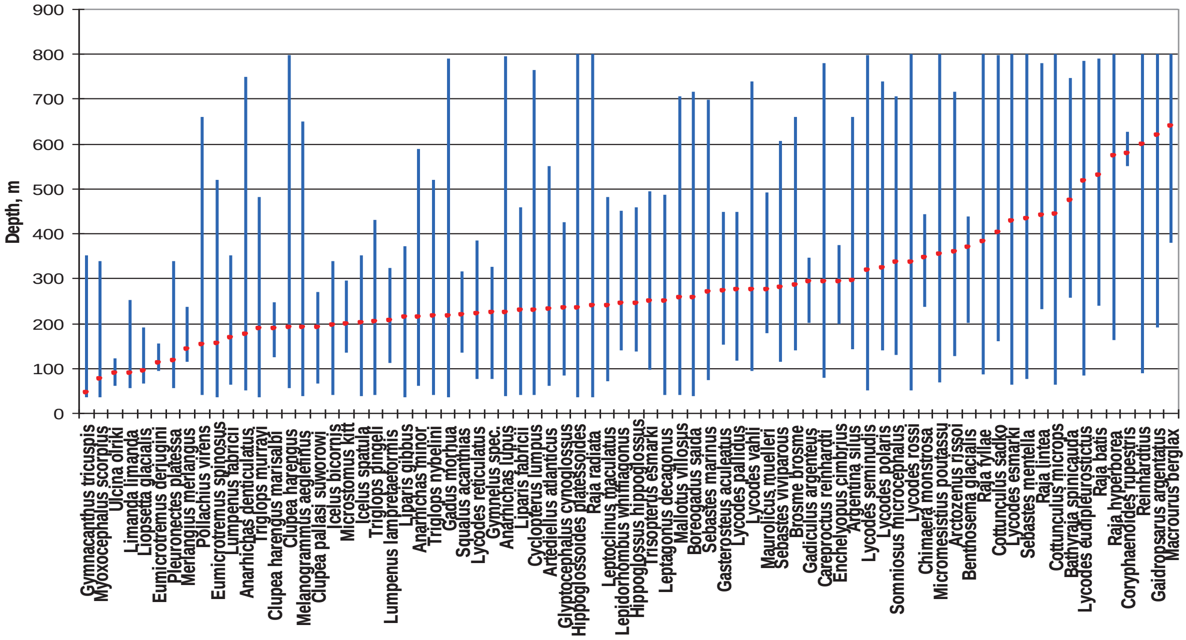


Figure 2. Highest, lowest and mean habitat depths of fish species in the Barents Sea, based on data from the Russian October-December survey 1998-2010.

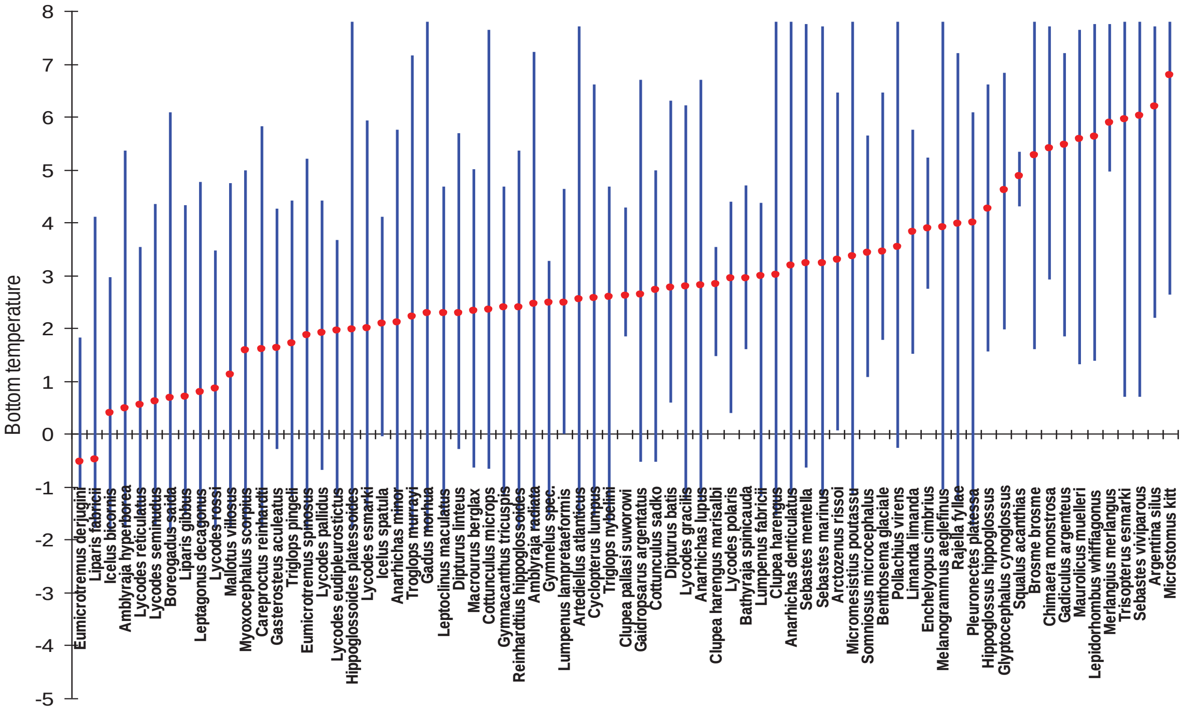


Figure 3. Highest, lowest and mean habitat bottom temperature of fish species in the Barents Sea, based on data from the Russian October-December survey 1998-2010.

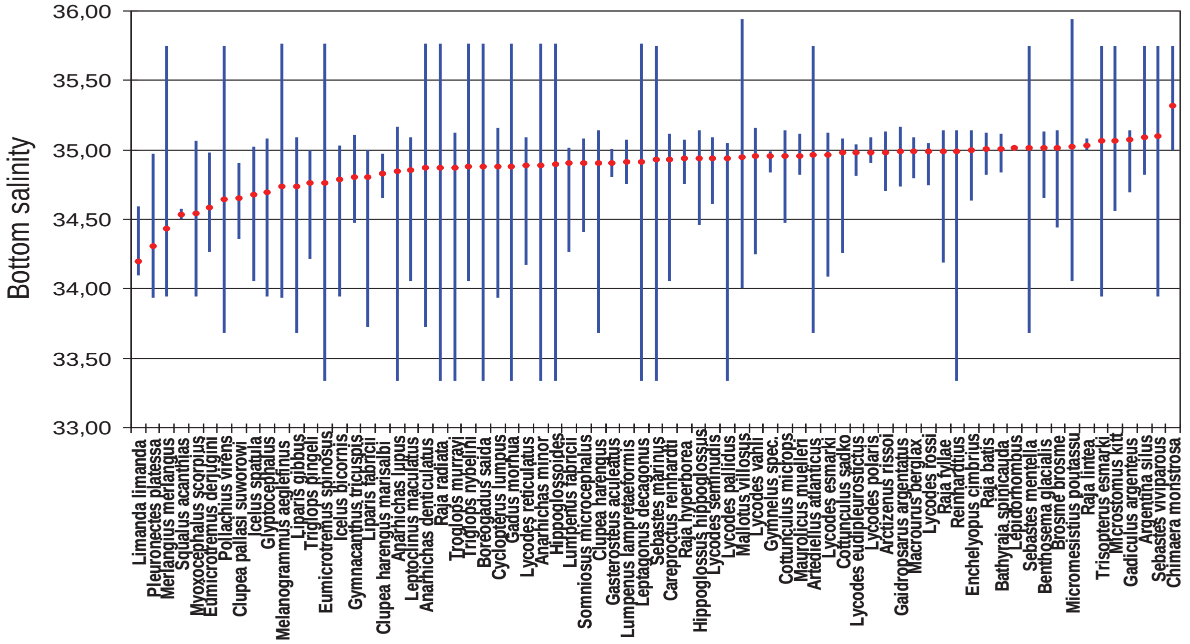


Figure 4. Highest, lowest and mean habitat bottom salinity of fish species in the Barents Sea, based on data from the Russian October-December survey 1998-2010.

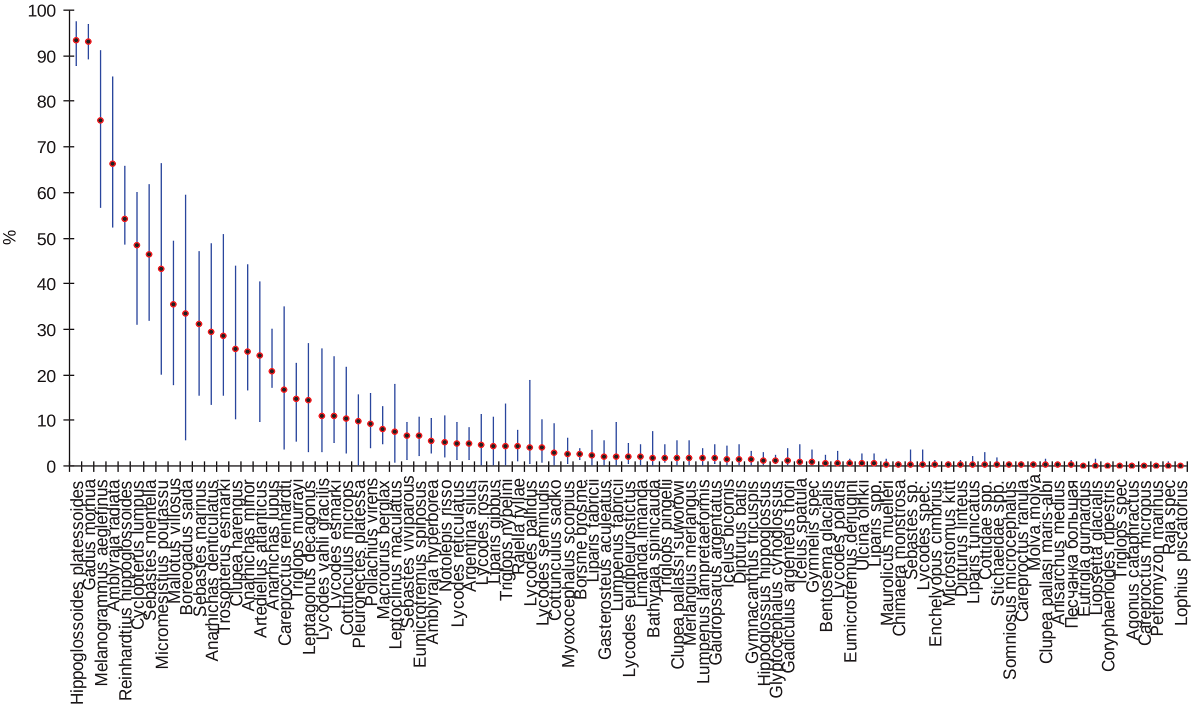


Figure 5. Occurrence of various fish species in the Barents Sea, based on data from the Russian autumn-winter surveys 1998-2010, percentages from all demersal tows.

Possible changes in fish distribution in the Barents Sea under conditions of warming

Pelagic fish species (herring, capelin, polar cod and others) are virtually unlimited to a particular range of depths and in principle, the whole of the Barents Sea would still be available to these species under conditions of warming.

Most demersal fish are limited to particular depths. Shallow-water species occupy areas with depths of < 50-100 m, the extent of which is a rather small proportin of the whole Sea. Under conditions of warming, warm-water species will be able to expand their areas of distribution only if the nearest shallow areas are located fairly near their current areas. If such areas are very far off, these species will be unable to migrate northwards in warm currents. For the same reason, cold-water species will totally disappear from shallow water area with high water temperature.

Deep-water species such as the roughhead grenadier *Macrourus berglax*, Arctic rockling *Gaidropsarus argentatus*, etc. occur mainly at depths beyond 500 m. Such areas are located alongside the continental shelf slopes between the Norwegian coast and Spitsbergen, between Spitsbergen and Franz-Josef land and in the trench between the Norwegian coast and Bear Island. Warming will produce a shift in deepwater fish distribution northwards to Spitsbergen and then eastwards to Franz Josef Land, though only alongof the slopes of the continental shelf.

Most fish species which inhabit the intermediate depth interval (100-300 m), such as cod, haddock, etc., will show the most distinct changes in patterns of distribution under warming conditions. As most of the Barents Sea has these depths, such warm-water species will expand their areas of distribution far northwards without any restrictions and their northern limits will depend only on water temperature. Cold-water species distribution will also shift northwards too and such species will probably even be able to migrate to the Kara Sea.

However, while we realise that such changes in fish distribution in the Barents Sea may be possible with further warming of water masses, oceanographic observations made during the past few decades have shown that the warmest years on the Kola section were 2006-2007 (Figure 6). Water temperature data on other standard oceanographic sections have also shown a tendency to decrease since the peak in 2006-2008 (Figure 7).

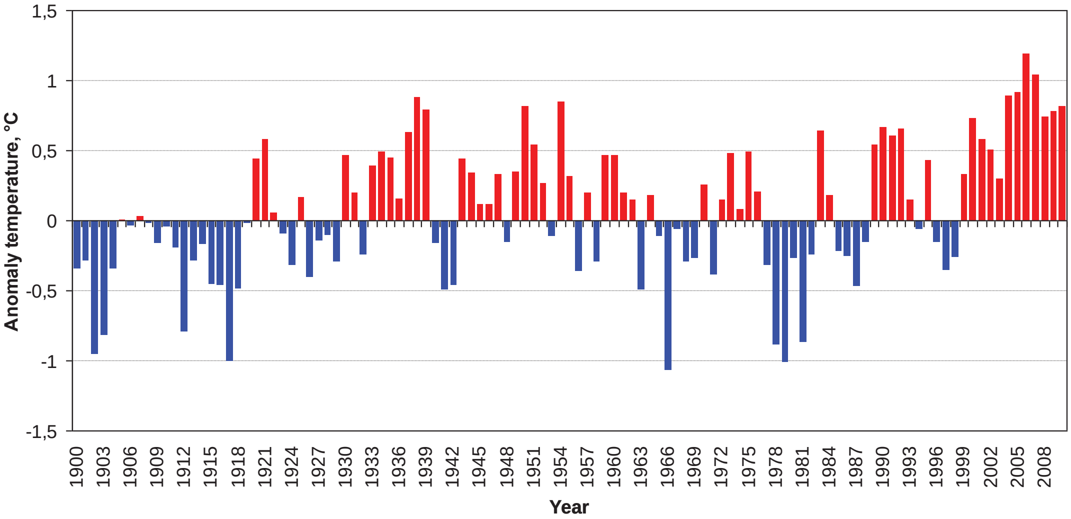


Figure 6. Water temperature anomalies in the 0-200 m layer on the oceanographic section "Kola meridian", 1900-2010.

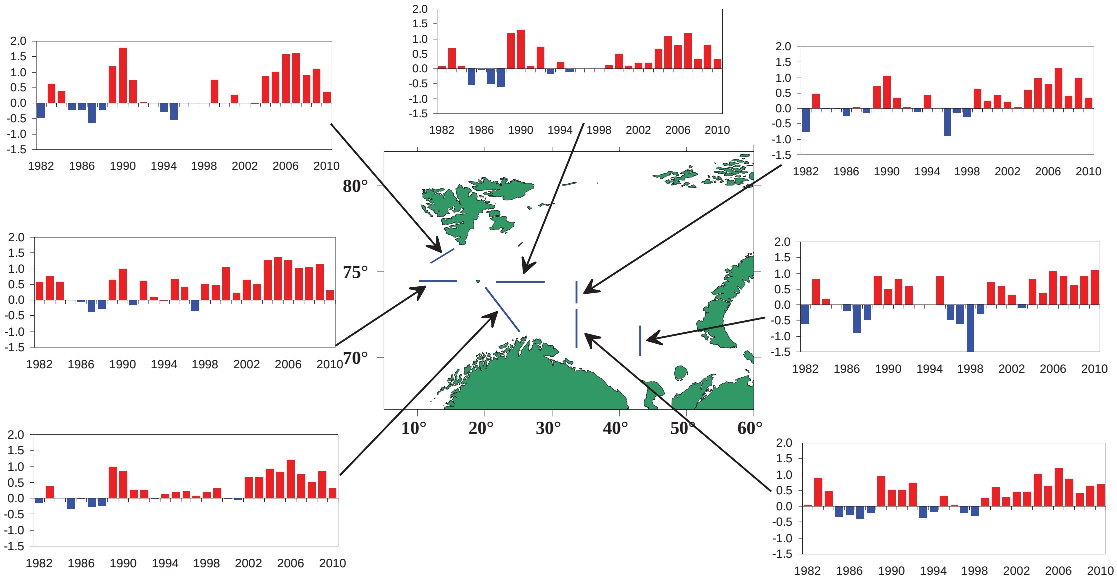


Figure 7. Water temperature anomalies on some standard oceanographic sections in the Barents Sea, 1982-2010.

Conclusions

Different combinations of habitat preferences are specific to individual species of fish. Habitat conditions determine distribution parameters (area, northern/southern and eastern/western borders) for each species. The impact of climatic changes will be different for species from different zoogeographical and ecological groups. However, when recent trends in water temperature in the Barents Sea are taken into account, drastic changes in fish distribution seem to be unlikely.

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2.18 Functional diversity of the Barents Sea fish community: preliminary data applied to recently developed methodology

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Functional diversity (FD) can be defined as the diversity of functional properties of species in an ecosystem, and has become subject of considerable attention in recent years (Diáz and Cabido 2001; Petchey and Gaston 2002a; Blackburn et al. 2005). Approach based on FD stands in addition to many traditional biodiversity measures (e.g. species richness). Indeed, classical approaches based on taxonomic diversity usually consider species as equally different, whereas functional diversity explicitly quantifies differences between species at the level of their functions within ecosystems. Approaches based on FD relies on the paradigm that more functionally diverse systems might have stronger ability to adapt to a changing environment.

In this study, we have implemented a measure of functional diversity for the demersal fish of the Barents Sea. This is one of the very first attempts to apply the FD approach to a marine population.

In the Barents Sea, there are about 150 fish species from 52 families (Gjøsæter 2009), and the area supports important fisheries (Gjøsæter 1995). Large global changes are expected in near future (Kerr 2001), and are reflected by a substantial temperature rise in the Barents Sea during recent years (Levitus et al. 2009). Such changes might trigger loss of species, and the quantification of FD can help to understand the consequences associated to the loss of a given species (Petchey and Gaston 2002b; Flynn et al. 2009).

The method chosen to quantify the FD for the Barents Sea fish community is based on th method developed by Petchey and Gaston (2002a, 2006) using R software (version 2.12.1; R Development Core Team 2011). We first built a life history trait matrix (Figure 1) for the 43 most abundant fish species in the Barents Sea. We assume that life history traits reflect the function of species within the ecosystem. Six life history traits were documented: habitat (demersal/pelagic), growth rate (K from the Von Bertalanffy equation), fecundity (number of eggs per female per year), max length, length at first maturity and diet (planktivorous/benthivorous/ichthiophage). Secondly, this life history trait matrix is the used for building a distance-based dendrogram, which in turn is coupled to presence/absence data for each species, collected from 357 demersal trawl samples in fall 2009 in the Barents Sea (Figure 2).

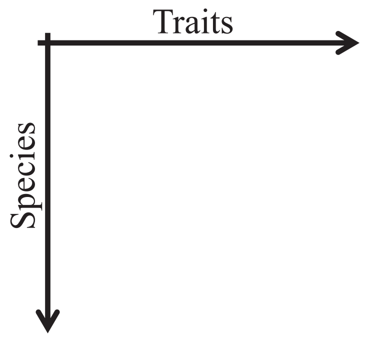

Figure 1. Outline for a life history trait matrix.

The choice of life history traits is obviously an important part of the methodology, since it to some degree will influence the final results. The traits should reflect the functional roles that the species are playing in the system, and they should not be too correlated to each other. In this study, we have coded the trait information in various ways. Habitat and diet are coded as binary variables, growth rate and the length measures are continuous variables, and fecundity is coded by means of counts. Correlation between traits and trait coding are two of the aspects that must be considered when the traits are weighted. Intuitively, trait weighting can be approached in at least four ways. First, that all columns in the trait matrix have equal weight; this simple approach will result in a larger weight for the categorically coded traits compared to e.g. the continuously coded traits. Second, that all traits have equal weight; the weight of each matrix column will thus be determined by the number of categories that each trait is divided into. Third, that all functions are given equal weight; for instance, the traits that are related to reproductive strategies are totally given the same weight as those related to trophic structures. Four, that some traits are regarded as more important that other in terms of system functioning, and therefore will have larger weight.

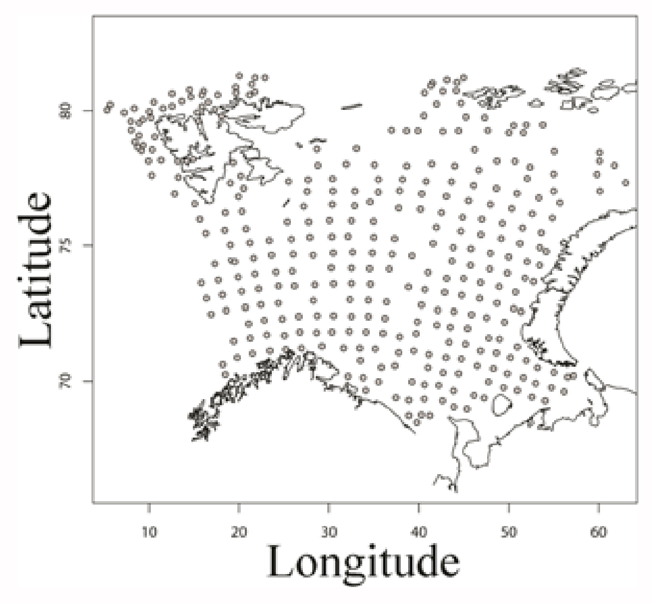

Figure 2. Overview of survey stations in the Barents Sea during the Russian-Norwegian ecosystem survey in 2009.

Due to the present lack of standardization when calculating FD, results obtained from one system will not necessarily be directly comparable to results from other systems. Standardization involves both the functional trait selection and the choice of computational methodology. Although the latter point recently has been discussed (e.g. Podani and Schmera

2006, 2007; Petchey and Gaston 2007, 2009a), no clear method has yet been agreed upon. We have presently chosen to use the Gower distance measure, which handles mixed types variables (e.g. continuous, counts and categorical). The choice of clustering method can be evaluated by calculating the cophenetic correlation between the distances in the original resemblance matrix and the distances resulting from the dendrogram (Legendre and Legendre 1998). Finally, several other measures of functional diversity exist and should also be considered, such as the Rao's quadratic entropy (e.g. Botta-Dukát 2005) and functional dispersion (FDis; Laliberté and Legendre 2010).

Conclusions

The functional diversity appro5. avsniach attempts to link species to ecosystem processes through the addition of the species' functional properties to the traditional biodiversity measures (Petchey and Gaston 2009a). Functional diversity can be related to ecosystem resilience (Petchey and Gaston 2009b), and a reduction in functional diversity, which is a consequence of species loss, might affect the ecosystem services (Flynn *et al.* 2009). Further studies will show whether the functional diversity methodology is a tool capable of identifying the relative robustness of sub-areas in larger marine ecosystems such as the Barents Sea.

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2.19 The effect of climate fluctuations on demersal fisheries in the Barents Sea and adjacent waters

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Abstract

Survey of the scientific literature on fish has showed that the majority of species demonstrated changes in distribution and migrations in periods of climate change. However these changes are seldom assessed qualitatively. The authors attempted to make qualitative assessments of the changes in distribution and migrations of cod in the Barents Sea and adjacent waters based on data from Russian demersal fisheries in the area.

Introduction

The Barents Sea is an important area for world and domestic fisheries. Its high biological productivity (800 kg/km^2), three times more than than in the World Oceans (225 kg/km^2) (Moiseev 1989), is caused by the inflow of warm (4-12 °C) and salty (34,8-35,2) waters of the Gulf Stream, as well as by other physical and chemical processes. As a result of interaction with the cold Arctic and warmer Barents Sea waters, an extended frontal zone is formed. The warm Atlantic waters penetrate far eastward into the Barents Sea, and establishes the conditions under which also boreal species can occur (Figure 1).

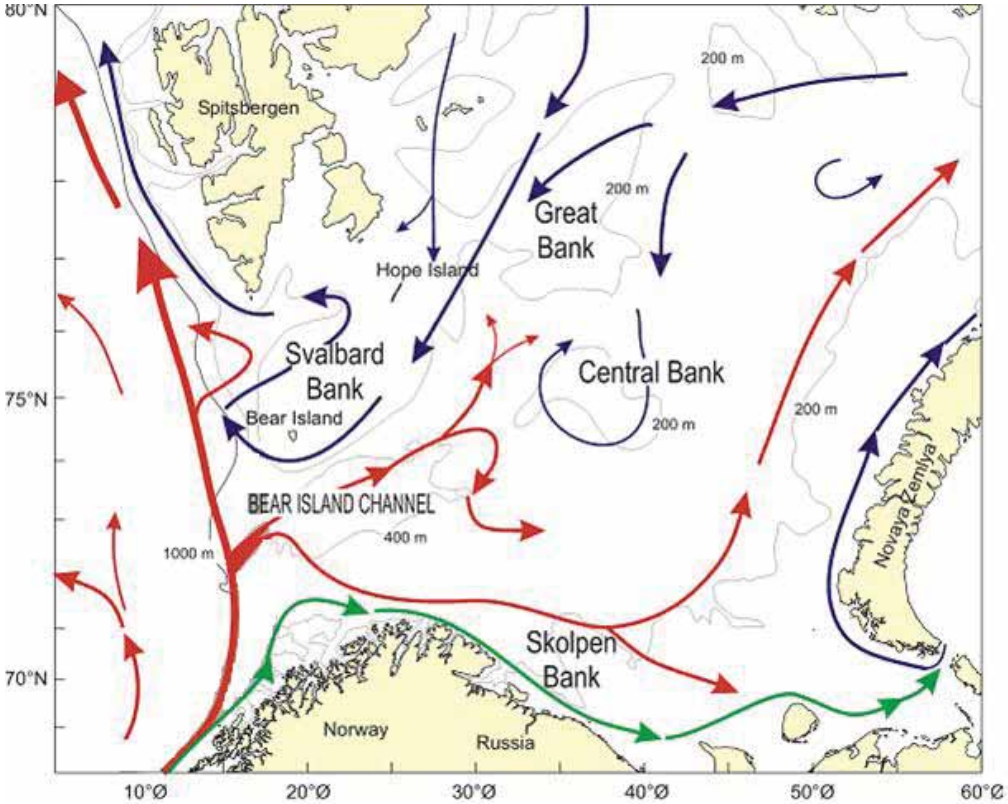


Figure. 1. The system of the predominate currents in the Norwegian/Barents Seas. Red (Atlantic waters) and green (coastal waters) – warm currents, dark blue – cold currents.

Nowadays, the Northeast Arctic cod (*Gadus morhua*) is the most important fish stock in the Barents Sea.

Water temperature, alongside with food accessibility and spawning ground availability, is the main factor influencing fish distribution and migrations (Loeng et al. 2005). This is explained by the differences in temperature range under which the various fish species occur (Coutant 1977; Scott 1982). Cod fisheries are associated with fish migrations which has an impact on the distribution of cod fishing concentrations in both time and space (Boitsov et al. 2003). Therefore, water temperatures also affects the cod fishery in the Barents Sea.

The goal of the paper is to study the impact of water temperatures in the Barents Sea on the fishery of Northeast Arctic cod.

Material and methods

Russian cod fishery in the Barents Sea is particularly characterized by one important feature; it is carried out throughout the whole year. Therefore, we assume that it is possible to study the effect of water temperature on the cod fishery when analyzing the fishery in cold and warm years.

The years 1966 and 2008 were used in the analyzes. Those two years were chosen for the following reasons:

1. These two years had similar cod stock size and catches (stock – 2.2-2.3 x 10^6 t; catches – 484 and 464 x 10^3 t, respectively) which excludes the effect of population density on fish distribution and, hence, the fleet dislocation.
2. These two years were particularly differrent with respect to temperature in the Barents Sea: 1966 was anomalous cold, while 2008 was anomalous warm (Table 1).

In PINRO, there is an electronic database on Russian fishing vessels, formed based on the daily vessel reports. The reports include information about catch size by species, vessel positions and others. The analyses applied daily databases of trawlers in cod fisheries by bottom trawl for 1966 and 2008. All bottom hauls under which cod were found in the catches were taken into account.

The whole area of the Barents Sea and adjacent waters was divided into squares, 10x10 miles each, and in every square, the catch of cod in three-month periods was calculated for 1966 and 2008.

In our opinion, it would not be correct to compare the catches in the absolute units for 1966 and 2008. In the period from 1966 to 2008, there was a significant development in fishing vessels as well as in fishing gears (bottom trawls, in our case). Therefore, it was decided to convert the absolute values of catches (t) to percent.

Table 1. Fishing stock of cod and the thermal state of the Barents Sea waters (data on biomass – ICES, 2011; water thermal state - Karsakov, 2009).

Year	Fishing stock, t	Water thermal state	Year	Fishing stock, t	Water thermal state
1951	3,1	Warm	1981	1,0	Anomalous cold
1952	3,4	Warm	1982	0,8	Normal
1953	3,6	Normal	1983	0,7	Warm
1954	4,0	Anomalous warm	1984	0,8	Normal
1955	3,5	Warm	1985	1,0	Normal
1956	3,2	Cold	1986	1,3	Normal
1957	2,5	Normal	1987	1,1	Cold
1958	2,2	Cold	1988	0,9	Normal
1959	2,4	Warm	1989	0,9	Warm
1960	2,1	Warm	1990	1,0	Anomalous warm
1961	2,1	Normal	1991	1,6	Warm
1962	2,0	Normal	1992	1,9	Warm
1963	1,7	Cold	1993	2,4	Normal
1964	1,4	Normal	1994	2,1	Normal
1965	1,4	Normal	1995	1,8	Warm
1966	2,2	Anomalous cold	1996	1,7	Normal
1967	2,9	Normal	1997	1,5	Cold
1968	3,4	Cold	1998	1,2	Cold
1969	2,8	Cold	1999	1,1	Warm
1970	2,1	Warm	2000	1,1	Anomalous warm
1971	1,6	Cold	2001	1,4	Warm
1972	1,6	Normal	2002	1,6	Warm
1973	2,4	Warm	2003	1,6	Warm
1974	2,2	Normal	2004	1,6	Anomalous warm
1975	2,0	Warm	2005	1,6	Anomalous warm
1976	1,9	Normal	2006	1,6	Anomalous warm
1977	2,0	Cold	2007	1,8	Anomalous warm
1978	1,6	Anomalous cold	2008	2,3	Anomalous warm
1979	1,1	Anomalous cold	2009	2,6	
1980	0,9	Cold	2010	2,6	

To make maps, to calculate fishing areas, and to determine the distance between the core fishing areas in the cold and warm years, software MapViewer 7.1 was applied.

Results and discussion

Figure 2 shows the positions of cod captures in 1966 and 2008. In 1966, in the northwestern areas, the cod were only distributed along the southwestern coast of Spitsbergen. In the central part of the sea, cod were found as far north as to the areas between Svalbard and the Central Bank. In the southeast, there were no cod to the east of 46° E.

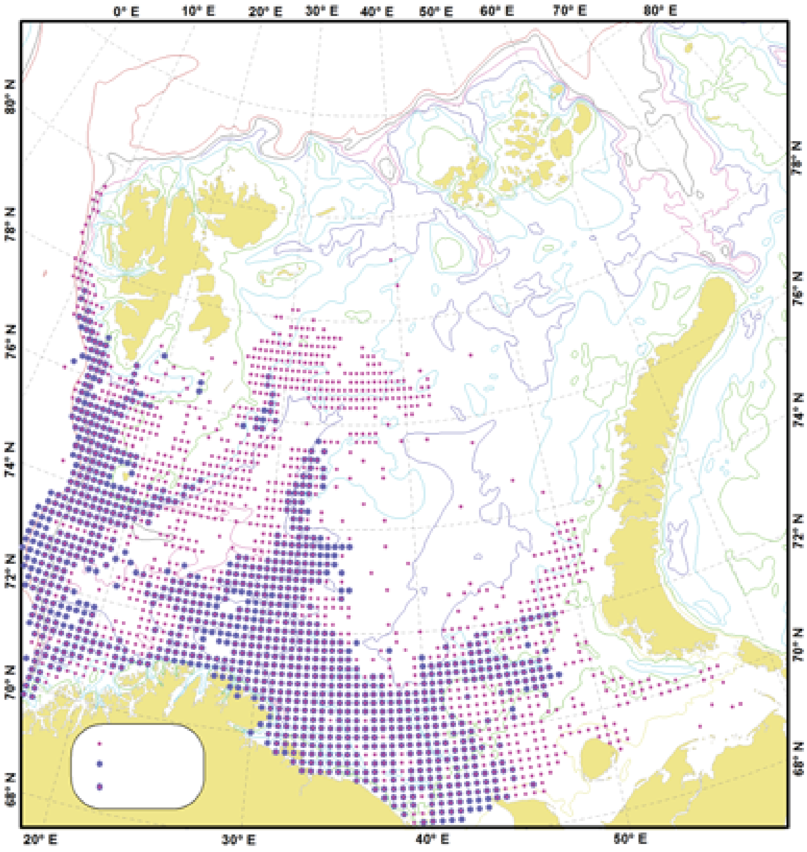
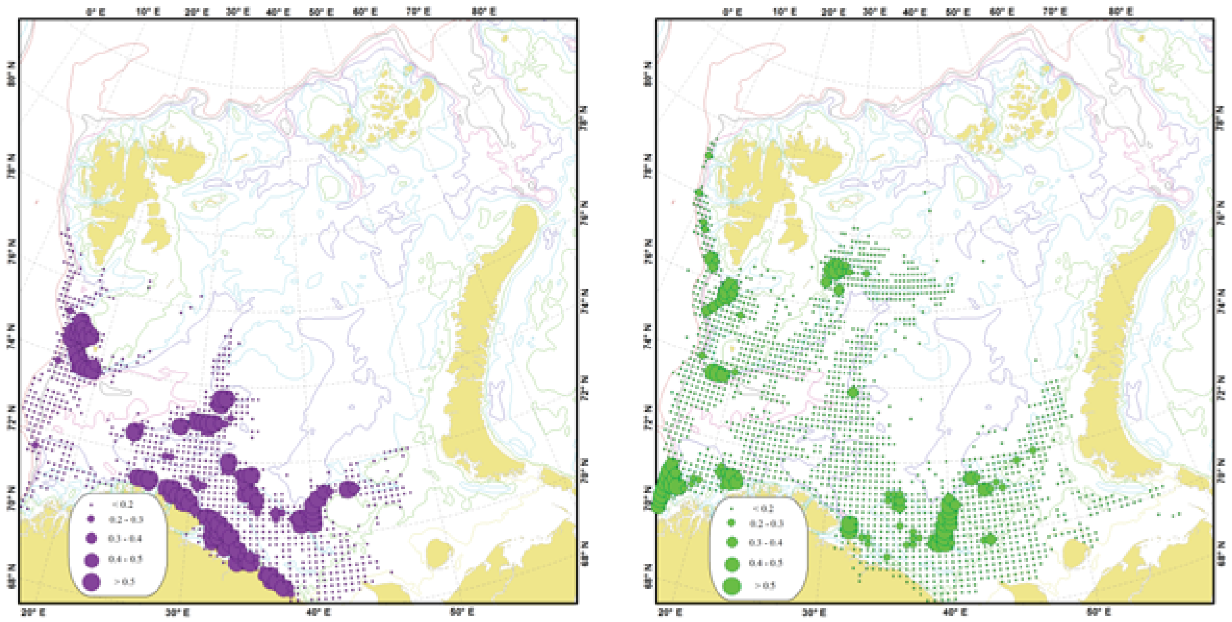


Figure 2. Positions of cod capture in 1966 and 2008.

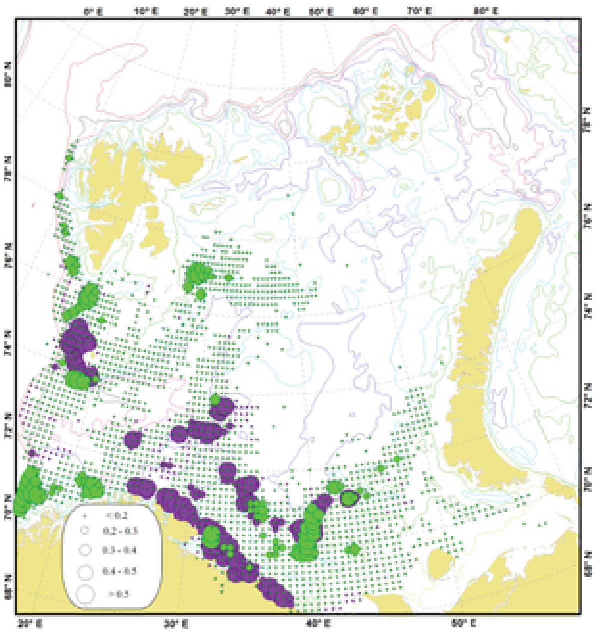
In summary, catches in 1966 were basically taken in the Bear Island area, along the southern coasts from 28° E to 40° E, on and northwest of the Skolpen Bank (Figure 3a). In 2008, cod were fished along the entire western coast of Spitsbergen, in the northwestern areas of the sea, and to the Novaya Zemlya and the Kara Strait in the east. In the central part of the Barents Sea, cod were found up to 78°N. The basic catches were taken from the area stretching from the northwestern coast of Norway, to the south of the Bear Island, to the south of Spitsbergen, in the Hope Island area, on the Skolpen Bank and in adjacent waters (Figure 3b). According to our estimates, the fishing area in the warm year 2008 was 1.5 times largeer than in the cold year 1966 (237 vs 147 10^3 nautical mile^2, respectively).

In the Barents Sea, the main cod fishery areas are related to the warm currents from the Atlantic. This was particularly typical for the cold year (Figure 3c).



(A) 1966

(B) 2008



(C) 1966 & 2008

Figure 3. Cod fishery in 1966 and 2008 (Circles show fishing squares, 10 x 10 nautical miles, a diameter indicates a portion of catch in this square from the total annual catch, %).

Regardless of the sea heat content, in the first quarter of each year the primary cod fishery areas were located in the southwestern Barents Sea. In the first quarter of 1966, cod were mainly fished in the area from 27° E to the Skolpen Bank. In the same period of 2008, two main fishing areas observed: at the northwestern coast of Norway and to the north and northeast of the Skolpen Bank (Figure 4a).

In the second quarter of the cold year, the densest concentrations (as determined from the results of fishing) are registered on the Bear Island slopes and along the southern coast, from 27° E to the Skolpen Bank. In the warm year and second quarter of the year, cod are distributed along the western coast of Spitsbergen and the stock is intensively fished in the area from the Bear Island to the southwestern coasts of Spitsbergen. In the east, the fish were distributed on the Skolpen Bank, where a strong fishery core occurred (Figure 4b).

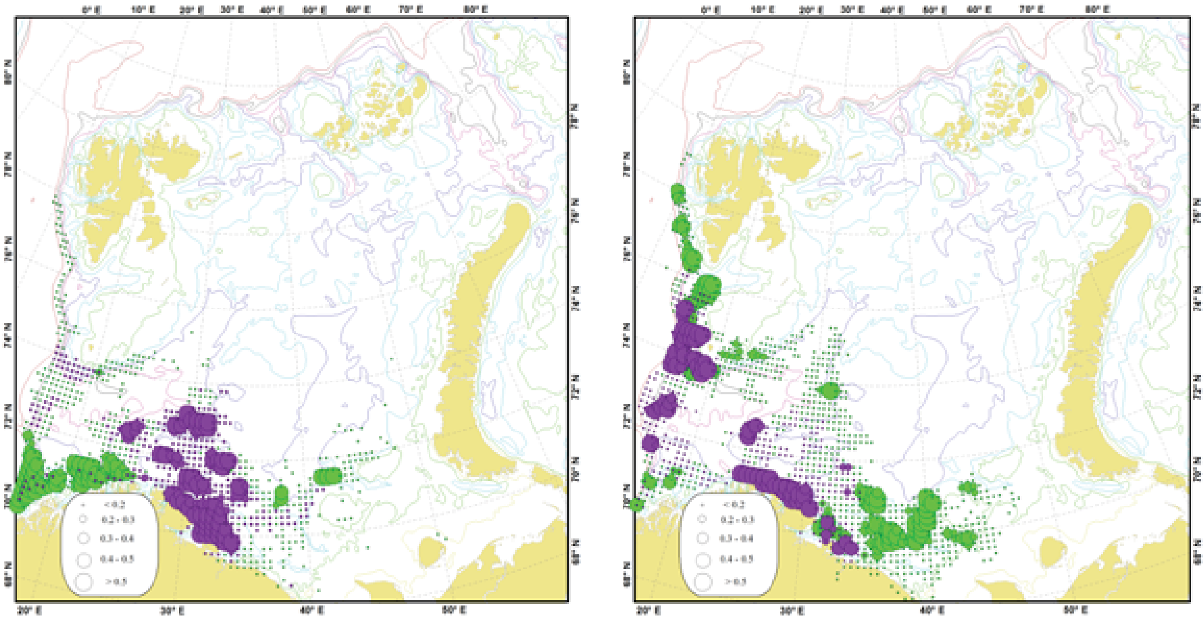
In the third quarter of the cold year, in the eastern part of the Barents Sea, fishing concentrations of cod were found along the southern and northern tips of the Skolpen Bank. In the central part of the sea, the fishing concentrations are related to the eastern tip of the Bear Island Channel, and in the west, to the Bear Island slopes. In the warm year, in the west, the fishery was primarily carried out at the northwest coast of Spitsbergen, in the central sea – to the south of the Hopen Island. In the southeastern part of the sea, some fishery cores occurred in the area from the Skolpen Bank to the southwest coasts of the Novaya Zemlya (Figure 4c).

In the third quarter, cod reach the margins of the feeding areas (especially in the cold year). For this reason we calculated the distance between the cod fishery cores for the cold and warm years, in the west, central and southeast parts of the Barents Sea. In the warm year, in the western areas, cod fishing concentrations were 340 miles further to the north than in the cold year; similarly, in the central and southeast areas these concentrations were, respectively, 240 and 50 miles further to the northeast.

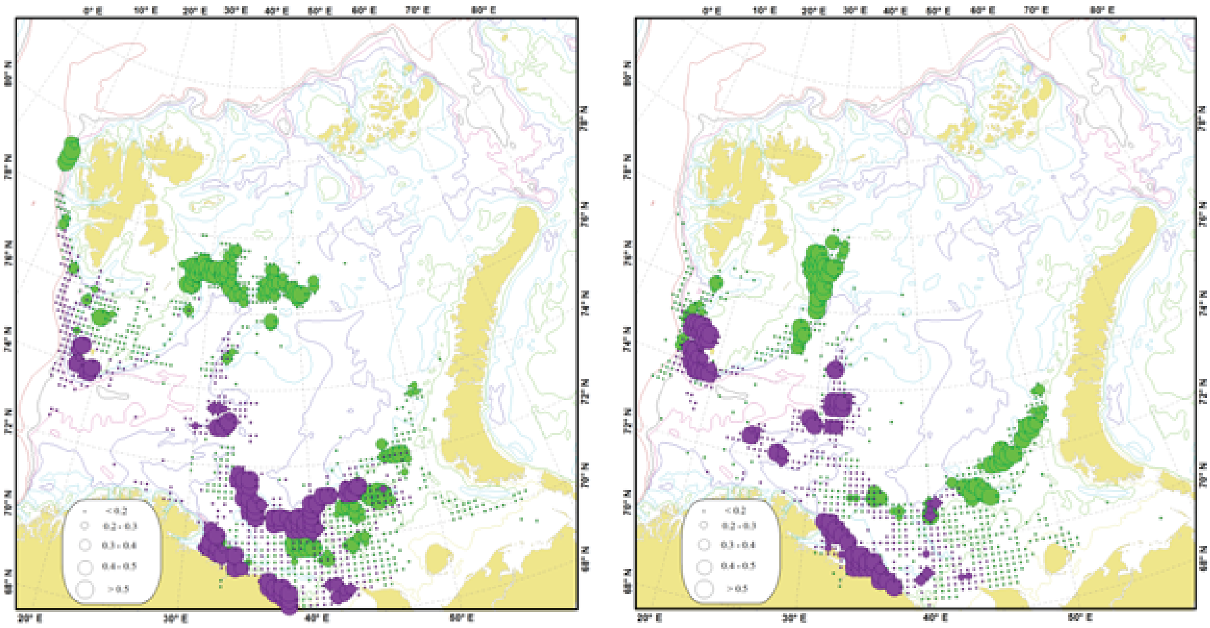
In the fourth quarter of the cold year, the main fishing concentrations were recorded along the southern coast from 31° to 38° E, to the east of the Bear Island Channel and on the continental slope, at the Bear Island. In the warm year, the primary cod fishing concentrations were in the west, on the continental slope, to the northwest of the Bear Island, in the central part – to the south of the Hope Island and in the southeast in the northeast direction from the Skolpen Bank (Figure 4d).

In the warm year of 2008, fish were distributed in a larger area, than in the cold year of 1966. Also, cod concentrations and fishery shifted north and northeastwards in the warm year, a feature not noted in the scientific literature on the Barents Sea cod (Marti 1980; Boitsov et al. 2003; Drinkwater 2005, 2006; Drinkwater et al. 2010).

Apparently, occurrence of concentrations of cod in the areas of the northwestern coast of Norway in the first quarter, and the fact that these concentrations are distributed more westwards in the warm year than in the cold year, may seem strange. However, in our opinion, this is not strange. In the first quarter of the cold year, the basic fishery is conducted in the area from 27° E to the Skolpen Bank, where the wintering aggregations of immature cod were fished. The same aggregations occurred in the warm year, but now they were distributed further to the east. Cod concentrations at the northwest coast of Norway are the result of both sea warming and the length-age structure of the cod spawning stock. In warm years, the area of cod spawning shifts to the north (Boitsov et al. 2003; Godø 2003; Sundby and Nakken 2005; Drinkwater 2005, 2006). In the 2000s, young fish predominated among the Barents Sea cod spawning stock (Kovalev et al. 2010), which increased the role of spawning grounds on the northwestern coast of Norway. Also, it was noticed that, together with mature cod, also large immature fish which were spawning in the following year, came to the spawning grounds making false spawning migrations (Boitsov et al. 2003). All this resulted in increased possibilities for cod fishery by the Russian fleet at the northwestern coast of Norway.



(A) Quarter 1 (1966 & 2008) (B) Quarter 2 (1966 & 2008)



(C) Quarter 3 (1966 & 2008) (D) Quarter 4 (1966 & 2008)

Figure 4. Cod fishery in 1966 and 2008 (Circles show fishing squares, 10 x 10 nautical miles, a diameter indicates a portion of catch in this square from the total annual catch, %).

On the whole, the area of the Barents Sea cod fishery in 2008 was very similar to that one observed in the warming period of the 1920s-1930s, when fishery was conducted in the northern and eastern parts of the Barents Sea, areas where there were no concentrations of cod in the cold years (Blacker 1957; Beverton and Lee 1965; Cushing 1982).

According to the expert forecast of PINRO, dramatic changes in climate are not expected in the North Atlantic (Figure 5). Therefore, it may be expected that the Barents Sea ecosystem will be functioning as at present and its fishery potential will remain as corresponding to the current level. Hence, all of us (politicians, managers, and scientists) should distinctly recognize that now and in future the choice of the stock management regime will have a stronger influence on the stock status of the commercial species in the Barents Sea and adjacent waters, than the changes of the environment.

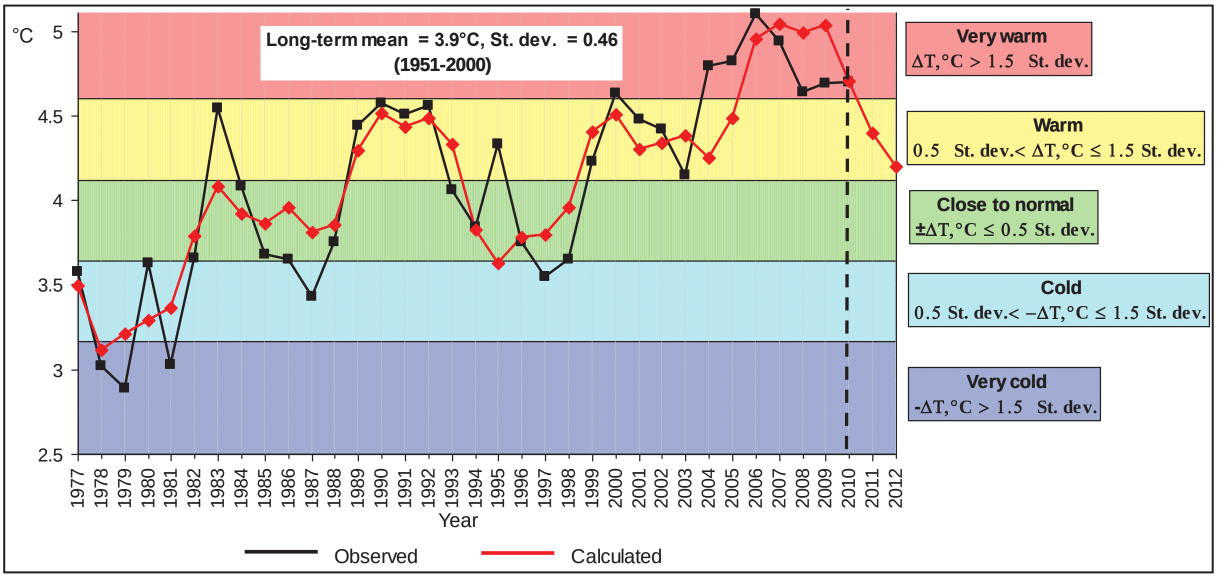


Figure 5. Observed and calculated temperature variation on the Kola section (0-200 m) in 1977-2010 and temperature development prognosis up to 2012 (PINRO's data).

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Photo: Institute of Marine Research

2.20 Structural changes in the macroplankton – pelagic fish – cod trophic complex caused by climate change

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On the basis of long-term data that reflect climatic fluctuations in the Barents Sea as well as their influence on important components of the ecosystem (macroplankton, planktivorous fish and predatory fish), we describe variability in biological parameters and various quantitative ratios in the trophodynamic structure of this region. The species composition and distribution of macroplankton, the abundance, distribution and food habits of capelin and polar cod and the state of the stock, migration distance and feeding peculiarities of cod are all analysed. The most remarkable changes were observed during three periods; cold 1970-1998, warm and abnormally warm 1999-2006 and 2007-2009, which characterise the main features of the functioning of this trophic complex.

The abundance, species composition and distribution of euphausiids in the Barents Sea are determined by the heat content of the water and by the level of transfer of their early stages from the Norwegian Sea. The most recent decade has been characterized by the wide distribution of the boreal euphausiids *Thysanoessa inermis, T. longicaudata* and *Meganoctiphanes norvegica* in the Barents Sea as well as by a sharp reduction in the range of the coldwater species *T. raschii*.

The nature of euphausiid consumption by capelin is determined by their abundance, age structure and distribution. The most intensive feeding on euphausiids is typical of large fish in the north and northeast of the Barents Sea, when warmwater species (mainly *T. inermis*) are delivered there by Atlantic waters.

The consumption of euphausiids by bottom fish does not depend on the thermal regime but is primarily a function of the state of the capelin stock and varies in antiphase with the dynamics of that stock.

An abrupt rise in the abundance of euphausiids at the expense of higher imports of early stages (eggs, nauplii, larvae) of warm water species in warm years has recently been observed. This is helping to stabilise the euphausiid stock even under conditions of high abundance of the fish that consume them.

2.21 Variability in population parameters of harp seals : Responses to changes in sea temperature and ice cover ?

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Harp seals are dependent on ice as a substrate for whelping, nursing, resting and moulting. Poor ice is particularly critical during the whelping period because early break-up of the ice may disrupt lactation and reduce the availability of haul-out platforms during the first weeks of independent feeding. This may lead to increased mortality of pups and long term cohort effects such as reduced growth and reproductive rates. Changes in sea temperatures and ice cover may also affect harp seals more indirectly by changing abundance, diversity and distribution of prey species.

Figure 1. Harp seals on thin ice off Newfoundland (Photo Garry Stenson).

The largest concentration of harp seals is found in the Northwest Atlantic with about 1.4 million females whelping annually off Newfoundland and Labrador and 200000 in the Gulf of St. Lawrence. In these areas, ice extent and ice thickness have decreased significantly since the early 1990s and have been particularly low in the past 5 years. Increased pup mortality has been observed in bad ice years and incorporated into population models. The overall trend in this population is, however, a significant increase in population size from about 4.5 million in the early 1990s to more than 8 million in 2008. Observed reductions in adult pregnancy rates over the same period may therefore be due to both density dependent effects and density independent environmental changes. Observation of northward displacement of breeding patches in recent years is, however, likely a response to a deterioration of ice conditions in traditional breeding areas.

Harp seals also traditionally whelp off Northeast Greenland, where population size has been estimated at 650000 in 2011 (100000 pups). In this area the most favourable breeding conditions are associated with formation of a tongue of ice, known as "Odden", in a gyre system to the north of the island Jan Mayen. The frequency of this event has, however, decreased significantly since the late 1980s and the breeding ice has become subject to a more pronounced southward drift. The ice floes have also generally become smaller and thinner. Recent data suggest a decline in body growth rates of young animals and an increase in age at maturity. It is not clear, however, if this is primarily due to density dependent changes or environmental changes.

A third traditional harp seal whelping area is found in the White Sea, where about 300000 pups were born annually over the period 1998-2003. A sudden drop in pup production was observed in 2004-2005 and since then the estimated pup production has been estimated at no more than 160000. Long term changes in ice conditions in the White Sea are less pronounced than in the other breeding areas, but the percentage ice cover was consistently below the long term average in the period 2000-2005. No alternative breeding areas have been identified so far by Russian reconnaissance flights, but further reconnaissance is needed to exclude this possibility. Alternatively, the sudden drop in pup production could be due to a decline in female pregnancy rates. Time series data on body condition and reproductive rates are being analysed to evaluate this hypothesis, but unfortunately sampling of biological material has not generally been done in the same years as pup production surveys.

For updated information about the status of the stocks, see ICES (2011).

Reference

ICES 2011. Report of the Working Group on Harp and Hooded Seals (WGHARP), 15-19 August 2011, St.Andrews, Scotland, UK. ICES CM 2011 / ACOM: 22: 74 pp.

Photo: Institute of Marine Research

2.22 On seasonal changes of the carbonate system in the Barents Sea: observations and modeling

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Increasing partial pressure of CO_2 in the atmosphere is interconnected with the CO_2 partial pressure in the surface layer of the ocean. This lead to the Ocean acidification, and increases the acidity of the seawater, expressed by a reduced pH (Cicerone et al. 2004). An increased concentration of dissolved CO_2 in seawater also implies reduced concentration of carbonate ions. This has consequences for the carbonate saturation state of the seawater and implies that it is becoming gradually more difficult for marine organisms to build carbonate shells. Corals including those living in cold water coral reefs, and some pelagic organisms, including potential key species of phytoplankton and zooplankton, are likely to be significantly negatively affected by the ongoing acidification.

The problem of estimation of ocean acidification, using observations, is that the interannual changes of pH are superposed with large temporal (daily and seasonal) and spatial variability (for example at the frontal zones). This situation is even worse in the Arctic region, where the amount of available data is poor.

This work aimed to study the role of seasonality of the biogeochemical processes of organic matter (OM) production and decay in the seasonal changes of the carbonate system (pH, pCO_2, aragonite saturation). Observations were performed on a transect Tromsø – Spitsbergen with a Ferrybox equipped Ship-Of-OPportunity (SOOP) cargo vessel MS "Norbjørn" - these data were used for verification. A simplified two-dimensional vertical model was used to parameterize the hydrophysical processes at a Coast-Open Arctic section positioned along the observed transect. The biogeochemical processes were parameterized using OxyDep (Yakushev et al. 2011), a simplified biogeochemical model using time scales that are seasonal and larger, and that considered inorganic nutrient (NUT), dissolved (DOM) and particular (POM) organic matter and biota (BIO).

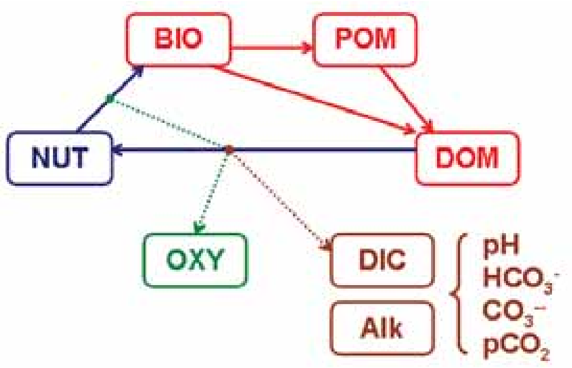

Figure 1. Flow chart of biogochemical model Oxydep (Yakushev et al., 2011) coupled with the carbonate system block used for the calculations.

Dissolved inorganic carbon (DIC) and alkalinity (Alk) were considered as independent model variables (Figure 1). DIC changes were correlated with NUT on the base of the Redfield ratio, Alk was changed in the marine boundary of the modeled transect. The carbonate system equilibration was considered as a fast process and calculated at every time step using the iteration procedure. The carbonate system modeling was described on the base of standard approach (Dickson 2010).

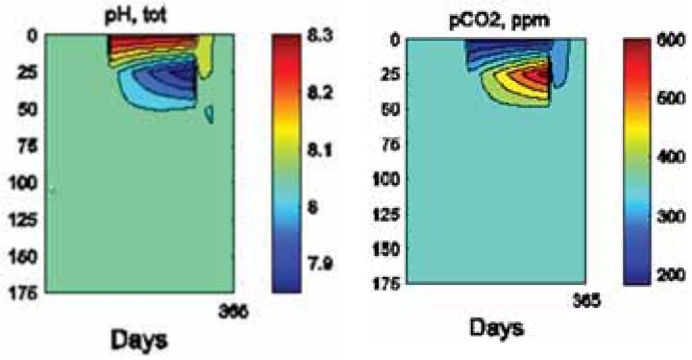

Figure 2. Modeled seasonal variability of pH (left) and pCO2 (right) in the vertical column near the Island Bjørnøya (Medvezhiy).

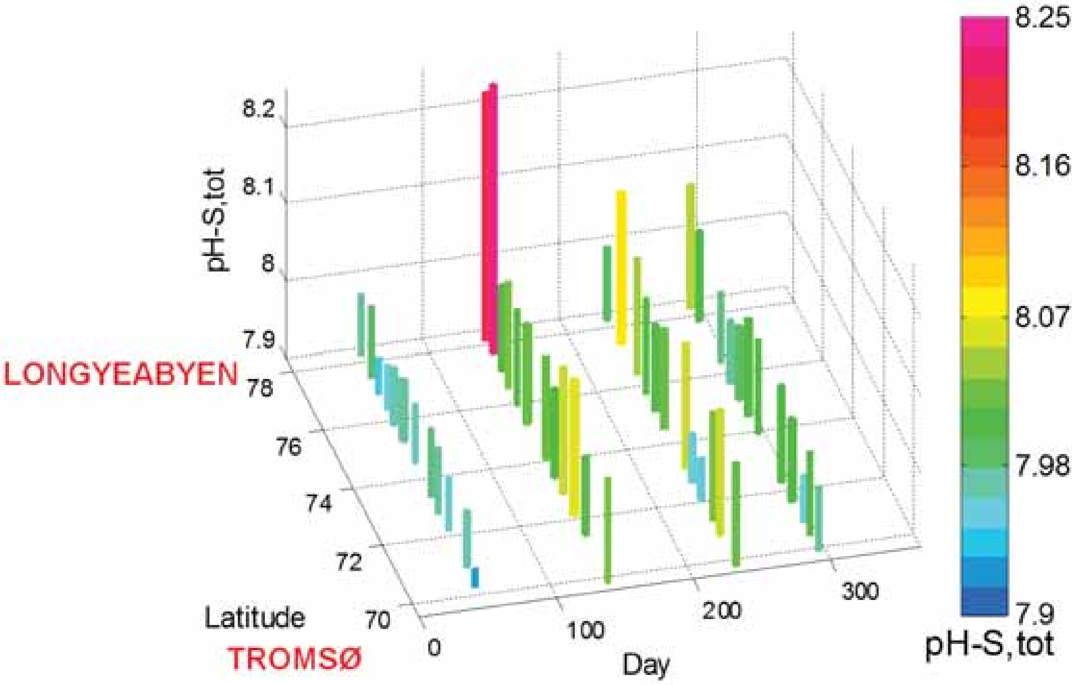

Figure 3. Observed variability of pH at a transect Tromsø-Longyearbyen. pH is given in the total scale.

According to the model estimates the summer formation of DOC and POC and their further destruction affected the carbonate system seasonal dynamics. The modeled seasonal variations of pH (~0.2) (Figure 2) are close to the observed ones t, i.e. 7.94-7.99 in February and 8.04-8.16 in August (pH(Tot)) (Figure 3). Therefore it is possible to conclude that the OM production and decay is the main factor influencing the seasonal variation of the carbonate system parameters in the in the surface waters of the Barents Sea while the role of temperature is supplementary.

The resulting observations allowed us to demonstrate that the upper layer water pCO_2 varies from 480 ppm in winter to minimum values of 280 ppm during the OM production period.

Therefore summer invasion of CO_2 should be replaced by winter evasion. The received results can be helpful for planning of expedition studies, analyzing of the archived field data, as well as for elaborating of the interannual and multidecadal variations models.

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Photo: Institute of Marine Research

2.23 Barents Sea Ecosystem Resilience under global environmental change, BarEcoRe: 2010-2013

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The influence of climate warming on the Barents Sea ecosystem is documented by the long-term ocean temperature increase observed since the 1960s and the projected increases of up to 3°C by 2050. The impact of climate warming on Barents Sea communities can be exacerbated by fisheries. The project addresses the effects of climate warming on the structure, dynamics and resilience of the Barents Sea ecosystem, integrated with the effect of fishery. Detection and forecasting of changes in ecosystem resilience and robustness under global warming and fisheries will be based on a broad battery of inferential tools including multivariate analyses of spatio-temporal changes in community structure, retrospective and prospective modeling of populations distributions, mapping of life history and feeding traits affecting species vulnerability, analysis of trophic interactions and food web structure, and early warning signals of abrupt changes detecting reductions in ecosystem resilience. The main outputs of the project, including a vulnerable species list, mapping of future populations distributions under warming scenarios, characterization of regime shifts, reliable early warning signals of abrupt ecosystem changes, provide tools needed for management of the Barents Sea ecosystem under global environmental change.


Photo: Institute of Marine Research

2.24 Realization of complementary reproductive strategies of *Calanus hyperboreus* and *Mallotus villosus* in the Barents Sea

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Introduction

Phyto- and zooplankton communities have undergone remarkable changes in the course of the past decade against the background of significant climatic changes in the Arctic caused by the retreat of the sea ice and rising air and ocean temperatures. The changes are most marked in the North and Norwegian Seas, where the changes have resulted in the decline in total zooplankton abundance and a northward shift in the distribution of dominant zooplankton - *Calanus finmarchicus* (Beaugrand *et al.* 2002). Similar changes are also taking place in the western part of the Barents Sea (Wassmann *et al.* 2008), which, according to these authors, may lead to dramatic changes in the ecosystem. Such features have already been observed in the Norwegian Sea: according to the Norwegian fisheries newspaper FiskeribladetFiskaren (journalist T. Jensen, Harstad), in August 2011 there was a shortage of food supply (plankton) there, leading to starvation of herring and mackerel.

In a comprehensive review, Falk-Petersen et al. (2009) concluded that the duration of blooms is an important factor in determining the life strategy of individual species and biodiversity of the Calanus complex; different species of Calanus have adapted differently to conditions at high latitudes. Those dwelling in the North Atlantic seas and other regions of the World Ocean have been described in more detail than those species in the Barents Sea except Svalbard waters.

The main concentrations of Arctic species in the Barents Sea are found in its northern and northeastern regions. Lately, owing to faster melting and the retreat of ice northwards, the boundary of their distribution extended to 80-81°N, but both these boundaries and the abundance of some species are subject to marked variations (Orlova *et* al., 2010b). Nevertheless, at the expense of three Calanus species - *C. finmarchicus, C. glacialis* and *C. hyperboreus*, high concentrations of zooplankton have formed in the northern and northeastern areas – 7-10 g and more of dry weight per m^2 (Orlova *et* al., 2009). The abundance of *C. hyperboreus* is lower than that of *C. finmarchicus* and other Arctic species (*C. glacialis*, *Metridia longa*). At the same time, as the largest of Calanus, with a lipid content greatly exceeding that of other species, e.g. *C. glacialis* by a factor of four and that of *C. finmarchicus* by a factor of 25 (Falk-Petersen et al., 2009), *C. hyperboreus* is important not only in the diet of pelagic fish such as capelin (Falk-Petersen et al., 2009; Orlova et al., 2010a), but also in that of representatives of higher trophic levels; sea birds such as the little auk *(Alle alle)* (Falk-Petersen et al. 2007), and marine mammals. Under such conditions, the accurate definition of some elements of the feeding strategy of *C. hyperboreus* is very important, particularly their vertical distribution pattern during the summer-autumn phytoplankton bloom at high latitudes as protection from predators.

On the other hand, it is important to assess the effect produced by capelin on their population (spawning stock before wintering) during their feeding in the northern areas, which in turn, reflects the feeding strategy of this fish, which influences the concentrations of Arctic copepods. This investigation aims at detection of the main adaptive properties of *C. hyperboreus* and capelin *Mallotus villosus* as prey and predator.

Materials and methods

In order to analyse the way in which *Calanus hyperboreus* are carried along the North Cape – Bear Island Transect, historical data were collected by PINRO in the 0-50 m layer during the ichthyoplankton spring-summer survey (May 1960 – 1989 and June 1960-1990). A Juday net with a diameter of 37 cm and mesh size 180 μm was deployed at a hauling speed of 0.8-1.0 m/sec. More details of survey design and section locations are given by Nesterova (1990). Water temperature and salinity for the same years were also recorded.

The quantitative distribution of *C. hyperboreus* in the Barents Sea was analysed on the basis of the data collected in August – early September 1982 to 1993 in the course of PINRO's oceanographic and hydrobiological investigations in the central latitudinal zone of the Barents Sea. The survey covered the area from Spitsbergen to Novaya Zemlya (74°30' - 77°00' N and 18°00' - 57°00' E). The maps of mesozooplankton distribution in 2007-2010 were based on the data of the Joint Russian-Norwegian ecosystem survey carried out in August-September. A comprehensive analysis of more than 900 samples was performed in PINRO for the above period; the abundance of mesozooplankton was given in individuals/m^3, biomass in mg/m^3 wet weight). The data on capelin feeding (2008) were collected during the ecosystem survey in August-September, and stomach were analysed by the quantitative-weight method.

Results

Oceanographic factors and distribution of *Calanus hyperboreus*

The availability of frontal zones is of great importance for the functioning of the marine ecosystem. Such areas offer favourable conditions for the growth and development of many zooplankton species. The northern stations of the oceanographic section North Cape – Bear Island discussed in this study cross the frontal zone (Figure 1).

The analysis of the age structure of *Calanus hyperboreus* showed that specimens of III-V stage drift during this season, thus forming the main biomasses. No clear pattern of *C. hyperboreus* occurrence at the stations has been identified. This species was found at each station of the section in 13-14 cases on the average. Thus, in the spring, *C. hyperboreus* are widely distributed in the Barents Sea Atlantic flows, with maximum concentrations along frontal zones crossing the section in its southern and northern parts.

Unlike the spring period, during the summer decrease could be observed in the occurrence of the species and reduction of its concentrations in the central part of the section (stations 3-10, Figure 2).

During the spring, two peaks in the mean biomass values were observed at the stations of the section (Figure 3).

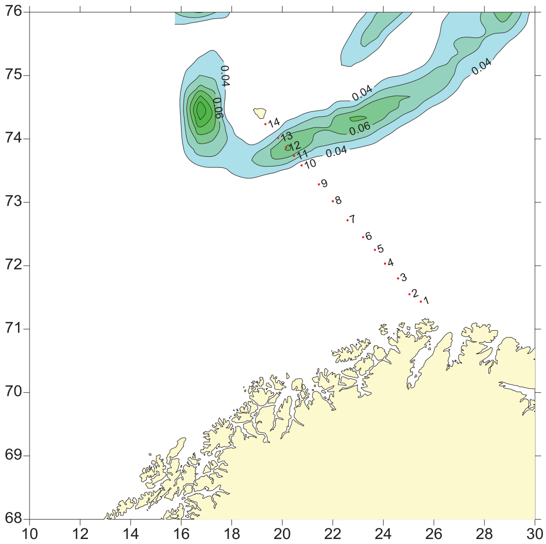

Figure 1. The location of standard stations of the North Cape – Bear Island section and the frontal thermal zone.

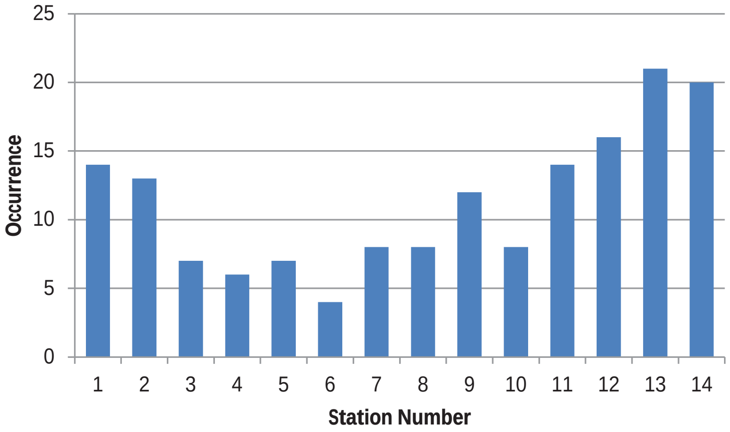

Figure 2. Frequency of *Calanus hyperboreus* in the 0-50 m layer at the stations of the North Cape – Bear Island section in summer.

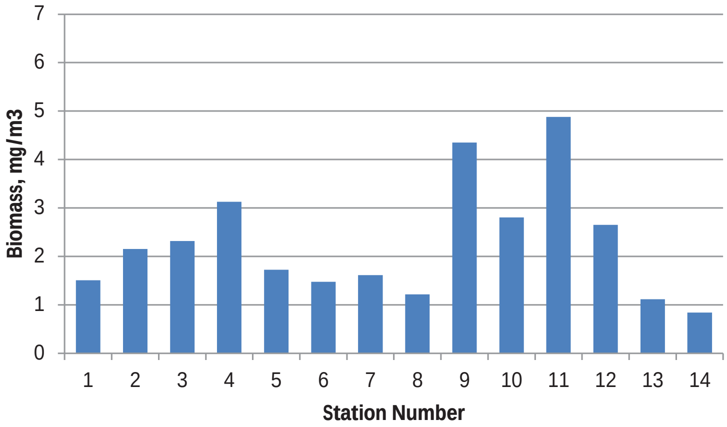

Figure 3. Mean long-term biomass of *Calanus hyperboreus* in the 0-50 m layer at the stations of the North Cape – Bear Island section in spring.

The first peak was located at stations 3-4 of the section (about 3.0 mg/m^3) in the flows of the main branch of the North Cape Current. In the upper layers of these areas, a haline frontal zone separated the salt waters of the Atlantic origin from desalinated coastal ones, and higher current speeds were observed. The second peak in the average values of *C. hyperboreus* biomass (4.0-4.5 mg/m^3) was recorded at stations 9-11 of the section. The southern margin of the frontal thermohaline zone, which is the boundary between the Atlantic and Arctic water masses, crosses the waters of these stations (Figure 1).

In summer another pattern of variations in the distribution of *C. hyperboreus* biomasses became apparent in the plane of the section (Figure 4). Their maximum values (more than 5-6 mg/m^3 on average) were registered in the northernmost part of the section at 13-14 stations. These stations are situated beyond the front line in the cold sector of the thermohaline gradient zone. The growth of *C. hyperboreus* concentrations in these areas is probably a special process of "accumulation", as it is more difficult to pass across sharp gradients than uniform ones, which results in high biomass values.

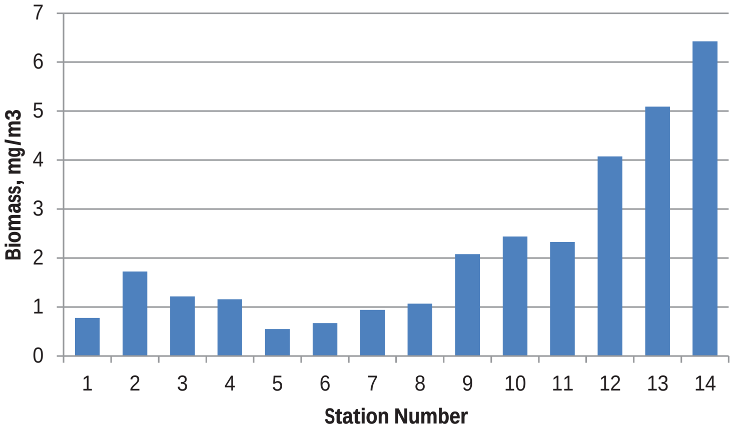

Figure 4. Long-term biomass of *Calanus hyperboreus* in the 0-50 m layer at the stations of the North Cape-Bear Island section in summer.

Another local maximum was evident at station 2 in the southern part of the section. The biomass of *C. hyperboreus* at the southern stations of the section fell to an average of 50% of its spring values. Plankton registered in the southern part of the section may be distributed in the southern and central parts of the Sea. The biomass of *C. hyperboreus* at the northern stations of the section is the basis for the distribution of this species in the Arctic zone of the Barents Sea.

Calanus hyperboreus spring distributions along the North Cape-Bear Island transect in years with different water temperatures are shown in Figure 5.

Analysis of the results revealed the existing differences in concentrations. In warm years, denser concentrations of *C. hyperboreus* were found in the northern part of the section with maximum biomass (about 5 mg/m^3) at station 11, in a warm sector of the thermohaline frontal zone. In cold years, a relatively high biomass (2-3 mg/m^3) of this species was related to coastal Norwegian water masses. It should be mentioned that in years with low heat content, *C. hyperboreus* was not found at the northernmost station of the section, which may be accounted for by the presence of ice fields that hampered studies in the field. The difference in distribution from year to year may also have largely been dependent on the intensity of certain flows of warm currents, which, in turn, had an impact on general distribution of zooplankton.

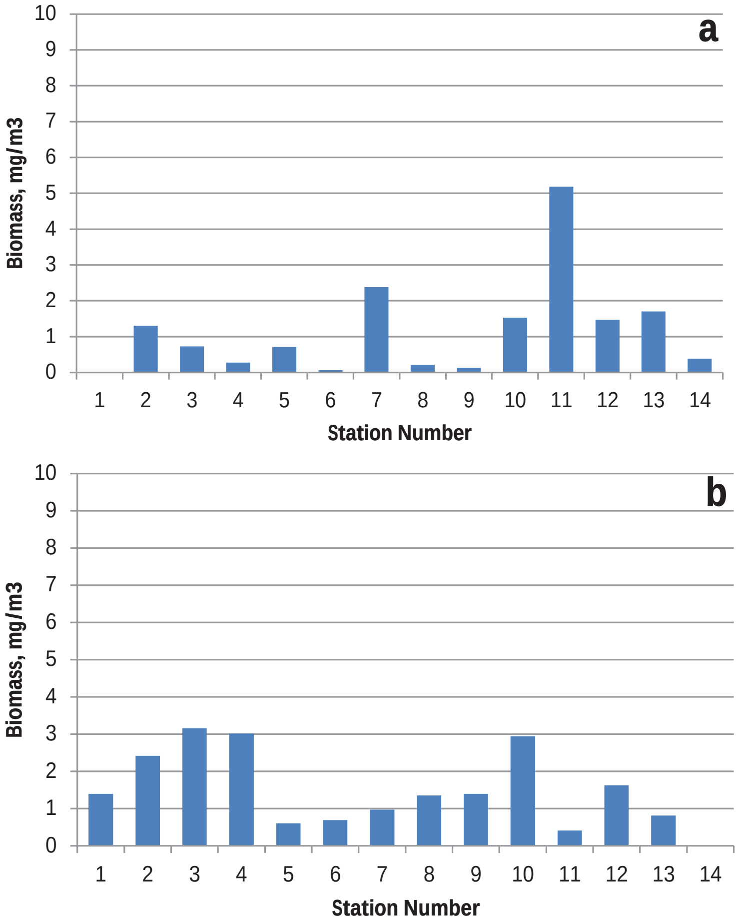

Figure 5. Distribution of *Calanus hyperboreus* biomass in spring in the 0-50 m layer at the stations of the North Cape – Bear Island transect in warm (a) and cold (b) years.

In summer, the distribution of *C. hyperboreus* along the North Cape – Bear Island transect also had some peculiarities, depending on the temperature conditions of the water mass (Figure 6).

In warm years *C. hyperboreus* did not form dense concentrations at the stations . Some local maxima were observed near the thermohaline front in the north (station 13) and salinity frontal zone in the south (station 2). In low-temperature years high densities and biomasses of *C. hyperboreus* (7.5 – 9.5 mg/m^3) were registered at the northern stations of the section. Considerable concentrations of this species in cold years may have been caused by weakening of the intensity of Atlantic water flows, and zones of higher concentrations of *C. hyperboreus* near the front were formed owing to the difficulties in overcoming steep gradient areas. On the other hand, dense concentrations may have been formed due to a good supply of zooplankton that resulted from long processes of ice melt and thus intensive phytoplankton production. In cold years, there is also a significant possibility of a long spawning period and later migration cycles of *C. hyperboreus*, which may also lead to greater concentrations of this species in the northern parts of the section.

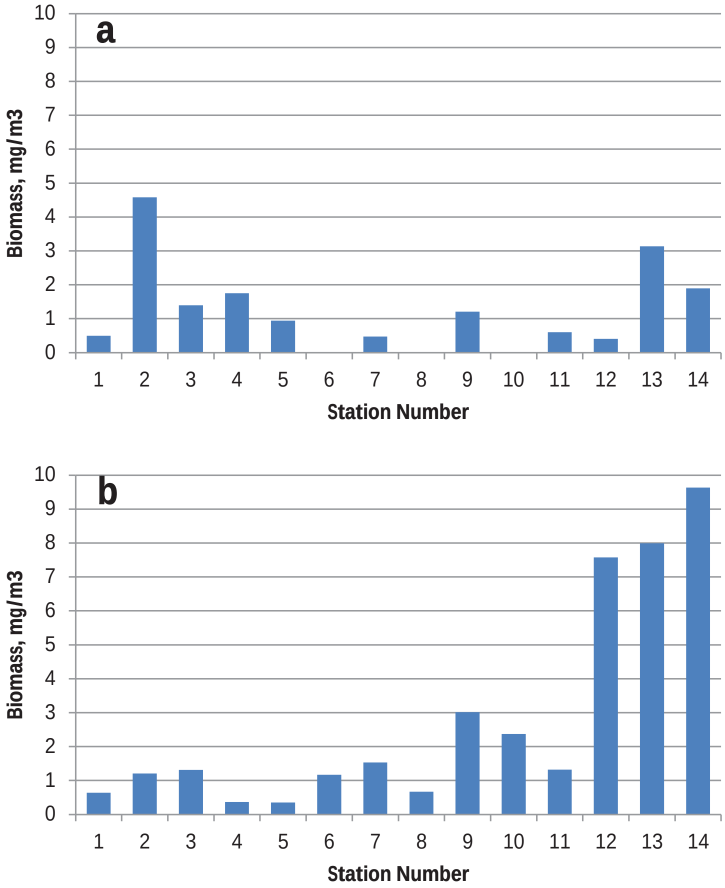

Figure 6. Distribution of *Calanus hyperboreus* biomass in the 0-50 m layer at the stations of the North Cape – Bear Island Transect in warm (a) and cold (b) years in summer.

In August 1992 – early September 1993, PINRO carried out oceanographic and hydrobiological investigations in the central zone of the Barents Sea. The survey covered the area from Spitsbergen to Novaya Zemlya Archipelago (74°30’ - 77°00’ N and 18°00’ - 57°00’ E).

The abundance of *C. hyperboreus* was highest in the northern and eastern survey areas as well as in the shallow waters of Spitsbergen Bank. The spatial distribution of *C. hyperboreus* is much affected by the pattern of vertical migrations of this species. The subsurface minimum (–1.5 - –1.7 ºC) at depths of 50-75 m was a distinctive feature of the vertical structure of these Arctic waters. The variations in the depth of this minimum in the years different temperatures were marked, which in turn affected the distribution of the cold water *C. hyperboreus*. Thus, in a cold 1987, *C. hyperboreus* dominated in the survey area at depths of 50-100 m (Orlova et al, 2004), while in a warm 1989 its presence in the total abundance of plankton was insignificant.

General warming of the Barents Sea in the 2000s led to a significant northward shift in the range of of *C. hyperboreus*. The range ofthis highly abundant species was the greatest in 2006-2007, spreading as far as 82º N (Figure7). These years were characterized by minimum ice coverage of the Barents Sea. Active ice melt may have created favourable conditions for phytoplankton production, which, in turn, were food for *C. hyperboreus*.

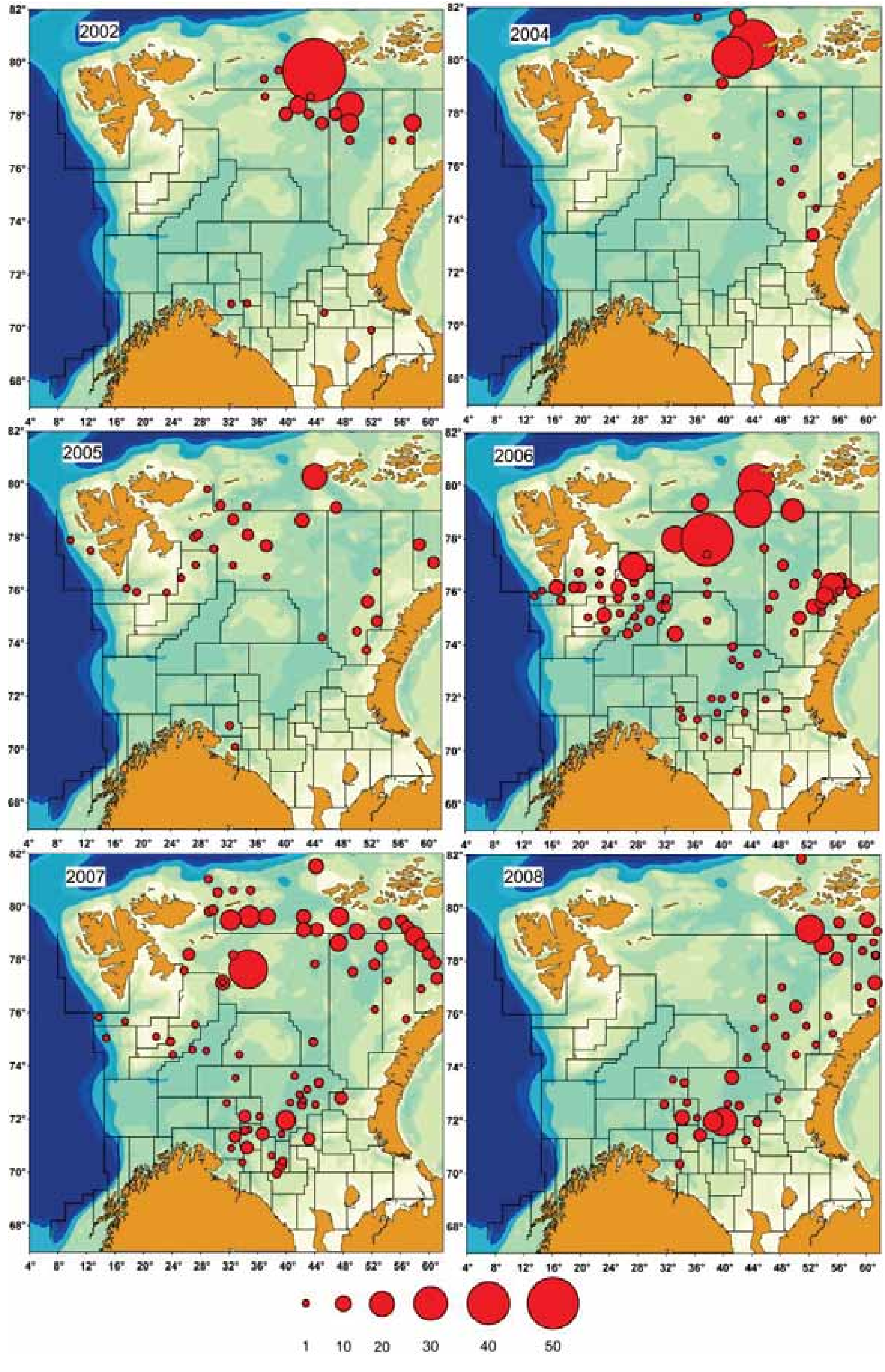

Figure 7. Abundance (individuals/m^3) of *Calanus hyperboreus* in the Barents Sea in the 0-bottom layers in 2002-2008.

In 2007-2009, *C. hyperboreus* were the least abundant species (Figure 8), making up a significant part of the total biomass only due to their large size (Figure 9). In 2010, C. *hyperboreus* concentrations were close to those of 2007 (with maximum values of 20 individuals/m^3) similar to biomass values, but the latter underwent large variations (maximum 38-77 mg/m^3). In 2009-2010 there were thus clear tendencies towards a fall in total abundance and biomass of the Arctic species in northern areas.

Spatial fluctuations in copepod abundance, together with other factors, are connected with the pattern of their vertical distribution throughout the day. The latter depends on differences in the feeding strategies of herbivorous species of copepods, which include, among other elements, the intensity of feeding on phytoplankton and duration of dwelling in the upper layers that enables them to avoid a dangerous "trophogenic zone" (Pasternak, 2010). According to studies (Pasternak et al., 2001; Falk-Petersen *et al*. 2007) in the area around Svalbard, the start of downward migration of different species varies in time. Females of *C. hyperboreus*, which is the fastest in food consumption (Pasternak, 2010), stop feeding and leave the surface layers in early summer when the concentration of food is highest, while older copepodites (stages CIV and CVdo the same a month later. At this time, *C. finmarchicus* not only continue to feed but are also most active while feeding.The descent of *Calanus* therefore protects them from predators, on the one hand, make makes them available for plankton-eaters (capelin) in the lower layers, on the other. This phenomenon is of great importance for the development of feeding behavior of fish as the main factor in providing them with accessible food. The feeding strategy of capelin,m which tends to maximum satiation on large prey species, namely, females of *C. hyperboreus*, prior wintering (Falk-Petersen et al., 2009), is realized, in its turn, at the expense of abundant crustaceans of older stages. This was exemplified in 2008, when in the area north of 78 °N large capelin fed intensively only on females of *C. hyperboreus* and *C. glacialis* of stages IV-VI, which enabled the fish to accumulategreater stores of fat (Orlova et al. 2010a,b).

We proved this taking the year of 2008 as an example, when in the area north of 79° N large capelin intensively consumed *C. hyperboreus* which, although they did not dominate their diet in terms of quantity, constituted the main portion by weight (Figure 10). In this year, *C. hyperboreus* amounted to 40-70% of the food weight of large capelin (Figure 11).

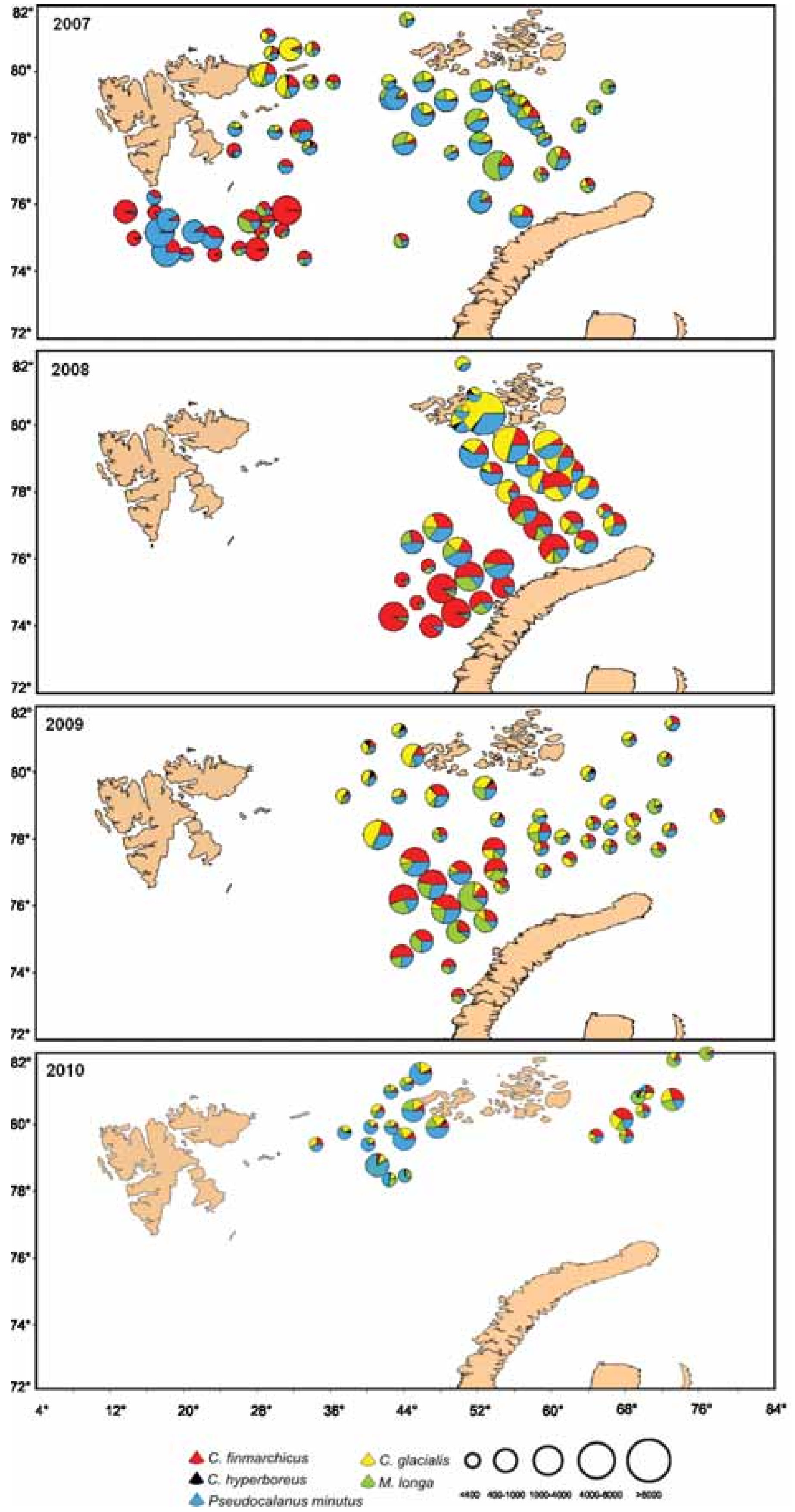

Figure 8. Quantitative distribution of different species of copepods in the 0-bottom layer of the Barents Sea in August-September 2007-2010 (ind./m^3).

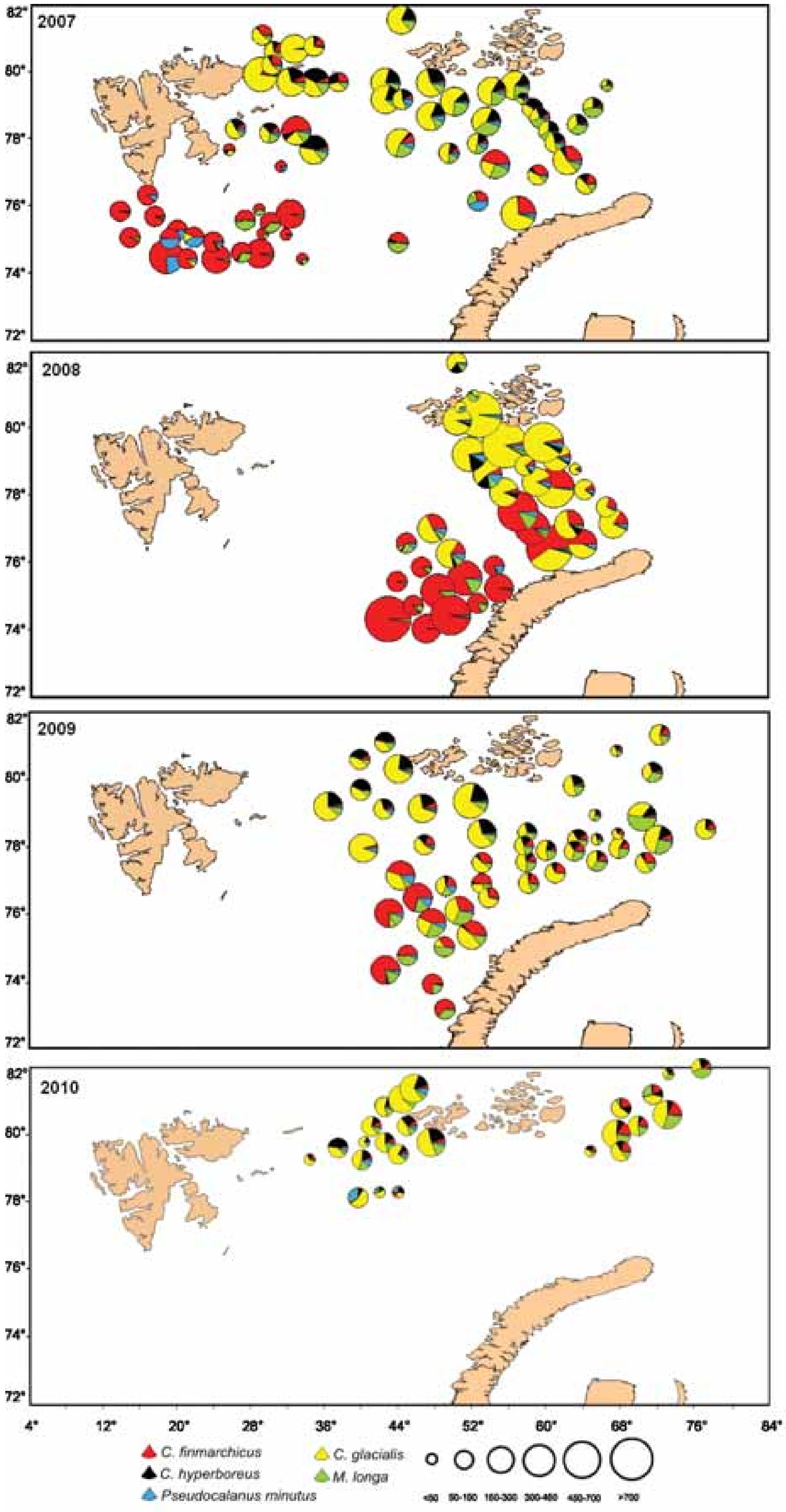

Figure 9. Biomass of five species of copepods in the 0-bottom layer of the Barents Sea in August-September 2007-2010 (mg/m^3)

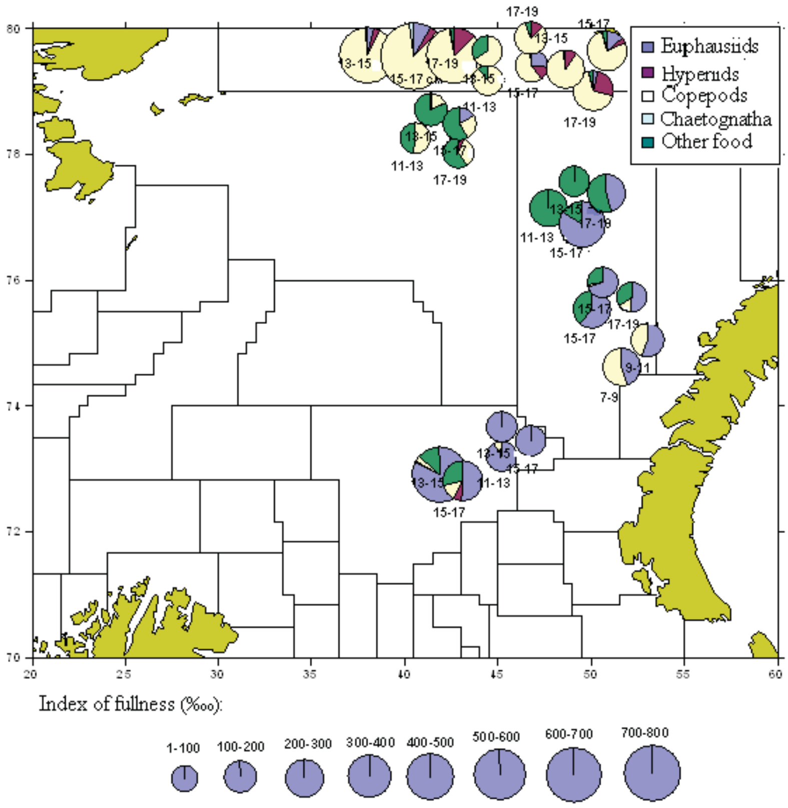

Figure 10. Food composition and feeding intensity of capelin of different size groups in August-September 2008.

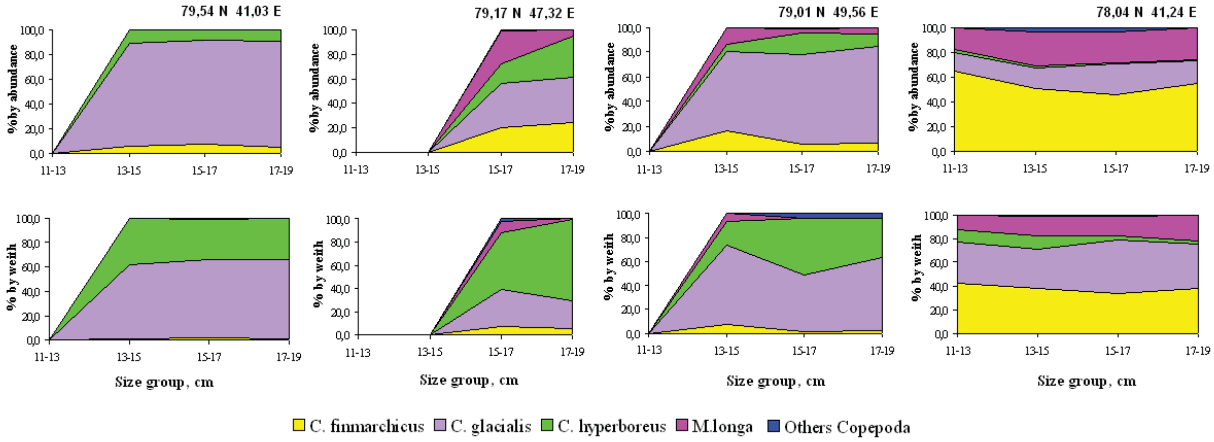

Figure 11. Species composition of food of capelin of different size groups in August-September 2008 (the upper row – in % by numbers, the lower one –percentage by weight.

Vertical distribution and seasonal development of Calanus

Several years of PINRO data, with regular zooplankton sampling at four-hour intervals, demonstrated a pronounced diurnal rhythm of migrations of herbivorous *Calanus finmarchicus, C. glacialis* and *C. hyperboreus.* At the same time, there were significant differences in the pattern of vertical distribution of these species and crustaceans of different stages (Orlova et al., 2004).

In the Barents Sea, in the first half of 1984 in the area 74 30'-75 30'N 52-54 E, where there still was an intensive phytoplankton bloom, the distribution of *C. finmarchicus* of different stages was characterized by the constant presence of nauplii and younger copepodites in the upper layers during most of the day, with a gradual descent of more mature (stages IV-V) specimens to lower layers. The vertical distribution of *C. glacialis* was highly dependent on its age composition. In most cases both in the dark and during the hours of daylight, the older stages, including females, remained in the 50-100 m layer and deeper. Only in the area 76-77 ^{o}N, where juveniles of these species at stage I-III were found in great numbers, did they remain in the 0-50 m layer for long periods (17-23 hours). The vertical distribution of *C. hyperboreus* was more specific since, as it reproduces during the winter, early juveniles of stage I-II were actually missing from the population in August, having turned into stage III copepodites. In the dark season, the latter, like the juveniles of other species, were mainly distributed mainly at depths of up to 100 m, while older copepodites and females were mainly in the 50-100 m layer and at the bottom. Specimens of Stage IV *C. hyperboreus* built up maximum concentrations at the same depths during the day.

In the first half of August 1989, in the area 74°30'-77°00'N, 40-48°E, an intensive phytoplankton blooming had been observed and the copepods of different species were characterised by their irregular distribution in different layers (Orlova *et al.* 2009).

Nauplii and copepodites of *C. finmarchicus* of stages I-II thus occupied nearly the whole of the upper layer throughout the day, with copepodites of stage III amounting to 40% in this layer. In daytime, 20-50% of individuals migrated to the 50-100 m layer, while between 16.00 and 21.00, when the illumination changed, up to 15-30% migrated to the lower layer. Only older copepodites made up not more than 20% in the upper layer in the daytime, descending gradually to 50-100 m and to lower layers, where they made up as much as 30-50% of the population throughout the day. *C. glacialis* individuals of early (CI-II) stages were most irregularly distributed. Their relative amount, which amounted to 40-70 % in the upper layer in the daytime, fell to a minimum between 16.00 and 21.00 and then grew sharply (to 60%) and remained at this level until 05.00. The distribution of copepodites of stage CIII was more regular, with 20% of them occupying the upper layer for most of the 24 hours. However, their distribution became more dynamic at the depth of 50-100 m, with 40-70% of copepodites remaining there during the day, descending to the lower layer at 16.00 where they remain until morning. Individuals of older stages were more consistent. Their proportion in the upper layer throughout 24 hours did not exceed 20% on average, as also in the 50-100 m layer (22-25%), while the bulk accumulated in the lower layer (45-50%). The vertical distribution of *C. hyperboreus* was more specific as its reproduces in winter time, and in August individuals of early stages CI-II were absent. *C. hyperboreus* stage CIII individuals, along with young specimens of other *Calanus* species, remained mainly at depths of up to 100 m during the dark period, while individuals of older stages were found in the 50-100 m layer; females were found only in the bottom layer and in 70% of cases they occurred near the bottom. However the females of this species were exclusively registered in the bottom water layer, making up almost 70% of the samples instead of the 64% registered in 1984.

The similar differences in vertical distribution of three species of Calanus were observed in the waters around Franz Josef Land from August, 27 until September, 4, 2007. At the same time, some variation in Calanus behavior in relation to the intensity of phytoplankton bloom in different parts of the above area was observed. A number of situations have been analysed. On August 27-31, in the area 79°45' -80°45' N 34°54'-42°31'E, there was an intensive development of phytoplankton at the expense of representatives of *Haptophyta* (*Phaeocystis* spp.) and *Chaetoceros*. The zooplankton community was characterized by an abundance of Calanus nauplii (along with rare occurrences of eggs) and early juveniles of *C. finmarchicus* and *C. glacialis*, while the crustaceans of older stages of these species were less plentiful. *C. hyperboreus* was found sporadically at stages III-IV.

The densest concentrations of copepods were found in the western part of the Franz Josef Land area (79°45' N, 34°54'E), where *Phaeocystis* spp. still remained in moderate bloom. Here, early in the day, the upper layer (0-50 m) was dominated by juveniles of *C. finmarchicus* (at an overall concentration of 277 individuals/m^3, copepodites of stage I-II made 84%) and by *C. glacialis* (at a total concentration of 438 individuals/m^3, where copepodites of stage III prevailed – 66%). In the 0-100 m layer, the proportion of juveniles decreased and that of older crustaceans of these species grew insignificantly (up to 29-30 individuals/m^3). The abundance of stage IV – VI *C. hyperboreus* increased with depth, ranging within the depth range 0-50 m, 0-100 m and 0-bottom between 5.5, 6.0 and 16 individuals/m^3, females being found only in the near-bottom layer. A similar vertical distribution of three species of Calanus was also observed at the easterly station (79°45' N, 42°31'E), where the bloom was most intensive but copepods were less plentiful.A similar tendency was maintained at the station at 80°45' *N*, where the bloom was also fairly intensive. In the morning, in the 0-100 m layer, *C. finmarchicus* was found mainly at stage I-IV (85% at stage IV), *C. glacialis* at stage I-IV (56% at stage III), but this species was reproducing in lower water layers.

Further north (81°40' N, 44°16'E), the pattern of Calanus distribution was similar to that at station 3, but, at the same time, it reflected the peculiarities of this area: *C. finmarchicus* was scarcely to be found, while *C. glacialis* and *C. hyperboreus* were found mainly in the 0-100 m layer, the former at stage V-VI (77%), and the latter at stage IV-V (about 90%). In the lower layer, judging by the presence of females and males, the latter species was reproducing. It is probable that the time of day was also of importance since, in the second half of the day, during the transition from daylight to darkness, copepods usually change their location, ascending to the upper layers to feed.

At the end of August and the first five days of September, around Franz Josef Land, *Chaetoceros* diatoms dominated in phytocenosis (3-4 points), while numbers of eggs and nauplii sharply decreased in the western part of the area. The distribution of *Calanus* species had common features, but some peculiarities in the distribution of individual species were discovered that can be regarded as typical for night-time distributions . In particular, at station (79°32' N, 32°16'E), maximum concentrations of *C. finmarchicus* accumulated in the 0-100 m layer, their bulk (46%) being composed of crustaceans of stage IV in early morning (85%), in contrast to daytime values, when crustaceans of stage I-II dominated in this layer (89%). The distribution of *C. glacialis* was also characterized by higher concentrations in the 0-100 m layer and dominance of stage III, the relative percentage of which at different times of the day varied only slightly (56, 64 and 60% in the morning, afternoon and night, respectively). At lower depths, crustaceans were less numerous, but the tendency of vertical distribution followed that in the 0-100 m layer and in both layers *C. glacialis* and *C. hyperboreus* were reproducing.

In late August, phytoplankton at station 6, bordering on the Persey Elevation (79°57' N 29°17'E), were missing. This was not a coincidence, as in adjacent areas only traces of *Ceratium* spp. were found at that time. Zooplankton still contained some Calanus eggs, though nauplii were plentiful, which indicated recent completion of Calanoid reproduction. This was also confirmed by the abundance of early juveniles of *C. finmarchicus*, the abundance of which in the 0-50 m layer came to 380 individuals/m^3 during the night (copepodites of stage III making up 63% of the total), but crustaceans of older stages were also numerous here (more than 430 individuals/m^3). The quantity of *C. glacialis* in the upper layer was much lower, and only few specimens of *C. hyperboreus* were found. At the same time, a large proportion of the young crustaceans could be found at depths of 0-100 m, where *C. glacialis* formed the densest concentrations (up to 270 individuals/m^3). *C. finmarchicus* juveniles were less plentiful here, but older stages were also abundant (up to 200 indiividuals/m^3). The density of concentrations of both species decreased with depth, and only that of *C. hyperboreus* increased.We can thus assume that under the existing conditions *C. hyperboreus*, which descended to lower layers earlier than other species, was less dependent on the availability of phytoplankton food while *C. glacialis* and *C. finmarchicus* needed it greatly.

On the whole, the situations characterizing feeding strategies of three species of herbivorous copepods (*C. finmarchicus, C. glacialis* and *C. hyperboreus*) during their summer-autumn feeding largely confirm their patterns of behavior in other areas and allow us to distinguish *C. hyperboreus* as a species adapted to seasonal shortage of food in the Barents Sea. On the other hand, as a preferred (favourite) food for fish and other predators, this species is the most accessible and vulnerable, and this may mask its advantages when realizing a feeding strategy based on predator avoidance .

That a high proportion of all three species of *Calanus* remained in the lower layers in early August testifies to their accumulating sufficient fat, which enables them either to perform vertical migrations less frequently, or to enter the diapauses. These data confirm the data of various authors, that cold-water species capable of accumulating large amounts of lipids at the expense of intensive feeding on phytoplankton (Heinrikh *et al.* 1980; Kosobokova, 1980; Conover & Corner 1968; Pasternak *et al.* 2001), perform less clearly marked vertical migrations.

Quantitative assessment of wintering stock of copepods

The phenomenon of zooplankton wintering stock formation in near-bottom layers in the autumn and winter connected with the cessation of predation is well known.Unlike the wintering concentrations in the Norwegian Sea, which have been thoroughly described, information on those in the Barents Sea is currently scarce,largely due to inadequate availability of zooplankton concentrations in lower water layers for sweeping by traditional gear; the Juday net in autumn and winter. PINRO has traditionally (since 1952) used trawl-attached nets in the assessment of macroplankton (euphausiids, hyperiids) abundance, and such mesoplankton as are found in the net are not usually recorded. Only their biomass is occasionally estimated in terms of volume.

In order to justify the use of the trawl-attached net when assessing the abundance of a wintering stock of copepods in lower water layers (including analysis of their species and age structure), simultaneous hauls by two nets (Juday net and trawl-attached net) were made in the lower water layer in September 2009. Comparison of the results showed that, like the resuilts obtained by the trawl-attached net, copepods dominated in abundance in lower water concentrations that exceeded even those hauled by the Juday net.These data also confirmed the descent of a large proportion of copepods to lower water layers in September. The Juday net was fairly regularly used to haul euphausiid larvae nauplii, and even eggs of Copepoda, which usually remain in the water column. Chaetognatha (juveniles and adult specimens) were the most numerous, while 12-18 mm-long juveniles dominated the euphausiids (about 65% of the total abundance of euphausiids). As a result, the total biomass of zooplankton was determined by the abundance of euphausiids, and the total biomass compared to that in the hauls made by Juday net was higher by a factor of roughly 2.5 – to the limit of 0.45 g/m^3.

The structure of the wintering stock of copepods depended on their zoogeographical and ecological status, as well as on the duration of life cycles of the speciesevaluated. Voluminous data characterizing the distribution of the wintering stock in November-December 2009 were bounded by 76-77°N, which was connected with seasonal trawling conditions (formation of ice coverage). The North Atlantic species *C. finmarchicus* that formed local concentrations typically dominated throughout the area under investigation. A wintering population of *C. finmarchicus* was the most abundant one in the area off Western Spitsbergen and in the southern regions of the central and eastern parts of the sea.

The main concentrations of *C. finmarchicus* with a 1-year life cycle consisted mostly of crustaceans of stage V, supplemented by those of stage IV; specimens of stage VI (females) were found even more rarely. The main biomasses with maximum values of 180-210 mg/m^3 were formed at the expense of crustaceans from these age groups.

The population of less numerous Arctic species in this area,e.g. *C. glacialis*, which has a two-year life cycle, consisted of two specimens from two generations with different terms of spawning: stages III-IV and V-VI. Crustaceans of stage V from an earlier spawning period formed the bulk of the biomass.

The highest concentrations of *C. hyperboreus* were found in the West Spitsbergen area (Figure 12). Despite the relatively high water temperature in the Barents Sea, the temperature of the near-bottom layer was close to the mean long term value west of Spitsbergen, where adjacent waters were the warmest (with temperatures higher than 3.0 °C and anomalies about 0.5 °C). In general, the temperature range in the near bottom of the area ranged from 1 to 3 °C.

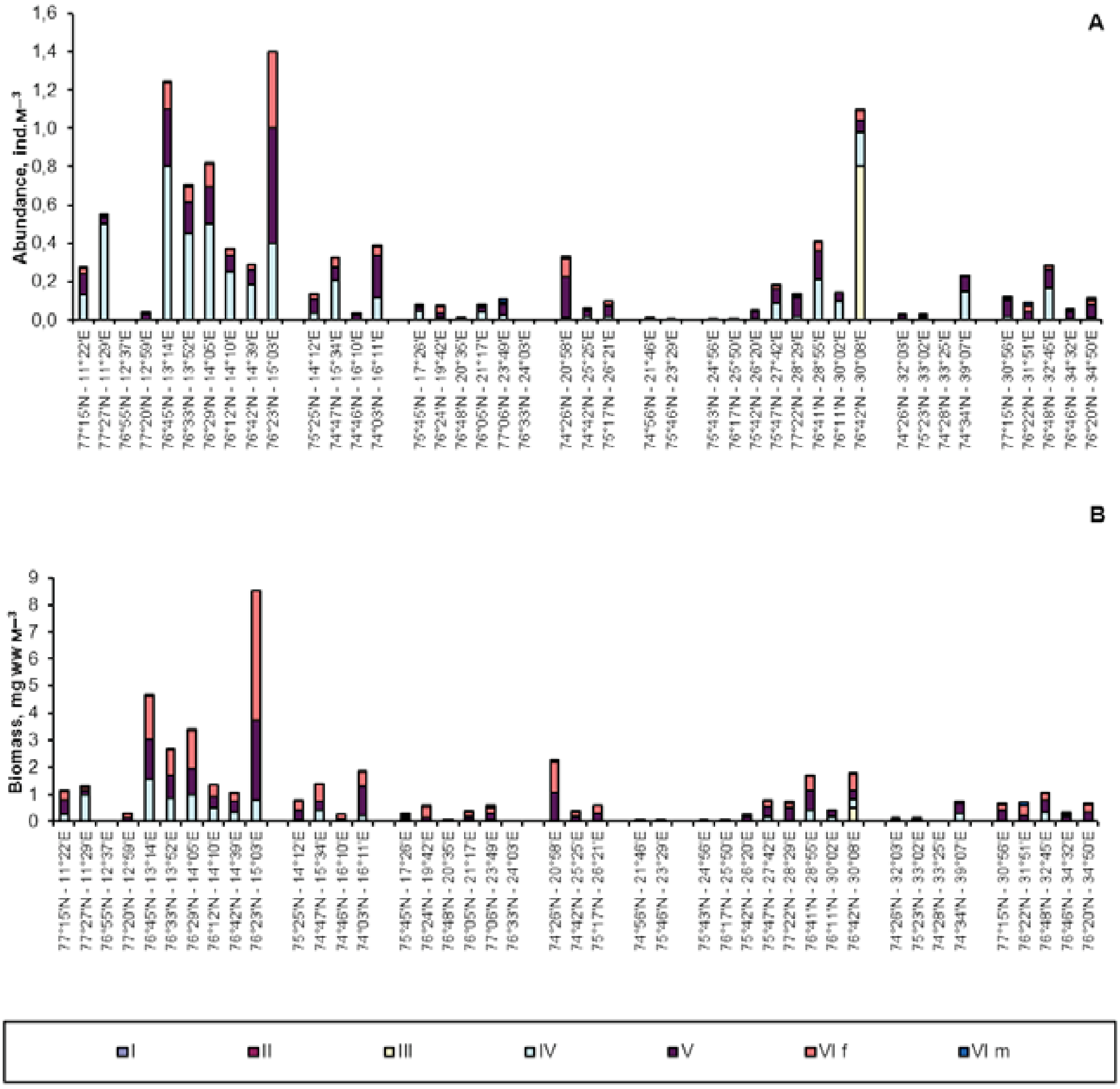

Figure 12. Age structure of *Calanus hyperboreus* in winter concentrations in the northern part of the Barents Sea in November-December 2009: A – abundance (ind./m^3), B – biomass (mg/m^3)

The structure of the *Metridia longa* wintering stock, which is smaller than Calanus Arctic copepods, which are highly tolerant to temperature conditions and have a long period of reproduction, was related to faster development and the formation of a spawning part of the population, which was basically composed of males and females of stages V-VI.

The main features of the quantitative distribution of wintering concentrations of copepods in the southern part of the sea in 2009, compared to that in the northern areas, included a higher density of *C finmarchicus* (with maximum concentrations up to 300-400 individuals/m^3 in the central areas) along with *C. hyperboreus* and *M. longa*, higher maturation rates of mass species of copepods including the Arctic *C. glacialis* and *M. longa*, with a high percentage of mature males and females in their populations, and higher biomasses formed by all species except *C. glacialis*.

Conclusions

According to the results of the survey, *Calanus hyperboreus* is transported during the spring into the Barents Sea across a wide front and is found everywhere along the North Cape – Bear Island section, with maximum biomass located at the southern and northern stations. In the summer, the species most frequently occurs near the thermohaline frontal zone in the north and saline front in the south of this section, where it forms denser concentrations. In cold years concentrations of greater density and higher biomasses of *C. hyperboreus* formd, perhaps due to reduced advection of Atlantic waters and delayed development of the phytoplankton that provide favorable feeding conditions for copepods.

The vertical distribution of *C. hyperboreus* as an element of its feeding and reproductive strategy characteristic of the northern ocean regions is also typical of the north and northeast of the Barents Sea. This distribution pattern is of great importance for the development of feeding behavior of the fish as the main factor in providing them with their preferred food. The early descent of fed females and older specimens of *C. hyperboreus* protects them from predators, on the one hand, but makes them available to fish predators (capelin) in lower water layers, on the other hand.

In the early years of this century, the range of *C. hyperboreus* shifted gradually northwards, with their abundance among Copepoda declining compared to the prevalence of *C. finmarchicus* in northern areas. However, they still remained significant for biomass formation. At the same time, in 2009-2010, a clear tendency towards a reduction of the total abundance and biomass of Arctic species in northern areas became apparent.

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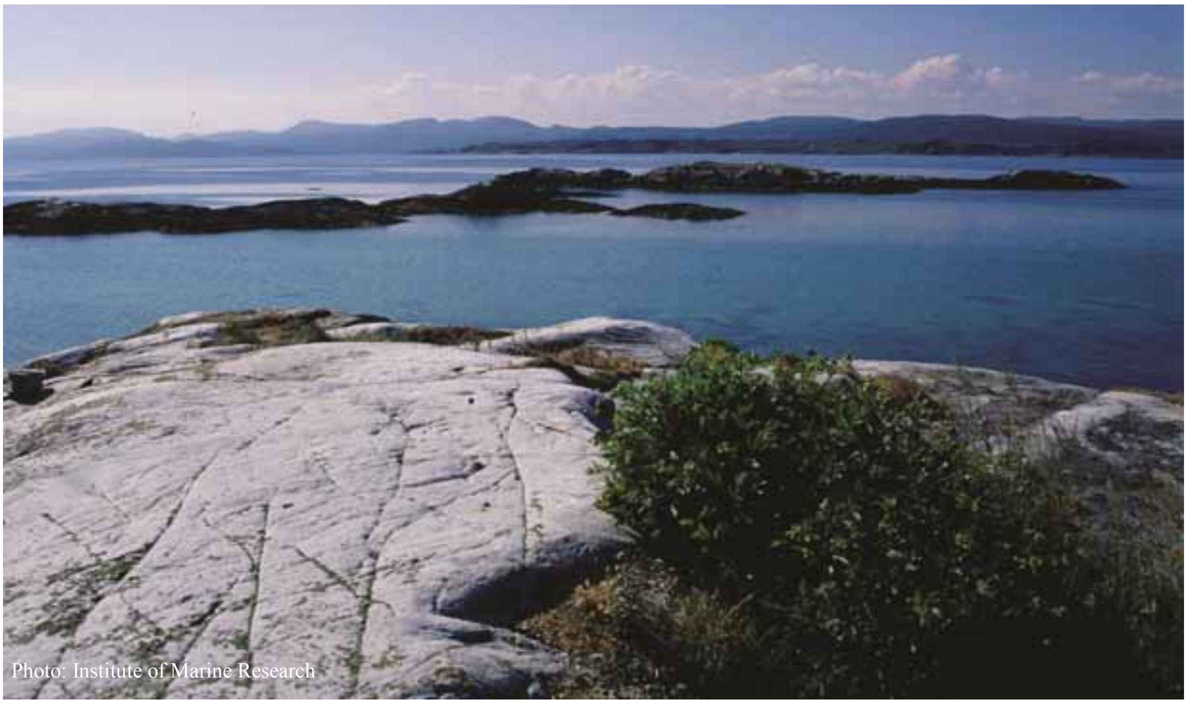

Photo: Institute of Marine Research

2.25 Spatial variation in density of 0-group cod and its influence on yearclass strength

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Abstract

North East Arctic cod is a commercially and ecologically important fish species in the Barents Sea. Survey data on 0-group fish have been collected annually in August-September for more than 30 years. During this period, the climate in the Barents Sea is characterized by a strong increasing temperature trend, from the cold late 1970s to the warm 1990s-2000s. In addition to environmental changes, large human activity, mainly through fishing, influences the Barents Sea ecosystem. Historically, the cod landings have varied dramatically from large landings during the 1950s-70s, leading to decreasing spawning stock biomass and weaker recruitment, to strong decreasing landings in the 1980s. Here we analyse the dynamics in the geographical distribution of cod and specify a main area, which contain the major part of the 0-group fish abundance. We discuss this with regards to the effect of climate variation, spawning stock and other factors on the geographical distribution. Data from the scientific surveys (1980-2011) is used to answer the questions: What is the variation of the geographical distribution and which factors influence this? How does the dynamics in occupation area influence on the year class strength?

Keywords: 0-group cod, Barents Sea, geographic distribution

Introduction

North East Arctic cod (*Gadus morhua* L.) has been an important commercial species for several hundreds of years in the Barents Sea. A substantial increase in cod catches were observed during the 19th century, from 50 to 200 thousand tonnes. The catches continued to increase during the 20th century, with a maximum in 1956 of above 1.3 mill tonnes, until the dramatic decline (down to 250-300 thousand tonnes) of the cod stock in 1980s due to overfishing (Øiestad 1994; Hylen 1993). Severe restrictions on the fisheries contributed to the stock recovery in the 1990s followed by an increase of the cod stock and catches in 2000s.

Cod is an ecologically important species in the Barents Sea and prey on both pelagic fish, mostly capelin, demersal fish species, and crustaceans, mostly *C. finmarchicus* and Euphausiids (Boitsov et al. 1996; Johansen 2002; Dalpadado et al. 2009; Dolgov et al. 2011). The spawning take place outside the Barents Sea, along the coast of Norway between 62°N and 71°N latitude (Bergstad et al., 1987). The cod arrives at the spawning grounds from late January and onwards (Bergstad et al., 1987; Jørgensen, 1989). Spawning starts in the middle of February and lasts until end of April/early May. The eggs and larvae are transported north-eastwards with the Norwegian Atlantic and the Norwegian Coastal Currents (Marti 1956; Bergstad et al. 1987; Gjøsæter 1998; Orvik et al. 2001). The numbers of eggs and later survival of larvae are dependent on the biomass and the condition and age-structure of the spawners (Ponomarenko 1973; Marshall et al. 1998; Hylen et al. 2008). The 0-group is dispersed over wide areas in the Barents Sea, and abundant year classes occupy larger areas (Marti, 1956; Bergstad et al. 1987; Eriksen and Prozorkevich, 2011).

Environmental factors are commonly found as driving forces for the distribution and survival of juvenile fish (Sætersdal and Loeng, 1987; Loeng and Gjøsæter, 1990; Ottersen and Loeng, 2000; Hylen et al. 2008). Several studies from the 1970s to the beginning of the 1990s, suggested that warmer conditions were favourable for 0-group cod, haddock and herring and unfavourable for capelin. However, although the 2000s was the warmest-on-record decade (Levitus et al., 2009), several successful year classes of capelin, but only a few successful year classes of cod, occurred during the decade (Eriksen et al, in press). The influence of temperature on the general distribution has been reported in several studies (Loeng and Gjøsæter, 1990; Ottersen and Loeng, 2000). However, few studies focus on quantifying of the occupation area and describe the importance of specific areas with regards to strong/weak year class occupation areas (Eriksen et al. in press).

In this work, which is based on a 31-year long time series of 0-group survey data from August-September, we analyse the variation in occupation area and density of age-0 of juvenile cod, and how these influence the year class strength. We discuss the observed variations in relation to ocean climate fluctuations and previous findings.

Material and methods

Study area

The Barents Sea is a high-latitude, arctoboreal shallow shelf sea. The circulation is dominated by the Norwegian Atlantic Current that enters through the Bear Island Trench. Some of the Atlantic Water flow eastward parallel to the coast towards Novaya Zemlya while another part flows north-eastwards and into the Hopen Deep. The relative strength of these two branches varies with the atmospheric fields (Ingvaldsen et al. 2003). South of the Atlantic inflow, the Norwegian Coastal Current flow along the Finnmark and Kola coasts. These two current systems keep the southern part of the Barents Sea relatively warm. Cold Arctic Water flows south-westwards near the surface in the northern part of the Barents Sea. The Atlantic and Arctic water masses are separated by the Polar Front. In the western Barents Sea the position of the front is relatively stable, although it seems to be pushed northwards during warm climatic periods (Loeng 1991; Ingvaldsen and Loeng 2009). In the eastern part the position of the front has large seasonal, as well as year- to-year variations. The largest inter-annual temperature variations in the Barents Sea are associated with changes in the position of the Polar Front, and are particularly strong in the eastern Barents Sea.

Data source

Fish distribution data: We study distribution of age-0 juvenile cod using survey data. Since 1965, 0-group surveys have been conducted annually by the Institute of Marine Research, (IMR), Norway and the Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Russia. Prior to 2003, the survey was conducted in late August - early September.

Since 2003, the 0-group survey has been a part of the Joint Norwegian-Russian Ecosystem survey in the Barents Sea carried out from early August to late September (Anon. 2010).

The trawling procedure consisted of tows in a depth profile between 0 and 40 m or more when acoustic registrations were observed. In general, 0-group of cod, haddock, herring and capelin are distributed between 0 and 50 m during the survey period. In this study we used survey data from 1980 to 2011. Core areas for age-0 cod, haddock and herring was defined in Eriksen et al. (in press) as the areas which contains the highest densities of the species. The present work uses the core area and the area outside the core area, as contrasting regions in the further analyses.

Data treatment and statistical analyses

The fish density (individuals per nm2) for each trawl haul was calculated with regard to catch and trawl data (depths interval, effective opening and distance trawled). The method is described by Dingsør (2005) and Eriksen et al. (2009). Further these densities were used to quantify and visualise the occupation area:

- The Barents Sea was divided into 40*40 nm grid cells and fish densities were categorized into 4 groups: no catches, low densities (lower than 16% below average), average densities (long term average density ±16%, and high densities (higher than 16% above average). Mapping was done in Lambert Azimuthal Equal Area projection, with centre position at 75° N and 35° E.
- Grid cells with fish occurrence within and outside of the core area were calculated
- The mean densities within and outside of the core area were also calculated.
- Year classes strength were divided into 3 categories: weak (lower than 16% below average), average (long term average abundance ±16%, and strong year classes (higher than 16% above average). Abundance indices were taken from "Survey report from the joint Norwegian/Russian ecosystem survey in the Barents Sea August-October 2010" (Anon 2010). The long term mean 0-group cod abundance from 1980 to 2011 was 23.6 $*10^9$, with a minimum of 72 million and a maximum of $119.7*10^9$.

In Analysis we used followed time series: i) occupation areas, ii) mean densities within and outside the core areas, iii) cod spawning stock biomass (Anon., 2010), and iv) the temperature conditions, influenced by inflow of Atlantic Water were averaged from 50 to 200 m depth in the Fugløya-Bear Island section (FB) (http://www.imr.no/sjomil). The relationship between the distribution variables and time series was tested with Pearson correlation and the difference between the occupation areas at different year class strength (weak, average and strong) were tested with variance analysis.

Results

Cod usually distributed widely throughout the entire Barents Sea with an occupation area ranging between 82 and 254 million square nautical miles. The occupation area varied between years, and was generally large in the mid 1980s, the beginning of the 1990s, and at the end of the 2000s (Figure 1).

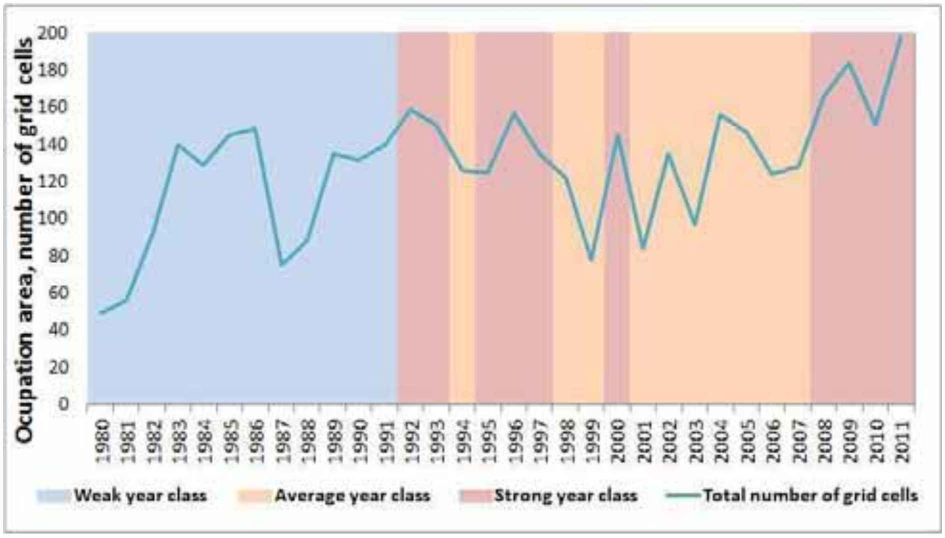

Figure 1. Occupation area (number of grid cells) where cod were observed. Weak (blue), average (yellow) and strong (red) year classes are shown in colours.

Large occupation areas were observed for all three categories (weak, average and strong) of year classes (Figure 1 and 2). However, the range of the occupation area was 49-146, 78-156, and 125-198 grid cells for weak, average and strong year classes, respectively. Additionally, the variance analysis showed that the occupation area was significantly larger for strong year classes than for weak and average year classes (r^2=0.3381, d.f.=2;29, F=7.405, p=0.002523). This result was also evident as a positive correlation (0.52) between the occupation area and the 0-group cod abundance index.

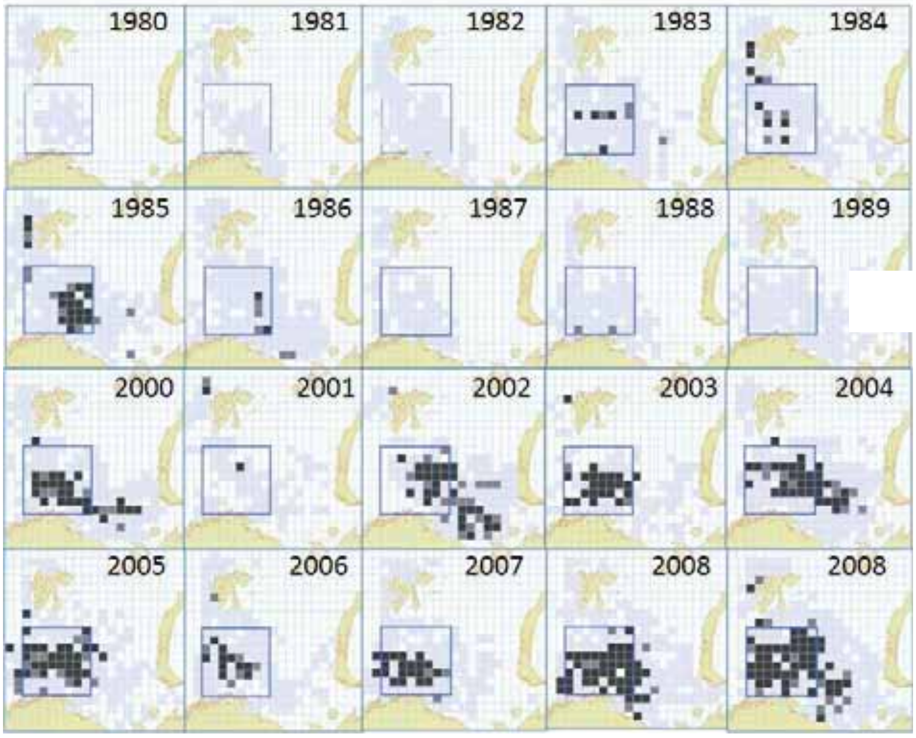

Figure 2. Spatial distribution of age-0 juvenile cod densities (light/dark grey) in the 1980s and the 2000s. The intensity of the colours corresponds to the fish density (< the long term mean ±16% <). The squares indicate a core area for age-0 juvenile cod.

The highest densities were observed within the core area (Figures 2 and 3). At strong year classes the density both within and outside the core area increased. This was also evident as a positive correlation (0.74) between the densities within and outside the core area, although the densities were considerably higher within the core area (Figure 3). The relationship between year class strength and densities was also observed as a high positive correlation between the 0-group index and the densities both within (0.98) and outside (0.85) the core area.

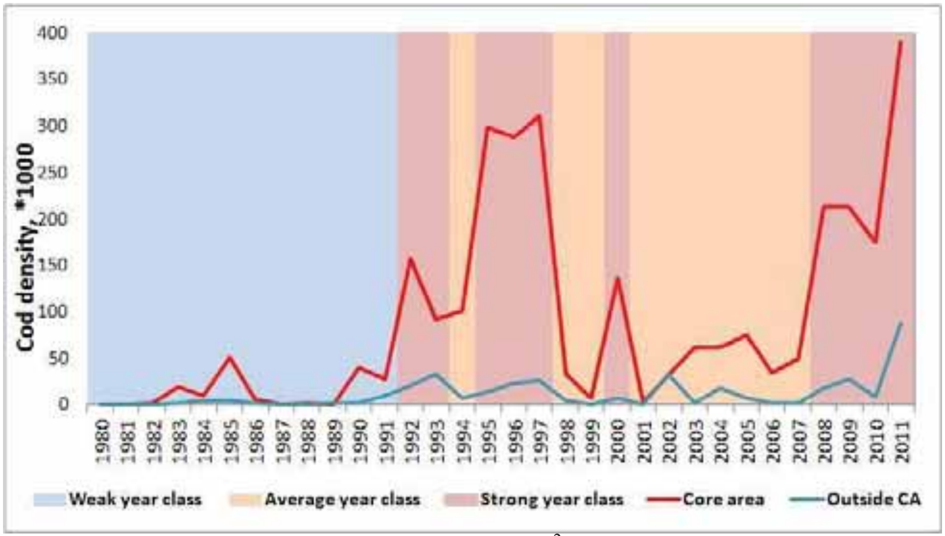

Figure 3. Cod densities (in 1000 individuals per nm^2) within and outside the core area (CA). Weak (blue), average (yellow) and strong (red) year classes are shown in colours.

The fish densities within the core areas represented approximately 74% of the total densities of age-0 juvenile cod in the Barents Sea. In 1989 and 2002, cod densities were found mostly outside the core area (Figure 4). These two years represent weak and average year classes, respectively.

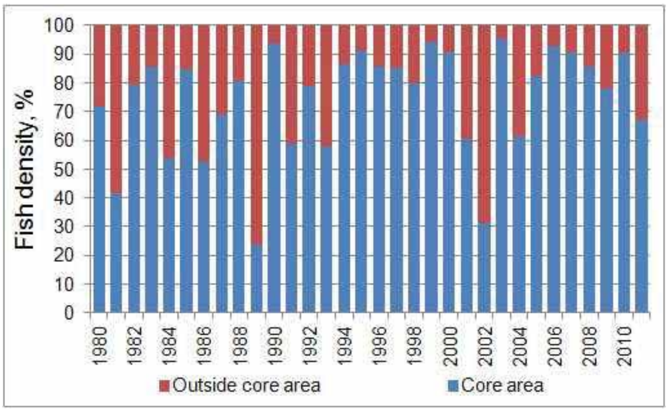

Figure 4. Densities (%) of age-0 juvenile cod within and outside the core area.

During the 1980s only weak year classes of cod were observed, while in the mid 1990s and the end of the 2000s mostly strong year classes of cod were observed. The 0-group index increased with the spawning stock biomass (correlation coefficient of 0.74).

Discussion

In the last 30 years worldwide positive temperature trends have been observed (IPCC 2007), and this may influence fish distribution and abundance. The variance analyses showed significant differences in occupation area in years with weak and average year classes compared to years with strong year classes. In general, strong year classes occupy larger areas in the Barents Sea compared to weaker year classes. However, the large variations in occupation areas, irrespective of year class strength, indicate that some year classes are spread out thin densities over large areas. This seems to have been a common situation in the 80's. The cod spawning stock biomass varied dramatically during the study period (1980-2011) from 85 thousand tonnes in 1987 to ca 600 thousand tonnes in 2005-2008. Earlier studies have suggested a positive link between spawning stock biomass and 0-group abundance (Ponomarenko 1973; Hylen et al. 2008; Eriksen et al. 2009). Thus, during the 1980s the low cod spawning stock biomass, due to overfishing over a long period (Hylen et al. 2008), caused only weak year classes.

However, the temperatures were also low during the 1980s, and this decade can be characterized as cold (Ingvaldsen et al. 2003). It is well known that the temperature conditions influence directly on 0-group fish by metabolism rate and indirectly by the plankton production, including Calanus, and thereby growth of 0-group fish during summer (Ellertsen at al., 1989; Ottersen and Loeng 2000). Additionally, several studies have indicated temperature-related shifts in spawning areas. In cold periods a greater portion of the spawners migrate to the southern spawning areas than in warm years, while in warm periods spawning in the areas north of Lofoten (the main spawning area) increases (Sundby and Nakken 1998; Nakken 2008). This may have influenced egg and larvae transport into the Barents Sea. Thus because the 1980s were characterised by both low SSB and low temperatures, it is difficult to distinguish between their effects on the 0-group abundance.

Our results showed that occupation area and fish densities varied between years in 1990s, but that the densities were much higher than in 1980s. The majority of the cod was found in the core areas, and several strong years classes occurred. During the 1990s the cod stock was recovering and the cod SSB was almost doubled during the decade. Simultaneously, the temperatures gradually rose, and warmer temperature conditions are commonly found as favourable juvenile cod (Sætersdal and Loeng, 1987; Loeng and Gjøsæter, 1990; Ottersen and Loeng, 2000). These led to the occurrence of several relatively strong year classes.

A large and stable occupation area was observed during 2000s. The majority of the cod was found in the core areas, like in 1990s, although high densities were also observed outside the core area. During this period the combination of high SSB and favourable temperature conditions most likely led to higher 0-group juvenile cod densities and the occurrence of several strong year classes. However, no strong year classes occurred in 2005-2007, which were years with high SSB and the record high temperatures. Instead, the fish densities within the core area decreased and the occupation area were weakly reduced. Several studies have suggested that temperature have dome-shaped effect on the growth and the abundance of juvenile fish (Peck 2003; Pörtner and Peck 2011). Thus, the higher temperatures, especially in the core area, may be suboptimal with respect to growth and survival (Eriksen et al., in press). In this paper, we compile earlier findings and re-analyze long term trends in the 0-group data. We observed positive correlations between cod SSB, cod 0-group density, occupation area, and 0-group abundance index. The lack of a prominent temperature effect on these variables points towards SSB as a necessary first condition for successful recruitment. Temperature at Fugløya-Bear Island section was positively correlated with SSB, but not with the 0-group related variables. An increase in temperature may indicate a general increase of areas with Atlantic water masses in the Barents Sea, and favourable conditions (some of them we discussed above). However, further increases in temperatures may also have negative effects (Eriksen et al., in press).

Related to earlier findings and assuming that SSB is kept at a sufficient high level it seems that; i) lower temperatures negatively influences the 0-group cod densities, although the occupation area may be large or small ii) temperature is a proxy for sufficient transport of the eggs and larvae, as well as for suitable feeding conditions and a high growth rate. This has positive influence on the 0-group cod densities, although a further temperature increase may also have negative effects.

In most of the years, the highest densities occurred in the core area, and this density was positively correlated with the 0-group cod abundance indices. Therefore, during planning of the annual survey conducting 0-group observations, care must be taken to secure sufficient coverage of this area. Partial lack of coverage in the core area may reduce the precision of the 0-group index calculations.

Acknowledgements

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Photo: Institute of Marine Research

2.26 The possibility of forecasting the impact of climate change on Herring and cod stock dynamics

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Federal Research Institute of Fisheries and Oceanography (VNIRO), Moscow, Russia

According to data from to the main Arctic research centres: the *International Arctic Research Center* (IARC, Alaska), the *Hadley Centre* (UK) and the *Arctic and Antarctic Research Institute* (AARI, Russia) the Arctic air surface temperature (Arctic dT) fluctuates cyclically, having reached its maximum value in the 1940s, minimum in the 1970s and a new maximum in the 2000s. The temperature dynamics of the 200 m water column on the "Kola meridian section" virtually corresponds to the Arctic dT trend (Figure 1).

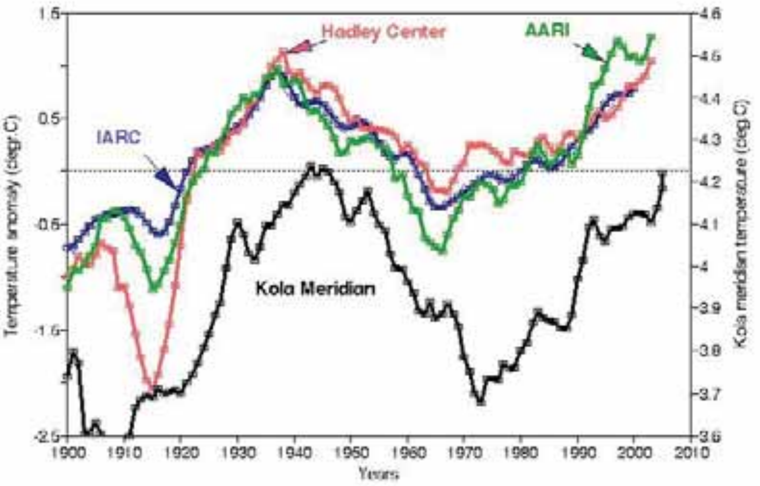

Figure 1. Comparative dynamics of Arctic air and "Kola meridian" temperatures according to data of 3 main Arctic research centers (1900-2008).

Herring recruitment dynamics and Arctic dT changes have been varying in synchrony for the past 100 years. The same relationship was observed between herring recruitment dynamics and the mean temperature of the 200m water column at the "Kola meridian" section for the past 100 years.

Cod recruitment lags by roughly 10 years relative to both the Arctic dT trend and the "Kola meridian" section water column Shifting the cod recruitment curve back by 8-10 years synchronises it with the Arctic dT and "Kola meridian" temperatures.

According to the forecast of the AARI, the Arctic long-term thermal dynamics follows a roughly 60-year cycle, with maxima in the 1940s and 2000s. The forecast for the coming 20-30-year period indicates a gradual fall in Arctic temperatures.

Conclusions

The AARI predicts a gradual decrease in Arctic dT for the future 10-20-years. On the background of such an Arctic dT trend, herring stocks are likely to decrease for the next 10 years, while cod stocks are likely to display a rising trend in the coming decade.

2.27 Structure of the Barents Sea fish community as result of climatic fluctuations

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Abstract

Interannual variations in catches of warm-water and cold-water fish species in various seasons, depending on changes in oceanographic conditions, are analyzed on the basis of data from Russian and Norwegian surveys for 1998-2010. The proportion of fish in the catches from different zoogeographical groups among different taxonomic, ecological and functional groups and their differences in warm and cold years are also examined.

Introduction

Climate change is having a significant impact on marine ecosystems, not least on fish populations. Besides salinity, water temperature is the main factor directly influencing changes in distribution of individual species. Changes in sea temperatures lead to alterations in the distribution of species and hence in the structure of fish communities and interspecific relationships.

Surveys of demersal fish in wide areas of the Barents Sea have been performed by the Russian Polar Research Institute (PINRO) and the Institute of Marine Research (IMR) in August-September (since 2004) and October-December (since 1982). Originally, only commercially important species were studied, but since 1998 all fish species from catches began to be investigated. This has enabled changes in the abundance and distribution of most fish species in the Barents Sea during the past decade to be studied.

The main objectives of this project were to study inter-annual variations in catches of warm-water and cold-water fish during different climatic periods, using data from Russian and Norwegian surveys between 1998 and 2010 and changes in the proportion of fish from different zoogeographical groups

Materials and methods

Data from two main surveys are shown in Figure 1. The Russian autumn-winter survey that estimates juvenile year classes and demersal fish stocks (TAS) has been carried out by PINRO in October-December since 1982. A total of 400-500 bottom tows were performed every year. The joint Russian-Norwegian ecosystem surveys have been carried out by PINRO and IMR since 2004 in August-September, with 500-600 bottom tows being performed a year. Relative abundances were calculated as number of individuals per one-hour tow (the autumn-winter survey) or per nautical mile (the ecosystem survey). The species were classified into zoogeographical groups based on Andriashev and Chernova (1995).

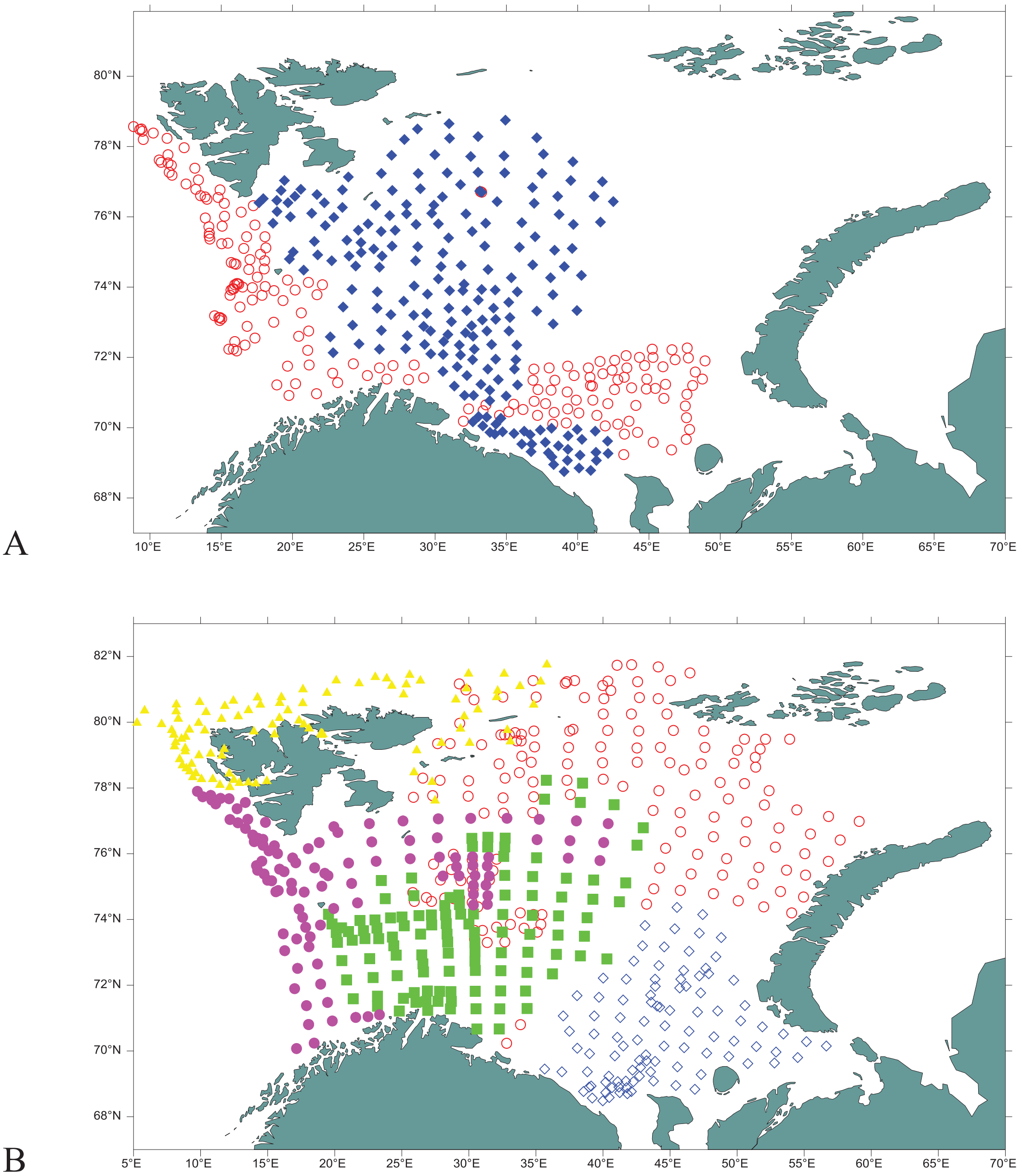


Figure 1. Bottom trawl stations during the Russian autumn-winter survey (A) and the joint Russian-Norwegian ecosystem survey (B).

Results and discussion

Families

Six families (Rajidae, Clupeidae, Macrouridae, Cyclopteridae, Liparidae, Zoarcidae) out of 31 families displayed a falling trend in their mean catch rates (Figure 2), while mean catches of two families (Gadidae and Scorpaenidae), rose (Figure 2). In the other families examined (5-7 of a total of 27 families), no obvious trend was detected (Figure 3). Data from the ecosystem survey and TAS generally showed the same trends, but were opposite for Gadidae and Pleuronectidae.

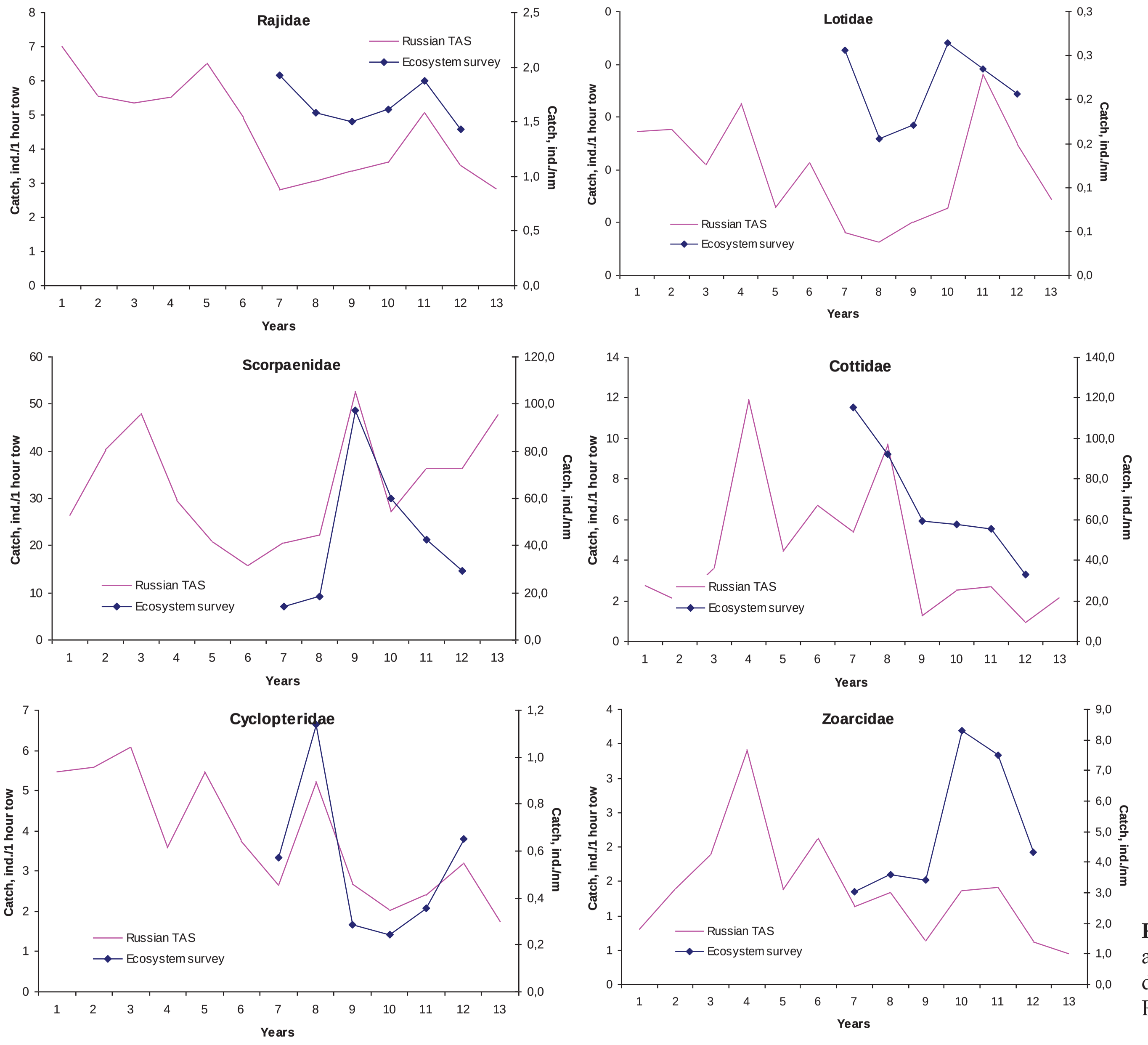


Figure 2. Interannual dynamics of relative abundance of some families based on the data from the ecosystem survey and the Russian TAS.

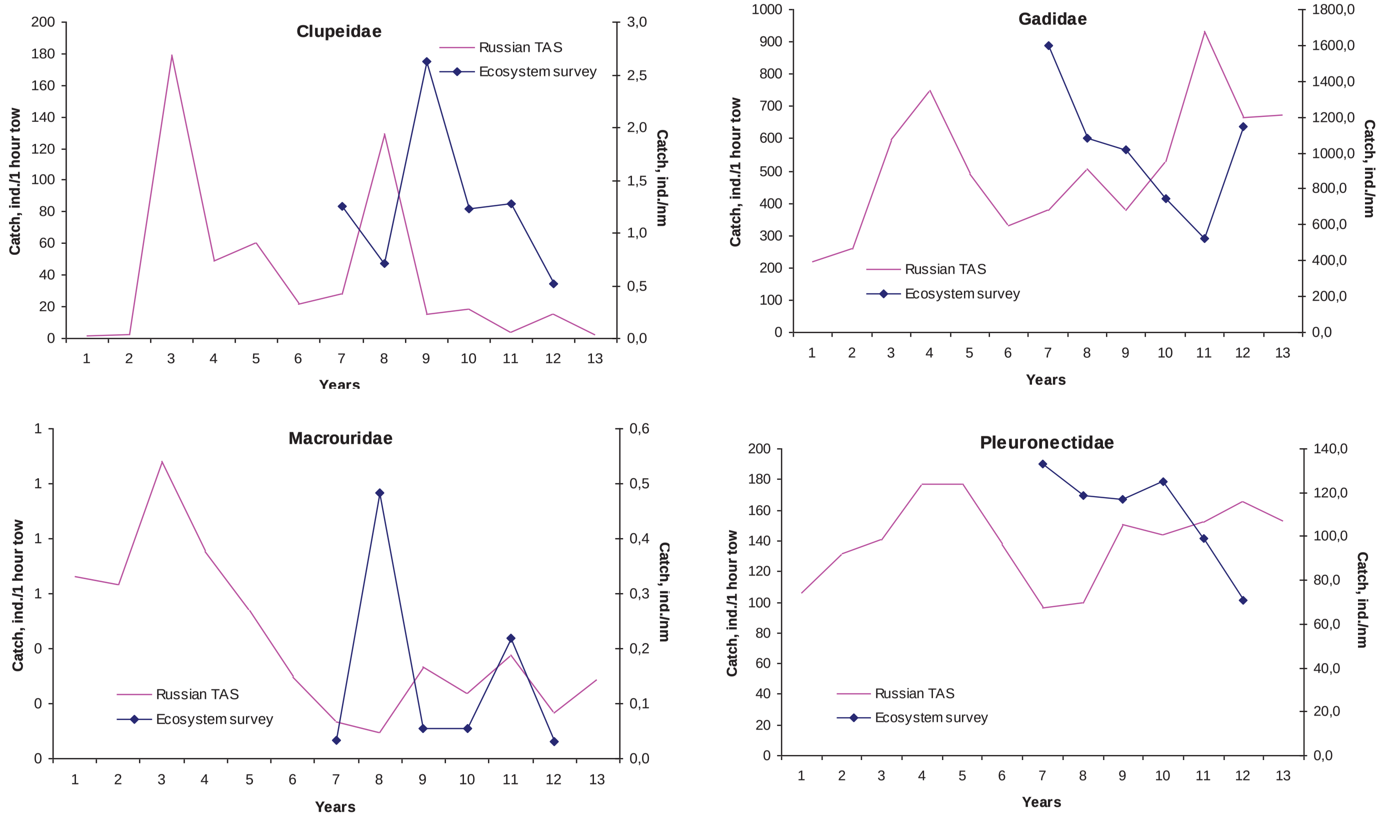


Figure 3. Inter-annual dynamics of relative abundance of some commercially important families based on the data from the ecosystem survey and the Russian TAS.

Species

Inter-annual dynamics differed between fish species from different zoogeographical species

Widely distributed species showed different dynamics in the two surveys (Figure 4). The Russian data showed higher abundance of ribbon barracudina in 1998-2004 and then a decrease in the last year, while catch rates from the ecosystem survey remained high until 2006-2008.

Most *south boreal* species, such as whiting, anglerfish, silvery pout and grey gurnard, increased in abundance from 1998- to 2009-2010 (Figure 5).

Many *mainly boreal* species differed in dynamics (Figure 6). Catches of haddock and Norway haddock increased during 1998-2010, while the abundance of other species such as Atlantic hookear sculpin and thorny skate was reduced.

Boreal fish species had different patterns of abundance dynamics (Figure 7). Catches of greater argentine and Norway pout greatly increased between 1988 and 2010 in both surveys. The relative abundance of other species like roughhead grenadier had a tendency to decrease in this period. In contrast, a peak in the abundance of snake pipe-fish was observed in only two years (2006-2007). Most of the coldwater species (*Arcto-boreal, mainly Arctic and Arctic species*) became less abundant from 1998 to 2010 (Figures 8-10).

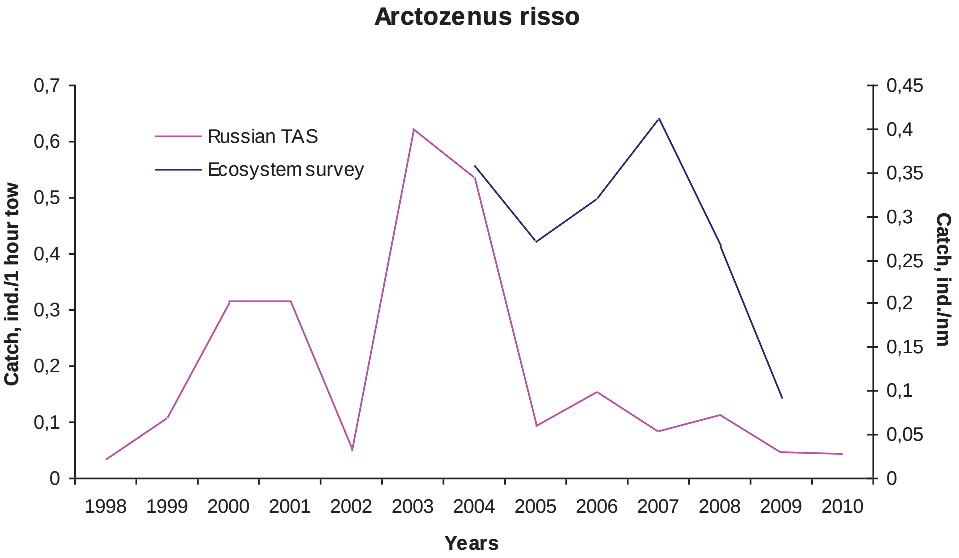


Figure 4. Inter-annual dynamics of relative abundance of ribbon barracudina (Arctozenus risso), a widely distributed species.

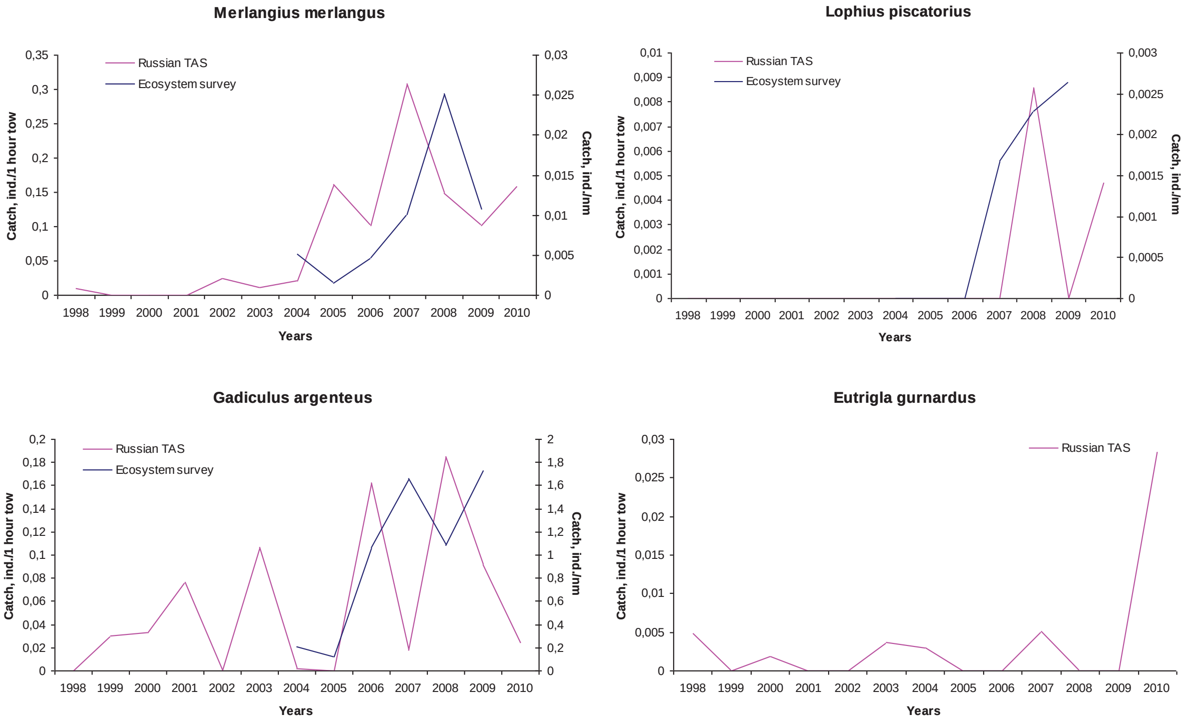


Figure 5. Inter-annual dynamics of relative abundance of some *South boreal* fish species based on the data from the ecosystem survey and the Russian TAS.

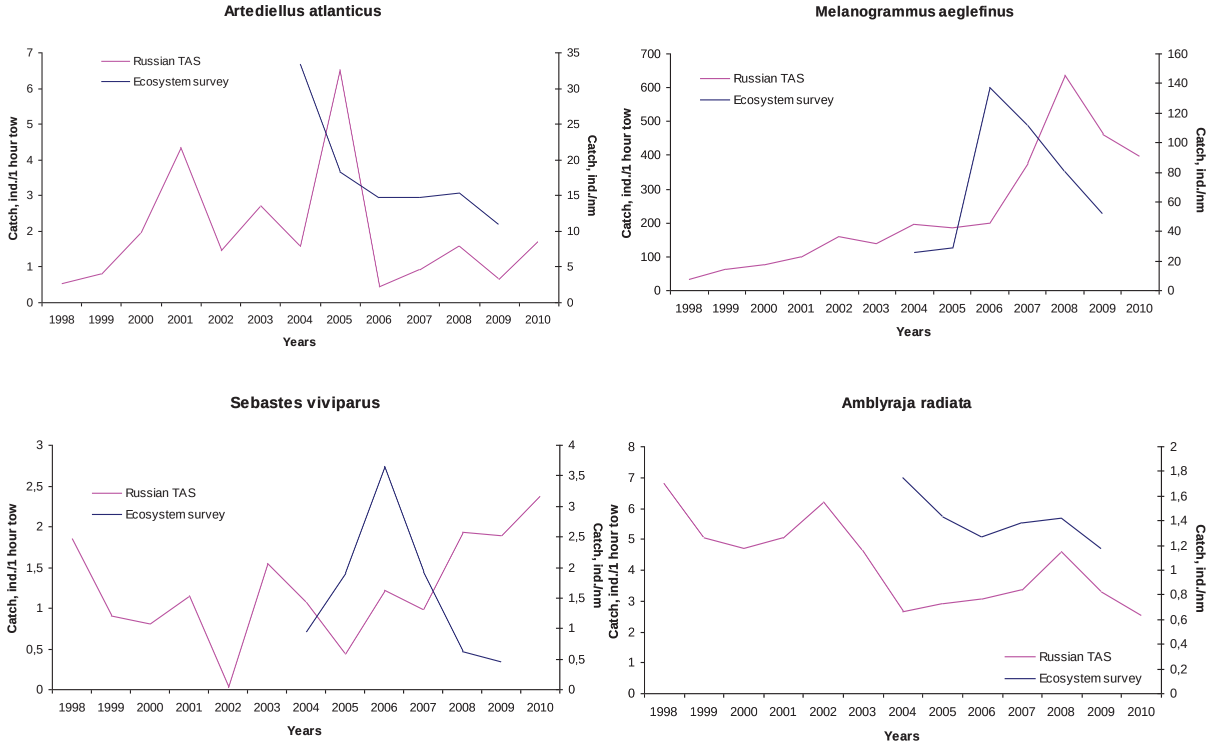
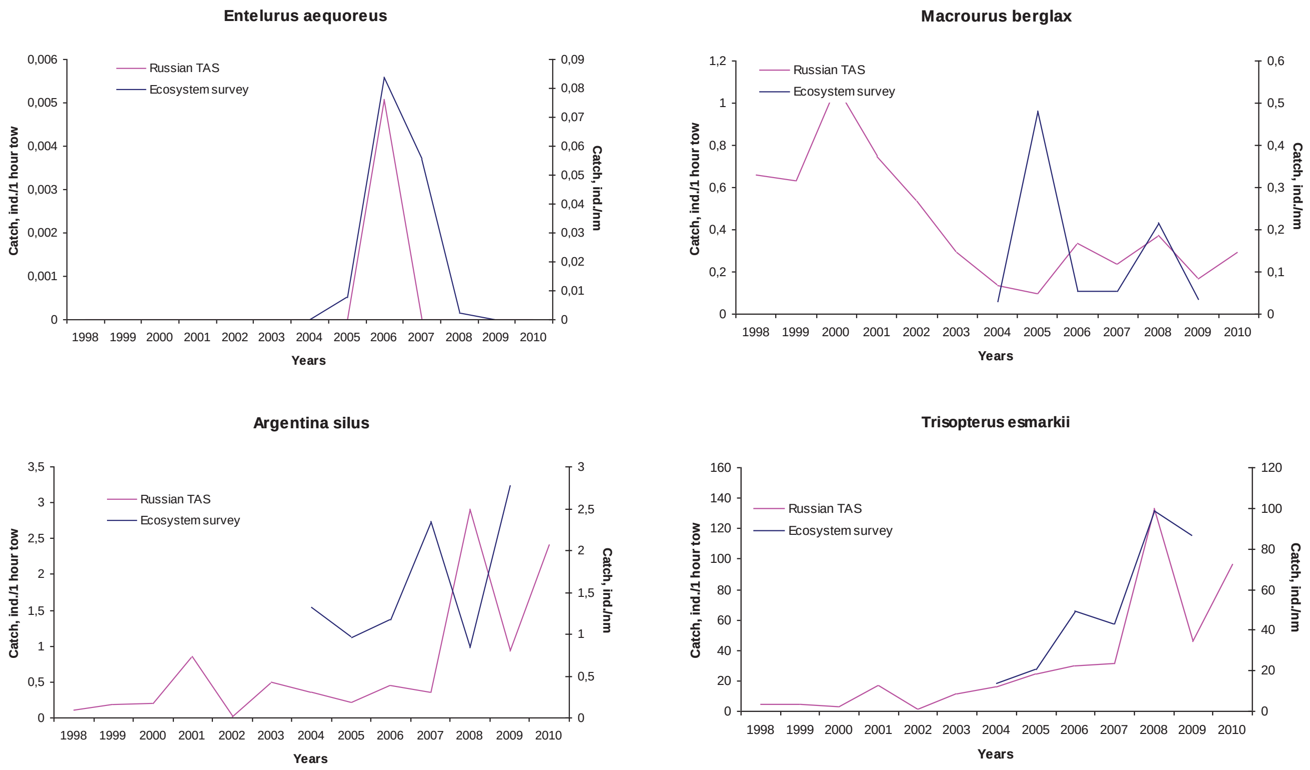


Figure 6. Inter-annual dynamics of relative abundance of some *mainly boreal* fish species based on the data from the ecosystem survey and the Russian TAS.

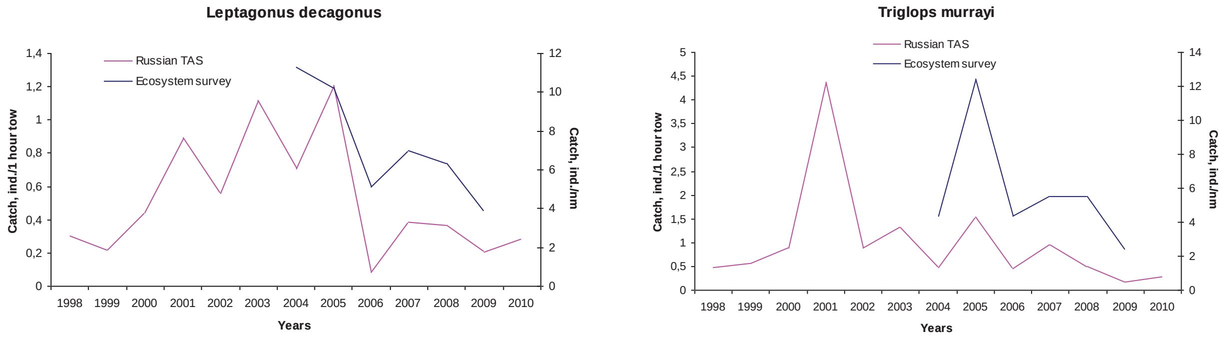

Entelurus aequoreus

Macrourus berglax

Argentina silus

Trisopterus esmarkii

Figure 7. Inter-annual dynamics of relative abundance of some *boreal* fish species based on the data from the ecosystem survey and the Russian TAS.


Leptagonus decagonus

Triglops murrayi

Figure 8. Inter-annual dynamics of relative abundance of some *Arcto-boreal* fish species based on the data from the ecosystem survey and the Russian TAS.

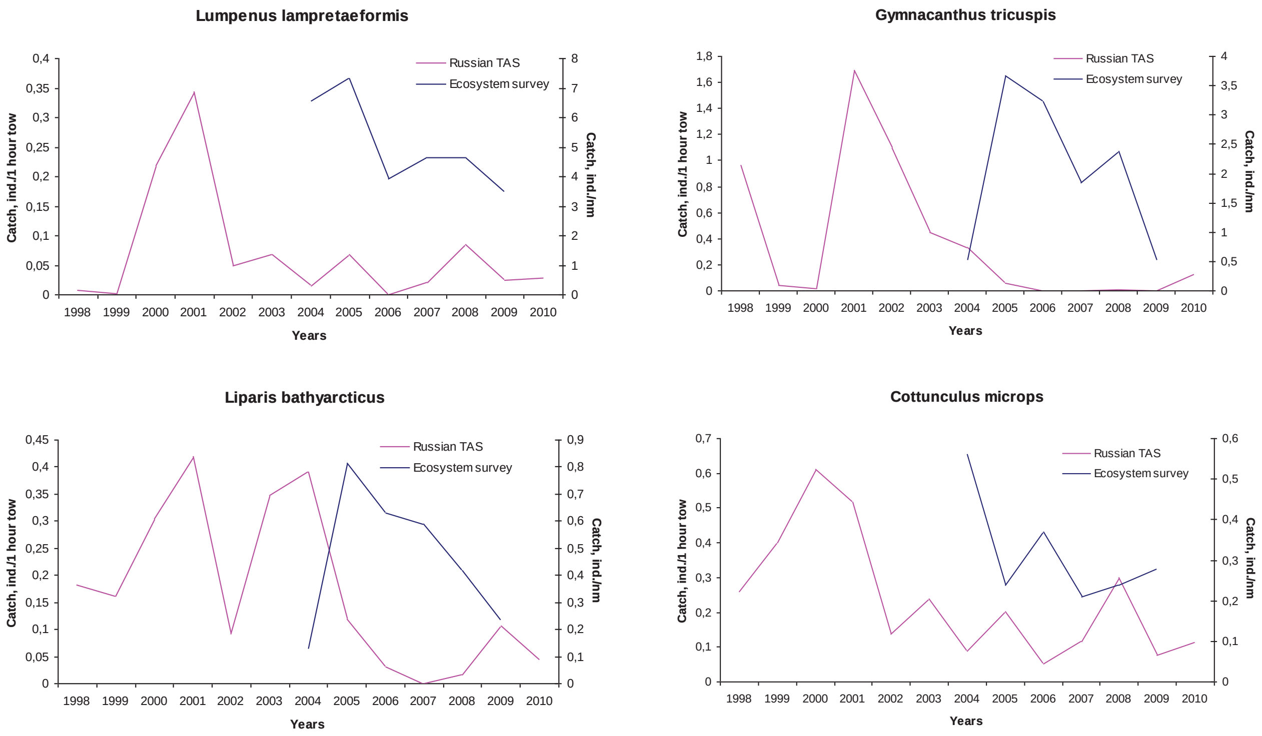


Figure 9. Inter-annual dynamics of relative abundance of *mainly Arctic* fish species based on the data from the ecosystem survey and the Russian TAS.

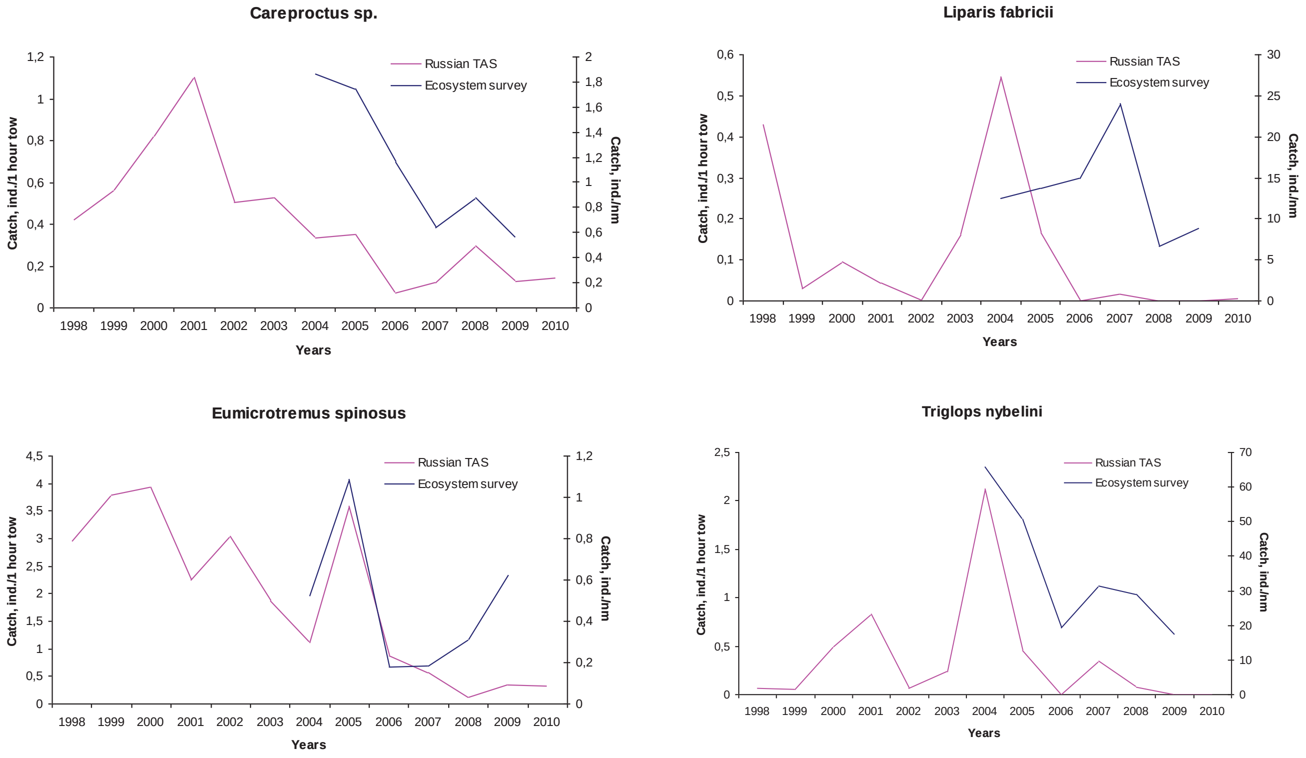


Figure 10. Figure 10. Inter-annual dynamics of relative abundance of some *Arctic* fish species based on the data from the ecosystem survey and the Russian TAS.

Ratio of cold- and warm-water species

Differences in the dynamics of abundance of species from different zoogeographical groups were also observed (Figure 10). Thus, mean catches of practically all the *widely distributed* and *South boreal* species displayed a tendency to increase in the Russian TAS. In contrast, most of *Arcto-boreal, mainly Arctic* and *Arctic* species (from 66 to 86% of species in these groups) decreased in abundance, while the abundance of only a minority of species (from 33% among *Arcto-boreal* to 8% among *Arctic* group) essentially did not changed, and only one *Arctic* species (*Ulcina olriki*) showed a slight rise in catches. The most numerous and widespread groups (*mainly boreal* and *boreal* species) had almost equal proportions of species that increased and decreased in abundance: 38-50% and 43-51%.

Differences in the catch rates of cold-water and warm-water species in the Barents Sea varied widely during 1998-2010 (Figure 11). Overall, warm-water species (*widely distributed*, *South boreal*, *mainly boreal* and *boreal*) dominated, the mean catch rates of this group being 93 times those of cold-water species. The ratio was 3-18 until 2005, while in 2006 and 2009-2010 the ratio increased to 311-376. In 2007-2008 the ratio 25 and 76.

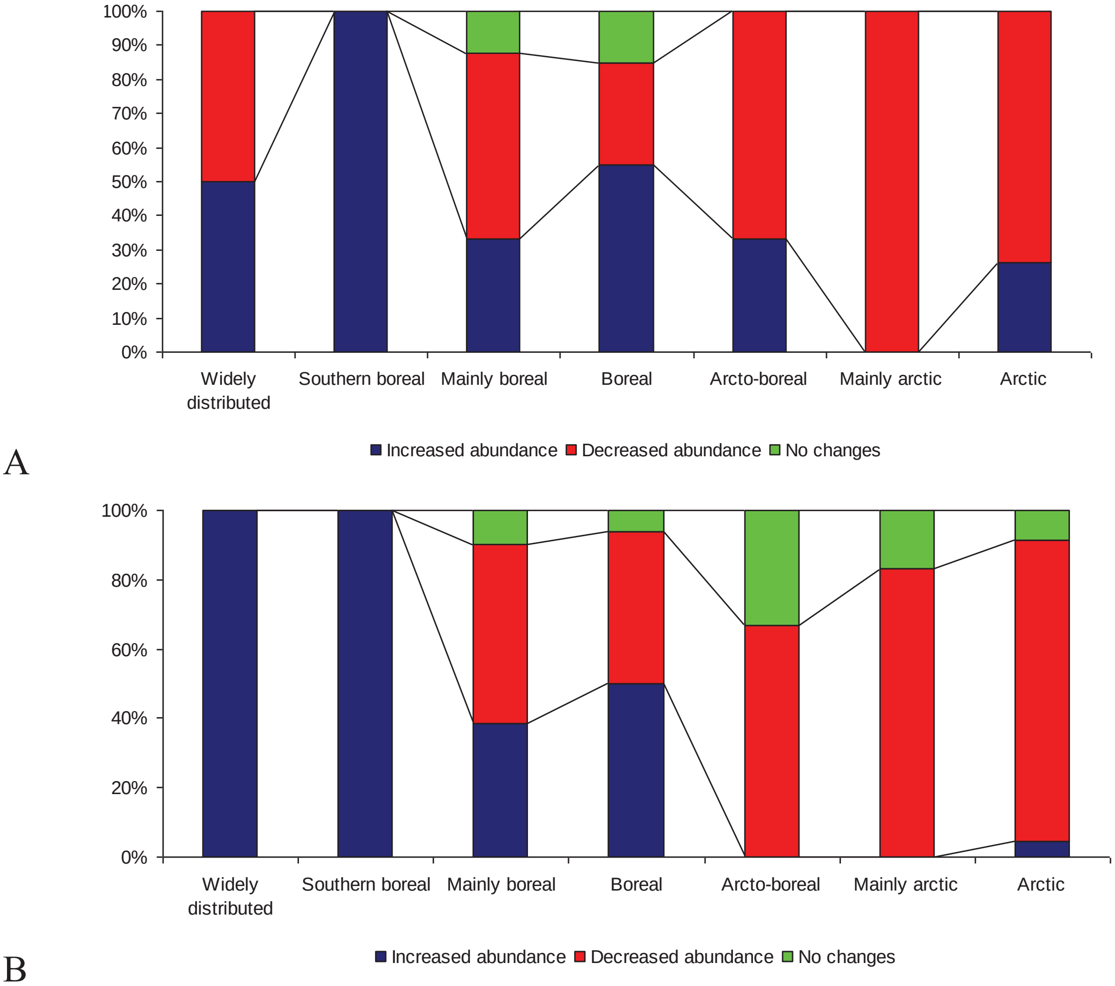


Figure 11. Percentage of species from different zoogeographic groups (widely distributed n=4, South boreal =7, mainly boreal n=38, boreal n=25, Arcto-boreal n=3, mainly Arctic n=6, and Arctic n=28 species) that had increased, decreased or displayed no changes in catch rates between 2004-2009 (ecosystem survey)(A) and 1998-2010 (TAS)(B).

Conclusions

Strong fluctuations in the relative abundances of various fish species were observed in the Barents Sea during 1998-2010. Generally mean annual catches of warm-water (*widely distributed*, *South boreal*, *mainly boreal* and *boreal*) species increased, while catch rates of cold-water (*Arcto-boreal*, *mainly Arctic* and *Arctic*) species decreased in this period. Warm-water species dominate the Barents Sea fish community, but the ratio in abundance between warm- and cold-water species varied greatly and was higher in the warmest years. In some cases data from the two research surveys showed different patterns in the abundance dynamics.

2.28 Feeding of polar cod (*Boreogadus saida*) in the Barents Sea related to food abundance and water masses

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Diet data for polar cod (*Boreogadus saida*) were collected in the Barents Sea during the joint Norwegian-Russian ecosystem surveys in August-September, 2007-2009. A total of 1182 stomachs were sampled at 93 stations, and the size of the polar cod ranged from 9-27 cm. Polar cod fed mainly on *Calanus* copepods, hyperiid amphipods, and euphausiids, and to a lesser degree on other invertebrates. Large polar cod (> 21 cm) may also prey on fish. Amphipods dominated the diet in Arctic water masses north of Svalbard, whereas copepods were the main prey east of Svalbard. The diet of polar cod in the Atlantic and mixed waters of the central Barents Sea was dominated by euphausiids (Figure 1).

In general, the samples analyzed in the Russian sector yielded higher stomach fullness than the Norwegian samples. This may be either due to fuller stomachs in Russian zone or to an inflated conversion factor (20%) used for of dry/wet weight. Comparisons between fish diet and zooplankton species composition in the Barents Sea, indicate that both polar cod and capelin (*Mallotus villosus*) seem to prefer copepods as prey. A secondary prey for polar cod was hyperiid amphipods, whereas euphausiids constituted the most important alternative prey for capelin.

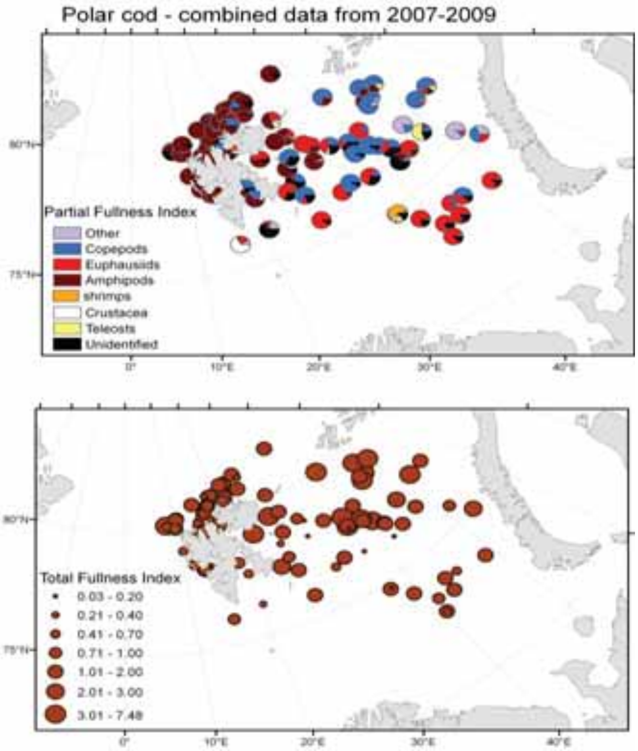

Figure 1. Diet composition and stomach fullness for polar cod (*Boreogadus saida*) in the Barents Sea in August-September 2007-2009.

2.29 Long-term variations in the importance of prey species for demersal fish in the Barents Sea under conditions of climate change

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Abstract

Spatial, seasonal and inter-annual variations in the importance of the most valuable prey species for cod and haddock (macroplankton, capelin, herring, polar cod, their own juveniles, etc) are examined on the basis of data from field and quantitative analyses of cod and haddock diets for 1949-2010. Special attention is paid to the effects of climatic changes on the importance of particular prey species in the cod and haddock diet and on shifts in dominant species during warm and cold periods.

Keywords: Cod, Haddock, climate change, diet, arctic ecosystem, predation

Introduction

The climate affects several ecological processes in ecosystems, including their productivity and the temporal/spatial distribution of species. Climate variations, therefore, are always under the close scrutiny of marine biologists as these variations determine the growth, reproduction and recruitment success of populations and the transfer of matter and energy through trophic levels of ecosystems as a whole. Understanding underlying processes that determine the links between lower and upper levels of the trophic web during climate change is a crucial topic for multidisciplinary research. One of the important fields for multidisciplinary research is the study of diets and feeding habits of individual species, especially those that are dominant in particular ecosystems.

Two main methods basic to studies of fish diet and feeding habits: a) the quantitative method based on measuring stomach content weight/volume and b) the qualitative method based on visual estimates of feeding rate (intensity) or stomach fullness and the frequency of occurrence of prey in stomachs. The first-mentioned method was used when Russian investigations on cod feeding in the Barents Sea were initiated at the turn of the 20th century (Idelson 1929; Zenkevich and Brotskaya 1931). Later, regular observations were made in 1934-1938 using the quantitative method but records in log-books of fishing vessels were also used as an essential additional source of information (Zatsepin and Petrova 1939). Since 1947, observations on cod feeding have been performed throughout the year from commercial and research vessels as part of a sampling program started by Russia in 1947. During sampling, the contents of cod stomachs were classified into the following categories: capelin, juvenile cod, redfish, herring, shrimp, euphausiids, and other; the degree of fullness of each stomach was also recorded. This qualitative method named “field feeding analysis” was widely used in Russian investigations of different fish species including cod (Antipova and Nikiforova 1990; Antipova *et* al. 1990; Simacheva and Glukhov 1990; Shvagzhdis 1990; Dolgov and Drevetnyak 1993; Zatsepin and Petrova 1939; Grinkevich 1957; Ponomarenko and Yaragina 1985; 1990a; Yaragina 1988). Nevertheless, the results of these investigations, obtained using this method in 1947-1985 and published in the Russian literature, remain mostly unknown to the international scientific community.

These long time series could provide us with a reliable basis for detailed analyses, for example, of interannual changes in the feeding of Northeast Arctic (NEA) cod, reflecting the dynamics of the Barents Sea ecosystem to a greater extent. Changes in the diet of cod, a dominant predator in the Barents Sea, revealed generalized feeding habits, and might show changes in species abundance on lower trophic levels of the ecosystem. The diet of species like cod adapts according to the availability of different potential prey species (Hill and Borges 2000). Data on the frequency of occurrence of capelin and young cod were used for analysis of their long-term variability (Marshall et al. 2000; Yaragina et al. 2009).

In 1984 a joint Norwegian–Russian stomach database was launched (Mehl and Yaragina 1992; Dolgov et al. 2007), which enabled us to compare the quantitative data obtained both from the database and Russian qualitative data for some species, in order to explore the possibility of hind casting some diet indices for the historical period.

The main objectives of this paper were the following: to consider interannual peculiarities of cod/haddock feeding on different prey during the period 1947-2010, on the basis of quantitative and qualitative data, to compare prey indices obtained from the quantitative and qualitative database in 1984-2010, and to analyze the applicability of different prey indices in demersal fish diet in studies of prey population dynamics.

We also aimed to investigate the long-term importance of different prey species in the diets of Barents Sea cod and haddock under various climate conditions and to identify any differences in the feeding habits of demersal fish in cold and warm years, and whether the feeding indices data reflect variations in the Barents Sea fish community related to climate change.

Materials and methods

Diet and trophic indices

The Russian qualitative data on cod and haddock diet from 1947-2010 and the joint Russian-Norwegian quantitative data from 1984-2010 were used for the analysis.

Year-round qualitative data from field visual observations were collected by both commercial and research vessels. Cod/haddock were selected at random from trawl catches. The degree of stomach fullness was recorded using a five-division scale, ranging from 0; stomach empty, to 4; stomach expanded and unfolded by food) as well as the presence of different prey items in the stomach. The mean stomach fullness index, calculated as the sum of degrees of fullness (including empty ones), divided by the total number of stomachs examined, was used as a measure of feeding intensity. The following categories of prey items observed in stomachs were recorded: capelin, juvenile cod, redfish (*Sebastes* spp.), herring (*Clupea harengus*), shrimp (*Pandalus borealis*), euphausiids, and other. FO_{prey} is the percentage of non-empty stomachs, which contained these prey (Ponomarenko and Yaragina 1978, 1979, 1984). This method, in spite of its shortcomings, has been shown to be a reliable tool for long-term analysis of cod feeding, given that large numbers of stomachs have been sampled all the year round over a wide area of cod distribution.

FO values were disaggregated into geographic regions: ICES area I (the southern Barents Sea: SBS), ICES subarea IIa (the northern Norwegian coast) and ICES subarea IIb (the Bear Island-Spitsbergen area). Area I and Subarea IIb include regions of cod feeding and parts of their wintering grounds, Subarea IIa covers mainly spawning and wintering regions. The total number of stomachs from the SBS region ranged from a minimum of 5129 in 1948 to a maximum of 75739 in 2000, while for the Bear Island-Spitsbergen area, the range was 2870 in 1948 and 109443 in 2002. The number of stomachs examined in subarea IIa was smaller than in the two other regions, ranging from 0 (1953, 1955, 1957, 1993, 1994, 1996) to 8514 in 2000.

The lengths of the fish sampled for the qualitative stomach database ranged from 15 to 125 cm, but usually, the fish sizes that dominated in trawl catches were most prevalent. The bulk of the trawl catches was made up of cod aged 4 to 7 in all years, though some shifts in the age composition from year to year were observed. Regular sampling of stomachs started in 1947 when older fish were found in trawl catches (Boitsov et al. 1996; Yaragina et al. 1996). However, from 68 to 92% of catches were fish aged 4-7 in all years, which means that the length of fish in the trawl catches mostly ranged from 45 to 80 cm. As fish sampled were selected at random, the same age distribution was assumed both in samples and in catches.

In general, the main shift in prey composition is observed in cod from age 1 to age 2 (3) (with size 15-25 (35) cm), when fish replace crustaceans in the diet. Gradual changes in the diet were also observed in cod aged 7-8 years and older. For cod aged 7-12 years (length >75 cm), euphausiids and shrimp become less important and larger fish, including cod, haddock, blue whiting and long rough dab, dominate among fish items (e.g. Orlova et al. 1995). Given that there are no great differences in the diet composition of cod aged 3-8 (length 40-85 cm) (e.g. Ajiad 1990; Orlova et al. 1995), we may assume that there was no significant bias in data caused by the length distribution of cod sampled in different periods/years.

The following three invertebrate groups were considered to be the most important for the analysis: euphausiids, hyperiids, Northern shrimp (*Pandalus borealis*); from fish, herring *Clupea harengus*, capelin *Mallotus villosus*, polar cod *Boreogadus saida*, young cod and haddock *Gadus morhua* and *Melanogrammus aeglefinus* were taken for our detailed consideration. Other fish species (blue whiting *Micromesistius poutassu*, young red fish *Sebastes mentella* and *S.marinus*, and Greenland halibut *Reinhardtius hippoglossoides*) were not earlier recorded separately in field analysis, as they played insignificant roles in cod feeding.Their dynamics in cod feeding were analysed only for the period 1984-2010.

Quantitative data on cod feeding cover the period from 1984 onwards (Mehl and Yaragina 1992; Dolgov et al. 2007). For the previous time period (from 1947) only accidental and limited quantitative stomach data are available (Grinkevich 1957; Zhabreva 1958; Novikova

1962). Frequency of occurrence (or frequency index or occurrence index) (%FO) and weight percent (%WP) were the main indicators of prey importance in a predator diet. Each of these measurements provides a different insight into the feeding habits of fish (Hyslop 1980).

FO (in %) was calculated as:

$$FO_{prey} = (N_{prey} \cdot 100)/N_f$$

where N_{prey} is the number stomachs that contain a given prey and N_f is the number of non-empty stomachs.

Weight percentage index WP (or gravimetric index; Hyslop 1980) was calculated as:

$$WP_{prey} = (W_{prey} \cdot 100)/ W_s$$

where W_{prey} is the weight of a given prey item in a stomach and W_s is the total weight of all prey in this stomach.

A new index modified from the Index of Relative Importance (IRI: Pinkas et al 1971) was introduced for purposes of this analysis; i.e. Index of Prey Importance (IPI):

$$IPI = FO_{prey\ i} \cdot WP_{prey\ i}$$

For each prey item this index was expressed as:

$$\%\ IPI_{prey\ i} = (IPI_{prey\ i}/\sum_{a=1}^{n} IPI\ ) \cdot 100$$

where *n* is the number of different prey items (i) in a year (y).

Eleven prey items assumed to be the most important for the Barents Sea cod were selected for analysis. This index integrates the frequency of occurrence and weight percentage indices. Prey numbers or the numeric index (NI) (percentage of the number of prey individuals over the total number of all prey individuals) were omitted from this index, as it seems to misinterpret the importance of different prey of bottom fish, characterized by the rather wide size range of prey in nature. Using the NI could overestimate small food items and underestimate large ones (e.g. small euphausiids versus capelin). We decided to omit this index and calculated %IPI that incorporates information on both prey weight in predator stomachs and its commonality (or regularity) in predator community diets, i.e. how common (and frequent) the food item is among a predator population.

Climate index

A cumulative climate index developed by Boitsov et al 2011 was used as a long-term climate index. This index was based on a combination of the air temperature (at Vardø and Kanin Nos coastal stations), the water temperature (0-200 m layer of the Murman Current in the Kola Section) and the ice coverage in the Barents Sea (May-July) in 1900-2009. Analysis of interannual variations in the climate index and their 60-year cycle demonstrated that, since 1900, long cold periods have twice alternated with long warm periods. The current steady warming of air and water masses in the Barents Sea began in the late 1980s. We assumed that for the period studied (the 1930-2000s, excluding the 1940s) three decades (1930s, 1990s, and 2000s) had presumably a warm climate and three decades (1960-1980-s) were characterized by a cold climate.

Statistical analysis

Microsoft Excel was used for analysis of results. Mean values of parameters and their significance were compared using STATISTICA 6.0 software (1984-2004 StatSoft Edition, Inc.) using Pearson's product moment correlation coefficient.

Results

Relevance of the qualitative method

The mean FO of different prey from the qualitative data and WP of the same prey in stomach bolus weight (WP) from quantitative data in 1984-2010 is shown in Figure 1.

Patterns of change in FO and WP of euphausiids in 1984-2010 were similar in Area I and Area IIb (Figure 1A)but not for the changes in hyperiid FO and WP in these areas. The correlation between the FO and the WP from the qualitative and quantitative data was strong for euphausiids in Area IIb and for hyperiids in Area I. FO_{shrimp} values were not correlated with WA_{shrimp} in Area I.

Both $FO_{herring}$ and $WP_{herring}$ values were higher in Area 1 than in Area IIb; these indices were correlated in Area I. Significant correlations were observed between $FO_{capelin}$ and $WP_{capelin}$ in both areas, while the correlation was higher in Area IIb (Figure 1B, Table 1). Significant correlations were observed between $FO_{polar\ cod}$ and $WP_{polar\ cod}$, and between $FO_{red\ fish}$ and $WP_{red\ fish}$ in the both areas. The strongest correlation was found for FO_{cod} and WP_{cod} (Figure 1C, Table 1). There were no links between these indices for haddock.

Significant correlations between WP and FO values were observed in seven prey species/groups out of the nine analysed (Table 1). Only haddock displayed no relationships between WP and FO.

	Coefficients of determination between FO and WP	
Prey species	Area I	Area IIb
Invertebrates		
Euphausiids	0.23	**0.39**
Hyperiids	**0.87**	0.26
Shrimp	0.05	0.39
Fishes		
Herring	**0.62**	0.03
Capelin	0.17	**0.49**
Polar cod	**0.59**	0.31
Cod	**0.70**	**0.68**
Haddock	0.14	0.08
Redfish	**0.53**	**0.53**

Table 1. Coefficients of determinations between frequency of occurrence (FO) and weight percent (WP) of various prey of cod stomachs during 1984-2010. Significant values are shown in bold.

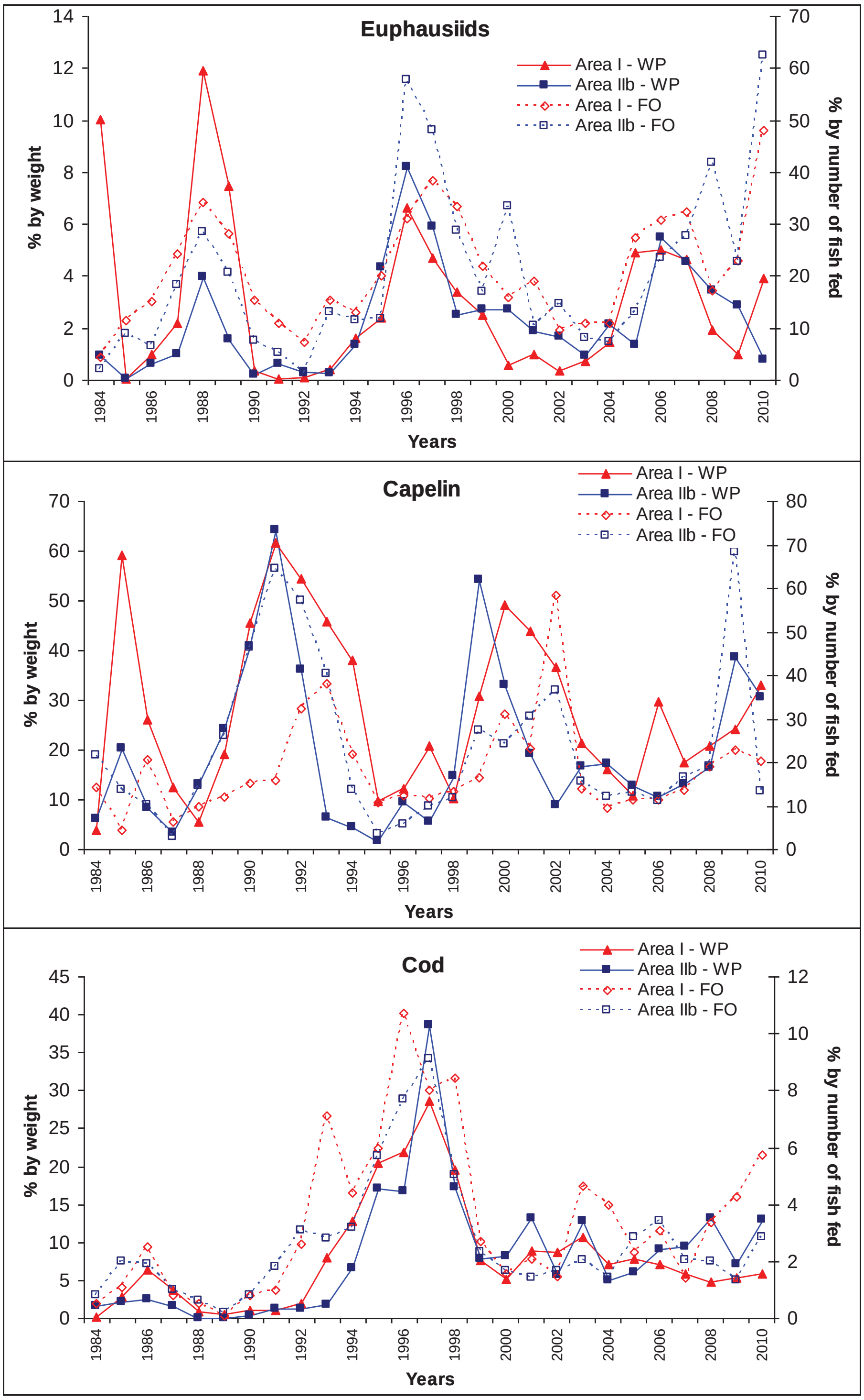


Figure 1. Frequency of occurrence and weight percent of prey (Euphausiids, capelin, and cod) in the Barents Sea cod diet during 1984-2010.

Prey importance

Prey groups were shown to have different significance in cod feeding.

Among nine prey species chosen for analysis only three species/groups appeared to have the highest FOs, also showing wide ranges, i.e. capelin (mean FO: 24.8%, range: 4.7-47.6%), shrimp (mean FO: 21.5%, range: 5.1-51.5 %) and euphausiids (mean FO: 19.5%, the range: 3.9-42.1%). The mean FO of hyperiids was lower: 9.8% with a range of 0.5-26.0%. The mean FOs of other prey were considerably lower, ranging from 0.03% (Greenland halibut) to 4.4% (juvenile cod). Changes in the mean FO of five species (polar cod, cod, redfish, herring and haddock) were rather wide (8-20%), while those of long rough dab, blue whiting and Greenland halibut did not exceed 1-2%.

The **main** prey group included species that determine the annual cycle of cod feeding and migrations (capelin, euphausiids, polar cod). Strong regularities in spatial, seasonal and interannual fluctuations were observed to be typical for these species. E.g., the FO of capelin showed distinct interannual fluctuations related to capelin stock biomass (Figure 2). The maximum FO values of capelin in Area I were observed in 1951-53, 1960-61, 1971, 1974-77, 1980-81, 1992-93 and 2002, i.e. they demonstrated 9-11-year periodicity with an extra peak in the mid-1970-s. The maximum FO values of capelin in Subarea IIb usually occurred 1-2 years earlier than those in Area I. The FO of capelin showed various patterns in Area I and Subarea IIb, being related to the fact that cod in the first-mentioned area consumed predominately spawning capelin in February-April while in the second area the most intensive feeding was on pre-spawning capelin in February-April and on grazing capelin in August-October.

The FO of euphausiids, which are prey for both cod and capelin, fluctuated asynchronously with the FO of capelin (Figure 2); the maximum FO values of euphausiids in Area I were observed in 1948-49, 1957-58, 1968-69, 1975-76, 1988-89, 1997-98 and 2007, i.e. they demonstrated 9-11-year periodicity.

Polar cod were consumed by cod mainly in Area I and in Subarea IIb during August-November, and they were totally absent from the cod diet in Subarea IIa. The lowest FO values of polar cod were registered in the mid 1970s. A rising tendency in FO values has been observed in the past 15 years.

The **additional** prey group included species whose importance can rise sharply when stock levels of main prey are low or their own stocks (hyperiids, herring, cod, haddock and redfish juveniles) are increasing. The highest FO values of herring in Subarea IIb were observed in 1951-53 and 1960, and in Area I in 1953-1955 and 1962-1965; the lowest FO values of herring were registered over a long period (1969-1984), followed by a slight increase in 1985-86 and again in 2003-2005. However, the current FO values of herring have not reached the level of the 1960-s. The FO of cod was rather high during 1947-1965, and then again in the mid-1990s. The low FO from the late 1960s to the end of the 1980s could be related to the fact that cod mainly consumed capelin due to the high biomass of capelin stocks at the time (Figure 3). Juvenile redfish were consumed by cod only during the 1980s and early 1990s, followed by the drastic decrease of the FOs of redfish (Figure 3). For these species, the strong seasonal or spatial relationships and short time peaks were typical; e.g., cod consumed hyperiids mainly in Area I and Subarea IIb in August-November, while they were totally absent in cod diet in Subarea IIa.

The **background** prey group included species that occur in cod diet regularly without any strong seasonal, spatial or interannual fluctuations (e.g. shrimp, long rough dab) (Figure 4). A rising trend in FO values of shrimp was registered up to the mid-1980s, followed by a decrease in 1993 and minor fluctuations afterwards. The lowest FO values of shrimp were registered in 1947-1955.

The **occasional** prey group included species that are eaten by cod only rarely (blue whiting, Greenland halibut). Thus, Greenland halibut juveniles were not registered in cod stomachs until 2002 (see Figure 3), but since 2003 their FO has risen sharply due to the appearance of several strong year classes and the overlapping of distribution areas of cod and Greenland halibut juveniles. No regular seasonality in FO of such prey was observed.

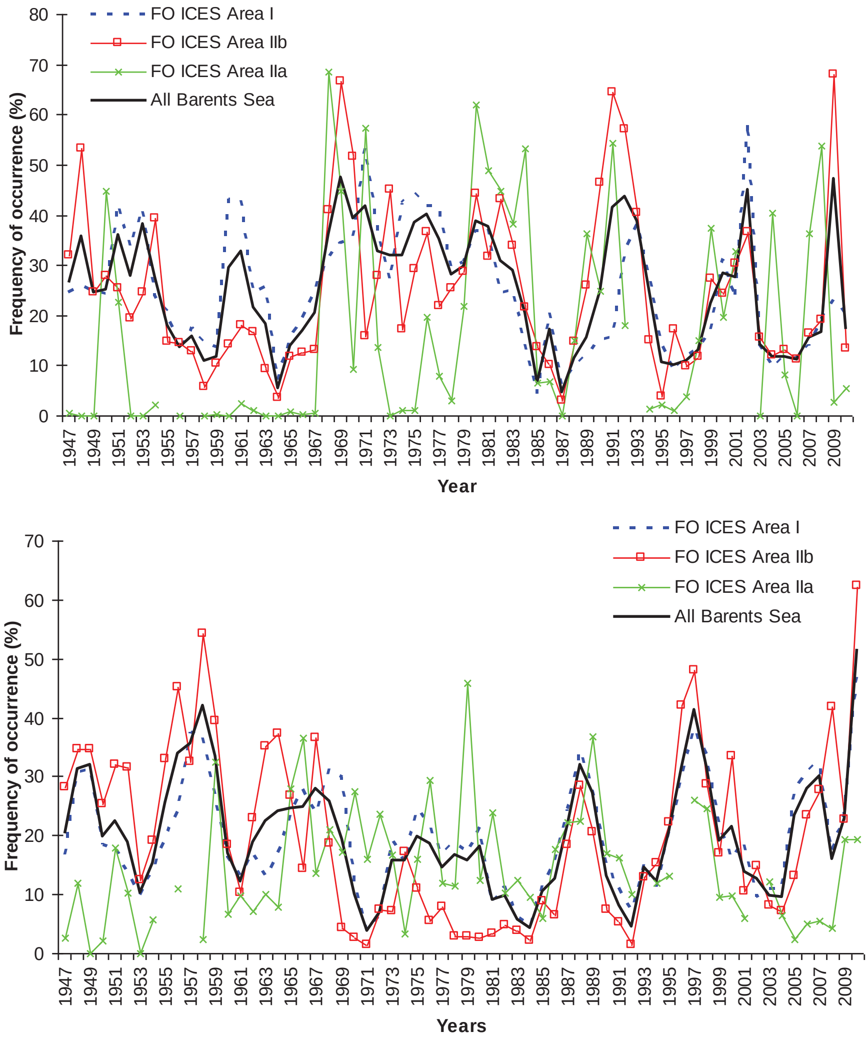
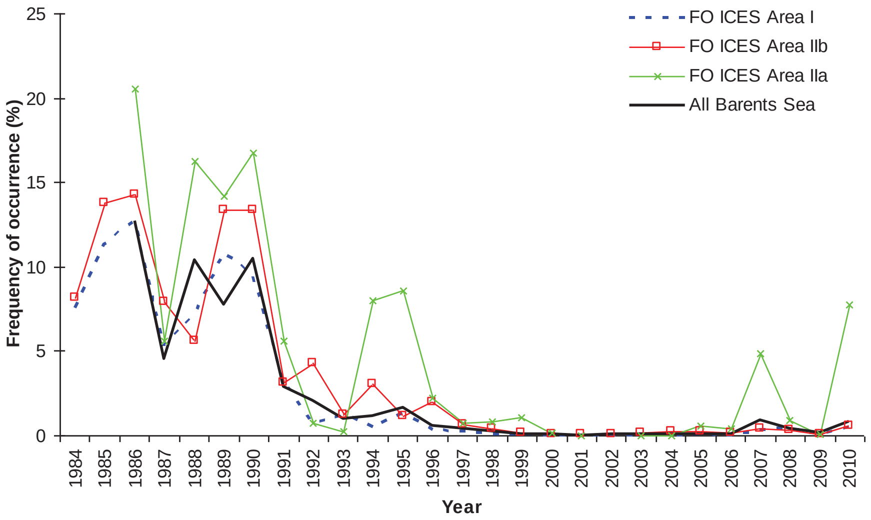
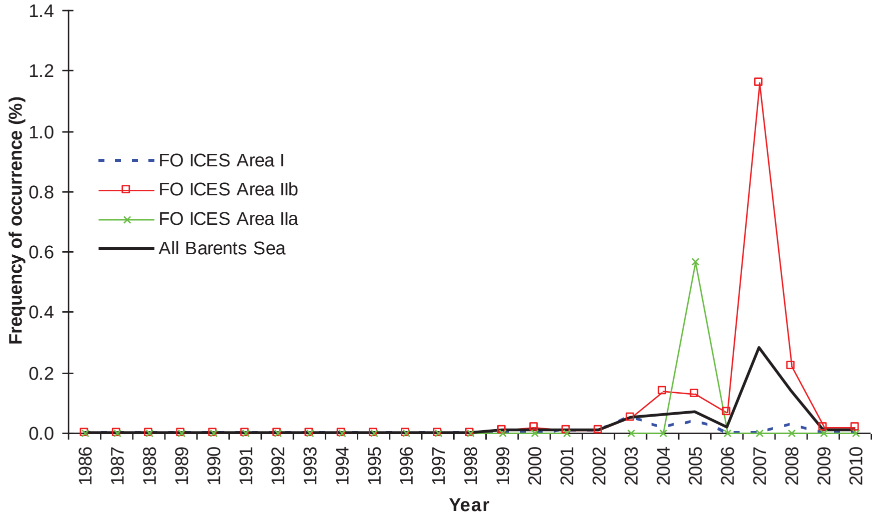


Figure 2. Interannual dynamics of frequency of occurrence of some principal prey (capelin, Euphausiids) of cod in 1947-2010.

Cod



Redfish



Greenland halibut

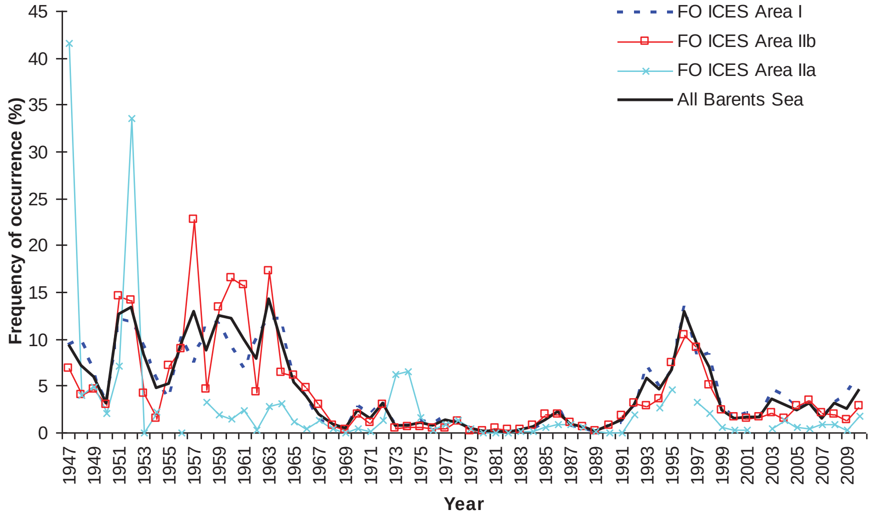
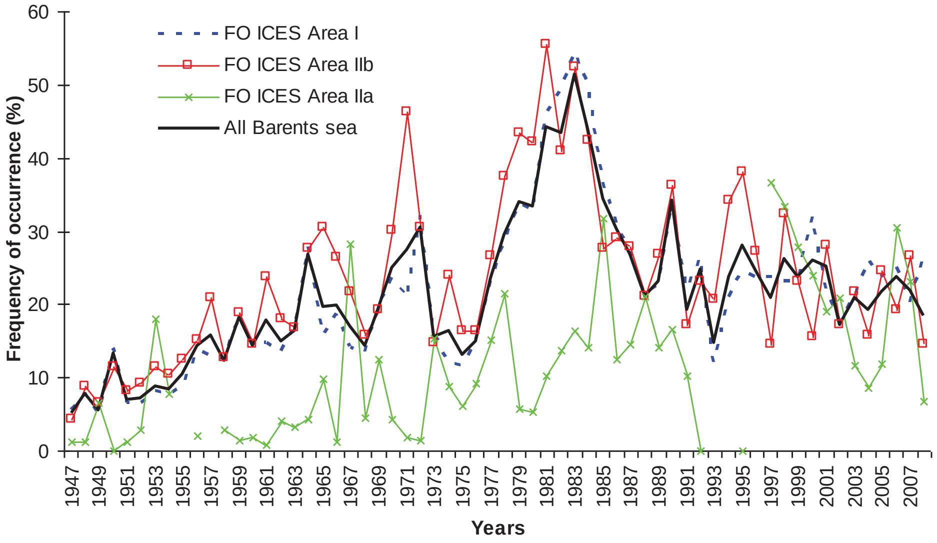


Figure 3. Interannual dynamics of frequency of occurrence of some additional prey (cod, redfish, Greenland halibut) of cod in 1947-2010

Shrimp



Long rough dab

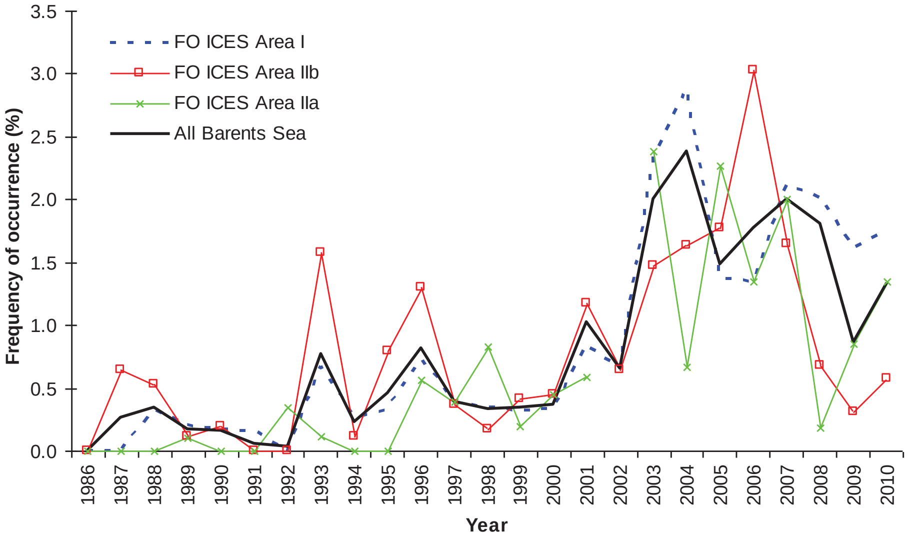


Figure 4. Interannual dynamics of frequency of occurrence of some background prey (shrimp, long rough dab) of cod in 1947-2010

Comparison of diets of cod and haddock

Comparison of cod and haddock diets demonstrated that interannual dynamics of FOs of some prey in cod and haddock diets were related (Figure 5). The FOs of capelin and euphausiids varied simultaneously, showing peaks and falls in the same periods. Relationships between the FOs of euphausiids in diets of cod and haddock were stronger (R^2=0.84) then those of the FOs of capelin (R^2=0.44).

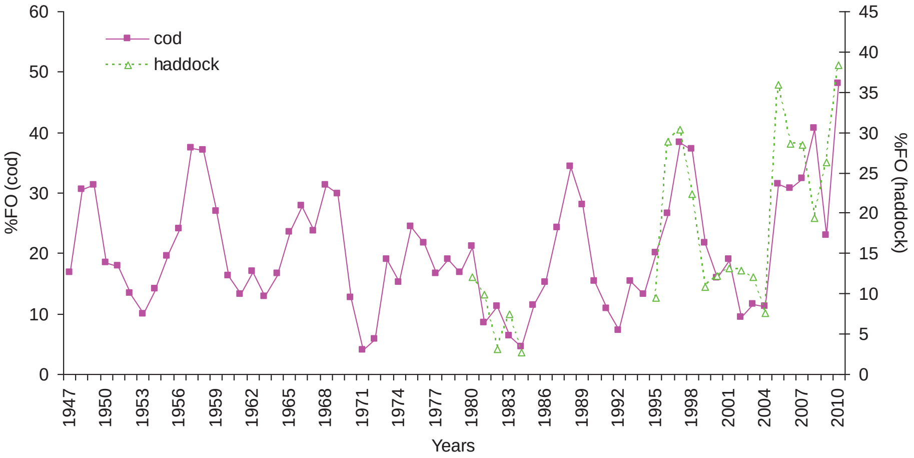
Comparison of cod diet during different climatic periodsThe most important prey groups of the NEA cod diet in 1940-2010 were analyzed for this purpose. Significant differences were observed in the FO values of cod prey (e.g. shrimp, bottom crustaceans, other bottom invertebrates like Mollusca, Echinodermata, Polychaeta, capelin, young cod, polar cod and other fish) in various climatic periods. Insignificant differences were observed for FOs of planktonic organisms (jellyfish, Ctenophora, etc.), krill (Euphausiids), herring, and young haddock (Figures 6, 7). For that matter, the FOs of shrimp, capelin, and other fish were observed to be significantly higher in the cold years than in the warm ones over the 62-year investigation period, while during the same period, the FOs of bottom crustaceans, other bottom invertebrates, young cod, and polar cod appeared to be significantly lower in the cold years. The percentages of empty stomachs showed only insignificant differences in years with various climatic status, suggesting that as generalist predators, cod were able to switch from warm-water species to cold-water species that expanded their abundance and distribution over the respective periods, so that the percentage of fed cod remained relatively stable.

The index of prey importance (IPI), modified to incorporate quantitative data (WP), available for a smaller number of years (1984-2010), also displayed significant differences in the values for shrimp and capelin in cold vs. warm years (Figure 6). However, the IPI values of capelin were higher in warm years, which probably reflected inter-annual variations in capelin stock dynamics, altered by fisheries. The IPIs of plankton organisms and krill appeared to be different in warm and cold years, showing opposite tendencies.

The dynamics of the IPIs in 1984-2010 are presented in Figure 8, and show that the most important prey of cod during the period were capelin (mean: 37.8%, range: 2.4-92.3%), Euphausiids (mean:16.7% range: 0.2-72.6%), other fish (mean: 16.1% range: 1.2-58.5%), and shrimp (mean: 13.9% , ranges :1.2-34.2%).

Comparison of our data for 1984-2010 (presumably warm years) with the 1934-38 data (Zatsepin and Petrova 1939) which were also warm years, also demonstrated that considerable differences were observed in the composition of the cod diet in the course of these 70 years (Figure 9). The IPI of herring and young cod/haddock fell dramatically, while the importance of capelin, other fish, shrimp, and polar cod increased.

Shrimp



Long rough dab

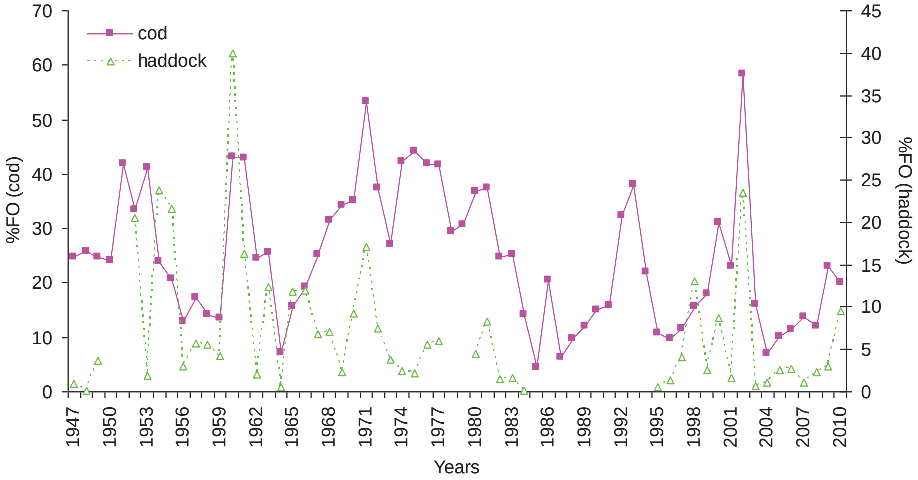
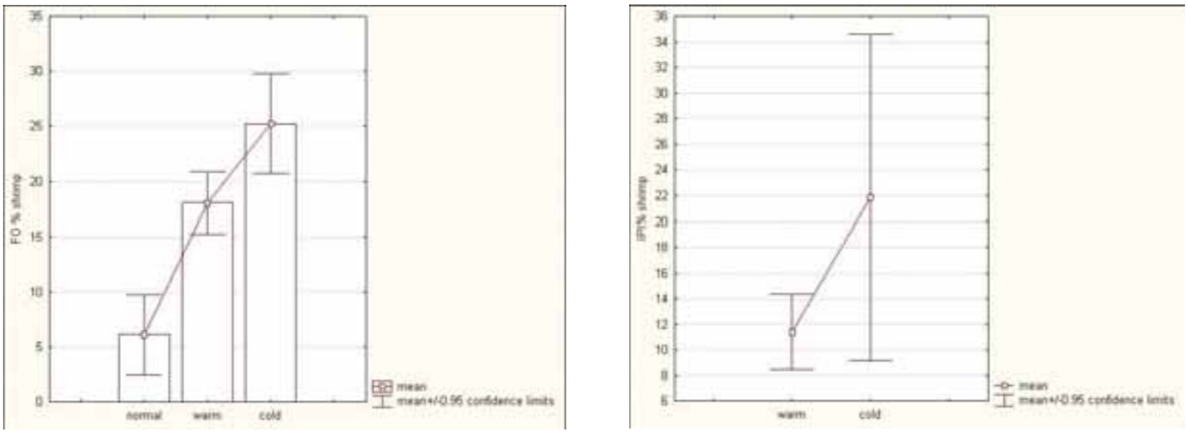
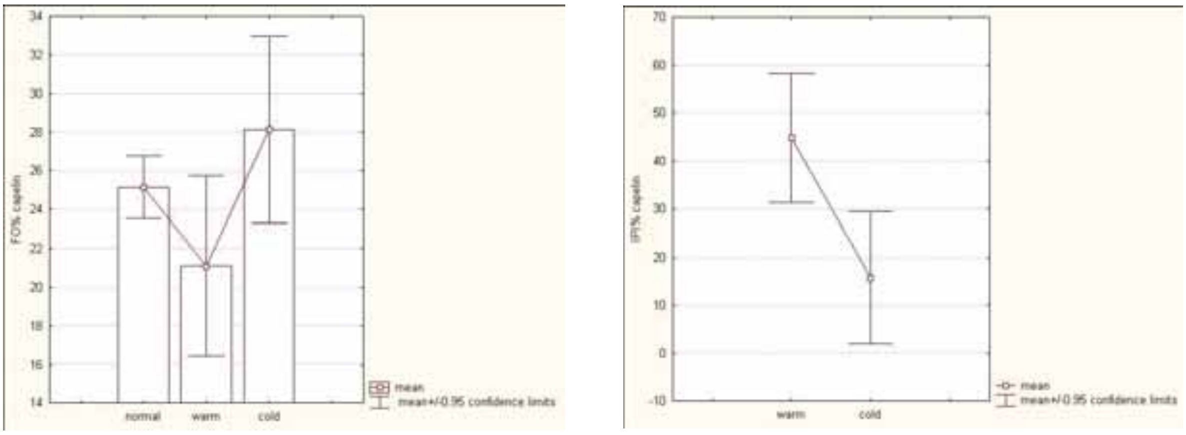


Figure 5. Dynamics of frequency of occurrence of euphausiids and capelin in cod and haddock diet in the southern Barents Sea (ICES subarea I) in 1947-2010.

1947-2010 (qualitative data) **1984-2010 (quantitative data)**



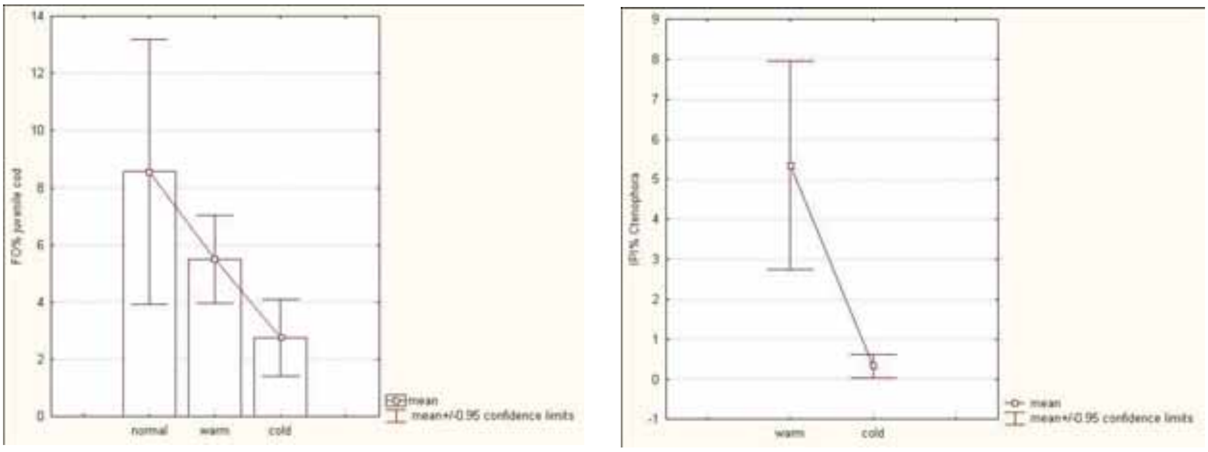
Shrimp



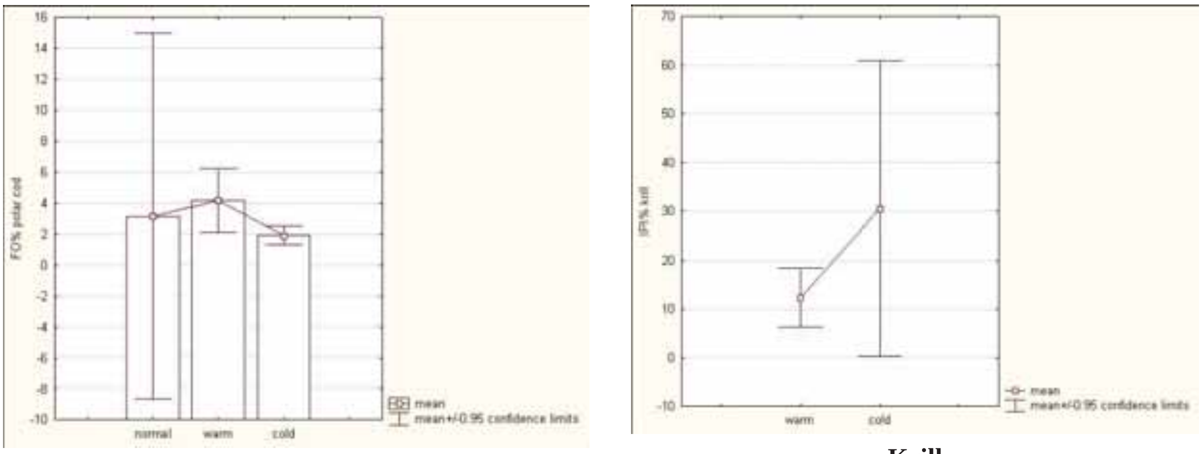
Capelin

Figure 6. Mean values and confidence limits of FO (1947-2010) and IPI (1984-2010) of shrimp and capelin in cold, normal and warm years (difference are statistically significant at $p<0.05$).

1947-2010 (qualitative data) **1984-2010 (quantitative data)**



Juvenile gadoids **Ctenophora**



Polar cod **Krill**

Figure 7. Mean values and confidence limits of FO (1947-2010) and IPI (1984-2010) of some prey (juvenile gadoids, Ctenophora, polar cod, and krill) in cold, normal and warm years (differences are statistically significant at $p<0.05$)

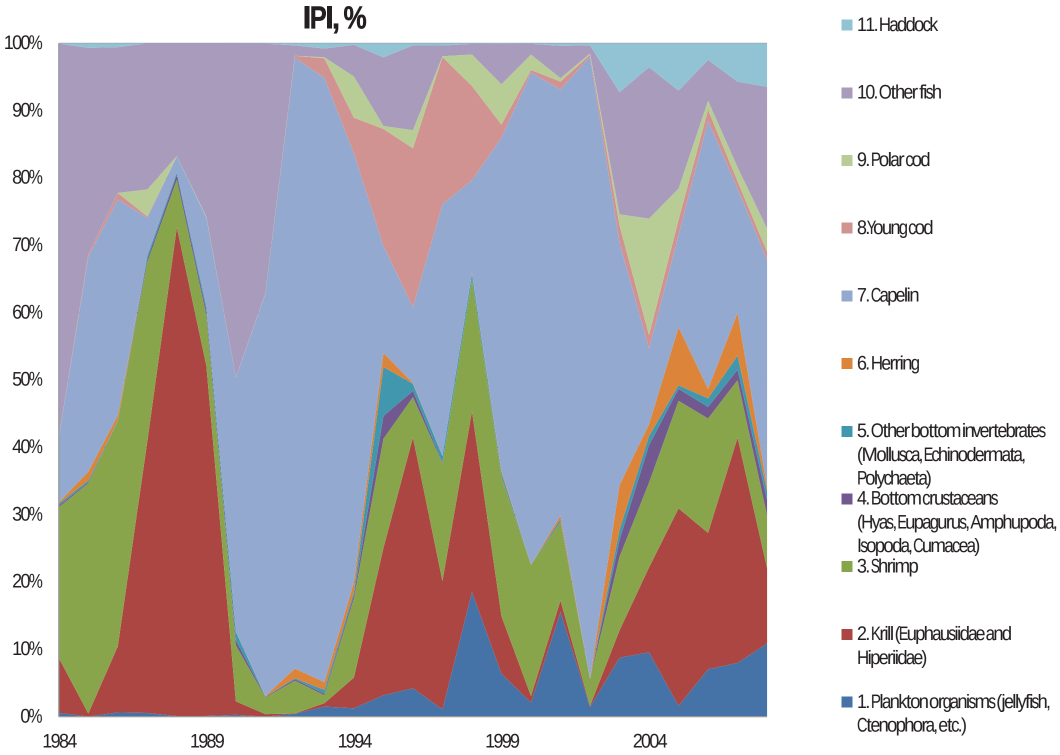


Figure 8. Dynamics of Index of prey importance (IPI) of the main cod prey groups in 1984-2010

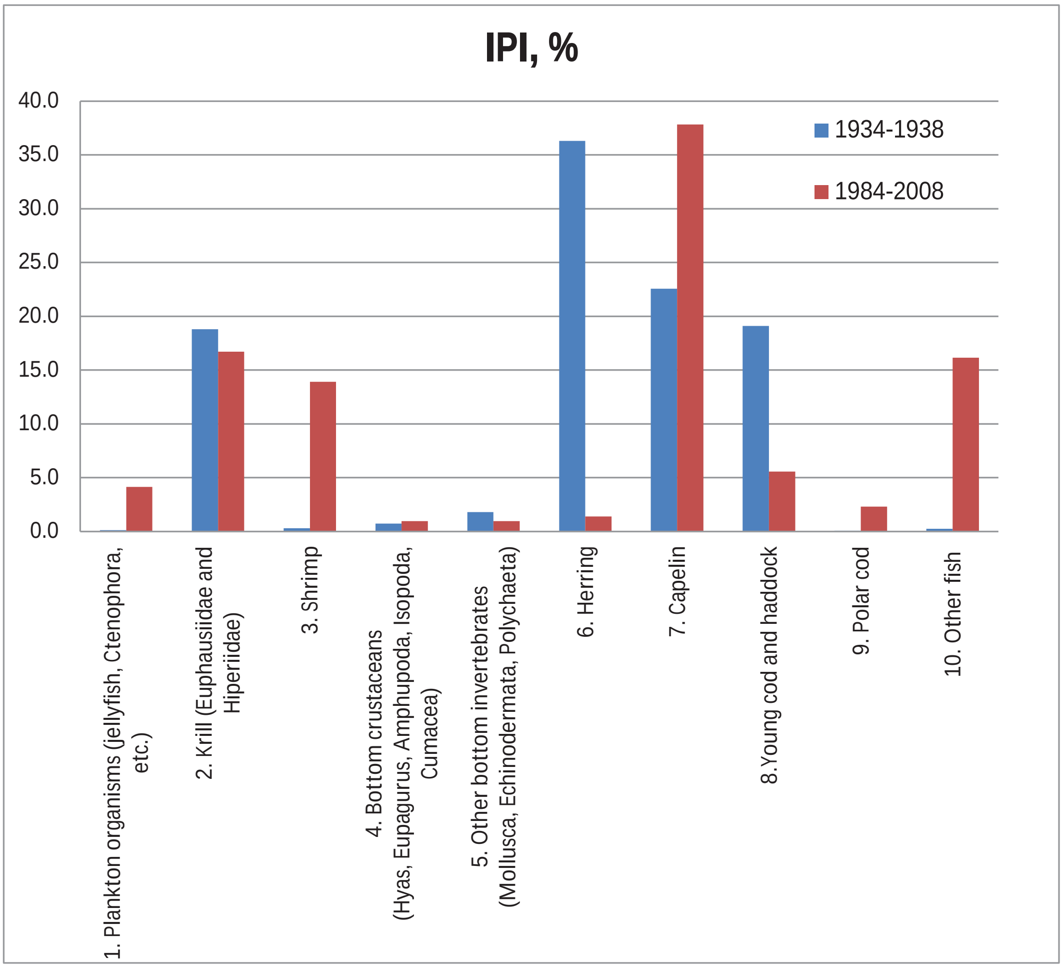


Figure 9. Importance of main prey groups in cod diet in 1934-1938 and 1984-2010.

Discussion

Relevance of the qualitative method

Two different indices of prey importance in cod diet, based on qualitative and quantitative methods of stomach analysis (FO and WP) were linked. Relationships between the FO and WP values were rather strong for most of the prey species/groups examined. Links were lacking only for haddock and herring in Area IIb, which was probably related to the sporadic variability in these indices. The strongest correlation between the FO and WP was registered for middle-sized and frequently occurring prey such as euphausiids, capelin, and young cod.

The numbers of samples taken by the two methods are different; more stomachs were usually sampled by the qualitative method, while material obtained using that method is more uniformly distributed over the seasons. The quantitative method of stomach analysis, which requires better qualified specialists, equipment and time is mainly used during scientific surveys performed in the Barents Sea during the I and IV quarters of the year. Since the sampling locations and seasons using the two methods may be different, indices derived from these two datasets can also differ to some extent. This means that each index provides a different insight into the feeding habits of fish (Hyslop, 1980). Using both methods is complex, while critical comparison of them provides a more reliable picture of how fish feed. We attempted to solve the problem inconsistencies between these data sets by combining both of them into a proposed new index.

Significance of various prey groups

The prey spectrum of the NEA cod was considerably diverse. Cod stomachs were found to contain more than 200 species (Zatsepin and Petrova 1939), although only 20-25 species turned out to be important, while others occurred rarely. Based on FO data, some groups of prey were shown to differ degrees of importance in the cod diet, being classified as main, additional, background and random prey groups.

The main prey group included species that determine the annual cycle of cod feeding and migrations (capelin, euphausiids, polar cod). Distinct patterns in spatial, seasonal and interannual fluctuations were found to be typical of these species.

The additional (or substitute) prey group included species whose importance may greatly increase when (?) stock levels of the main prey are low or their own stocks (hyperiids, cod, haddock and redfish juveniles) are increasing. For these species, the strong seasonal or spatial relations and short time peaks were typical.

The background prey group included species that occur in cod diet regularly without any strong seasonal, spatial or interannual fluctuations (e.g. shrimp, long rough dab). Most these prey are stationary (or not actively migratory) species widely distributed in the area (e.g. Berenboim 1992; Albert et al. 1994).

The random prey group included species that are only rarely eaten by cod . Greenland halibut and blue whiting juveniles can be observed in the cod diet when strong year classes appear and cod distribution areas overlap with these prey. No regular seasonality in FO of such prey was observed.

Capelin belongs to the main prey group of the NEA cod; the latter preys on capelin throughout the year, pursuing migrating capelin during much of the year in various local areas. However, the most intensive predation by cod on capelin is seen in the southern Barents Sea and coast of Northern Norway in February-April, and in the Bear Island-Spitsbergen area in July-October. Thus, cod preferentially consume capelin in the spring on capelin spawning grounds and in the autumn in areas where they have congregated to feed. A clear relationship was found between the biomass of the capelin stock and the FO of capelin in cod stomachs for the most recent period, enabling us to hindcast the dynamics of the capelin stock in the historical period (Marshall et al. 2000). Analogous hindcasting of other prey fluctuations (e.g. redfish, Greenland halibut, long rough dab, etc.) might be done using these cod diet data.

Six species of *Euphausiacea* are common in the Barents Sea (Drobysheva 1994), while *Thysanoessa inermis*, *Th.rashii*, *Meganictyphanes norvegica* dominate in cod diet. During the 1930s euphausiids were observed to make up an average of as much as 15% of the cod's annual ration (Zatsepin and Petrova 1939). Euphausiids are passive migrants, and their distribution is mostly related to the intensity and direction of water currents (Drobysheva and Nesterova 1992; Drobysheva 1994). Euphausiids are transferred northwards and eastwards after spring spawning takes place in the surface water layers, after which they settle down on the slopes of shallow banks from July to August and become available for cod consumption (Manteyfel 1960). The areas with the highest FO of euphausiids in cod stomachs are in shallow waters (100-150 m), and zones of warm and cold water mass mixing. The FO of euphausiids, which are prey for both cod and capelin, fluctuated asynchronously with the FO of capelin as well as herring.

Polar cod were consumed by cod mainly in Area I and Subarea IIb in August-November on the northern and eastern boundaries of cod distribution, and were totally absent from the cod diet in Subarea IIa. Cod feeding on polar cod was characterized by strong seasonality, as this occurred only during a short period in the farthest areas of cod distribution (e.g. near the Novaya Zemlya archipelago) when cod and polar cod schools might overlap.

Shrimp inhabit a silt bottom habitat at depths below 90 m, primarily between 200 and 400 m (Kuznetsov 1964; Berenboim et al. 1980). In contrast to the main prey group no pronounced seasonal variations of FO of shrimp were recorded, which means that the availability of shrimp for cod did not greatly change with the season. An inverse relationship between the FO of shrimp (in Area I and Subarea IIb combined) and the total cod stock biomass was derived from the 1947-1983 time series (Ponomarenkoand Yaragina 1984; 1990b; Berenboim et al. 1987) confirming a classical "predator-prey" relationship between cod and shrimp. In the course of the past ten years the FO values of shrimp have remained fairly stable , and it would be reasonable to continue to make a comparative study of cod diet indices using the Barents Sea shrimp stock biomass.

Comparison of diet of cod and haddock

Cod and haddock in the Barents Sea have different feeding habits. Cod have a very wide range of food items, with carnivorous tendencies, and can relatively easily switch to prey that are more abundant in a given season and area.

Haddock are typical benthophages (e.g. Tseeb 1964), although larger individuals occasionally consume fish. Depending on age and season, haddock vary their diet, switching between fish, plankton (mainly krill) and benthos. However, the interannual dynamics of FOs of some prey in cod and haddock diets were interrelated (Figure 6). The FOs of capelin and euphausiids varied simultaneously, showing peaks and falls in the same periods, that might be related to similar tendencies in macro-zooplankton and small pelagic fish communities in the Barents sea ecosystem. Nevertheless, the relationship between the FOs of euphausiids in diets of cod and haddock was stronger than for the FOs of capelin.

Comparison of cod diet in different climatic periods

In general, clear changes in the FO of various prey have been observed since the 1930s (Figure 9). The importance of herring and juvenile cod and haddock in cod diet has decreased since the 1930s, as a result of their shift from the main prey group to the additional group. The proportion of shrimp in the cod diet arose; this species began to be found all year round in 25-30 % of cod stomachs. The FO of capelin and euphausiids in cod diet remained practically constant.

Comparison of cod diet composition in different climatic periods over 1947-2010 showed that differences in the FOs of some prey in warm periods and cold ones were observed. The FOs of shrimp, capelin, and other fish appeared to be significantly higher in cold years than in warm ones. This was in accordance with the arcto-boreal character of such species (like capelin), assuming that their recruitment increases in cold years. On the contrary, for the same period, the FOs of bottom crustaceans, other bottom invertebrates, young cod, and polar cod appeared to be significantly lower in the cold years.

However, the index of prey importance (IPI), calculated for a shorter period (1984-2010) shown significant differences in the values of capelin in cold versus warm years (Figure 6), but with the opposite tendency: the IPI values of capelin were higher in warm years for that period, reflecting probably inter-annual variations in the capelin stock dynamics, altered by intensive fishing.

The most important prey for cod in 1984-2010 were capelin, euphausiids, other fish, and shrimp (Figure 8). Comparison of the data obtained in warm years (our data for 1984-2010 and the data for 1934-38, after Zatsepin and Petrova (1939)) revealed major differences in the cod diet (Figure 9). The importance of herring and young cod and haddock decreased dramatically, while the importance of capelin, other fish, shrimp and polar cod increased. Thus, these climatic climatic periods were similar, the cod diet underwent substantial changes.

It might be suggested that not only climate might cause these changes, but probably long-term alterations in functional structure of the ecosystem related to recruitment and/or reproductive success of populations under the mutual influence of climate changes and multispecies fisheries, which would modify the trophic structure of the ecosystem.

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Photo: Institute of Marine Research

2.30 Barents Sea Ammodytidae and their ecological significance for the top predators during summer feeding.

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Abstract

The non-commercial fish species of the Barents Sea, including Ammodytidae, have been poorly studied and their role in the ecosystem is largely unknown. The current study is based on long-term trawl monitoring of pelagically distributed Ammodytidae. Ammodytidae was mostly distributed in the south-eastern area of the Barents Sea and along the northern Norwegian and Murman coasts. In the core area fish densities were as high as ca 100 kg per nm^2, corresponding to ca 50 thousand fish per nm^2, with an avarege of 17 thousand fish per nm^2 over years 1980-2009 in the Barents Sea. In years with high availability of Ammodytidae, the fish may be an important component in the food web in the south-eastern area of the Barents Sea. The southern Barents Sea is important feeding area for several top predators (bearded seals, harp seals, grey seals, ringed seals, and minke whales in addition to fish and diving birds), and they have occasionally been observed to prey on Ammodytidae there. However, seal diets are often investigated based on digested food from the stomach and intestines, where particularly otoliths are used for fish identification. Our study showed that shape and length of *Ammodytes marinus* otholits varied considerable, and in addition to very small size of otholits, all these increasing uncertainties in diet analyses.

Introduction

Ammodytidae are small, schooling benthopelagic fish, which are usually found at depths of 10-150 meters, and in the brackish and marine waters of the Atlantic, Pacific and Indian Oceans, mainly in the northern hemisphere. In the Barents Sea Ammodytidae are represented primarily by *Ammodytes marinus* which are distributed along the Norwegian coast, in the Southeast and between Novaya Zemlya and Bear Island (Wienerroither et al. 2011). Two other species, *Ammodytes tobianus* and *Hyperoplus lanceolatus* are only rarely reported along the Murman and the northern Norwegian coasts.

A. marinus inhabit areas with sand bottom at depth 100-120 m. The species occurs in schools near the bottom, and burrow into the sand to avoid predation. *A. marinus* has been observed to migrate towards the Murman coast during summer (late June), schools were observed along this coast in late summer-early autumn, and they migrate back to the deeper areas before winter (Andriashev, 1954). *A.marinus* spawns during November-February in areas with sand bottom and strong water currents at depths ranging from 25 to 100 m, mostly at 50-75 m (Rass, 1949). Fish spawning near the Murman coast is larger and has higher fecundity than fish spawning near the Novaya Zemlya, with approximately 6.8 and 4.3 thousand eggs per female, respectively (Andriashev, 1954). Near the Murman coast *A. marinus* prey mostly on *Calanus finmarchicus*, but also Balanus larvae, Euphausidae and Amphipods were also observed in their diet during summer, and small copepods, mostly Microcetella, Acartia and Oithona during autumn (Bogorov, 1934; Mantejfel, 1945). Ammodytidae is important prey for a variety of predators, including fish, sea birds and mammals in the North Sea, the Mediterranean and Baltic Seas, and as such, constitute an important link between the pelagic community and organisms higher up in the food chain.

Several top predators have occasionally been observed to prey on Ammodytidae in the southern Barents Sea, including bearded seals *(Erignathus barbatus)* (Potelov 1971), harp seals *(Pagophilus groenlandicus),* (Nilssen et al. 1995), grey seals (*Halichoerus grypus*) (Tuominen 2005), and minke whales (*Balaenoptera acutorostrata*) (Haug et al. 1995, Nilssen et al. 1995). Additionally, Ammodytidae is an important food source for diving birds, including puffins (*Fratercula arctica*) and shags (*Phalacrocorax carbo* and *P. aristotelis*) (Barrett et al. 2002). For different reasons, the Barents Sea Ammodytidae is poorly studied, even though it is an important ecological component in the southern Barents Sea. Therefore, the goal of this study is to document the spatial and temporal distribution of Barents Sea Ammodytidae, describe variations in otholits shape and size, and monitor variation in pelagic catches during 0-group surveys conducted in 1980-2009. We also aim to compare our findings with information on distribution and abundance of potential predators.

Material and methods

Since 1965 an international 0-group fish survey in the Barents Sea has provided pelagic trawl data to give an early indication of year class strength of target (commercial) fish species (Anon. 1980, 2004). The 0-group survey has been a part of a Joint Norwegian-Russian ecosystem survey in the Barents Sea, designed and jointly carried out by IMR (Norway) and PINRO (Russia) since 2003. Since 1980 standard trawling procedures have been used on Norwegian and Russian vessels. The standard trawling procedure consists of pelagic tows at predetermined positions 25-35 nm (nautical miles) apart. A “Harstad trawl” having 7 panels and a cod end was used. The panels have mesh sizes (stretched) varying from 100 mm in the first panel to 30 mm in the last panel, and 7 mm in the cod end. The tows are done at three depths: head-line at 0 m, 20 m and 40 m, each tow is 0.5 nautical miles (nm) with a trawling speed of 3 knots. Additional depths are towed (60 and 80 m), at dense concentration of fish recorded deeper than 40 m depth on the echo-sounder (Anon. 1980, 2004). For various reasons (time pressure or difficulty with species identification), the non-targeted species, including species of Ammodytidae, were at times only identified to family level. Therefore, we combine all records to one group (Ammodytidae), and our results will be comparable with a previous study of Eriksen et al. (in press). Relative abundance and biomass indices have been calculated by stratified sample mean method for commercial fish species (Dingsør 2005; Eriksen et al. 2011) and small non-commercial fish species (Eriksen et al. in press).

To study pelagically distributed Ammodytidae we used pelagic catches from the 0-group investigations (1980-2009) from quality-checked Norwegian-Russian (IMR-PINRO) 0-group fish database (Eriksen et al. 2009). In this study we normalised pelagic catches by trawling distance and the number of depth layers. The fish density per station, N*s* (fish number per nm^2 (square nautical mile)), at each station, *s*, is estimated by the equation:

$$N_S = \frac{n_S \cdot 1852}{wsp * (td_S / dl_S)}$$

where n_s is the catch (fish number) at station *s*, *wsp* is the effective wingspread of the trawl (20 m), td_S (nautical mile) the total distance trawled at station *s*, and dl_S is the number of depth layers at station *s*. Abundance and biomass indices of Barents Sea Ammodytidae were taken from an earlier study of Eriksen et al. (in press).

To study variation of otholits shape and size we collected otholits from 20 fish (*Ammodytes marinus*) from 0-group trawl catches during Barents Sea ecosystem survey in 2008. The otholits were extracted, cleaned in water, dried on board, while age was determined by counting opaque zones according to Macer (1966) in the laboratory ashore. Fish were weighed and total lengths measured.

Results

During 0-group surveys in August-September in the Barents Sea, *A. marinus* was mainly distributed in the south-eastern area of the Barents Sea, and along the northern Norwegian and Murman coasts (Figure 1). The annual mean densities of Ammodytidae in the Barents Sea varied considerable during the period 1980-2009, and numbers of highest catches were taken in 1994. During years with high fish abundance (1980, 1982, 1986-87, 1994, 1996, 2005-06, and 2009), fish were distributed more densely between 38°00 E - 55°00 E and 68°00 N-71°30N (Figure 1 and 2), and fish densities were as high as ca 100 kg per nm^2, corresponding to ca 50 thousand fish per nm^2.

A. marinus otholits from 20 fish were collected and analysed. Otolith may be white, bright and oval. Figure 3 show variations in of otolith shapes and sizes. Inside of the otholits is convex, while outside is flat. Dorsal and ventral margins are rounded and smoothed. Rostrum is straight, short, wide in the basis and pointed. Sometimes rostrum not protruded from otolith body (Figure 3 B, C). Antirostrum is indistinct. Posterior is rounded, margin smooth (Figure 3 A) or divided into two (Figure 3D).

Fish length varied between 5.2 cm, and mean length of 0-group fish was ca 6 cm, 1 year old fish 7 cm, 2 year old fish was 10 cm and 4 years old fish was 14 cm. Fish weight also varied and was ca 0.4 g (0-group fish), 0.6 g (1 year), 2.7 g (2 year), and 5.6 g of 4 years old fish. The length of otoliths varied also, and was between 0.4 and 2.3 mm, and was ca 0.6 (0-group fish), 0.7 mm (1 year), 1.2 mm (2 year), and 1.8 mm (4 years old fish). Figure 4 show variation of fish length, weight and otholits length.

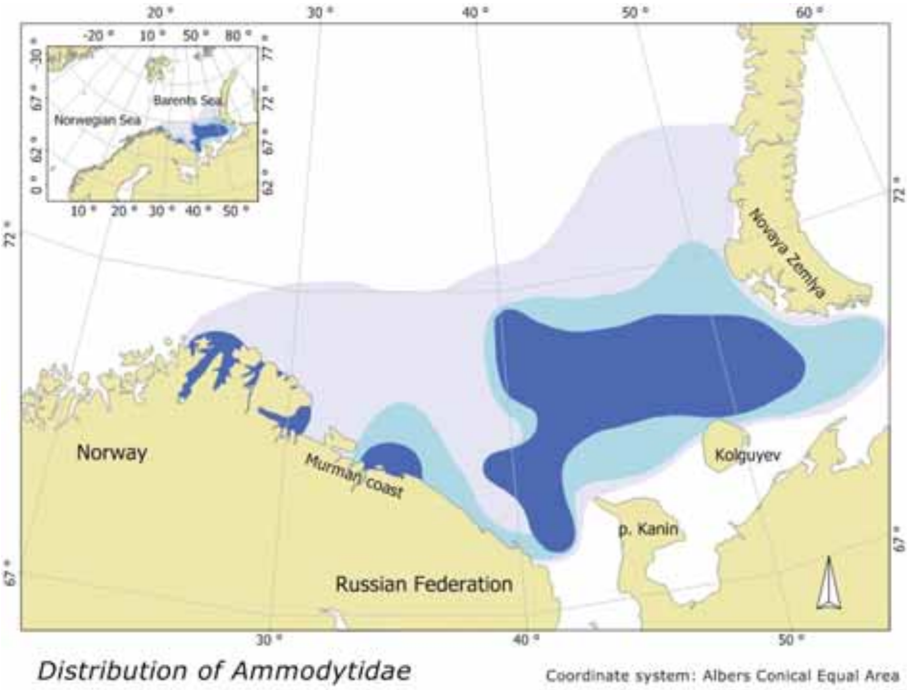

Figure 1. Schematic geographical distribution of Barents Sea Ammodytidae over years with high fish abundance ((1980, 1982, 1986-87, 1994, 1996, 2005-06, and 2009) in the Barents Sea, based on 0-groupe survey. High fish densities (≥1 million fish per nm^2) shown in blue, average fish densities (10 - 750 thousand fish per nm^2) shown in light blue and low fish densities (100 -10 000 fish per nm*2*) shown in light grey.

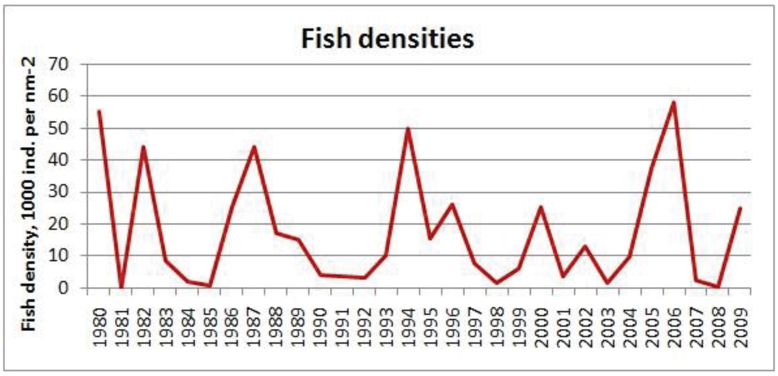

Figure 2. Annual mean densities of Ammodytidae over years 1980-2009, based on 0-groupe survey in the Barents Sea. The long term mean for the period 1980-2009 was ca 17 thousand individuals per nm^2.

Figure 3. Sand eel otoliths with lengths (OL): 2.0 mm (A), 2.2 mm (B), 2.4 mm (C), 2.3 mm (D).

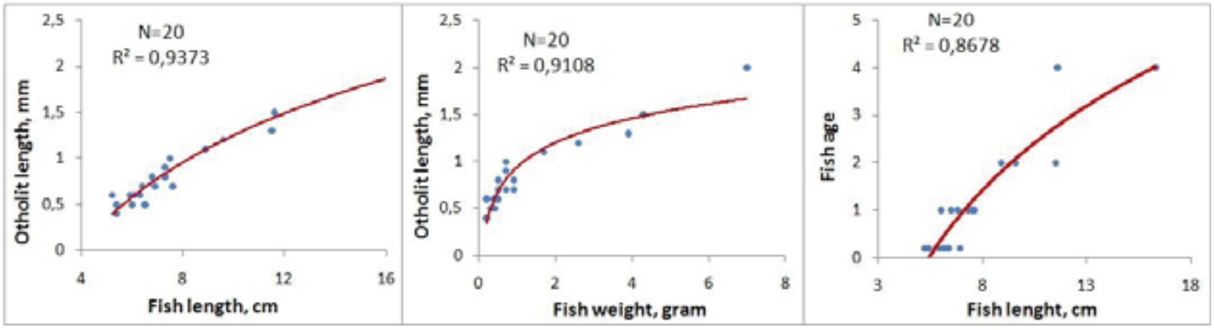

Figure 4. Relationship between otholits and length and weight, based on 20 otoliths. Additionally, growth rate for the Barents Sea Ammodytidae is shown.

Discussion

The Barents Sea Ammodytidae is represented by three species (*Ammodytes marinus, Ammodytes tobianus* and *Hyperoplus lanceolatus),* but is dominated by *A. marinus* (Andriashev, 1954). Two additional species have been observed sporadically along the Northern Norwegian coast and in the western and central part of the Barents Sea (Andriashev, 1954).

The Barents Sea Ammodytidae is mostly distributed over limited areas with local biomasses as high as 80 thousand tonnes (Eriksen et al., in press). Our results showed that the highest fish densities were generally observed in a core area between 38°00’E-55°00’E and 68°00’N-71°30’N (Figure 1), but also locally along the northern Norwegian coast. The fish densities varied regionally and were observed as high as 12.5 million fish per nm^2, corresponding to ca 25 tonnes per nm^2. Densities varied between years as well, and were very low during 1981, 1983-85, 1990-92, 1997-99, 2001-03 and 2007-08. During these years Ammodytidae were very rare along the Norwegian and Russian coast. These regional and temporal variations in abundance obviously represent, among other things, a challenge for top predators usually feeding on Ammodytidae, especially coastal seals and sea birds.

Annual abundance, as observed in the 0-group surveys and ecosystem surveys, varied between 98 and 165192 millions, with an average of 36694 million individuals, and the biomass was almost twice as high in cold years as in warm years, ranging from 300 to 175 thousand tonnes (Eriksen et al., in press)). Our results showed that during the years 1980, 1982, 1986-87, 1994, 1996, 2005-06, and 2009 Barents Sea Ammodytidae was very abundant, with numbers of station densities at magnitudes of ca 1 million fish per nm^2, corresponding to ca 2 tonnes per nm^2. In years with high availability of Ammodytidae, the fish may be an important component in the food web in the south-eastern area of the Barents Sea.

In the southern Barents Sea large pelagic stocks (capelin, polar cod, blue whiting) are less abundant than in the northern and central area (Figure 4). The Norwegian spring-spawning herring occupies generally the southern and central parts of the Barents Sea, and the stock biomass (1 and 2 years old fish) may be as high as 2.5 million tonnes. Young herring is being the important food items for several top predators (fish, sea mammals and sea birds, see, e.g., Wassmann et al. 2006). In years with low herring stock, Ammodytidae may probably be an alternative food source for many top predators.

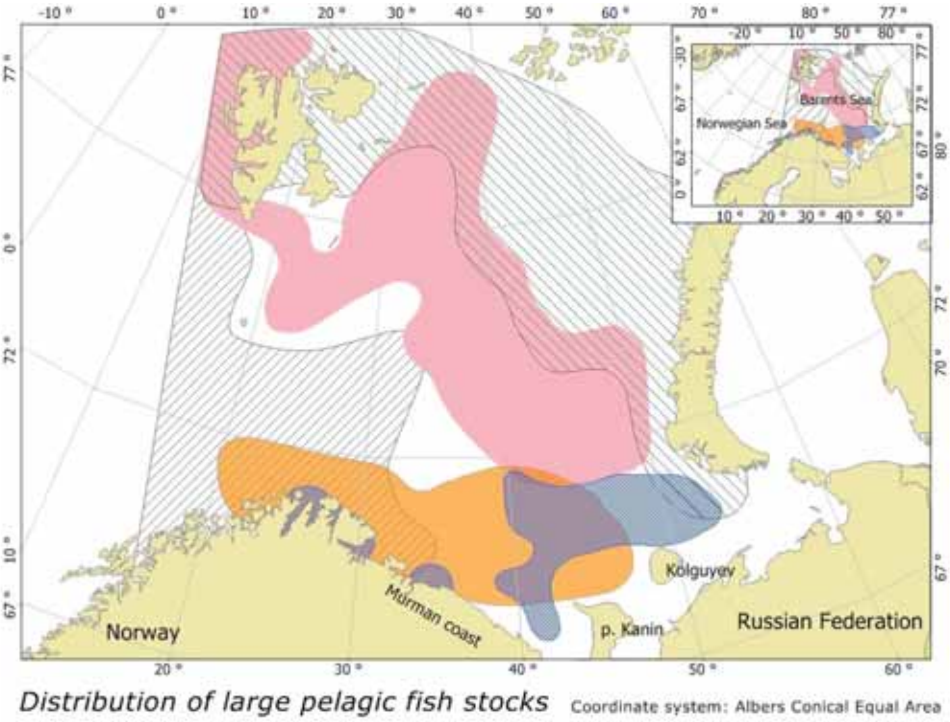

Figure 5. Typical distribution of large pelagic stocks (capelin (pink), young herring (yellow), blue whiting (stripes in the west) and polar cod (stripes in the north) and Ammodytidae (blue) in August-September, based on 0-group survey (1980-2003), capelin (1973-2003) and ecosystem surveys in the Barents Sea.

The southern Barents Sea is important feeding area for several top predators. Bearded seals are distributed in shallow water areas along the northern Norwegian and Russian coasts, Novaya Zemlya and in the north part of the sea, whereas ringed seals occur in shallow water along the coast of Novaj Zemlja, in the southeastern parts of the Barents Sea and in the White Sea (Potelov 1998). Harp seals are common in the coastal waters of the northern Russia and Novaya Zemlya during winter and spring, and in Svalbard and Franz Josef Land waters during summer and autumn (Haug et al. 1994, Nordøy et al. 2008). The grey seals are also common along the north Norwegian and Russian coasts, i.e., the coastal southern parts of the Barents Sea (Nilssen & Haug 2007, Ziryanov & Mishin 2007). Minke whales are widely distributed in the Barents Sea throughout the entire period from spring to late autumn (Jonsgård 1951, Skaug et al. 2004, Skern-Mauritzen et al. 2011). And along the southern coasts several seabird species both breed and feed (Barrett et al. 2002).

These predators overlap with Ammodytidae in the southern parts of the Barents Sea and along the northern Norwegian and Russian coasts, either during winter and spring (the harp seals) or during summer-autumn. Their main prey is usually comprised of more abundant species such as capelin, polar cod and krill, but the significance of interactions between top predators and Barents Sea Ammodytidae is poorly documented. Ringed seals have been observed to feed on Ammodytidae in the White Sea (Svetocheva, 2003, 2004), but there is so far no documented evidence that ringed seal predation on Ammodytidae occur in the Barents Sea .

Seal diets are often investigated based on digested food from the stomach and intestines, where particularly otoliths are used for fish identification (e.g., Nilssen et al. 1995). Although some Ammodytidae otoliths of 0.5-1.2 mm length have been found in seal intestines, difficulties in otolith identification and missing of otoliths due to digestion may increase uncertainties in diet analyses substantially (see e.g., Berg et al. 2002). Our results supported studies of Svetocheva (2003) that showed variance of Ammodytidae otholits shape. Exanimation of 20 otholits showed that both shape and size of *A. marinus* otholits varied, and otholits of the 0-group fish was not longer than 0.6 mm and 4 years fish not longer that 2.3 mm (2 and 3). Such small otoliths are very likely reduced or completely disappearing in predator digestion, thus increasing uncertainties in diet analyses (see Berg et al. 2002).

We have ignored several factors impact the occurrence of Ammodytidae in the upper pelagic layer (trawl avoidance, vertical feeding migration, light level, zooplankton abundance, and the risk from predation); and therefore our results are crude approximations. However, we believe that the densities are too low and that the actual fish densities may be considerably higher. Despite the shortcomings, this unique long term data set provides valuable information of long term fluctuation of pelagically distributed *Ammodytidae*, hopefully will be useful in studies of food availability for sea birds and sea mammals.

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2.31 Monitoring external pathologies in fish as a method of integral estimation of changes in the ecosystem of the Barents Sea under the influence of natural and climatic factors

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Introduction

Virtually all species of land and aquatic animal species are impacted by different parasites and diseases, whose survival is largely limited by environmental temperature conditions. Long-term temperature anomalies are produced by changes in solar activity and climate, creating favorable conditions for the appearance of new diseases and outbreaks of epidemics (Chizhevski, 1995).

The distribution of human parasites extending to high latitudes due to climate change has recently been observed (Lobzin & Kozlov, 2008). It seems that a similar process takes place in aquatic ecosystems but to date, this phenomenon in fish has been very little studied.

The main objective of this report is therefore to describe a new disease of commercial fish species with the tentative name of “red eyes syndrome”, which was discovered in the course of monitoring external pathologies in fish and is related to climatic change in the Nordic seas.

Results

Epizootic data

The first reports of individual rare cases when red eyes were found in the Barents Sea fishes appeared in 1997-1998. The “red eyes syndrome” in cod and haddock was recorded in the PINRO database in 2000. In 2006 this disease was discovered in blue whiting, and in 2007-2008 in capelin and polar cod. The syndrome has now been registered in 16 species of fish in the Barents Sea, eight species in the North-East Atlantic, and in cod, polar cod and capelin yearlings.

Symptoms and histopathology

A wide spectrum of pathologies has been observed in fish affected by this disease. Cataracts, reddish eyes, soft tissues and degeneration of the bones of the head are the main symptoms (Figure 1).

A specific tissue containing parasitic organisms develops in the eyes, leading to morbidity of the anatomical structures of the eyes (Figure 2).

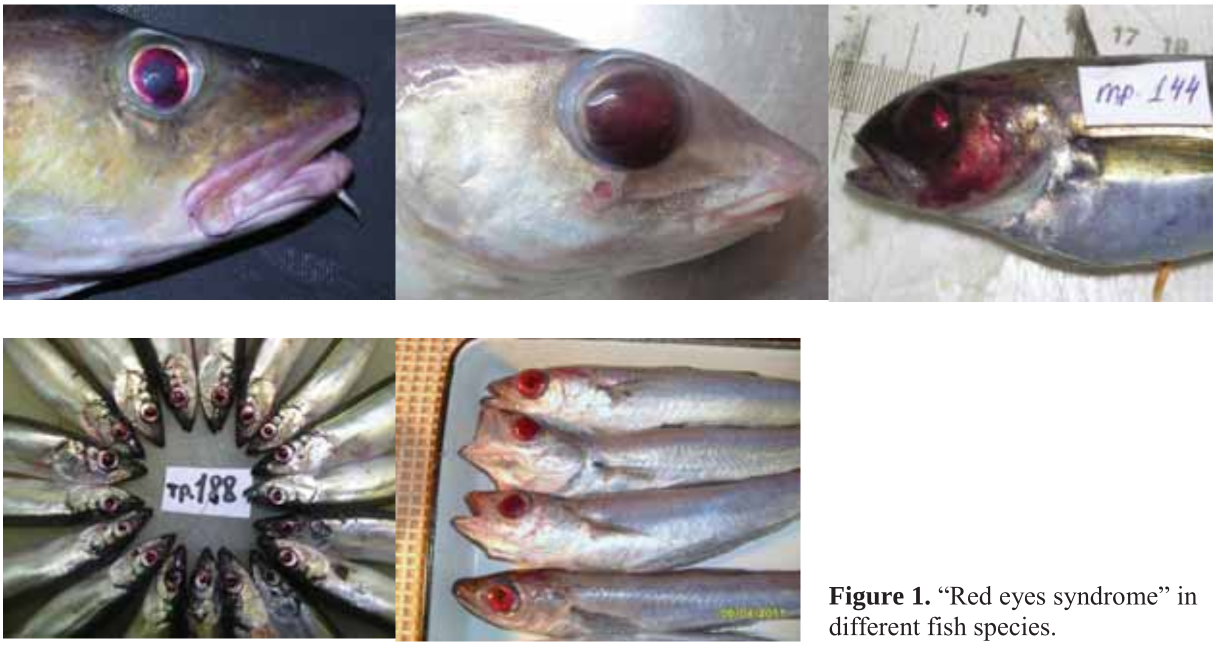

Figure 1. "Red eyes syndrome" in different fish species.

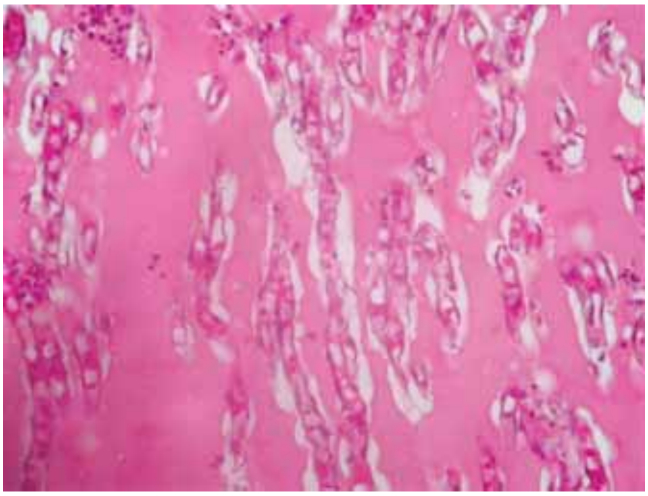

Figure 2. Parasitic organisms with small spores of *Protozoa incertae sedis* within a cod eye. Histological section stained with hematoxylin-eosin. Magnification x600.

Fish morbidity

In 2000-2010, morbidity in cod and haddock was low and did not exceed 0.7%. The peak occurrence of this disease in these species was noted in 2007-2008 (Figure 3). In 63% of cases, the "red eyes syndrome" was registered in cod, 35% in haddock, and 2% in wolffishes.

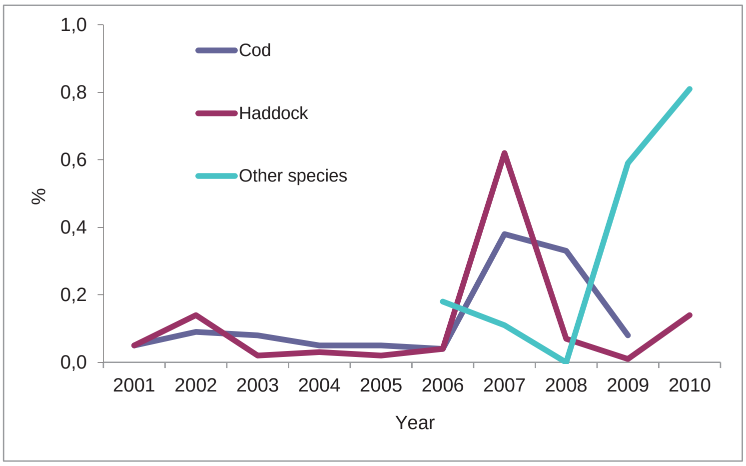

Figure 3. Dynamics of morbidity in demersal fish in the Barents Sea in 2000-2010.

In capelin and in polar cod, the disease started as an epizootic outbreak and was characterized by a high degree of morbidity (Figures 4 and 5).

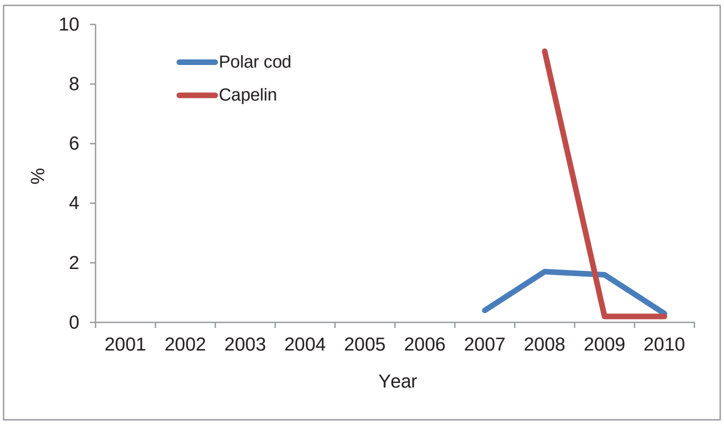

Figure 4. Dynamics of morbidity in pelagic fish in the Barents Sea in 2006-2010.

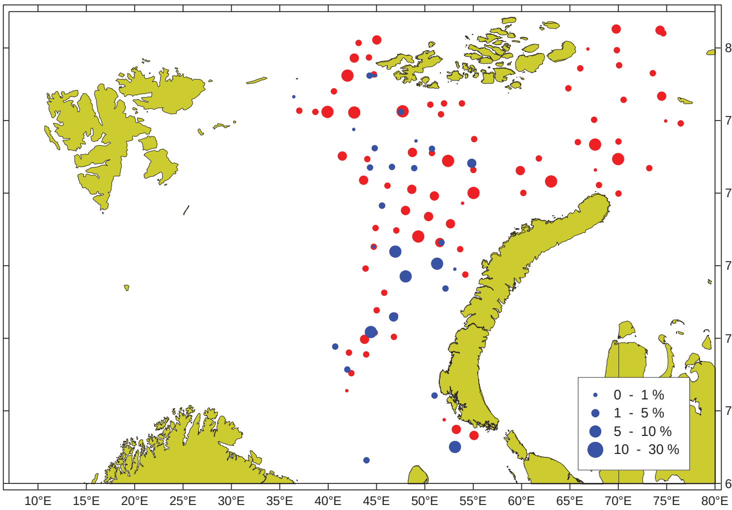

Figure 5. Morbidity and distribution of affected polar cod and capelin in the Barents Sea in 2009-2010.

The number of the affected specimens of blue whiting in March 2010 in different parts of the North- East Atlantic varied in the range 0.9- 4.0%, in average 2.8%.

In spite of a general tendency for morbidity to fall in 2009-2010, the proportion of fish affected by “red eyes syndrome’ was 97-77% of all pathologies found in the Barents Sea (Figure 6).

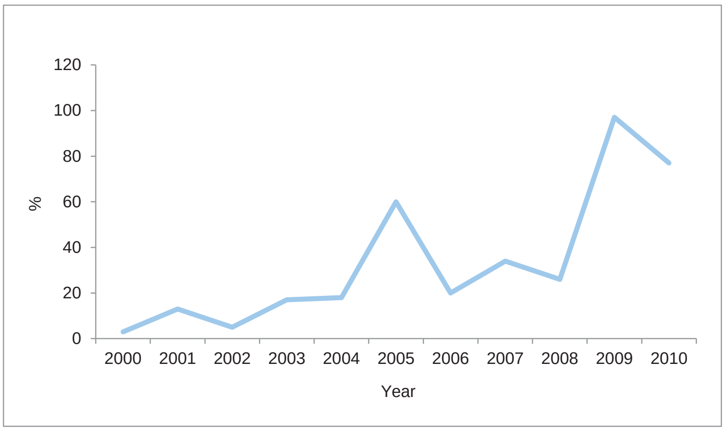

Figure 6. Dynamics of red eyes syndrome as a component of Barents Sea fish pathologies in 2000-2010.

Potential consequences of the disease for a fish stock

In our opinion, the distribution of the disease in the population is primarily conditioned the vertical transmission of the agent from mature to younger individuals. From this point of view a rise in mortality is more to occur among larvae and fingerlings, which are more sensitive to the pathogens than mature adults.

In adults, chronic disease is leads to additional energy expenditure, which is needed to overcome the disease. It is supposed that the energy aspect of the disease impacts individual fecundity and spawning cycle.

It is quite possible that this new disease is one reason for the depressed state of the blue whiting population, and that it may have contributed to poor spawning in other species.

Discussion

New epidemiologically significant fish diseases are a rare phenomenon in nature. Such new diseases may either have recently appeared or were already present, but the number of cases either begins to rise rapidly or are occur in a new geographical area (Supotnitsky, 2005).

The "red eyes syndrome" discussed here matches all the above-mentioned criteria, and we believe that it is associated with the climatic changes and temperature anomalies registered in recent years.

Today, because a wide range of species are affected, this "syndrome" is characterized as epizooty and, consequently, has biological impacts at organism, population and ecosystem levels. It is well known that instability of even one element of a system can make a whole system unstable (Ashby, 1959)

Living organisms are the first to respond to the environmental changes. Pathology and fish diseases reflect the responses of organisms to the unfavorable impact of both biotic and abiotic factors.They are thus valid indicators of any changes occurring in the environment.

The effects of epizooty at population level take longer to develop than those at individual organism level. Science still lacks reliable methods for estimating the moment at which epizooty takes place in a population. The consequences of epizootics tend to be analyzed 15-20 years after the outbreak of the disease (Winters, 1976; Kramer-Schadt et al., 2010;).

The problem of the impact of climatic and environmental changes in the ecosystem obviously involves a large number of questions that require thorough study. The results of our investigation suggest that one of the results of these changes might be the appearance in the Barents Sea of new kinds of parasites and diseases. Systematic observations are the only way to establish these facts. External lesions in fishes may be used for direct observations and do not demand instrumental methods.

Monitoring external pathologies in commercial fish species is a valuable and effective method for the timely identification of dangerous parasites and diseases, and for the general evaluation of the wellbeing of marine ecosystems.

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Photo: Institute of Marine Research

2.32 The potential influence of marine mammals on fisheries under current conditions in the Barents Sea

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Abstract

The heat content of the Barents Sea has been anomalously high during the past five years. This has led to important changes in species distribution, number and structure. Our research has revealed increases in the number and range of species that inhabit the Barents Sea all year round, and a rise in the amount of time spent in the region by species that are not permanent residents. In our opinion, these changes in the distribution, number and species structure of marine mammals could have a powerful influence on fish stocks and fisheries in the Barents Sea.

Materials and methods

PINRO has traditionally employed research vessels, commercial fishing vessels and “Arktika”, a specially equipped Antonov-26 twin-engine aircraft for observations of marine mammals on a “platform of opportunity” basis. Coastal vessels and small boats are utilised for dedicated surveys. The most important surveys of opportunity are the annual Russo-Norwegian ecosystem surveys.

On board Russian research and commercial vessels, observations are made by a single observer who covers a 180^o sector from the bridge roof, usually 7 – 10 m above the surface of the sea. Observers cover transects only between trawling and oceanographic stations, and species are recorded continuously along the transects. Figure 1 illustrates observations of marine mammals be made on board R/V “F. Nansen”.

Observations from “Arktika” are made by two observers through bubble windows on both sides of the aircraft. The observation swath from each side is equal to the altitude, which means that with two observers, it is double the altitude. All the information is entered into the onboard computer system in real time and with geographical coordinates. Figure 2 shows an observer on board the “Arktika” aircraft.

Observations are limited by poor weather conditions such as limited visibility, heavy precipitation, darkness, fog, high waves (above 4 on the Beaufort Scale). Under such conditions, no observations are made and flights are abandoned (these are also limited by low-altitude cloud conditions; less than 50 m).

Figure 1. Observing marine mammals from R/V "F. Nansen".

Figure 2. Observing marine mammals from the Antonov An-26 "Arktika".

Results

The number and distribution of marine mammals recorded during the latest annual Russian-Norwegian ecosystem survey cruise (2010) are shown in Table 1 and Figures 3, 4 and 5. The most frequently observed species are white-beaked dolphin, humpback whale and harp seal. This is similar to the observations for the past several years, but the numbers of animals and their ranges of distribution are growing every year. During the past few years, the length of time spent in the Barents Sea region by species not permanently resident in the region has also increased. Most of the marine mammal observations were of:

1. White-beaked dolphin. This species of toothed whale was usually observed close to or directly attached to large aggregations of capelin; more rarely, the species was observed in migration. This suggests that, at the time of year of the observations, the principal diet of white-beaked dolphins consists of capelin. Figure 6 illustrates white-beaked dolphins hunting a school of capelin in the Barents Sea.
2. Humpback whale. This species of baleen whale was usually observed close to or directly attached to large aggregations of capelin, and occasionally observed close to or directly attached to schools of herring, cod or polar cod. This suggests that, at the time of year of the observations, the principal diet of humpback whales consists of capelin, occasionally supplemented by herring, cod or polar cod.
3. Harp seal. This pinniped species was usually seen close to the ice edge, where large concentrations of capelin, polar cod or zooplankton could be observed. This suggests that, at the time of year of the observations, harp seals mainly feed on capelin, polar cod and zooplankton.

The heat content of the Barents Sea was registered as being usually high at the present time.

Table 1. Marine mammals registered during the annual Russian-Norwegian ecosystem survey cruise in 2010.

	Species name	Johan Hjort	Jan Mayen	G.O. Sars	Vilnus	F. Nansen	Total	%
Cetacea/ baleen whales	Blue whale	-	4	-	-	-	4	0.12
	Fin whale	57	106	15	2	3	183	5.38
	Humpback whale	181	352	1	110	-	644	18.94
	Minke whale	31	107	10	25	5	178	5.24
	Unidentified whale	39	7	-	1	-	47	1.38
Cetacea/ toothed whales	Sperm whale	20	5	1	-	-	26	0.76
	Killer whale	25	-	-	6	-	31	0.91
	Harbour porpoise	4	-	-	11	-	15	0.44
	White-beaked dolphin	55	218	872	39	37	1221	35.91
	White whale	-	-	-	3	-	3	0.09
	Dolphin spp.	77	57	37	-	-	171	5.03
	Harp seal	-	241	-	609	-	850	25.00
Pinnipedia	Ringed seal	-	2	-	1	-	3	0.09
	Bearded seal	-	-	-	-	-		
	Walrus	4	15	-	1	-	20	0.59
	Hooded seal	-	1	-	-	-	1	0.03
Other	Polar bear	-	1	-	2	-	3	0.09
Total		**493**	**1116**	**936**	**810**	**45**	**3400**	**100**

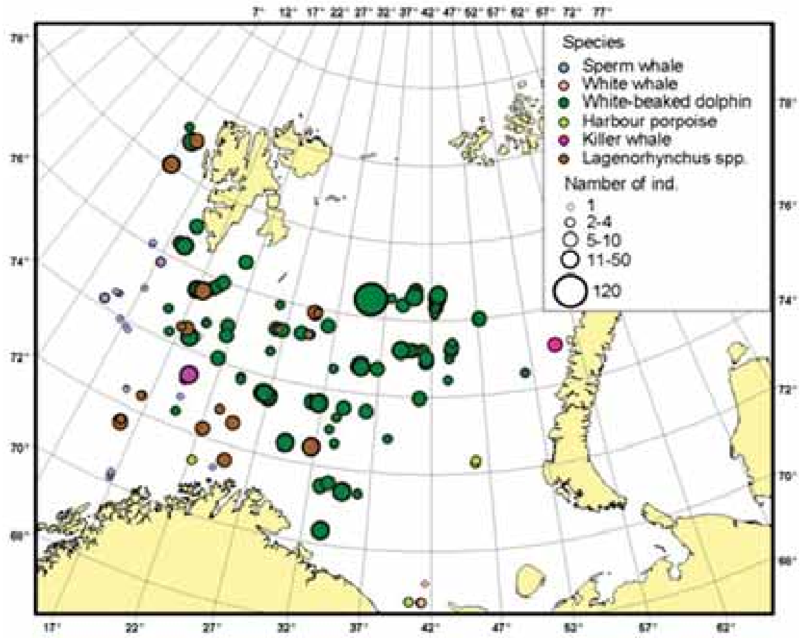

Figure 3. Distribution of toothed whales registered during the annual Russian-Norwegian ecosystem survey cruise in 2010 (Anon. 2010).

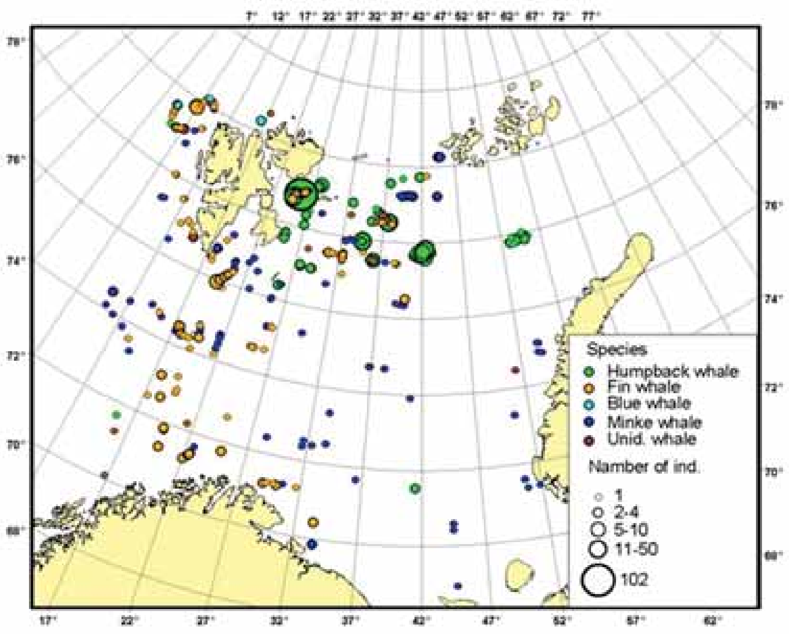

Figure 4. Distribution of baleen whales registered during the annual Russian-Norwegian ecosystem survey cruise in 2010. (Anon. 2010).

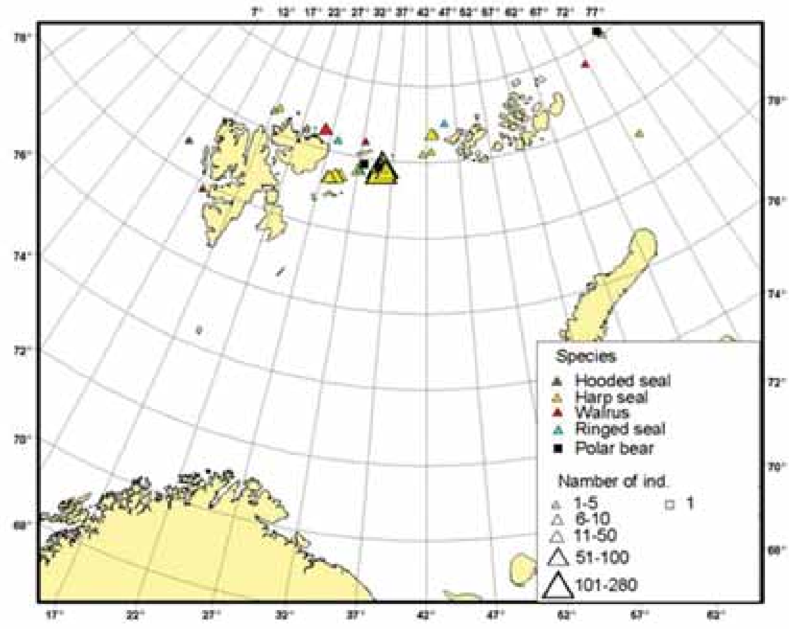

Figure 5. Distribution of seals and polar bears registered during the annual Russian-Norwegian ecosystem survey cruise in 2010. (Anon. 2010).

Figure 6. White-beaked dolphins hunting a school of capelin in the Barents Sea.

Conclusions

The situation described above regarding the number and distribution of marine mammals permits us to draw the conclusion that these species can have a major influence on fish stocks and fisheries in the Barents Sea, and this should be taken into account when rational fisheries management policies are being considered.

References

Anon. 2010. Survey report from the joint Norwegian/Russian ecosystem survey in the Barents Sea August-September 2010. IMR/PINRO Joint Report Series, No. 4/2010. ISSN 1502-8828. 108 pp.

Photo: Institute of Marine Research

2.33 Modeling of PCB propagation in the Barents Sea

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[2] *NIVA, Norway*

PCB is one of the most dangerous pollutants present in the seawater. In certain Sea regions this pollutant accumulates in the bottom layers, which leads to an increase of its content in fish above the maximum allowable concentration level. The goal of this study was to understand the reasons of formation of the patchiness of PCB distribution in the Barents Sea.

As a basic hydrophysical model we used the 3D model ECOSMO/HAMSOM. Processes of advection and turbulence were parameterized for the years 1966 and 1990 that are characterized by different circulation intensity. The boundary conditions for the model were taken from the existing model estimates and observations. To parameterize the processes of accumulation in biota and organic matter we used a simplified 4-component biogeochemical model (biota, detritus, nutrient and dissolved organic matter,). The application of the model allowed us to analyze the role of effecting factors, i.e., flux from the atmosphere, river input, formation and melting of the sea ice, sinking, burying and exchange with the neighboring regions.

The simulated model results allowed us to demonstrate that in the case of an intense circulation regime we can expect higher PCB concentrations propagating further into the Barents Sea and increasing in bottom water as compared to the weak circulation regime. The model also predicted higher concentrations in surface waters of the western Barents Sea in case of less intense winds and weak circulation. The modeled PCB concentrations thereby covered the full range from 0-40 pg/l, indicating a large degree of spatial variability in the Barents Sea. Specifically, the bottom concentrations might vary considerably in neighboring regions.

Photo: Bjørnar Isaksen, Institute of Marine Research

Theme session III: Management implications and challenges

3.1 Implications of Climate Change for the Management of Living Marine Resources

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Climate change is one of the major issues of our time. The potential effects of change on the physical and biological properties of the oceans have been widely studied (Brander 2010). Increasingly, the potential economic, social and political effects of climate change are under discussion, including for living marine resources. A number of international institutions related to fisheries have voiced their concern in this regard, such as the FAO Committee of Fisheries (COFI) (FAO 2009) and the UN General Assembly in its 2007 fisheries resolution (UN General Assembly 2009). It is also a growing area of academic research (see, for example, Stern 2009).

The questions concerning the consequences of climate change for fisheries are not something we can provide definite answers to (Browman 2008). A main conclusion of the Arctic Climate Impact Assessment (ACIA) regarding fisheries was that good management of fisheries is important to confront the challenges posed by climate change (ACIA 2005). By reducing fishing effort and fish mortality, stocks will become more resilient to change. And we also know that our management systems over the past decades have proved capable of adapting to substantial changes in the marine environment.

The question addressed here is how the legal and political frameworks for resource management are likely to be affected by issues related to climate change. Specifically, we point to two areas: the reduction of emissions from the fishing fleet, and adaptation to changing conditions in the oceans.

The institutional context

The institutional context for fisheries management is constituted by a complex set of political and legal frameworks at the global, regional and national levels of governance. This applies globally, and is of particular relevance in the North Atlantic where most major fish stocks are shared between two or more countries.

At the global level of governance, the Law of the Sea Convention and the UN Fish Stocks Agreement constitute the legal framework, supplemented by the FAO Code of Conduct for Responsible Fisheries. These instruments provide the major principles for the management of living marine resources, including responses to climate change.

At the regional level of governance, coastal state cooperation in various forms is important to the management of shared stocks. For waters areas beyond national jurisdiction, RFMOs play an increasingly important role in managing fisheries at the high seas (Russel and

VanderZwaag 2010). In the Northeast Atlantic, the North East Atlantic Fisheries Commission (NEAFC) has this role.[1] For fish stocks that are shared between two or more countries, bilateral or other types of arrangements are critical. The Joint Norwegian – Russian Fisheries Commission is an example of such cooperation (Hoel 2008).[2]

The implementation of the rules and principles adopted by the institutions in this international framework is carried out at the domestic level, by national fisheries administrations. Good governance in fisheries is associated with three elements of policy: scientific knowledge, regulations of fishing activity, and enforcement of regulations. Scientific knowledge in fisheries management essentially entails knowledge about the status and development of fish stocks, as a basis for regulatory action. The regulatory element includes restrictions on access to a fishery, limitations on quantities to be taken from any given stock, and restrictions on when, where and how to fish. Regulations depend upon enforcement systems for their effectiveness.

Over the last decades, environmental concerns have become increasingly important in fisheries (Hoel 1998). This has become manifest through the introduction of the precautionary approach and ecosystem-based approaches to fisheries management, mandated by the 1995 UN Fish Stocks Agreement (Balton 1996).[3] The point of the precautionary approach is to be explicit about and take account of risk. The issue in ecosystem-based management is to take account of the interaction between the environment and fisheries and to reconcile the concerns that arise.

Climate change raises two sets of policy in for fisheries. One is the need to contribute to reduced emissions of climate gases that contribute to global warming – *mitigation*. The other is the need to adapt to a changing environment – *adaptation*. In both cases scientific knowledge, regulations of fishing activity, and enforcement of regulations are important.

Mitigation

The global climate regime consists of the 1992 UN Framework Convention on Climate Change (UNFCC) and its 1997 Kyoto protocol. The latter requires developed countries that are party to the protocol to cut their emissions to an average of 5,2% of 1990 levels by 2008-12. This is a tall order, and will not be achieved. Also, several developed countries, most importantly the US, are not party to the protocol and are therefore not bound by its regulations. Furthermore, Rapid economic growth in developing countries brings increased emissions there as well, and China is now the world´s #1 climate gas emitter. Developing countries are not bound by the Kyoto Protocol.

In a longer time perspective (2050), emissions have to be reduced to 50% or less of 1990 levels in order to avoid CO2 concentrations in the atmosphere and therefore temperature

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[1] http://neafc.org/

[2] See also http://www.jointfish.com/

[3] See the Web site of the UN Secretary General: http://www.un.org/Depts/los/convention_agreements/convention_overview_fish_stocks.html

increases that are inconsistent with the maintenance of the current state of the natural environment.

In fisheries, mitigation is about reduction of emissions. Globally, shipping contributes 2-3% of the emissions of climate gases. The role of fisheries in that picture is very small, but nevertheless significant. While the fishing industry today to varying degree is subject to CO2 levies, it is unrealistic that any industry in the future can escape this. Other mitigation measures include energy friendly fishing methods and the introduction of markets for CO2 quotas.

Among the potential *direct* measures in this regard are CO2 taxes, requirements to fish in more energy-friendly ways, and purchase of CO2 quotas. In Norway, fishing vessels are subject to a CO2 tax. The tax is however subject to a refund arrangement and its effect therefore questionable (Isaksen and Hermansen 2009). There are also *indirect* effects: capacity reduction in the fishing fleet may generally contribute to reduced emissions, as will regulatory programs that encourage short trips and fuel-efficient fishing practices.

An important concern here is the need for a level playing field. If the industry in one country has to pay CO2 taxes and those in another country not, the latter will have a competitive advantage. Also domestically such arrangements and their abolition has a trade-distorting potential.

Adaptation

Predicting the impacts of climate change on fisheries is complex and difficult (Brander 2007). The fishing industry is by nature in the business of adapting to change in the natural environment. Adapting to fluctuations in resources and changes in geographical range is an area of expertise in the industry and its managers.

There is wide agreement among those who have studied the issue is that good management is essential (ACIA 2005, Eide 2007). Climate change does not demand a "total makeover" of current management systems and policies. Rather, what is needed is greater margins of safety in regulatory arrangements and policies that promotes the resilience of fish stocks. In practice, that translates into more conservative reference points and reduction of fishing pressure. Measures relating to reference points and reduction of fishing pressure will in practice often be decided at the domestic level or in bilateral negotiations between countries concerned. Reduction in fishing pressure can be achieved through for example access arrangements, which are typically decided at the national level.

Other adaptation challenges may be more international in nature, in particular when it comes to the allocation of fishing opportunities for stocks that straddle the jurisdiction of several states and/or international waters. In the Arctic Climate Impact Assessment (ACIA 2005) it was considered likely that the geographical distribution of fish stocks may change as a result of increasing ocean temperatures. It is now recognized that this is a complex issue. Fish has always moved and changes in migratory ranges are nothing new (see, for example, Hjort

1914). What is new – in a historical perspective – is the establishment since the 1970s of boundaries in the oceans out to 200 nautical miles (Exclusive Economic Zones), defining who owns what and who can decide what where. While a fishing vessel forty years ago could follow the fish, today it cannot do so if the fish enter the waters under the jurisdiction of another country or the high seas. Viewed in a historical perspective, this is an new situation where the effects of climate change raise new issues.

The law of the sea as it has evolved over the last decades has established that coastal states can have 200 mile Exclusive Economic Zones where they have sovereign rights over the natural resources (Burke 1994). That is, a fish stock that exists in the EEZ of a country, belongs to that country. Complicating this is the fact that fish stocks often straddle boundaries and occur in the waters of more than one state and in addition also international waters beyond national jurisdiction. The law of the sea[4] contains principles for distributing resources on several ”owners” in the case of trans-boundary resources. There are basically two: *zonal attachment* and *traditional fishing*. That is, a state may have an ownership share in a fish stock that corresponds to the share of the stock occurring in its waters, and/or a share corresponding to its historical share of the catch. Also bargaining power plays a role in determining distributional outcomes (Henriksen and Hoel 2011).

Particularly difficult are the cases where a fish stock is found in international waters beyond national jurisdiction. In such instances Regional Fisheries Management Organizations (RFMOs) and similar arrangements play a critical role in ensuring that management measures are adopted also for the high seas (Balton 1996).

Over the last decades we have seen a number of fish stocks changing their migratory range considerably, to enter other EEZs and/or international waters. One example is Norwegian spring spawning herring, a major, international fishery. Herring has sees its geographical range changing substantially. However, the coastal states concerned have managed to establish a functioning regime for the management of the stock. Total quotas are set annually, most recently in October 2011.[5] Occasionally, such cooperation can also break down, as in the case currently is with Northeast Atlantic mackerel.

This demonstrates that although it is difficult and takes hard bargaining and political will to reach agreement on regulations, such situations of changing geographical distribution can be handled by the existing institutional arrangements and/or by adjustments to these. The capacity to adapt to change depends on the level of change in time. If major changes occur over short time spans, it is more difficult to handle than a situation with minor changes over

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[4] The 1982 Law of the Sea Convention: http://www.un.org/Depts/los/convention_agreements/convention_overview_convention.html

[5] Five-party negotiations between Norway, Russia, the EU, Iceland and the Faroes. http://www.regjeringen.no/nb/dep/fkd/pressesenter/pressemeldinger/2011/hempartsavtale-om-forvaltning-av-norsk-v.html

longer time. Another factor is the status of fish stocks: it is easier to reach agreement on allocation when stocks are growing than in the face of stock reductions.

Conclusions

Climate change will remain one of the major political issues, domestically as well as globally, for the foreseeable future. As demonstrated by the ongoing talks in preparation for the meeting of the parties to the UNFCC in Durban late in 2011, this also an issue where international agreement on measures and action to remedy the impacts of change on the natural environment as well as societies are far off. In the Arctic, the effects of change are likely to be substantial, not least for the people living in the region (Kolbert 2006).

In fisheries, important to the economies of the coastal communities in the North, change is widely perceived to be the order of things. Impacts of anthropogenic climate change on marine ecosystems is growing, but has to be assessed in the context of natural climatic variability (Brander 2010). An important consideration, therefore, is the difficulty of separating the effects of climate change from that of other drivers of change. This pertains in particular to economic and political issues, where it is difficult to isolate the "climate signal" and specify its effects.

The measures to address climate change basically fall into two categories: that of mitigation by reduction of emissions, and that of adaptation to change. As regards the first, a number of direct as well as indirect measures have been identified above. As to adaptation, measures can be taken at various levels of governance. The essence of here is that good management is still critical: effort reduction and less fishing pressure are beneficial also in terms of climate policy. Also, existing institutions have proved capable to adapt to situations where the geographical distribution of a fish stock has undergone major change.

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Photo: Institute of Marine Research

3.2 Should living marine resources management be affected by climate change?

Evgeny Shamray (keynote) and Yuri Lepesevich
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Climate change has a marked influence on the spatial and seasonal distribution of marine living resources, and the condition and structure of stocks. In particular, in warm years, highly migratory fish are more widely distributed than in cool periods, shifting the main wintering, spawning, feeding and fishing areas. This process generally improves feeding condition, due to diet diversification, reduced intraspecific competition and higher survival of juveniles, and it has a positive impact on the abundance of subsequent year-classes.

The distribution areas of marine organisms that do not perform extensive migration also change, but these species often move into new areas that are unable to provide them with adequate conditions for survival.

The influence of climate changes on the stock status of living marine resources involves more than changing their distribution range. Extending the range of some species may lead to increasing their predation on juveniles of other species or the intensification of food competition between species that had previously occupied different areas. This may lead to changes in the status of stocks.

However, we should not forget that changes in the distribution of marine organisms in space and time may not always be closely linked to climate change. Such changes may also be due to oceanographic conditions during a particular year or period. Cyclical natural processes are well known. However, although our current knowledge is extensive, we cannot unequivocally say that any “ordinary” situation is due to current conditions alone.

Let us take as an example mackerel in the North-East Atlantic. In the 1970s, the wintering, spawning and nursery areas of the Western component of mackerel were defined (Figure 1). Of course, this is a classic scheme and we know that mackerel spend different periods of their life in other areas as well. In the mid-1980s, it was found that the wintering area had changed significantly (Figure 1). The question arose whether it was an effect of climate change or just of oceanographic conditions during a few years? The answer has an impact on many things, such as the allocation of rights to fish mackerel.

In the early 2000s, the mackerel fishery was regulated out for the whole region, and the TAC allocation was established, including the zonal distribution of the mackerel. We do not discuss this issue here, but on the basis of available sources, it can be argued that the zonal distribution known at that time was significantly different from the present one. Nowadays, in summer, mackerel are distributed farther north and west than in the 1970s and 1980s (Figure 1 and 2). It has long been known that mackerel live west of the Faroe Isles and around Iceland, but in the past few years in these areas a significant proportion of feeding mackerel has become more widely distributed. Evidence of this has been confirmed not only by the results of pelagic fish stock surveys, but also by the fishery (Figure 3). In fact, there was no fishing for mackerel west of the Faroes before 2003, while there has been a large-scale fishery in recent years.

The change of areas causes the redistribution of stocks between the areas of different jurisdictions and, thus, a high probability of the fishing regime changing. That we are seeing at present in respect of mackerel fishing.

During the past few years, there have been disputes over the distribution of the allocation rights for the mackerel fishery. It is clear that countries that have been unable to catch a mackerel in the waters of their own jurisdiction, and that now have a high level of biomass, now wants to catch more. Of course, this is contrary to the interests of other countries that had earlier defined the conditions for the fishery. The result is a lack of agreement that leads to a total catch that is significantly higher than the recommended TAC. The mackerel stock is currently in good condition and has high reproductive capacity. However, we must not deceive ourselves. The combination of one or two poor generations and an excessive fishery will lead to the collapse of the stock, just as has been observed several times in other species. Multi-million stocks of blue whiting and capelin, which appeared to be inexhaustible, decayed rapidly (Figure 4 and 5), and even led to a ban on fishing. We have already experienced a catastrophic decline in the blue whiting stock, but who can guarantee that this stock will recover quickly? How will climate change affect the survival of future generations of blue whiting?

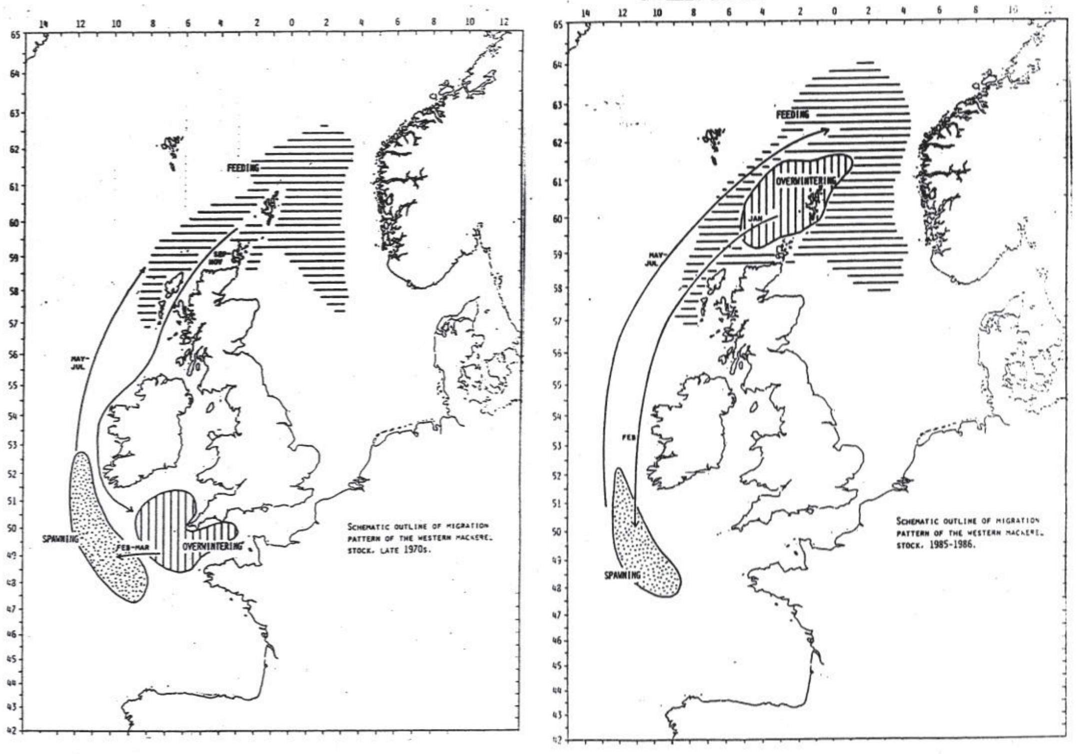

Figure 1. Schemaric distribution of mackerel during various periods in their life cycle in the late 1970s (left) and 1985-1986 (right). (ICES 1982; 1989).

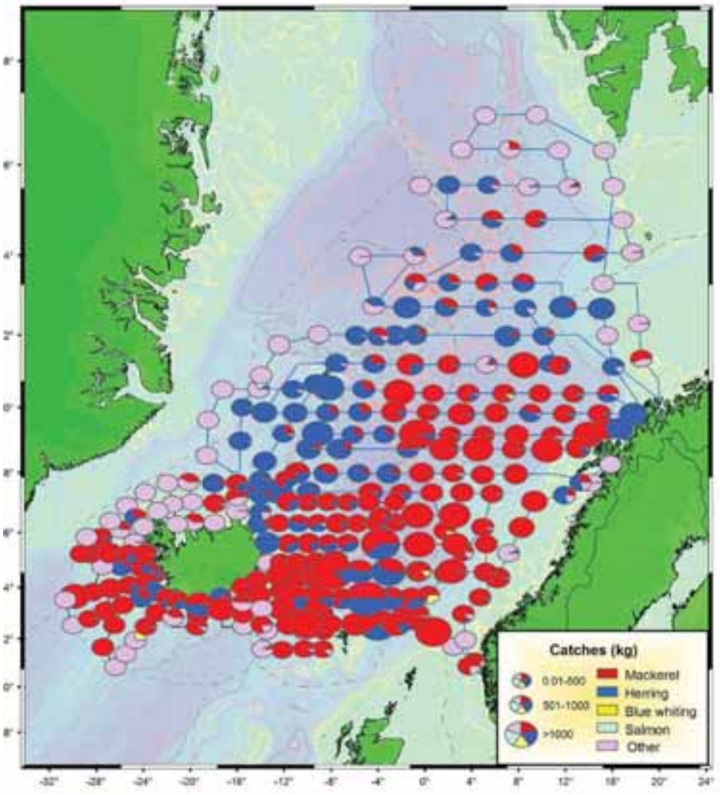

Figure 2. Distribution and spatial overlap between mackerel (red), herring (blue), blue whiting (yellow), salmon (turquoise) and other species (violet) in the Norwegian Sea and surrounding water from 9 July and 20 August 2010. (From ICES 2009).

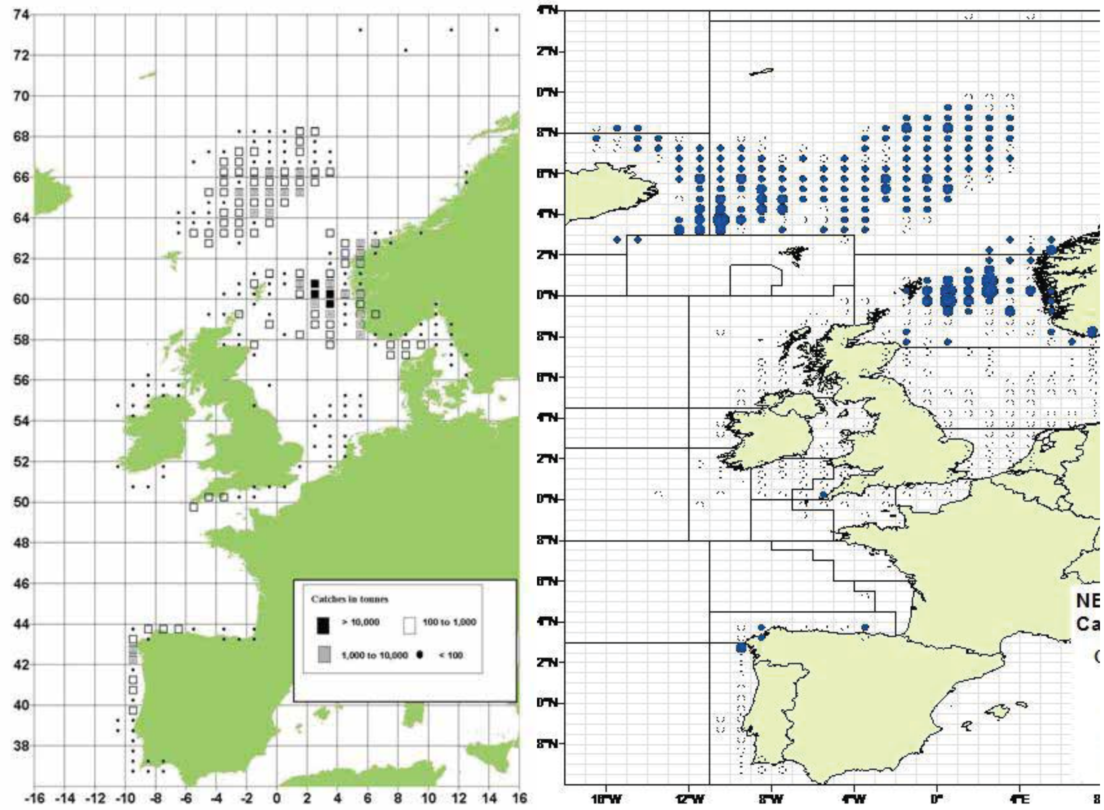

Figure. 3. Distribution of mackerel commercial catches in third quarter 2003 (left) and 2009 (right). (From ICES 2005; 2009).

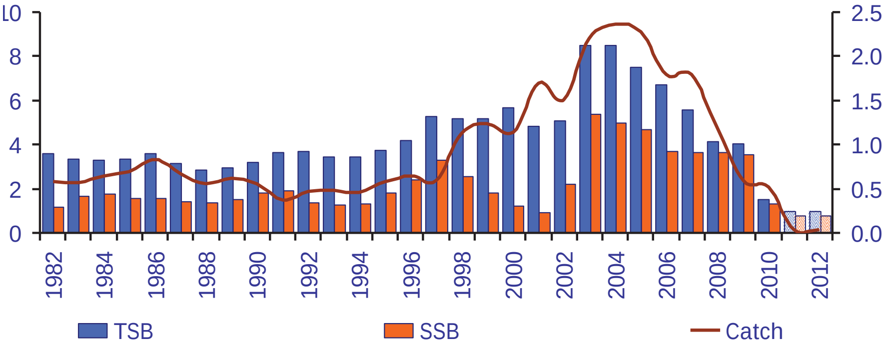

Figure 4. Blue whiting stocks and catch in the North-East Atlantic.

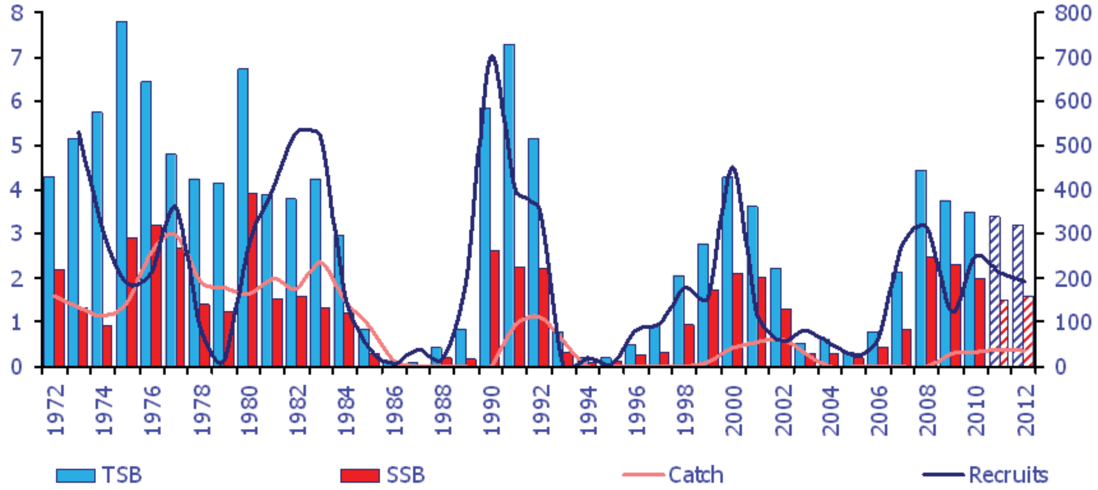

Figure 5. Barents Sea Capelin stocks and catch.

The Barents Sea and adjacent waters make up a unique ecosystem. Because of its location, the Barents Sea has high biological productivity, being a nursery ground for important commercial fish species, as well as a feeding and reproduction ground for many species of fish, mammals and birds, in addition to being an area of intensive fishing.

Recently, the Barents Sea has been a focus of attention in the light of global climate change. As evidence of significant effects of climate change, we may for example mention reduced ice cover, which in general is not objectionable, to changes the status of stocks and distribution of aquatic organisms.

As mentioned above, some changes in the distribution of aquatic organisms may be caused by the oceanographic situation at the time concerned.

It is often claimed that in recent years, the distribution of cod has changed significantly due to climate change. An example is the differences between the distribution of fishing for cod in 1981-1990 and 2001-2009 (Figure 6).While this may be the case, we should also take a look at the distribution of the cod fishery in 1991-2000 (Figure 6). It is obvious that the spatial distribution during this decade is very significantly different from both the 1980s and 2000s. In fact, that change in the distribution of cod did not occur in the last decade, but in the previous one, i.e. the distribution of cod depends on many other factors: the state of the cod stock itself, the state of food organisms, current oceanographic conditions, the fisheries management regime, etc.

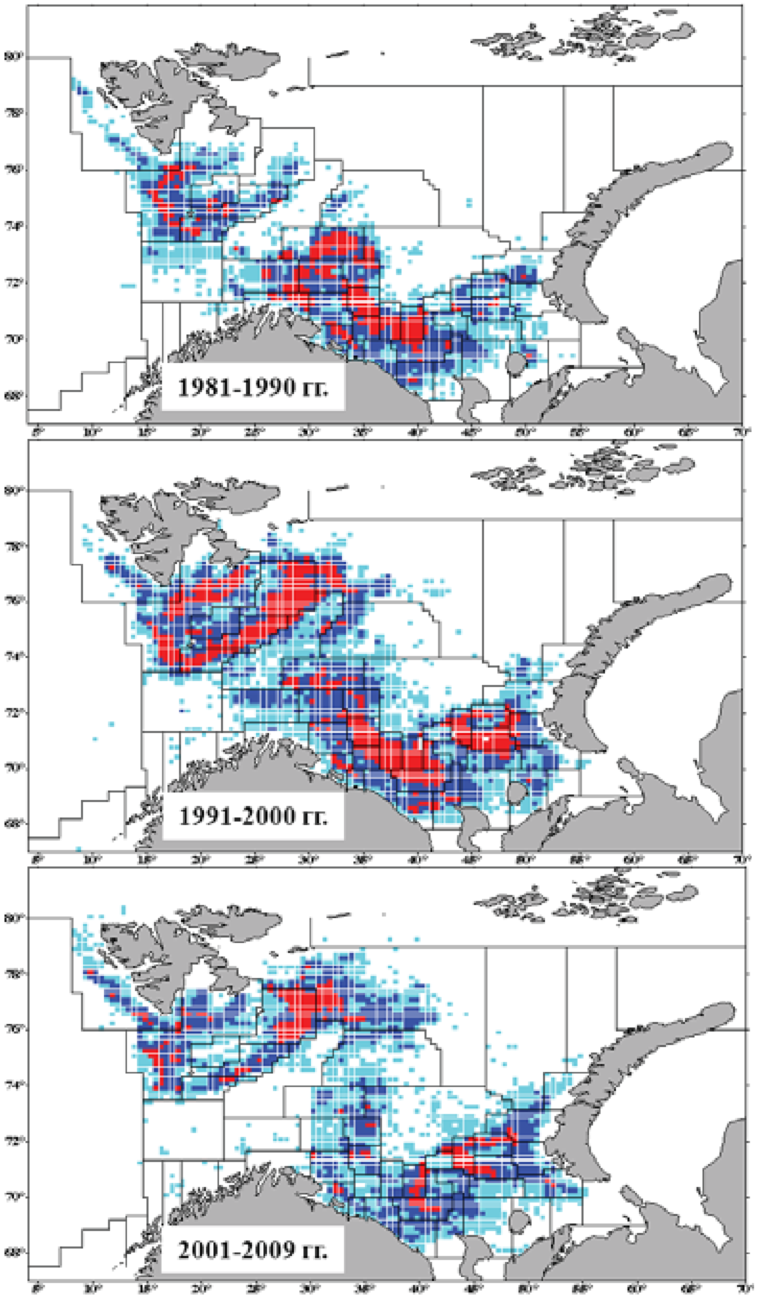

Figure 6. Cumulative cod trawl fishery distribution during 1981-1990, 1991-200 and 2001-2009.

Why has, in recent years, the eastern and northern distribution of haddock been the ”usual”? Is this evidence of global warming? Again, although this may be the case, the results of long-term monitoring show that the distribution of haddock depends on the temperature conditions of the year (Figure 7), as well as the quantity of haddock. The larger the haddock stock and the more immature fish there are, the more easterly are the haddock distributed.

Climate change affects not only the spatial distribution of stocks, but also their qualitative composition and size. In other words, if stocks move away from one area, they will inevitably appear in another, where they will occupy a specific ecological niche. However, proving that this is a consequence of global climate change can be very difficult. Let us assume that this is so. But in such a case we should see some significant changes not only in the state of stocks but also in the total catch, which is an even better indicator.

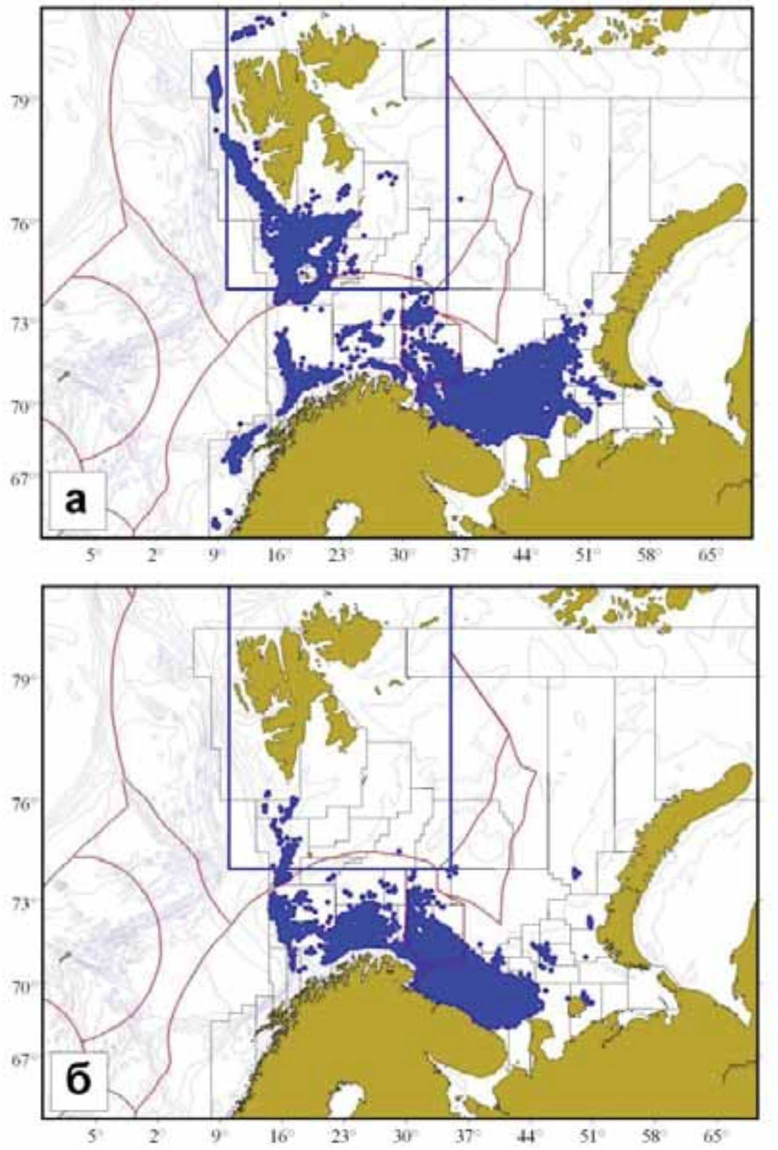

Figure 7. Distribution of haddock in warm (a) and cold (b) years.

However, the total catch in the Barents Sea and adjacent waters in the past 20 years has remained at approximately the same level (Figure 8). Of course, the value of stocks of individual fish species has changed, as is reflected in the catch, which in 1970-1980 was more than twice as high as at present. In principle, this can be taken as evidence of significant climate change. However, climatic change leads to significant changes at lower trophic levels. Consequently, the food supply of fish also undergoes significant changes. Euphausiids are the main item in the diet of many fish species in the Barents Sea, so the state of their community is an important indicator. However, during the past 60 years, no significant changes in abundance of euphausiids have been observed (Figure 9). So what is the reason for the decline of the total catch of haddock in the Barents Sea?

The main factor appears to be inefficient and, in some cases, even a lack of fishery management. Against the background of ample food supply and a lack of awareness of global climate change, the capelin fishery was virtually without restrictions, as were the fisheries for cod, haddock and herring. The appearance of several consecutive poor generations and overfishing has led to a catastrophic decline in stocks of most species of fish.

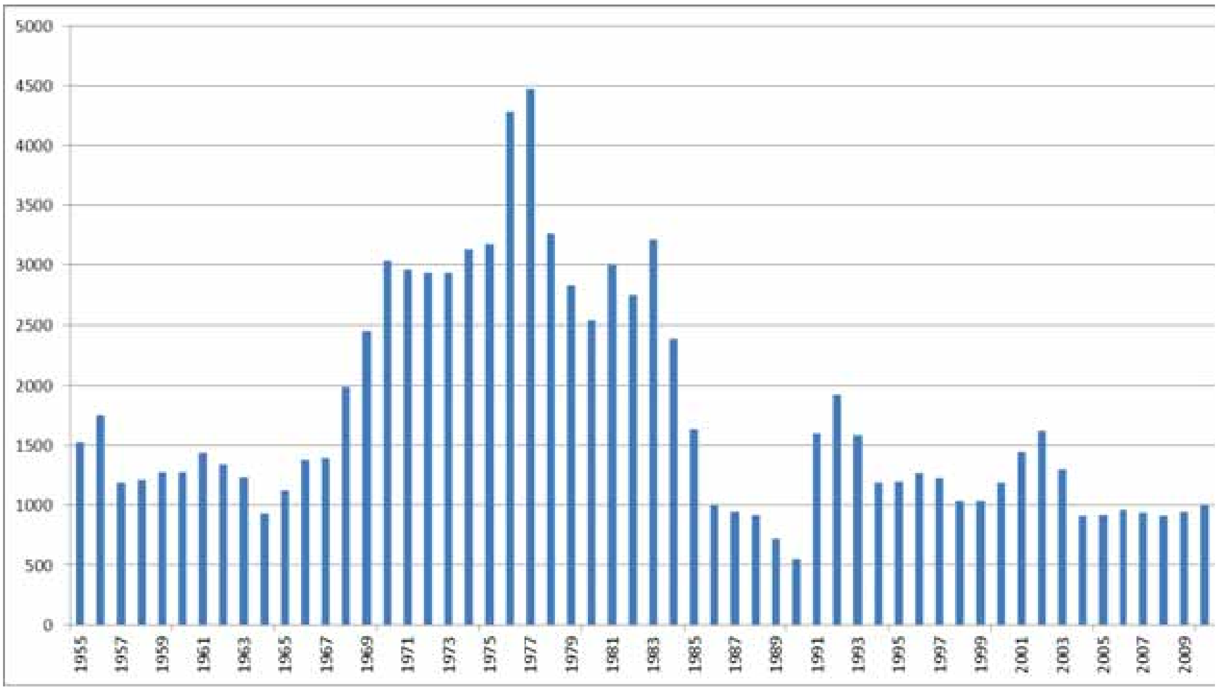

Figure. 8. Total catch of fish in the Barents Sea and adjacent waters.

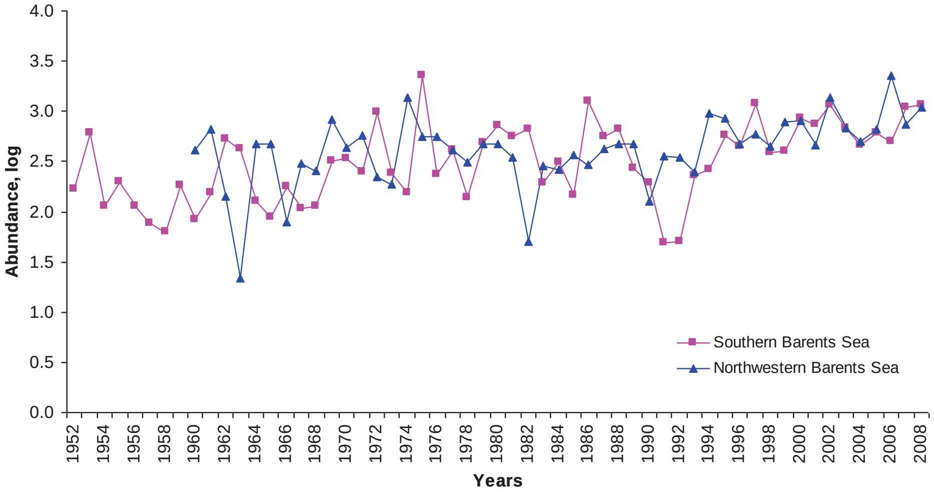

Figure 9. Abundance of euphasiids in the Barents Sea.

Should the management of marine living resources respond to climate change? The answer is simple - "yes." However, decision-making requires a qualitative analysis of all available data regarding the situation.

Often, when dealing with such problems we do not analyze all the scientific information available. If we consider only the state of the haddock stock in the last 30 years it could be argued that the cause of such a substantial increase in the stock (Figure 10) is nothing more than global climate change, or at least a substantial overall warming of the Barents Sea. It is hard to dispute the obvious reduction in ice cover in the Barents Sea, the shift in the feeding area, the higher than usual temperature of the water masses and the appearance of several extremely rich year classes of haddock. However, if we look at the stock dynamics from 1950, it becomes apparent that the earlier haddock stock was in a better condition. In the late 70s and early 80s, the stock was sharply reduced and the fishery was practically stopped, was due to a lack of fishery regulation and a series of poor year classes. In 1976, the Joint Soviet-Norwegian Fisheries Commission was established, and this began to regulate the fishery of the jointly exploited stocks in the Barents Sea. An inventory management strategy was not immediately identified, nor was the principles of the stock exploitation developed, but even at that early stage, a fundamental decision was adopted: exploitation of stocks must be based on scientific advice.

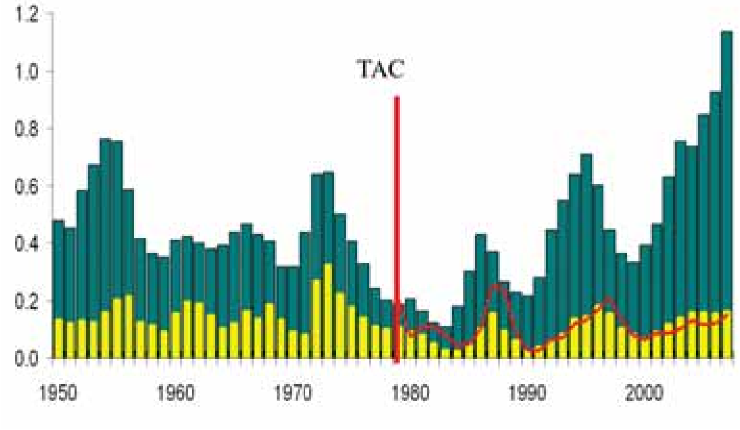

Figure 10. Barents Sea haddock stocks and catches.

Capelin is a key species in the Barents Sea ecosystem, being a prey of many aquatic organisms. We have already mentioned unfavourable periods for this species, but it can be argued that these were primarily the result of human activity. The stock is currently in a satisfactory state, and is the result not of climate change but of the scientific approach to the management of this species. Scientists from Russia and Norway have carried out a great deal of research, not only on capelin but also on the Barents Sea ecosystem as a whole. Current recommendations on the of fishery management take into account the role of capelin in the Barents Sea ecosystem, often referring to changes in the distribution of capelin as evidence of climate change (Figure 11). However capelin, especially in the immature stage, are always widely distributed and any analysis should probably take into account the value of the capelin stock. In 2007 the total stock was low, while in 2008-2010 it was significantly larger (Figure 5).

Reducing ice cover in the northern part of the Barents Sea enabled us to expand our areas of research. Our main interest is now Greenland halibut, whose distribution in the Barents Sea has been clarified as a result of research done in 2007-2010 (Figure 12). The lack of ice around Franz Josef Land enabled scientists to locate concentrations of Greenland halibut that may be regarded as evidence of the influence of climate change. However, observations have shown that in these regions most of these fish are immature; a group whose habitat was previously unknown. On the other hand, the decrease in ice cover will allow a fishery to be organized, which is likely to have consequences for the Greenland halibut stock.

Assuming that the ice in the Barents Sea will continue to decline and the trend to shifts in aquatic habitats will continue, the question of the preservation and exploitation of biological resources, not least in new areas, inevitably rises.

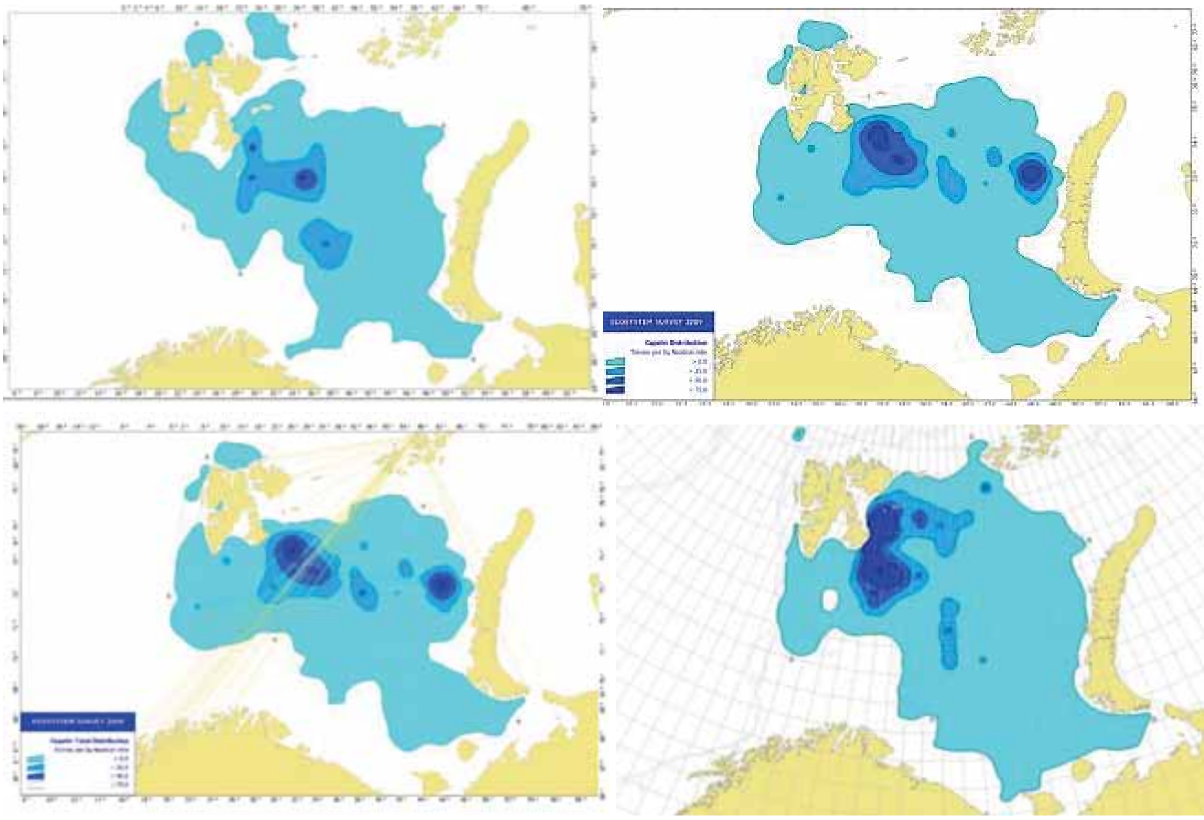

Figure 11. Geographical distribution of capelin during the acoustic survey in autumn 2007-2010 (From Anon. 2007, 2008, 2009, 2010).

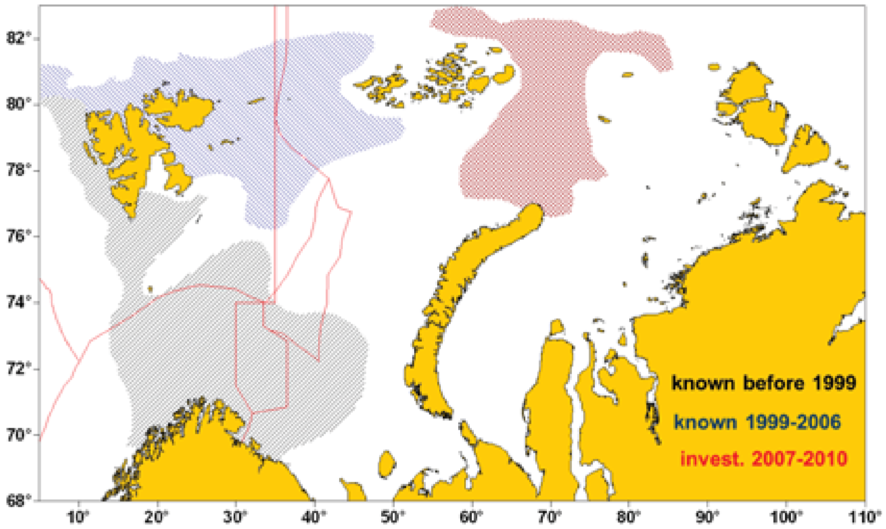

Figure 12. Distribution of Greenland halibut.

Implementing a comprehensive regulatory regime primarily necessitates scientific knowledge of all aspects of the biology of marine living recourses, oceanography and climatology. An ongoing monitoring system is essential, not only to accumulate data, but also to see each small changes in ecosystem health within a holistic context as well as at individual stock level. Of course, we also need to develop an appropriate system of control of fishing activity and harvest control rules. In the Barents Sea and adjacent waters, these are all necessary. EEZ cover all the Barents Sea and adjacent waters (Figure 13) in which most commercial species occur (Figure 13), and the exploitation most resources is part of the responsibility of the Joint Russian-Norwegian Fisheries Commission. The effectiveness of fishing regulations under the umbrella of the Joint Russian-Norwegian Fisheries Commission is under no doubt; the majority of stocks are in good condition. International waters in the Barents Sea are regulated by North-East Atlantic Fishery Commission, whose members have intergovernmental agreements, including with Russia and Norway.

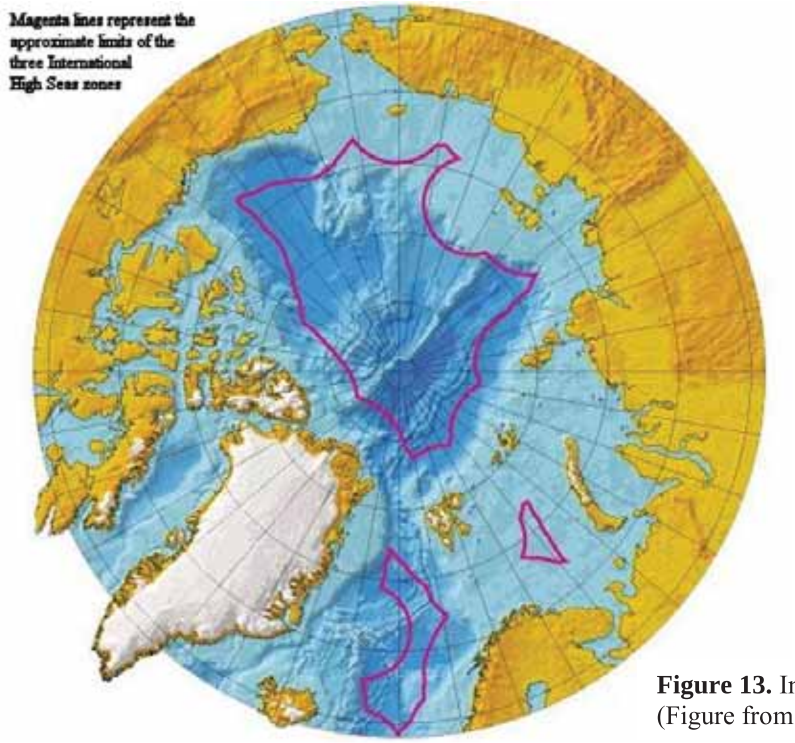

Figure 13. International waters in the Arctic region (Figure from http://www.globalsecurity.org/).

Long-term scientific research in the Barents Sea and adjacent waters is extensive and most of it is performed under the auspices of international programs.

Even though scientific and management organizations of a different level have developed the diverse package of fishery regulation and stock protection, there is an urgent need to improve it under current conditions of climate change.

Fisheries should be carried out on the basis of long-term management plans based on the most complete scientific data, including the prohibition of fishing in a new area until scientific advice is available.

The redistribution of fish stocks opens up new possibilities for their economic development. However, this may also result in conflicts arising between states that already have the right to fish marine living resources and the new claimants to their exploitation.

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3.3 The collapse of Norwegian spring-spawning herring stock; Climate or fishing?

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Abstract

The stock of Norwegian spring-spawning herring collapsed in the beginning of the 1970s. The fishery and climatic change have been stated as the main factors behind the stock collapse. In 1999 the agency for the management agency of Norwegian spring-spawning herring decided on a harvest control rule that at present forms the basis for the annual TAC. The starting point for the present paper is a counter-factual method that considers the effect from the fishery on the stock if this harvest control rule was applied from 1949, 50 years before it actually was implemented. A central part of the paper is an analysis of stock/recruitment relations that incorporates climate (temperature) changes that took place in the period 1950-1990.

Keywords:
Norwegian and Barents Sea, long term simulations, harvest control rules, climate change/recruitment

Introduction

The stock collapse of Norwegian spring spawning herring around 1970 was a spectacular event, the herring stock was reduced from over 10 million tonnes in 1950 to may be less than 10 000 tonnes around 1970, and the fishery was reduced from over 2 million tonnes to zero. The stock collapse had grave consequence for the societies in Faroe Island, Iceland, Russia and Norway that depended on the fishery. There have been several descriptions and analyses of the stock collapse, Røttingen (2004), Toresen and Østvedt (2000), Dragesund et al (1980), Toresen and Jakobsson 2002), Tjelmeland and Røttingen (2009). In these studies the following explanations for the stock collapse have emerged:

1. Environment: A change in the environmental conditions that were unfavorable for the development of the stock

2. Fisheries: A strong increase in fishing mortality due to the introduction of new effective advances in fisheries technology, with a corresponding lack of an international legal system that could restrict the fishery. Also, there was an unfavorable fishing pattern, with substantial large catches of juvenile herring.

These studies have only discussed the combined impact of fishing and environmental impact. The aim of the present paper is to seek out the *relative importance* of climate change and fisheries as an explanation of the stock collapse.

Methods

Which type of changes in the environment took place?

The most common indicator for environmental change is long-time series of water temperature. In the present paper we use several long time series on water temperature, but also the NAO and AO are used as indicators for environmental change.

Impacts on the life history of the Norwegian spring-spawning herring caused by changes in the environment.

The spawning, feeding and wintering areas of the adult herring is in the Norwegian sea, but the Barents Sea is the main nursery area. The environmental changes in these areas can influence several elements of the life history of Norwegian spring spawning herring:

1. The migration pattern. Significant changes of the migration pattern took place in the 1960s. The feeding conditions north of Iceland deteriorated due to an unfavorable development in the ocean climate (Astthorsson et al 1983), and the western border of the feeding herring moved eastwards and northwards (Dragesund et al 1997)

2. Biological parameters such as growth and mortality

3. Recruitment

In the present paper we only consider element 3.

The stock-recruitment relationship

In order to evaluate the impact from the environment on the recruitment throughout the historic period an assessment of the historic population must be made. Based on the historic stock, recruitment functions are built in order to evaluate the historic recruitment for SSBs resulting from a different management. The assessment is based on the assessment tool SeaStar (Røttingen and Tjelmeland 2003; Tjelmeland and Lindstrøm 2005; Tjelmeland and Røttingen 2009), which was used for assessing the stock prior to 2009. For the present paper, SeaStar was set as close to the present-day assessment tool TASACS as possible without compromising using an overall likelihood function for the estimation. Data on weight and maturation at age are taken from the ICES assessment. For the environmental impact on the recruitment throughout the historic period, 3 different proxies have been used:

The temperature along the Kola section. In addition to the yearly mean which was used by Toresen and Østvedt (2000), mean over the months 4-6, 1-6, 6-9 and 7-12 are used, based on the rationale that the importance of environmental conditions for recruitment may be different in different parts of the year. Only one temperature index was used at a time.

The NAO index and AO indexes : These time series have been used as covariates in recruitment functions, alone or in combination, together with the spawning stock biomass and cannibalism. Similar to what was done by Tjelmeland and Røttingen (2009). parameters in a large number of recruitment functions were estimated, from the rationale that the best functional form is not known a priori. The model uncertainty is reduced by selecting the best of many plausible forms using the Akaike Information Criterion (AIC, Burnham and Anderson, 2002).

A modified form of the Beverton-Holt relationship has been used

$$R = R_{max} \frac{S^{P_s}}{H^{P_s} + S^{P_s}} e^{-P_{c1} S^{P_{c2}}} e^{P_t T} e^{P_{NAO} NAO} e^{P_{AO} AO}$$

Where S is the spawning stock biomass, R_{max} is the maximum recruitment and H is the spawning stock biomass when the recruitment is half the maximum recruitment. R_{max} and H are parameters that are estimated in every replicate. T is the temperature for one of the temperature series, NAO is the NAO index and AO is the AO index. All combination of the parameters P_S, P_{C1}, P_{C2}, P_t, P_{NAO} and P_{AO} are estimated in the various replicates, including none and all of these parameters. When a parameter is not estimated, it is set to a non-effective value (1 for P_S and P_{C2}, 0 for P_t, P_{NAO} and P_{AO}). Only one of the temperature series is used at a time. It is assumed that the logarithm of the recruitment data follows a normal distribution with the logarithm of the above recruitment relation as expectation.

For each model replicate the small-sample AIC value is calculated:

$$AIC_c = -2 \log L(\hat{\theta})) + 2K \frac{n}{n - K - 1}$$

Where $L(\hat{\theta})$ is the likelihood evaluated at the estimated value of the parameters, K is the number of estimated parameters and n is the number of data points. The recruitment replicate with the smallest AIC value incorporates the effect of the Kola temperature (Figure 1) meaned over the months 7-12 and ignores the NAO, AO and cannibalism covariates, as well as the power parameters P_S.

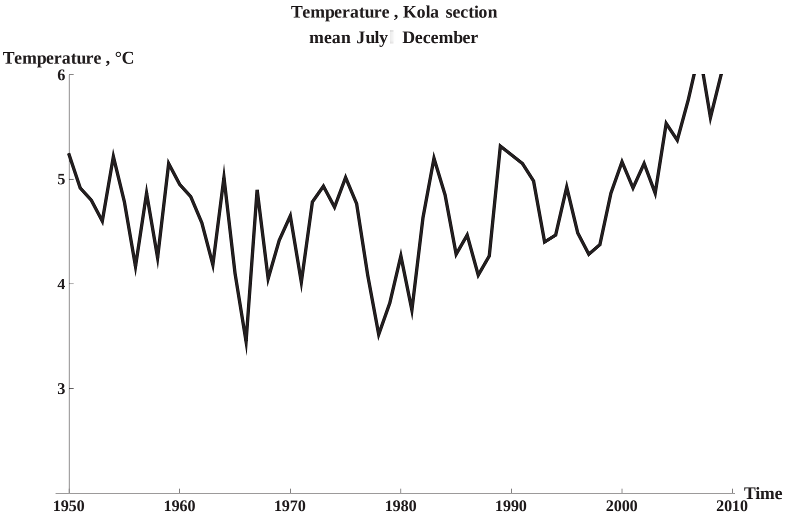

Figure 1. Temperature of the Kola section meaned over the months 7-12.

Figure 2 shows the recruitment from the assessment and the expectation value of the modeled recruitment for the best recruitment function for different values of the environmental driver. With the exceptions of 1985 and 1983 there have always been poor recruitment when the SSB has been below 2 million tonnes. At intermediate values of SSB, the recruitment has always been fair. At large SSBs there have been fair to good recruitment, but also some years of low recruitment. The red line shows the modeled recruitment function for the best environmental conditions (2004), the green line for median environmental (represented by 1974) conditions and the blue line for the poorest environmental conditions (1966).

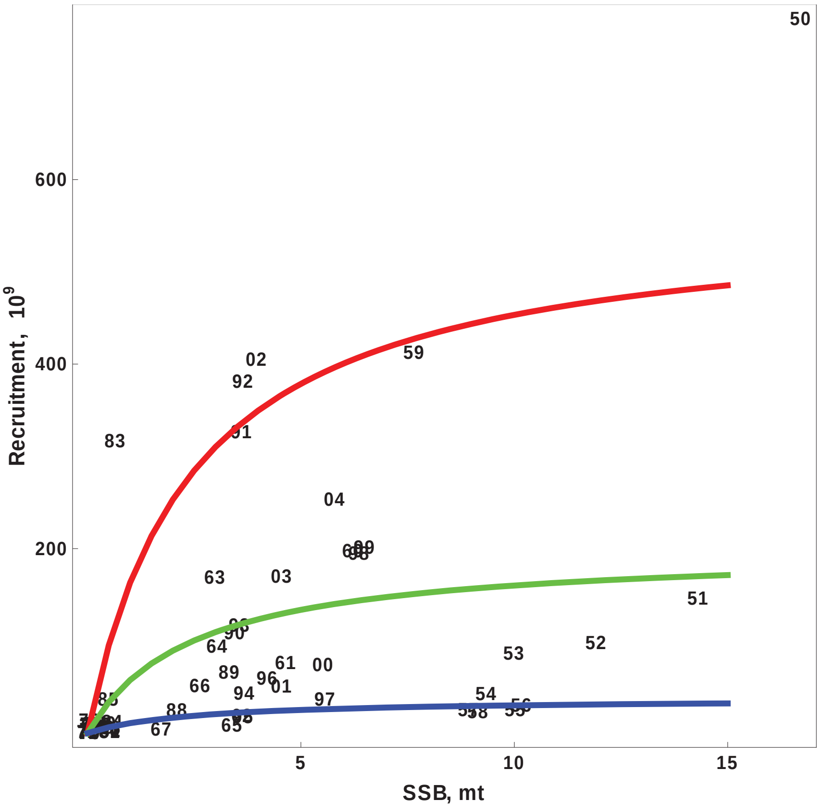

Figure 2. Different realizations of the best recruitment models) as function of spawning stock biomass: the red curve shows the recruitment relation for the best environmental conditions, the blue line for the poorest environmental conditions and the green line for intermediate environmental conditions. In addition recruitment for the assessment (black) is added.

The year classes 1950, 1952, 1983, 1991 and 1992 stand out as being particularly large, with an almost linear relationship with a high intercept at the y-axis. Given the expectation value of the recruitment is adequate, these year classes seem to follow a different error distribution. Alternatively, the model for the expectation value for these year classes is not adequate, and they might be modeled by a separate function, as did Tjelmeland and Røttingen (2009).

Fishing mortality and the Harvest Control Rule (HCR)

The development of the herring fisheries from the mid 1940s were dramatic. From a near shore fishery with small vessels on the spawning and feeding areas, the fishery for adult herring expanded to a large unregulated around the year offshore international fishery using large vessels and sophisticated electronic search instruments, power blocks and large fishing gears (Røttingen 2004). Much of the same development took part in the Norwegian small herring fishery. Previously, this was a fishery restricted to the fjord areas, in the 1960s it expanded to the open areas in the Barents Sea. This resulted in a development that is also known from other fisheries. Increasing fishing lead to increasing catches which again lead to an increase in the fishing pressure.

A lesson was learnt, and after the collapse there was agreement on the objective to rebuild the stock, and when eventually rebuilt the stock should be managed sustainably. This path has been followed, the stock was regulated with a low fishing mortality (maximum 5%) during the rebuilding period, and through international agreement after the rebuilding aim was obtained. Further, there is a minimum size limit of 25 cm (enforced from 1971) in Norwegian waters that effectively eliminates the fishery for immature herring . However, the natural mortality of the young herring is an uncertain factor and makes analyses of the impact of this fishery in the period 1950-1970 very uncertain. The harvest control rule from 2001 is shown in Figure 3.

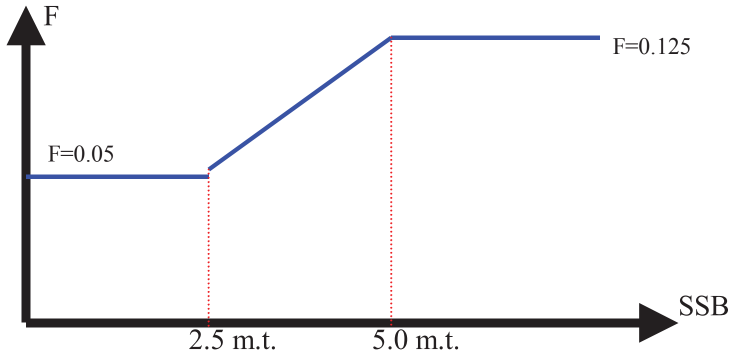

Figure 3. Harvest Control Rule (HCR) for Norwegian spring-spawning herring implemented by the Costal States Regional Management Organization (Tjelmeland and Røttingen 2009).

The B_{lim} level of the spawning stock (i.e. the level were an impaired recruitment is thought to take place is 2.5 million tonnes. Avoiding this level is an important management objective for this stock. Stochastic simulations indicated that the probability of reducing the spawning stock to this level was low, approximately 0.1 (Røttingen 2003).

What was really the impact on the stock from the fishery? To get a step forward we suggest using a counter-factual method. *What if* the present harvest control rule and other fishery regulations were decided on in 1949, 50 years before they actually were implemented? In such analyses the actual observed recruitment each year cannot be applied since these regulations would lead to a larger spawning stock with a presumably larger recruitment. Consequently the modeling of the recruitment, taking into account changing environmental conditions is the main scientific challenge of the present study.

Combining the application of the harvest control rule and the influence of environmental changes

Simulations over the historic period have been performed with the present HCR, using both the recruitment from the assessment and the estimated recruitment relation, taking into account the recruitment conditions in each year. In the latter case the simulations were run using two variants for weight at age and maturation at age, either using historic weight at age and historic maturation at age or using a simple empiric abundance-dependent model, where weight at age and maturation at age are interpolated between historic values using the total stock biomass. For simplicity, the weight at age in the catch is assumed equal to the weight at age in the stock throughout.

Using the present HCR during simulations over the historic period will lead to a different size of the spawning stock. The resulting recruitment will then differ from the actual recruitment from the assessment. The simulated recruitment will depend both on the spawning stock –

recruitment model and on the actual recruitment conditions in each year. The recruitment conditions determine where the actual recruitment is situated in the uncertainty distribution around the expected value. Thus, the CDF (cumulative density distribution) value of the actual recruitment is calculated and thereafter used for the new expectation value resulting from the changed perception of the spawning stock. All simulations start in 1950 with the age distribution from the assessment.

Results

Simulations using the actual environmental condtitions

Figure 4 shows the results of the simulations when the actual recruitment conditions each year are used. For reference, the actual history and a simulation using the expectation value of the recruitment relation and mean environmental conditions are shown.

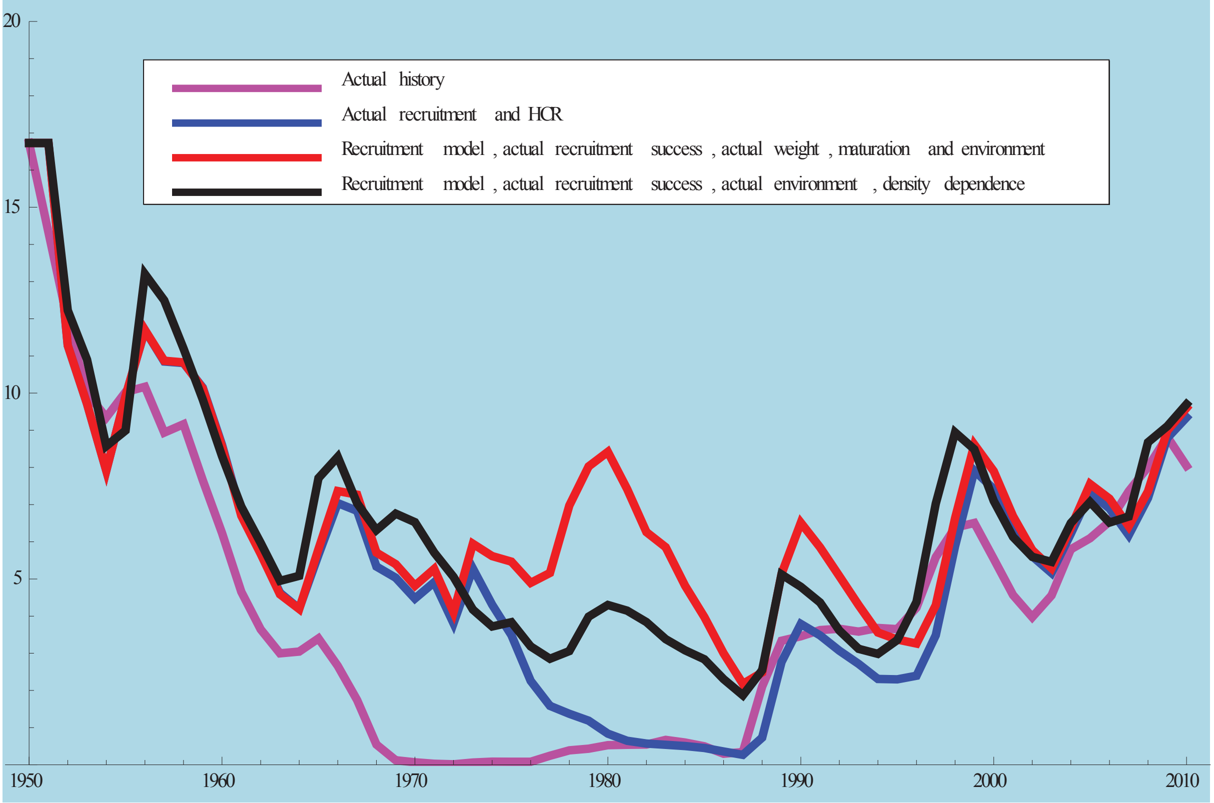

Figure 4. Spawning stock biomass (million tonnes) from historic simulations. The magenta line shows the SSB from the assessment. The blue line shows the SSB when the present HCR is applied, recruitment, weight at age and maturation at age from historic values. The red line shows the SSB using simulated recruitment with actual recruitment success, weight at age and maturation at age from historic values. The black line shows the SSB using simulated recruitment, weigth at age and maturation at age from an abundance-dependent model.

Using the present HCR but recruitment from the assessment delays the collapse and leads to it being less severe. If we take into account that the large spawning stock in the first half of the 1970s would have given rise to a higher recruitment, the spawning stock would not have fallen below 2 million tones.

The total catch using assessment data over the historic simulation period is 39.4 million tonnes. Using the assessment data but the present HCR the total catch is 39.9 million tones, using the present HCR and the recruitment model with historic recruitment success in combination with an abundance-dependent model for weight and maturation the total catch is 54.0 million tonnes. Using the expectation value of the recruitment model and historic environmental conditions the total catch is 62.3 million tones.

Discussion

The results of the present study indicate:

1) The stock collapse is due to the increased fishing mortality from 1960 and not from changing environmental conditions . If the present harvest control rule had been enforced, the spawning stock at the time of the collapse (1970) would have been approximately 6-7 million tonnes.

2) Environmental changes can affect the recruitment in a negative way as was the case in the 1970. Even with a low fishing mortality applied to the fishery, the stock seems to decline from 6-7 million tonnes in 1970 to approximately 2 million tonnes by 1978, but this environmental driver on the stock is not strong enough to generate a stock collapse.

The present study does not contradict the conclusions from earlier studies on the collapse of the Norwegian spring-spawning herring. However, the present results takes the discussion on the reasons for the stock collapse on step forward as the combined impacts contributing to the stock collapse can be studied separately. Further, the study indicates that to manage a fish stock on basis of a harvest control rule including a low fishing mortality and relevant recovery measures is a relevant mitigation element to counteract negative environmental impacts caused by climate change.

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Photo: Institute of Marine Research

3.4 Sea surface temperature dynamics and year class strength of capelin (*Mallotus villosus*) in the Barents Sea

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This study attempted to establish the relationship between sea surface temperature (SST) conditions in the Barents Sea and the capelin year class strength. The temperature data were derived from satellite monitoring, and year class strength data were based on the results of the annual Russian-Norwegian 0-group and hydroacustic surveys. There was a positive correlation between indices of capelin larva abundance in June and the biomass of the parent spawning stock. However, this correlation had disappeared by the time of the 0-group survey (September). Against the background of significant correlation of 0-group with subsequent ages of the same generation, this fact indicates that conditions of larva survival, in particular the availability of microzooplankton, create a bottleneck in the formation of new capelin year classes. In turn, the zooplankton biomass and period of its intensive development are related to seawater temperature regime. For the 1995-2010 period, there was a significant negative correlation of capelin 0-group abundance with the duration of the cooling season as estimated by presence of 5 ^{o}C-isotherm west of 35^{o} E. Since the duration of the cooling season depends on its starting date, it should be possible to forecast the abundances of new capelin year classes for the 0+ group some eight or nine months in advance.

Key-words: capelin, larvae, year class strength, spawning stock, young herring, “predator-prey”, sea surface temperature, prognosis

Introduction

Scientific monitoring of the Barents Sea capelin stocks started in 1972, when an acoustic survey enabled the first reasonably accurate assessment of the stock of this species to be made. Such annual assessments reveal both a general pattern of stock behaviour and some peculiarities of its annual dynamics through almost four decades (Figure 1).

It is noteworthy that since the mid 1980s there have been several 8-9 year cycles of decrease and increase in the stock abundance. In the course of 3-4 years, the stock biomass could drop from 3-7 mln t (1984, 1991) to 0.1-0.2 mln t (1987, 1994), which has led the Joint Russian-Norwegian Fisheries Commission (JRNC) to ban the capelin fishery three times in the past 25 years.

The capelin is obviously important for the Barents Sea ecosystem. This species is the main component of the diets of several fish predators, seabirds, and marine mammals, whose abundance often depends on availability of capelin stocks. In its turn, capelin depends on abundance of its predators, as well as on hydrological and climatic conditions, which affect its spawning success, egg production, duration and direction of the larval drift, and the availability of ample stocks of micro- and macrozooplankton to capelin at its various life stages.

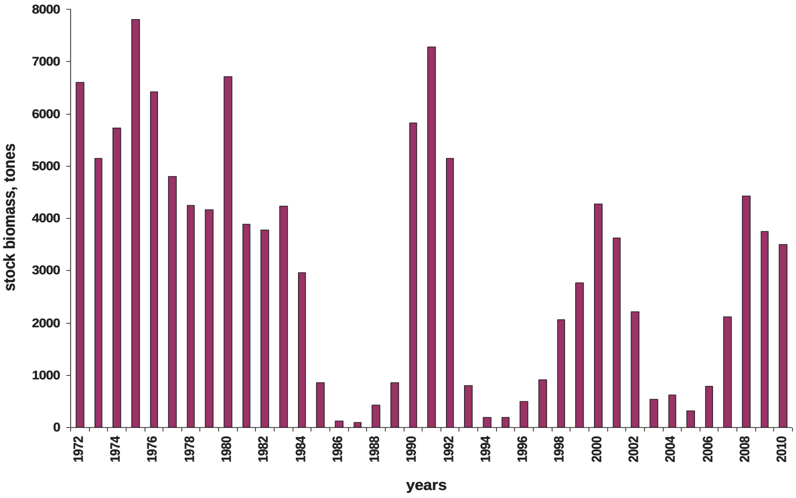

Figure 1. Dynamics of capelin total stock biomass.

Taking into account all the above points and the importance of capelin for Norwegian and Russian fisheries in the Barents Sea, the rising interest in the observed variations in capelin stocks is easily understandable. Numerous studies of biological characteristics of this species and the impact of various factors on capelin stock dynamics have not provided an unambiguous answer to the question of what factors should be considered of primary importance.

Besides its the wide distribution and high abundance in the Barents Sea, this short-lived species is characterized by post-spawning mass mortality, low fecundity (4.5-22 thousand eggs) (Pozdnjakov, 1957), and high schooling density even in years of minimum abundance (Prokhorov, 1968) which makes capelin fairly vulnerable to intensive fishing. Overexploitation is considered to be a cause of the observed collapses of the capelin stock (Hjermann et al., 2004a), as large catches of spawners significantly decreased the abundance of larvae (Hjermann et al., 2010). In 1979, understanding the impact of fishing mortality on year-class abundance, JRNC started to set TACs that would not negatively affect the stocks (Hamre, 1985).

The negative impact of overexploitation is likely to be greater in years of increased predation on the larvae by young herring (Hjermann et al., 2004b). Hamre's working hypothesis (1994, 2003) regarding the close interactions of abundances of capelin, herring, and cod has received widespread support, particularly concerning the negative impact of young herring feeding on capelin larvae; in some years, this predator turned initially strong year-classes of capelin into weak ones (Gjøsæter & Bogstad, 1998; Huse & Toresen, 2000; Godiksen et al., 2006; Hallfredsson & Pedersen, 2009; Wiedman, 2010).

Fossum (1992) analyzed how the recruitment success of the capelin stock in 1983-1985 depended on the mortality rates of larvae during their first stage of feeding, but did not find the anticipated feedback. However, there is a relationship between capelin recruitment and and the abundance of young herring that feed on capelin larvae. Modeling a scenario of spatial and temporal overlapping of distribution areas of young herring and capelin larvae, Pedersen et al. (2009) found out that the young erring could consume 20-50% of the initial stock of the capelin larvae in the course of only two weeks.

Obviously, among other factors which significantly decrease capelin stocks, we should mention cod, as capelin often become the main component of its diet (Bogstad & Gjøsǽter, 2001). This explains appearance of the term “capelin cod” or “loddetorsk”, which characterizes a particular feeding period (winter and spring) when immature cod follow capelin schools and feed exclusively on this species (Boitsov et al., 2003). Moreover, pelagic cod of age group 0 feeding on capelin larvae when their distribution areas overlap can decrease the number of larvae by 1.5% per day (Hallfredson et al., 2007), which obviously affects capelin recruitment.

Capelin are definitely a leading grazer of plankton in the Barents Sea ecosystem (Prokhorov, 1968; Panasenko, 1984; Hamre, 1994, Gjøsæter, 1998).The state of capelin stocks are therefore generally dependent on the abundance of suitable food. The timely presence of zooplankton aggregations with suitable species composition and biomass in the capelin distribution area is rightly regarded as a factor limiting capelin abundance and biomass. The growth and survival of young capelin depend on the availability of small-sized plankton, while the growth rate of adult capelin correlates well with the abundance of large-sized zooplankton (Gjøsæter et al., 2002). Larvae are most selective about food, particularly at the initial stage of active feeding. Larvae under 35 mm can only consume small-sized phyto- and zooplankton, as their mouths are smaller than those of herring or cod larvae of the same size (Pedersen & Fossheim, 2008).

Resorption of the yolk-sac leaves capelin larvae with minimum energy reserves, so that even a brief deficit in preferred small-sized prey (nauplii and eggs of *Copepoda*, copepodites *Acartia spp*., *Temora longicornis*, *Bivalvia* veligers, and larvae of other invertebrates) (Karamushko O. & Karamushko L., 1995; Fossheim et al., 2006) may lead to high mortality.

Without decrying the importance of these factors for the long-term dynamics of capelin stocks, we are still inclined to see hydrology as the essential driving force. Hydrological conditions in any given year influence capelin directly, as well as their own feeding stocks and predators which, in their turn, affect capelin. The water temperature, including sea surface temperature (SST), is the most relevant index of annual and seasonal variations in hydrological conditions.

Here we use the the Barents Sea SST satellite monitoring data to clarify impact of the duration of warm and cold seasons on successful survival of capelin during their first year of life. Moreover, the relationship between the onset of these seasons and their duration may enable us to forecast the strength of the capelin year-classes far in advance.

Materials and methods

This study was based on sequential analyses of the main stages of the Barents Sea capelin life history, with the aim of identifying the stages which are most sensitive to changing environment. To a certain extent, the analytical framework resembled that employed by Gundersen & Gjøsæter (1998), who compared the abundance of the capelin generations of 1981-1994 at various stages: larvae, age group 0, and age group 1. Our time series also included the generations of 1995-2010.We also used data on the capelin spawning stock biomass in 1980-2010 and the abundance of age groups 2+ and 3+, as well as the biomass of young herring feeding in the Barents Sea (Anon, 2010).

The seasonal dynamics of temperature regime in the Barents Sea were characterized using satellite data on SST in 1995-2010 and the resultant weekly SST charts (Vanyushin et al., 2005, 2011).

Analysis of the abundances of various age groups revealed that in some generations, the abundance of elder age groups was close to or even exceeded that of younger age groups. The causes of this anomaly are primarily associated with the greater rates of escape of small fish through the survey gears, or with the fact that survey stations did not cover the entire area of the young capelin distribution. Attempts to correct the results of these surveys have been published (Ushakov & Galkin, 1983; Eriksen et al., 2009).

One reasonable approach to the correction of the survey results could to employ the mean annual mortality rate estimated for separate generations, as this decreases its abundance quite plausibly from age to age. Such an approach enables us to reconstruct the year-class abundance at age *i-1* by its abundance at age *i* (Table 1).

Without corrections, it is difficult to evaluate the survival success of capelin larvae in the summer, when we know that in the autumn, age group 0 was underestimated. To estimate the role of young herring in variability of the capelin abundance in different years it is also necessary to know the capelin abundance at age 0, at least approximating the actual indices.

Figure 2 illustrates the comparative dynamics of year-class abundances based on survey and corrected data for age groups 1+ and 0+.

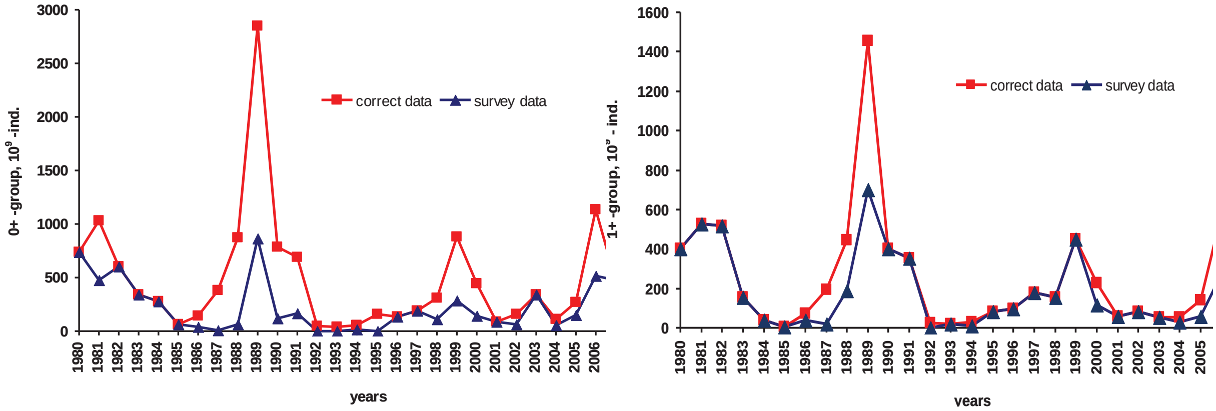

Figure 2. Comparison of survey and correct data of capelin 0+ and 1+ group abundances.

Correcting the abundance data did not lead to significant changes in the general pattern of abundance dynamics by year. Generations that were classified (according to their abundance at age 0) as strong (1980-1983, 1989, 1999, 2006-2009), average (1984, 1985, 1988, 1990, 1991, 1996-1998, 2000-2005), and weak (1986, 1987, 1992-1995) were unchanged after correction. Absolute values, however, revealed marked discrepancies. First, when they related to strong year-classes, their corrected values were found to be far higher. This indicates that the most serious underestimates of young capelin concern the strongest generations, as is also indirectly confirmed by comparisons of the abundance of various year classes estimated via more reliable assessments of age group 2+ (Prozorkevich, 2010). The weakest generation of 1985 ($2 \cdot 10^9$ individuals) was 290 times smaller than the strongest one of 1989 ($580 \cdot 10^9$ individuals). However, if we compared these two generations at age 0+ ($64 \cdot 10^9$ and $862 \cdot 10^9$ individuals, respectively), they would only differ by a factor of 13.5. Such a large discrepancy could only have one cause; underestimation of the strong year class of 1989 at age 0+.

Table 1. Number of Barents Sea capelin by age and year mortality

Year class	0+ abundance (10^9 ind.)			1+ abundance (10^9 ind.)			2+ abundance (10^9 ind.)			3+ abundance (10^9 ind.) survey data
	survey data	correct data	year mortality %	survey data	correct data	year mortality %	survey data	correct data	year mortality %	
1980	740		45.5	403		63.3	148		74.3	38
1981	*477*	1035	**49.0**	528		62.1	200		76.0	48
1982	600		14.2	515		63.7	187		88.8	21
1983	340		54.4	155		69.0	48		93.7	3
1984	275		85.8	39		87.7	5		100.0	0
1985	64		90.6	6		66.7	2		100.0	0
1986	*42*	143	**49.0**	*38*	73	**60.1**	29		89.7	3
1987	*4*	382	**49.0**	*21*	195	**60.1**	*18*	78	**79.4**	16
1988	*65*	875	**49.0**	*189*	446	**60.1**	178		81.5	33
1989	*862*	2851	**49.0**	*700*	1454	**60.1**	580		77.8	129
1990	*116*	788	**49.0**	402		51.2	196		91.3	17
1991	*169*	688	**49.0**	351		84.9	53		92.5	4
1992	*2*	49	**49.0**	*2*	25	**60.1**	*3*	10	**79.4**	2
1993	*1*	39	**49.0**	20		60.0	8		75.0	2
1994	*14*	59	**49.0**	*7*	30	**60.1**	12		83.3	2
1995	*3*	161	**49.0**	82		52.4	39		71.8	11
1996	137		27.7	99		26.2	73		63.0	27
1997	189		5.3	179		43.6	101		66.3	34
1998	*113*	306	**49.0**	156		28.8	111		72.1	31
1999	*288*	880	**49.0**	449		51.2	219		77.2	50
2000	*141*	447	**49.0**	*114*	228.1	**60.1**	91		87.9	11
2001	90		33.3	60		83.3	10		40.0	6
2002	*67*	161	**49.0**	82		69.5	25		92.0	2
2003	341		85.0	51		74.5	13		53.8	6
2004	*54*	108	**49.0**	*27*	55	**60.1**	22		81.8	4
2005	*148*	271	**49.0**	*60*	138	**60.1**	55		54.5	25
2006	*516*	1135	**49.0**	*277*	579	**60.1**	231		73.6	61
2007	480		34.8	313		47.0	166		63.2	61
2008	*995*	629	**49.0**	*124*	321	**60.1**	128			
2009	673		63.0	248						
2010	319									
Mean mortality %			***49.0***			***60.1***			***79.4***	

Note: Doubtful or erroneous survey data are shown in italics; estimated annual mortality rates are shown in bold.

Seasonal dynamics of heat content in areas where young capelin were present were analyzed in terms of the time at which the 5 ^{o}C isotherm passed the 35 ^{o}E meridian (from the shore till 72 ^{o}N). The 35 ^{o}E meridian and the 5 ^{o}C isotherm were chosen as reference points because there was a stronger relationship between the time when the 5 ^{o}C isotherm passed the 35 ^{o}E meridian (shifting eastward and back) and the duration of warm and cold seasons at sea. Furthermore, the 35 ^{o}E meridian divides the Barents Sea into almost equal eastern and western parts and, according to fairly informative maps in Olsen et al. (2010), actually crosses all distribution areas of capelin, including spawning grounds, larvae, young fish and adult fish (Figure 3).

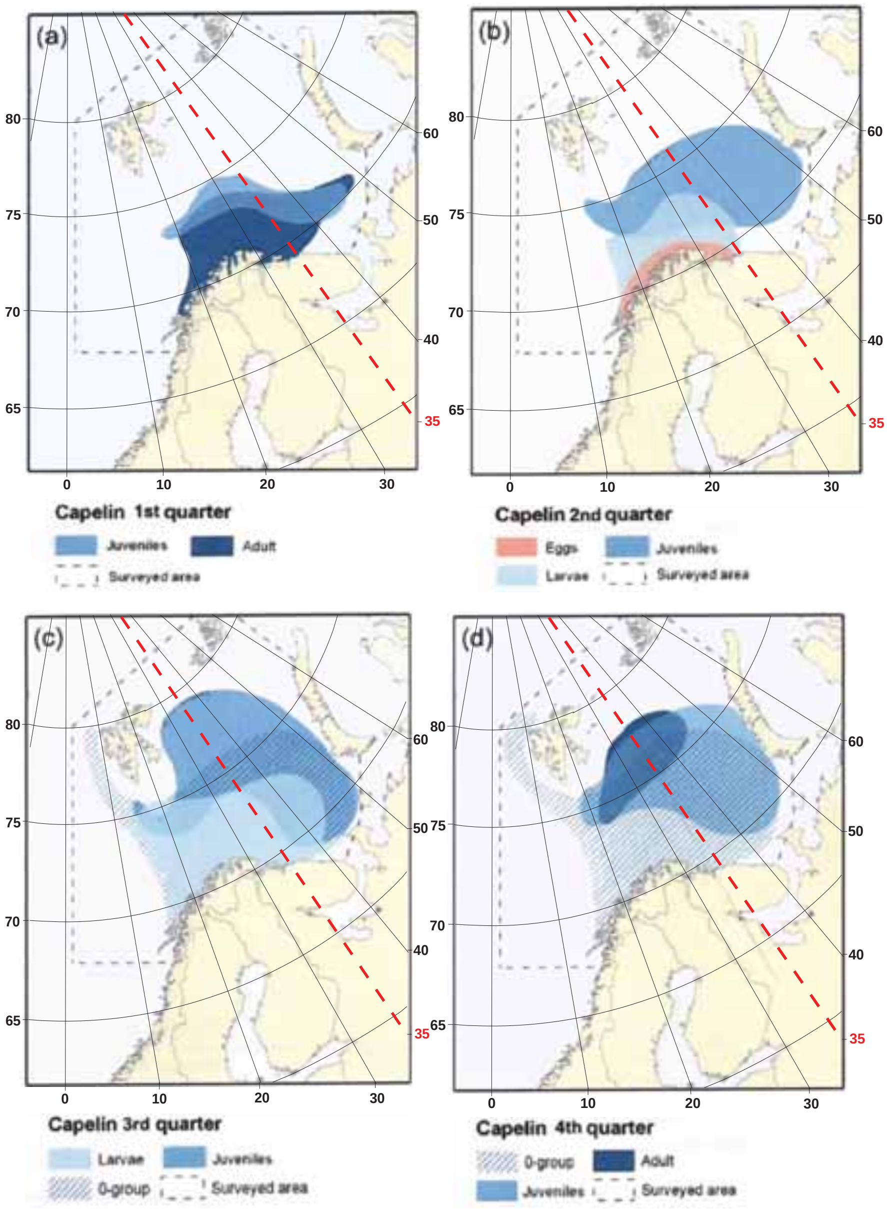

Figure 3. Distribution of capelin eggs, larvae, juveniles and adult spawning areas (Olsen et al. 2010).

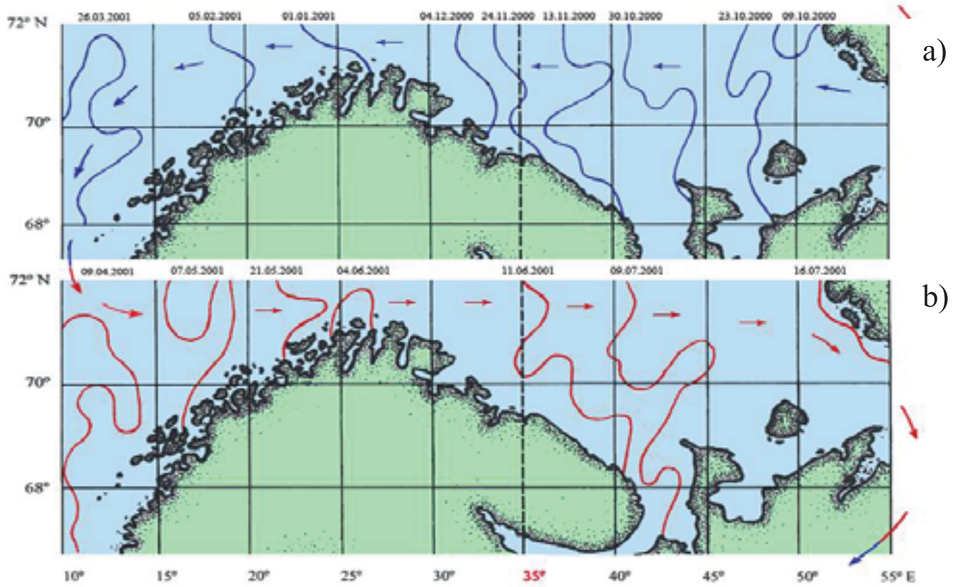

Figure 4. Location of the 5 °C isotherm in autumn-winter and spring-summer seasons by SST-data 2000-2001.

Location of the 5 °C isotherm to the east of 35 °E in summer (Figure 4b, right) and its reverse shift to 35 °E in autumn (Figure 4a, right), and in some years including December, which could be regarded as a warm season in the eastern Barents Sea (Table 2).

Table 2. Dates at whichthe 5 °C isotherm crosses 35 °E on its eastward shift and reversal (warm season).

Years	Date of 35 °E crossing			Warm season duration (days)
	Eastward crossing		Westward crossing	
	Conditional date	Calendar date		
1995	12	06.06	16.11	163
1996	22	16.06	26.11	163
1997	1	26.05	14.12	202
1998	18	12.06	16.11	157
1999	16	10.06	23.12	196
2000	4	29.05	24.11	179
2001	16	11.06	05.11	147
2002	13	07.06	25.11	171
2003	18	12.06	15.12	186
2004	13	07.06	29.11	175
2005	2	27.05	25.12	212
2006	4	29.05	27.12	212
2007	3	28.05	31.12	217
2008	17	11.06	27.12	199
2009	14	08.06	16.12	191
2010	6	31.05	24.11	176
2011	6	31.05		

The displacement of the 5 °C isotherm to the west of 35 °E, which usually occurs at the end of the year and its persistence there till spring of the next year (Figure 4a, left) with the following change in direction and another passing of the reference meridian in late May – early June (Figure 4b, left) which could be regarded as a cold season in the eastern Barents Sea (Table 3).

Table 3. Dates, when the 5 °C isotherm crosses 35 °E at its westward shift and backward (cold season).

Years	Date of 35 °E crossing			Cold season duration (days)
	Westward crossing		Eastward crossing	
	Conditional date	Calendar date		
1995	12	07.11		
1996	22	26.11	16.06	221
1997	40	14.12	26.05	181
1998	12	16.11	12.06	180
1999	49	23.12	10.06	206
2000	20	24.11	29.05	157
2001	1	05.11	11.06	199
2002	21	25.11	07.06	214
2003	41	15.12	12.06	199
2004	25	29.11	07.06	174
2005	51	25.12	27.05	179
2006	53	27.12	29.05	155
2007	57	31.12	28.05	152
2008	53	27.12	11.06	163
2009	42	16.12	08.06	163
2010	20	24.11	31.05	166
2011			31.05	188

The procedures involved in the annual determination of the duration of warm and cold seasons can be illustrated by examining the 2000-2001 season. In spring of 2000, the 5°C isotherm moving from the western to the east crossed 35°E on May 29 (Table 2). This date would be regarded as the onset of the warm season in the eastern Barents Sea. By the middle of autumn, the 5 °C isotherm started its reversal. Moving west, it crossed 35 °E again on November 24 (Figure 4a), i.e. the duration of its persistence in eastern waters (warm season) was 179 days. Then, from November 24, 2000 till June 11, 2001, i.e. for 199 days, the 5 °C isotherm lay to the west of 35 °E (Table 3, Figure 4a,b, left), i.e. the eastern Barents Sea was under the cold regime.

In order to identify the relationship between the onset and duration of warm/cold periods, we established a conditional date for their onset instead of calendar one. Methodologically this involved the following: the time series for 1995-2010 revealed that the date on which the 5 °C isotherm passed 35 °E on its way to the east varied from May 26 (1997) to June 16 (1996), i.e. the range of onset dates was 22 days. We could thus establish a relative value of 1 for the earliest date and a relative value of 22 for the latest date (Table 2).

Similarly, the difference between onsets of cold seasons totaled 57 days: from November 5 (2001) till December 31 (2007). Consequently, in 2001, when the 5 °C isotherm crossed 35 °E at its earliest, the conditional date of the cold season onset would be 1, while in 2007, it would be 57 (Table 3).

Results

Recruitment of the capelin fish stock undoubtedly depends not only on abundance (biomass) of spawning stock, i.e. on the initial abundance of produced eggs, but also on the environment. We could *a priori* assume different susceptibilities of capelin to the impact of environmental factors at each stage of its growth. For forecasting purposes it would be particularly interesting to identify the most vulnerable stage that actually determines future recruitment. In analysing the results, we followed the stepwise principle.

Spawning stock, larvae, and juvenile capelin

In 2002, taking into account long-term data on catches, stock dynamics, and the management approach proposed by Gjøsæter et al. (2002), JRNC decided not to permit decline in the capelin spawning stock below the established B_{lim}. The management strategy based on B_{lim} = 200 000 t is still used. In accordance with it, it is assumed that if the spawning stock biomass (SSB) ≥ 200 000 t, the appearance of weak generations is unlikely.

The ideology of this management strategy is based on a fairly reasonable assumption regarding the positive relationship between recruitment and SSB. To a certain extent, it is confirmed by comparison of long-term data on the capelin spawning stock and the abundance of the larvae produced (Figure 5).

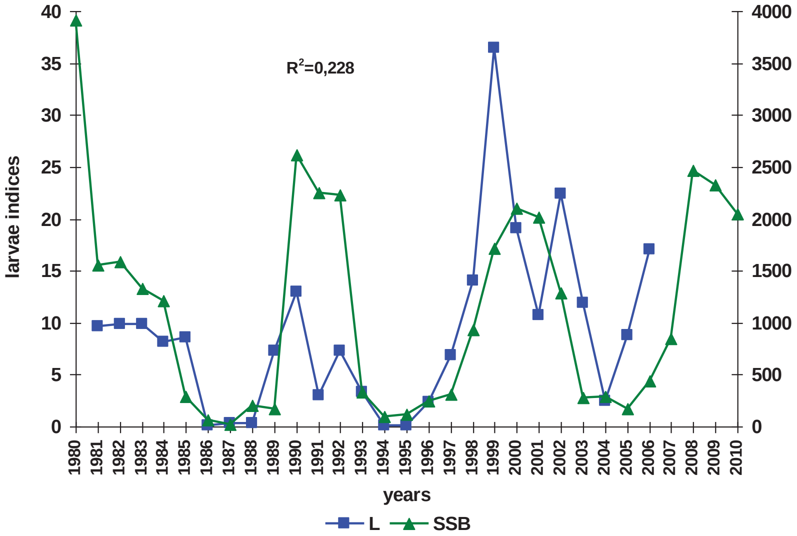

Figure 5. Relationship between abubndance of capelin larvae (L) and spawning stock biomass (SSB).

The general pattern of curves plotted with these data shows that at the stage of egg incubation, hatching of larvae, and till the finishing of summer survey (June), i.e. first 3-4 months of the generation life, the quantitative relationship of the number of larvaewith the spawning stock abundance remains. Surveys of young capelin, however, show that by August-September, the expected relationship between SSB and abundance of the 0 age group has disappeared (Figure 6a); naturally it is absent at the next stage, the 1+ age group (Figure 6b).

Comparison of data on larvae indices with abundance of the 0 age group over 25 years (Figure 7) revealed an absence of any significant relationship between these two factors. This finding confirms earlierconclusions based on data for 13 years (Gundersen & Gjøsæter, 1998).

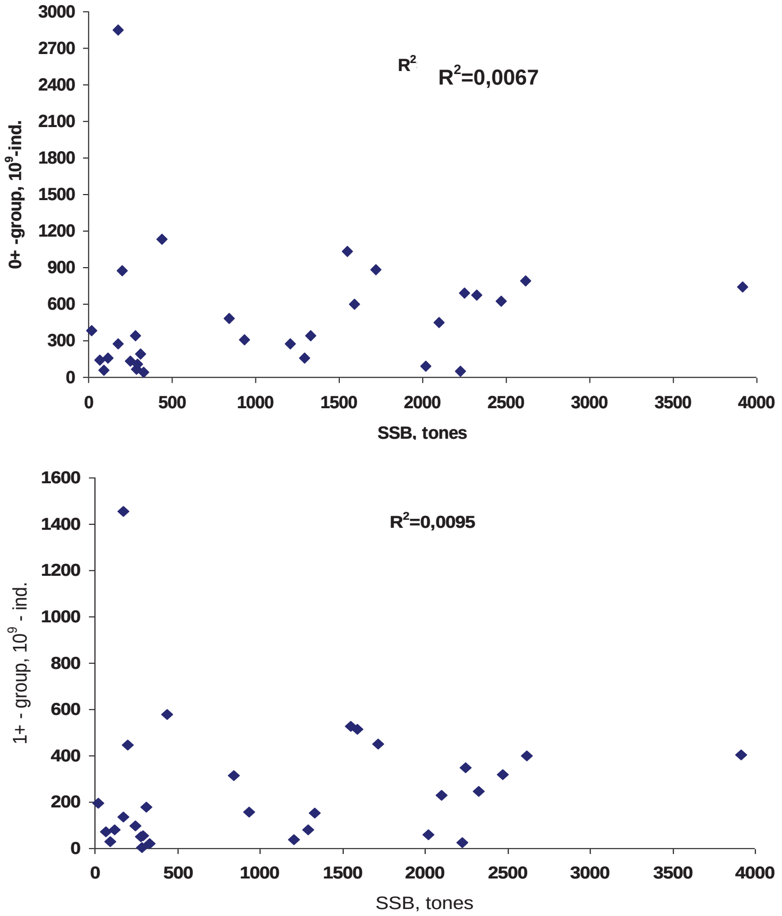

Figure 6. Correlation of capelin 0+ -group (a) and 1+ -group (b) abundance with SSB.

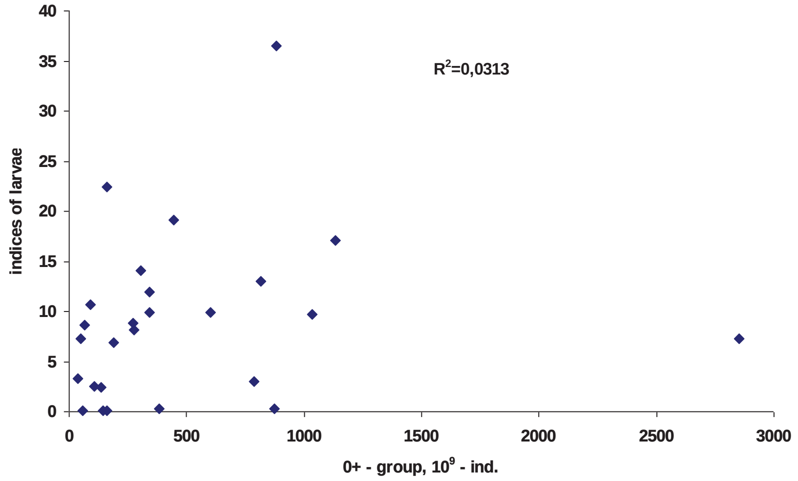

Figure 7. Correlation of capelin larva and 0+ - group abundance.

Meanwhile, analysis of the relationship between the abundance of age group 0 and that of older capelin (age groups 1+ and 2+) of the same generation shows good consistency. This was revealed both by the survey data (Figure 8a), and by corrected estimates (on the procedure see Materials and Methods) (Figure 8b).

Thus, on the one hand, there is a correlation of SSB with the larvae abundance indices in the absence of link between SSB and age groups 0+ and 1+. On the other hand, there is good consistency between the abundances of age groups 0+, 1+ and 2+, which was absent when we compared abundance of larvae with the 0+ age group. All of the above supports the following proposition: the destiny of each new generation is mainly determined during the months of summer, or rather in the period between larva and 0-group surveys, i.e. from June to September. The environmental conditions that develop during this or previous periods predetermine the current situation and specify whether the new generation will be strong, average, or weak.

Young herring and capelin larvae

Researchers have been keenly interested in studies of interactions between herring and capelin in the Barents Sea, pioneered by Hamre (1985, 1994, 2003), especially the impact of juvenile herring on capelin larvae. Hamre's hypothesis that juvenile herring (1+, 2+, and partly 3+), which feed mainly on capelin larvae in the southern part of the sea, are the main cause of appearance of weak year-classes of capelin, was repeatedly confirmed by new evidence (Fossum, 1992; Huse & Toresen, 1996, 2000; Gjøsæter & Bogstad, 1998; Godiksen et al., 2006; Pedersen & Fossheim, 2008; Pedersen et al., 2009; Hallfredsson & Pedersen, 2009; Wiedman, 2010). However, the justness of the principle: "abundant young herring – high rates of the capelin larvae mortality and weak capelin recruitment" is generally based on three or four of the most illustrative years (Figure 9).

The presence of asynchronicity in these curves during certain periods is undoubtedly evidence of the importance of the "herring" factor in capelin reproduction.It would also be interesting to carry out a statistical analysis of the entire long-term time series.

Figure 10 shows the distribution of points in the coordinate field "young herring biomass – capelin 0-group abundance" reveals a negative correlation between these two indices, which is weak and statistically uncertain (under <<?? $r = -0.33$; $p>0{,}05$).

This forces us to acknowledge that, in some cases, the herring factor was smoothed out by the strong influence of other factors that are directly or indirectly related to variations in the hydrological situation, depending on season, year, and period. It can be useful to retrace these variations by dynamics of temperature regimes, in particular by using SST-satellite data.

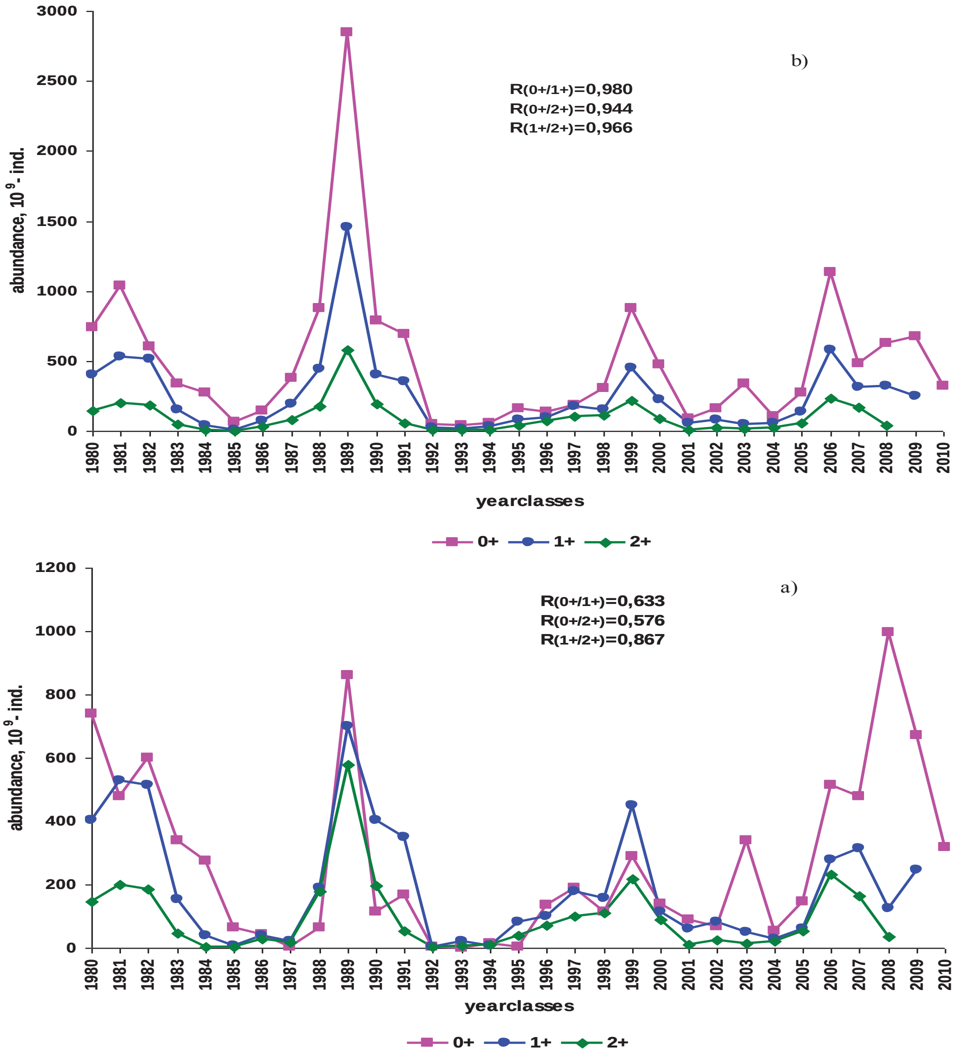

Figure 8. Relationship of 0+, 1+ and 2+ - group capelin abundance by year class survey data (a) and correct data (b).

Impact of temperature regime on capelin year-class abundance

The We analysed the dynamics of annual and seasonal temperature regimes as described in Materials and Methods above. The analysis showed that the durations of warm and cold seasons respectively in 1995-2011 ranged on the intra-annual scale from 147 to 217 (Table 2) and from 152 to 221 days (Table 3). It is noteworthy that the total duration of warm and cold seasons did not always completely coincide with the length of the calendar year. For example, the warm season of 1995 took 163 days and was followed by the cold season of 1995-1996 which was 221 days long, i.e. together they took 384 days, while the total duration of warm and cold seasons in 1996-1997 was only 344 days.

Analysis of these data revealed that duration of each season depended on the calendar date of its onset. In most cases, the earlier the 5 ^{o}C isotherm crossed 35 ^{o}E moving eastward or westward, the longer was the duration of the respective season (Tables 2 and 3, Figure 11a and 11b).

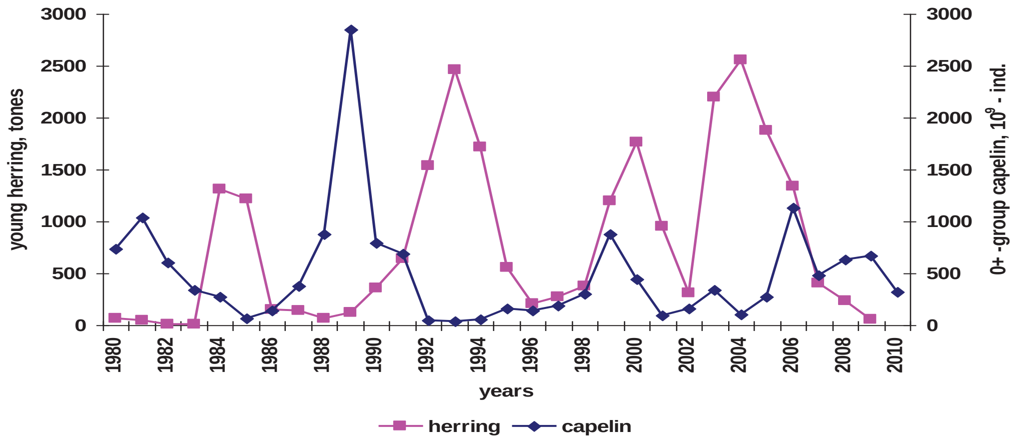

Figure 9. Comparison of long-term curves of young herring biomass and capelin 0+ -group abundance.

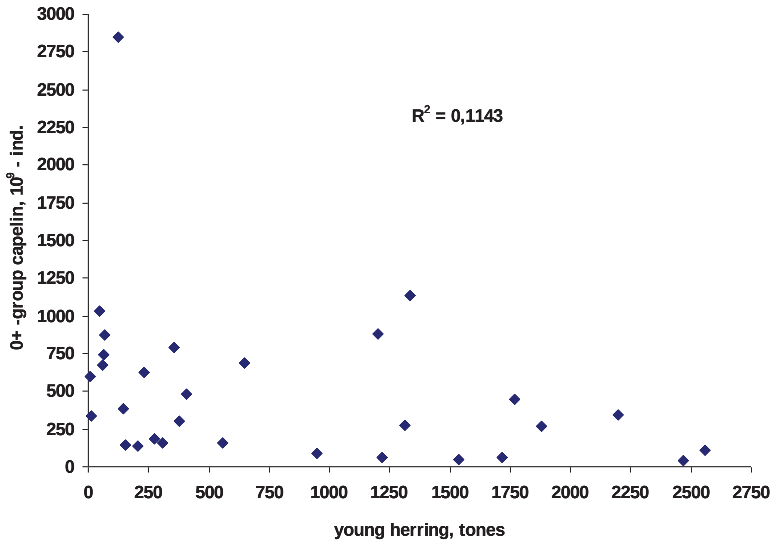

Figure 10. Correlation of capelin 0+ - group abundance and young herring biomass.

When we compare these relationships we find that the duration of warm seasons is less dependent on their date of onset (Figure 12a) than that of cold seasons (Fig. 12b). The date of onbset of the cold season (x) enables us to estimate its duration (y) quite reliably, using the following linear regression:

$$y = -1.1377x + 217.97, \qquad (1)$$

whose utility for hydrological forecasts is obvious.

Further analysis also showed that the duration of warm and cold seasons somehow influenced the survival of young capelin during their 1st year of life. Without discussing possible mechanisms of such influence, we merely note that more numerous age groups 0 occurred in years with a longer warm season (Figure 13a) and a shorter cold one (Figure 13b).

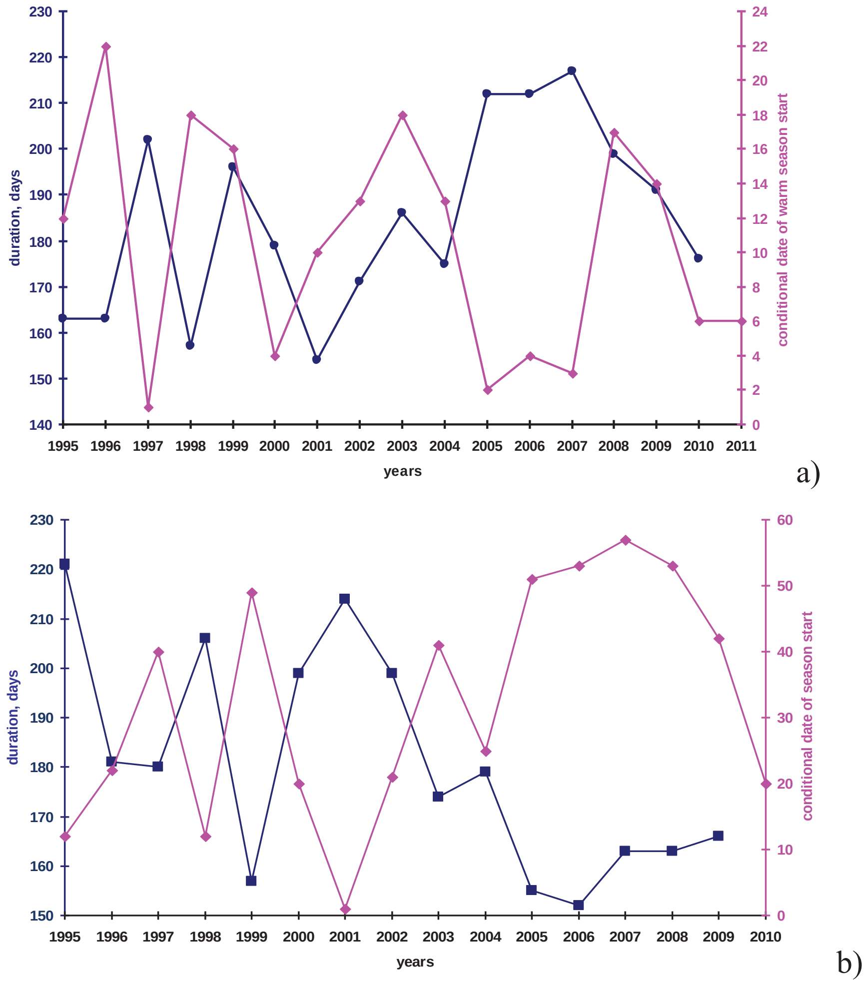

Figure 11. Dynamics of warm (a) and cold (b) season duration and their dates of onset.

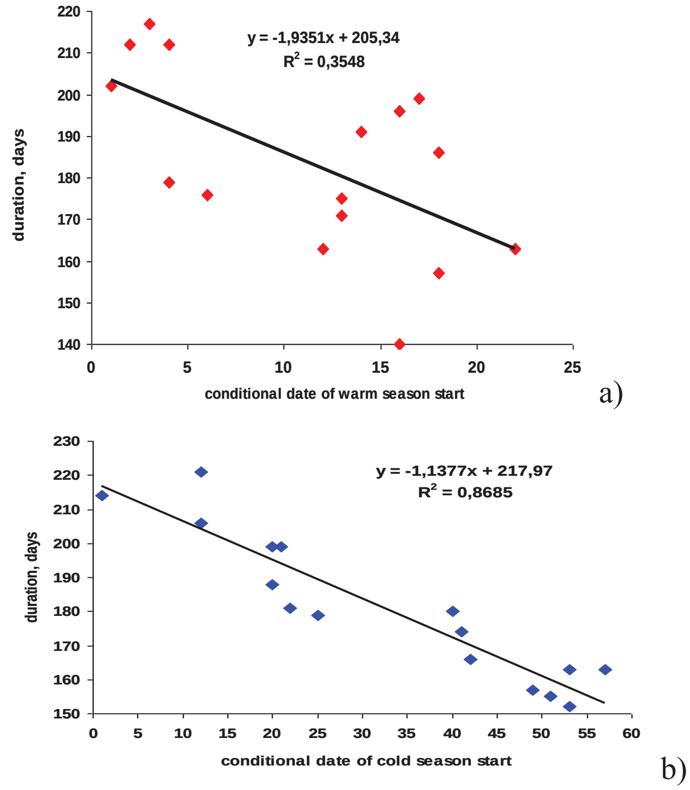

Figure 12. Change in duration of warm (a) and cold (b) seasons, depending on their dates of onset.

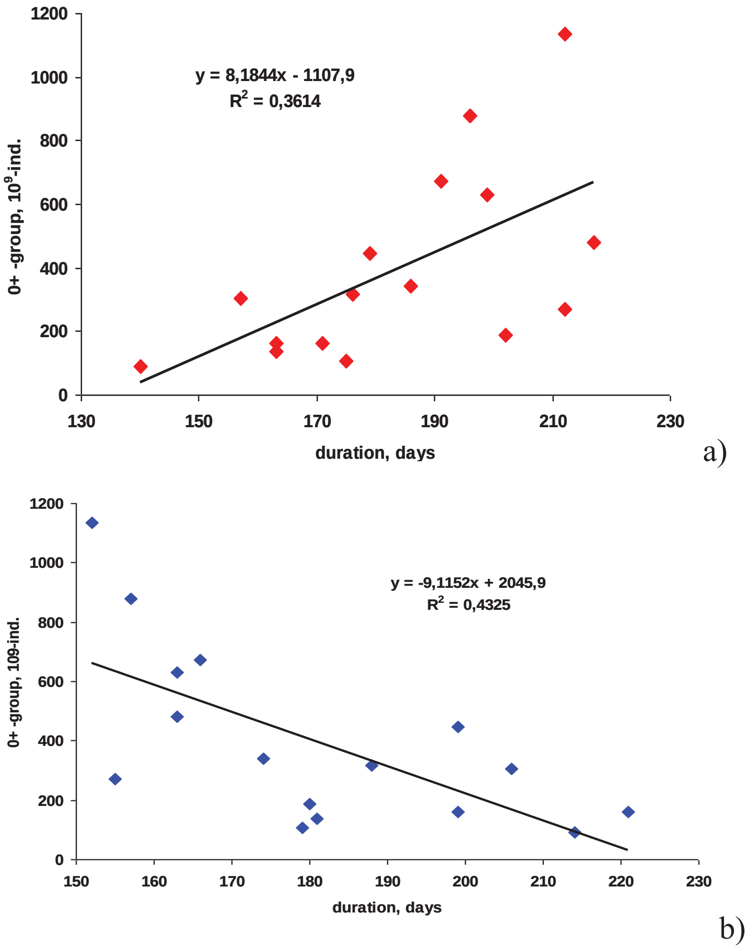

Figure 13. Relationship between duration of warm (a) and cold (b) season and capelin 0+ group abundance.

As the positive correlation between the 0 group abundance and the duration of the warm season (R = 0.601) is lower than its negative correlation with that of the cold season (R = -0.658), forecasting should be preferably be based on regressions describing cold seasons:

$$N_o = -9.7023D_c + 2146.7, \qquad (2)$$

where N_o is the 0 group abundance and D_c is the duration of the cold season.

However, the applied value of equation (2) is low, because we could only obtain data on D_c after the cold season finished, namely in late May – mid-June (Table 2). Thus, advance forecast based on equation (2) is cut by 2.5 - 3 months, i.e. the period before the results of the autumn 0-group survey become available. However replacing D_c in equation (2) with its value obtained with equation (1), i.e. $D_c = y = - 1.1377x + 217.97$, we can find N_o as early as with the date of onset of the cold season:

$$N_o = -9.7023\ (-1.1377x + 217.97) + 2146.7 \text{ или}$$
$$N_o = 11.0383x+31.89 \qquad (3)$$

Equation (3) allows us to forecast new year-classes of capelin at age 0+ by term 8-9 months.

With this equation we can provide a definite answer about the abundance of the coming generation (which will actually be assessed in September of next year) as early as November-December of the current year, i.e. on the date when we know the onset of the cold season. For example, since in 2010 isotherm 5 ^{o}C passed 35 $^{\mathbf{o}}$E on November 24, i.e. the onset of the cold season is identical to the conditional date 20 (Table 2) the forecasted abundance of the capelin year-class of 2011 will be close to $253 \cdot 10^{\mathbf{9}}$ individuals. If we divide corrected abundance data for age group 0 (Table 1) into three clusters: $N_{\mathbf{o}} \leq 190 \cdot 10^{\mathbf{9}}$ (week), $190 \cdot 10^{\mathbf{9}} < N_{\mathbf{o}} \leq 500 \cdot 10^{\mathbf{9}}$ (average), and $N_{\mathbf{o}} > 500 \cdot 10^{\mathbf{9}}$ individuals (strong), the capelin generation of 2011 is likely to be average, similar to abundances of the 1984 and 2005 year classes.

Discussion

The relationship between the capelin SSB and abundance of the produced larvae (Fig. 5) is perfectly logical: the larger the SSB, the higher the population fecundity; the larger the number of eggs, the larger the abundance of larvae and juvenile capelin. This naturally leads us to the thought that the high level of SSB is the guarantee of abundant recruitment.

In some cases, however, Nature interferes with this quite acceptable logic. When the biomass of thre spawning stock is below 0.5 mln t, i.e. below the average level (0.5-2 mln t) not only weak year-classes (1985, 1986, 1993-1997, 2004), but also average (1987, 2003, 2005), and even strong year-classes (1988, 1989, 2006) may be produced, while on the other hand, spawning stocks with a biomass above the average (>2 mln t) produced not only strong year-classes (1980, 1990, 1991, 2008, 2009), but also average (2000, 2010), and even weak year-classes (1992, 2001) (Table 4).

When we group all the generations into either low, average, and high SSB groups (Table 5), we find that only in 17 cases out of 31 (54.8%) did the abundance of the generation correspond to the cluster rank of SSB. In another 14 cases there was no correspondence of clusters by N_o and SSB. Such discrepancies make us question the reliability of the chosen strategy of the capelin fishery management, which is only based on B_{lim}, i.e. keeping SSB > 200 000 t (Anon, 2010). In several cases this strategy is not sufficient, as is illustrated by weak generations produced by average and even high SSB levels.

The management strategy and the recruitment forecast should therefore be based not only on SSB, but also on other factors, including the expected impact of young herring on capelin larvae and the availability of the capelin larvae’s preferred food. The impact of young herring, however, depends on spatial and temporal overlapping of distribution areas of these two species and is determined by the intensity and direction of coastal currents (Wiedman, 2010), while the availability of food stocks depends on the time and duration of phyto- and microzooplankton development (Gjøsæter et al., 2002; Dalpadado et al., 2003; Orlova et al., 2010). Both of these factors depend in turn on the hydrological conditions in the given year, season, and synoptic period.

Table 4. Spawning stock biomass (mln t) and 0-group abundance (10^9 ind.) of capelin.

Year class	SSB	0+ abundance (10^9 ind.)	Year class	SSB	0+ abundance (10^9 ind.)
1980	3913	740	1996	248	137
1981	1551	1035	1997	312	189
1982	1591	600	1998	932	306
1983	1329	340	1999	1718	880
1984	1208	275	2000	2098	447
1985	285	64	2001	2019	90
1986	65	143	2002	1291	161
1987	17	382	2003	280	341
1988	200	875	2004	294	108
1989	175	2851	2005	174	271
1990	2617	788	2006	437	1135
1991	2248	688	2007	844	480
1992	2228	49	2008	2468	629
1993	330	39	2009	2323	673
1994	94	59	2010	2051	319
1995	118	161			

Table 5. Correspondence of capelin 0-group abundance (No) to different ranges of the spawning stock (SSB).

SSB mln t N_o(10^9 ind.)	Levels			Total
	Low <0,5	Average 0,5-2	High >2	
Weak <190	**8**	1	2	11
Average 190-500	3	**4**	2	9
Strong >500	3	3	**5**	11
Total	14	8	9	31

We we may therefore conclude that the physical and hydrological situation, onset and duration of warm and cold seasons, identified with the SST data, might be regarded as an integrating factor that regulates the intensity and vector of individual factors.

Our analysis supports previous studies in this field and shows that the weakest point in capelin recruitment is the transition of larvae to active feeding, mainly because 7-10-day old larvae with absorbed yolk-sacs cannot survive even one to two days of starvation (Pozdnjakov, 1960; Fridgeirsson, 1976). Compared to other species, capelin larvae of the size of 7-8 mm have very small mouths (Pedersen & Fossheim, 2008) and are limited in their choice of feed to eggs and nauplii of *Copepoda* and copepodites *Calanus finmarchicus* or *Oithona similis* of the size of 0.4-0.6 mm (Karamushko O. & Karamushko L., 1995). High rates of capelin larvae mortality associated with poor food stocks were also found in experiments by Moksness and Øiestad (1979).

We may reasonably suppose that if larvae of this phase (stage C_1) remain out of gatherings of small-sized zooplankton for at least one or two days, mass mortality is inevitable. The rate of mortality naturally depends on duration of starvation and the percentage of the population that is deprived of food stocks.

This situation would appear to be fairly realistic and corresponds to a well-known concept suggested by Hjort (1914) concerning a “critical period” in life of fish larvae. We would say that this is also true about dependence of recruitment on the larvae survival not at the early stage, but at later stages of growth (Leggett & Deblois, 1994), similar to Cushing's hypothesis (1990) regarding the impact on juvenile abundance of spatial and temporal mismatches in the distribution of larvae and food stocks.

Accepting the point of view of Ellertsen et al., (1995) on multi-factor dependence of recruitment, (we are inclined to think that in some cases, e.g. for application purposes, we do not need to assess the importance of each individual factor. The relative importance of these factors varies on an annual scale. Nevertheless, the conductor of this marine symphony is usually the hydrological situation in the given year, as this determines the duration of warm and cold seasons. The peculiarities of these seasons affect other factors and indirectly influence the abundance of new generations of fish species. Our attempts to identify such a relationship has yielded quite promising results. With the date of onset of cold season as a predictor, we can forecast abundance of the coming generation of capelin long before the results of the autumn 0-group survey are available.

Conclusions and suggestions

1. Surveys of capelin larvae in the Barents Sea are an important aspect of complex studies of the stock dynamics. Ichthyoplankton surveys (which ceased in 2006) ought to be resumed through the intense efforts of Norwegian and Russian scientists.
2. Analysis of data on abundance of the 0+ and 1+ age groups of capelin reveals underestimes of several year-classes relative to age group 2+. This discrepancy requires the development of techniques of both juvenile surveys and correction of survey data.
3. Management of the capelin fishery based only on keeping the SSB above B_{lim} = 200 000 t in a number of cases is not sufficient. The management strategy should be based on recruitment forecasts, including SSB and other factors, e.g. abundance of the main predators, and biomass of small-sized zooplankton in areas of where larvae are found.
4. The duration of cold seasons in the Barents Sea can be regarded as an integrating factor that affects mortality rates of capelin larvae directlyas well as via other environmentally determined factors. There is a negative correlation between the duration of cold seasons and the abundance of the age 0 group.

5. The high, statistically significant negative correlation between duration and onset of cold seasons enables us to forecast capelin recruitment eight to nine months in advance.

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Photo: Institute of Marine Research

3.5 Unquantifiable uncertainty in projecting stock response to climate change: Example from NEA cod

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Data from the years prior to 2005 suggests a positive relationship between recruitment of cod in the Barents Sea and the sea temperature at the Kola section during the year of spawning. However analysis of subsequent data indicates that this relationship no longer holds. This change in the recruitment dynamics will clearly have an impact on our understanding of future stock dynamics and long term yield. It also highlights the impacts on our ability to predict biological responses to climate change arising from possible future changes in similar relationships in other species and ecosystems. This paper uses a multi-species "STOCOBAR" forward simulation model to evaluate the dynamics under a variety of climate scenarios and recruitment hypotheses, presenting the differences in modelled SSB and yields under temperature-dependent and temperature-independent recruitment situations. The divergence between the modelled populations and yields under the different recruitment hypotheses indicates the impossibility of predicting the future evolution of a stock with any degree of certainty, or even with any quantifiable degree of uncertainty. These results highlight the importance of having a management regime that is robust to unpredicted and unpredictable changes in stock dynamics, and the need for management strategy evaluations under a wide range of possible future scenarios.

Keywords:
Barents Sea, NEA cod, modelling, uncertainty, STOCOBAR

Photo: T. de L. Wenneck, Institute of Marine Research

3.6 The joint Norwegian-Russian ecosystem survey: overview and lessons learned

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Abstract

The joint Norwegian-Russian ecosystem survey in the Barents Sea and is a comprehensive survey collecting a large number of parameters from the physical and biological components. The survey was initiated in 2003 by combining several previous surveys into one single investigation. The survey period has included the warmest period since the beginning of the 20th century. The associated decrease in sea ice has also increased the survey area and allowed access to the northernmost areas of the Barents Sea and the north-western part of the Kara Sea. Thus, the ecosystem survey has been a highly suitable platform for observing the system structure and functioning during a warming of the Barents Sea. The synoptic sampling of many components in the same survey, allows for an increased understanding of the processes of the Barents Sea ecosystem. Compared to the preceding surveys much more information about the ecosystem is now sampled. However, the distance between stations and the time spent at each station have increased and makes the data less synoptic over the survey period. In this report, data collected by the ecosystem survey in the Barents Sea will be described, lessons learned outlined, and suggestions for further improvements given.

Introduction

In a global perspective the Barents Sea is a productive area, with more than 200 species of fish, thousands of benthic invertebrate species and a diverse plankton community, seabirds and marine mammals inhabit or visit the area (Stiansen *et al.*, 2009). Only a few species is of commercial interest, but nonetheless, these give basis for one of the largest fisheries in the world (FAO, 2011).

Although often perceived as a ‘pristine’ environment, the Barents Sea is an area of intensive human activity. Historically, these activities have mainly involved fishing and hunting of marine mammals, but activities nowadays also include shipping, as well as oil and gas exploration. The total catch of capelin, polar cod, cod, haddock, redfish, Greenland halibut and shrimp are reported to be close to 2.9 million tonnes in 2010 (ICES, 2010; ICES 2011a; ICES 2011b). Such fishing intensity is likely to have effects on not only the fish standing stocks but also on the ecosystem as a whole. During demersal trawling, the impact from trawl doors and trawl gear might damage some species and increase the production of others. The total quantity fished does affect the biomass available for species to prey upon or to be preyed by. The length of the fish caught, at which time of the year the fishing is conducted and whether it is the mature or immature part of the stock that is caught, do all have an influence on the population structure and thus the ecosystem.

The monitoring of the BS ecosystem is a joint effort between Norway and Russia, and collaboration between the two countries has been developed since 1954 (Røttingen *et al.* 2007). In the vicinity of the Convention on Fishing in the North-East Atlantic in 1959, both countries agreed on a special attention on conservation and sustainable use of marine living resources and coordination of research in this area. Agreements have been signed between Norway and Russia on a reciprocal basis and under national laws to promote cooperation on fisheries management and practical issues of fishing (Haug et al. 2007). A collapse of the Norwegian spring spawning herring in the 1960s led to a total collapse of the herring fisheries for almost two decades. In order to avoid similar situations to occur in the future, the ICES Herring Committee recommended starting a survey that should investigate 0-group of commercial fish species. This survey started in 1965. The first annual surveys were rather specialized, practically considering only one species at the time, and they were devoted to the most abundant fish species (cod, capelin, and herring) and their habitat, as well as to methods and gears to estimate stocks. Later, new concepts relating to the dynamic mechanisms of stock functions and more available data has made scientists from Russia and Norway turn their attention to the interactions among populations. The Norwegian Institute of Marine Research (IMR) and the Russian Polar Research Institute of Marine Fisheries and Oceanography (PINRO) have until now mainly worked with assignments given by the Joint Norwegian-Russian Fisheries Commission. Currently, other tasks like environment, climatic changes, oil activity etc. are put on the agenda.

Prior to 2003, considerable time was spent in sailing to and from the investigation areas in order to change scientific staff. In addition, the area covered had a high degree of overlap in space among the surveys but without the possibility to combine data from different levels in the ecosystem. An examination of survey design and sampling routines for some of these surveys was done by Nakken and Pennington (2001). They asked whether or not such high effort was needed for stock assessment purposes. Another problem with the isolated surveys was the problems with combining information on the spatial and temporal patterns of environmental and biological variables to get information about species interactions. Due to international agreements, an attempt to improve the efficiency, ecological content and scientific merit of these surveys, the different surveys were gradually merged to form what is today called the joint Norwegian-Russian ecosystem survey, in the following referred to as the Barents Sea Ecosystem survey (BESS).

The year’s whit the BESS (2003-2010), the peak of a long-term warming period in the Barents Sea has been covered. In the years 2004-2007 higher temperatures than observed since the beginning of the 20th century (Levitus et al. 2009) have been recorded. The associated decrease in sea ice has allowed access to previously ice covered areas, like north of the Spitsbergen Archipelago (up to 82°N) and the north-western part of the Kara Sea. Change in distribution and abundance of various species has also been observed in the same period. The appearance and expansion of the snake pipefish (*Entelurus aequoreus*), started in the

Barents Sea in the period 2005 to 2007, has been associated with the temperature increase. During the same period increasing catches and distribution of snow-crab (*Chionoecetes opilio*) was observed, a new species of uncertain origin in the ecosystem. Several strong or record high year classes of herring, haddock and capelin occurred, and 0-group capelin showed distribution shift into the northeast. The capelin stock, a key component in this ecosystem for trophic transfer, collapsed in 2003, and recovered in 2007/2008. The survey also provides an excellent platform for studying responses in both prey and predator species, including the commercially important species in this system. Such changes highlight the need for large scale survey monitoring to identify changes in ocean climate and in species distribution and abundance, including the non-commercial ones. The survey period (August-October) has proven well-suited for providing essential new knowledge on the ecosystem and possibly on impacts of long-term climatic change and to provide data that with time can aid the interpretation and understanding of ecosystem function and variability.

In order to aid on further interpretation of the complex data collected at the BESS, we provide here a thorough description of the survey, outline lessons learned and make suggestions for further improvements.

Description of the study area and its various components

Basic information about the Barents Sea is given in the literature (Zenkevich, 1951; Dobrovolsky and Zalogin, 1982; Sakshaug *et al.* 2009; Stiansen *et al.* 2009; Jacobsen, 2011).

Abiotic components

The Barents Sea is a high latitude shelf sea of 1.6 million km2 (Carmack et al. 2006) with mean depth of 230 m. It is bordered by the Northern Norwegian and Russian coasts and the Novaya Zemlya Island, whereas 500 m depth contour is used to delimit the Barents Sea towards the Greenland Sea, Norwegian Sea and the polar basins. The Barents Sea meets the Kara Sea north of Novaya Zemlya and at the narrow Kara Gate. The ocean circulation is dominated by the Norwegian Atlantic Current bringing warm and salty Atlantic Water into the area from south. Atlantic Water extends over the western and central parts of the ocean, while cold and fresh Arctic Water dominates in the northern part. The borderline between the two main water masses is called the Polar Front, which is fairly sharp in the western parts of the Barents Sea. The northern areas are seasonally ice covered, and in winter the ice edge usually follows the oceanic fronts. The ice edge is usually at its northernmost position in September, when only the remote northern parts are ice covered. The Barents Sea climate has strong variability (e.g. Loeng et al. 1992). Over the last four decades there has been an overall increasing trend in temperature and area of the warm Atlantic part of ocean, and a decreasing trend in ice cover and the area of the cold Arctic part (Johannesen et al., subm). The warming trend has been particularly strong in the last decade, caused partly by a substantial increase in the oceanic heat transport into the southern parts (Smedsrud et al., 2010). Consequently, the warming is closely linked to the inflow of Atlantic Water, and has resulted in relatively high bottom temperatures in the entire western Barents Sea. In the northern, previously ice covered regions the temperature increase has been amplified and also transferred to the Arctic Water (Lind and Ingvaldsen, subm).

Biotic components

Phytoplankton community

In the pelagic zone over 300 species of planktonic algae are observed, which can be grouped into eight categories: *Bacillariophyta, Dinophyta, Chlorophyta, Haptophyta, Prasinophyta, Cryptophyta, Chrysophyta* and *Euglenophyta*. The main share of recorded species belongs to the *Bacillariophyta* (about 150 species, 50%) and *Dinophyta* (about 120 species, 40%) (Larionov, 1997; Kuznetsov and Schoschina, 2003). The bulk of phytoplankton (90%) occurs in the photic layer, from surface to ~100 m. The range of quantitative fluctuations of pelagic algae is quite wide: from 20 cells / L (biomass 0.5 g / l) in January and February to 1 million 600 thousand cells / L (biomass 3.7 mg / l) in May.

Zoo plankton community

Common zooplankton organisms in the Barents Sea are copepods, amphipods and krill, jellyfish, pelagic gastropods, arrow worms, larvae of crabs, and eggs and larvae of fish. Among the zoo plankton, copepods, krill and amphipods usually dominate in abundance and biomass in respective order. These three zoo plankton groups constitute a large part of the diet of planktivorous fish and top predators.

Copepods fall within the meso-zooplankton (0.2-20mm) category. The common copepods occurring in the Barents Sea belong to the genera *Calanus, Metridia*, *Pseudocalanus*, *Oithona* and *Oncaea*. The most dominant among copepod species in the Atlantic boreal waters is *Calanus finmarchicus,* and the larval forms of this species form the principal food of most fish larvae, while the adults are food for pelagic fish species. The large lipid rich *C. glacialis* form an important part of the Arctic zooplankton community in the Barents Sea.

Krill and amphipods are representatives of the larger zooplankton group, the macrozooplankton (2-20cm). In the Barents Sea ecosystem, *Thysanoessa inermis*, *T. longicaudata*, *T. raschii*, and *Meganyctiphanes norvegica* are commonly found krill species. In addition, in the recent years the warm water krill species, *Nematoscelis megalops* is regularly observed, most likely introduced by influx of the Atlantic current. The main copepod and krill species are predominantly herbivorous, constituting a key link to the higher trophic levels (Falk-Petersen *et al*. 2000; Pasternak *et al*. 2001; Dalpadado *et al*. 2008).

The pelagic amphipods are dominated by hyperiids; *Themisto abyssorum* in Atlantic boreal waters and *T. libellula* in the Arctic waters. Amphipods are primarily carnivorous, feeding mainly on *Calanus* copepods (Aurel *et al.* 2002; Dalpadado *et al.* 2008). In the Arctic food web, *T. libellula* is the main prey of polar cod, seabirds and whales (Karnovsky *et al*., 2003; Kovacs and Lydersen, 2006). The ice associated (sympagic) amphipods such as *Gammarus wilkitzkii*, *Apherusa glacialis* and *Onismus* spp. are also important components of the Arctic food web.

The benthos community

A total of 286 invertebrate taxa have been recorded during the ecosystem surveys from year 2006 to 2009. The most dominating megafaunal groups across all stations sampled are Ecinodermata and Crustacea in abundance and Porifera, Echinodermata and Crustacea in biomass. The echinoderms are widely distributed in the central parts of the Barents Sea, while the crustaceans have a biomass hotspot in the south eastern Barents Sea and porifera (sponges) one in the Atlantic current in the western Barents Sea. The composition of the benthic fauna is strongly influenced by bottom topography and water masses, and there is a strong biogeographical gradient across the sampling area. Arctic taxa are found in the northern parts and boreal subarctic taxa mostly on the shallow waters on the Spitsbergen Bank, but also in the south-eastern part of the Barents Sea. Boreal fauna largely occur in areas influenced by the Norwegian Coastal Current along the coast of Norway and Russia. A transitional zone, including both boreal and arctic taxa, is identified in deeper waters in central and in northern Barents Sea.

Boreal-arctic species dominate the biomass of benthos in the Barents Sea (as well as throughout the Arctic shelf). The optimal temperature range of these boreal-arctic species lies close to the long-term temperature mean. According to Galkin (1987), Kiyko and Pogrebov (1997), any deviations from the long-term mean have a negative impact on boreal-arctic species by decreasing their abundance and area of distribution. Widely distributed and dominant species in the Barents Sea such as the boreal-arctic *Ctenodiscus crispatus* and *Ophiura sarsi* shows increasing biomasses with increasing temperatures, while arctic species such as the bivalve *Bathyarca glacialis* are decreasing. The opposite is the case with decreasing temperatures (Frolova et al 2007).

The fish community

Both Arctic cold-water species and boreal temperate water species are found in the Barents Sea. The majority of these are demersal. Currently, > 200 species of fish have been registered in the Barents Sea (Stiansen *et al.*2009), while only 100 species turn up regularly in trawl catches during scientific surveys (Wienerroither *et al.*, 2011). The total biomass and number are dominated by a few species; the ten most abundant ones account for about 90% of the total number of all specimens caught in demersal trawls. During the period of the BESS, cod, capelin, haddock, Greenland halibut, polar cod (Boreogadus saida), blue whiting (Micromesistius poutassou), long rough dab (Hippoglossoides platessoides), Norway pout (Trisopterus esmarkii), bigeye sculpin (Triglops nybelini), and deep-water redfish (Sebastes mentella) dominated in abundance. Some species spend their entire life cycle in the Barents Sea (e.g. capelin, Greenland halibut, long rough dab). Others have their main feeding area in the Barents Sea, but spawn in the Norwegian Sea (e.g. cod, juvenile herring). Other species, whose main feeding areas are in the Norwegian Sea, regularly visit the Barents Sea during their feeding migrations in summer (e.g. blue whiting), and some species occasionally appear in the Barents Sea due to inflow of Atlantic water (e.g. snake pipefish). For many of the species, their life cycle, migration pattern and spawning areas are poorly known.

The top predator community

About 25 species of marine mammals regularly occur in the Barents Sea, comprising 7 pinnipeds (seals and walruses), 12 large cetaceans (large whales), 5 small cetaceans (porpoises and dolphins) and the polar bear (*Ursus maritimus*). Some of these species have temperate mating, calving and feeding areas in the Barents Sea (e.g. minke whale Balaenoptera acutorostrata), others reside in the Barents Sea all year round (e.g. white-beaked dolphin *Lagenorhynchus albirostris* and harbour porpoise *Phocoena phocoena*). Some marine mammals are rare because of historic exploitation, such as the bowhead whale (*Balaena mysticetus which is still on the verge of extinction*).

In the Barents Sea the marine mammals may eat more than the amount of fish caught by the fisheries. Both minke whales and harp seals are thought to switch between krill, capelin and herring depending on the availability of the different prey species and they may consume 1.8 million and 3-5 million tonnes of prey per year, respectively (Haug *et al*., 1995; Nilssen *et al.*, 2000).

The Barents Sea holds one of the largest concentrations of seabirds in the world (Anker-Nilssen *et al.* 2000). About 20 million seabirds harvest approximately 1.2 million tonnes of biomass annually from the area (Barrett *et al.,* 2002). About 40 species are thought to breed regularly around the northern part of the Norwegian Sea and the Barents Sea. The most typical species belong to the auk and gull families.

Description of the Ecosystem survey

Planning and survey effort

The joint Norwegian-Russian ecosystem survey (BESS) has been conducted in August to October and covers the ice free part of the Barents Sea and the Svalbard shelf break (Anon 2003, 2004, 2005, 2006, 2007, 2008 and 2010a and 2010b). Five vessels normally operate in the region, three Norwegian and two Russian. As an example of the area covered and the distribution of ecosystem stations, the cruise track of 2007 BESS is shown in Figure 1.

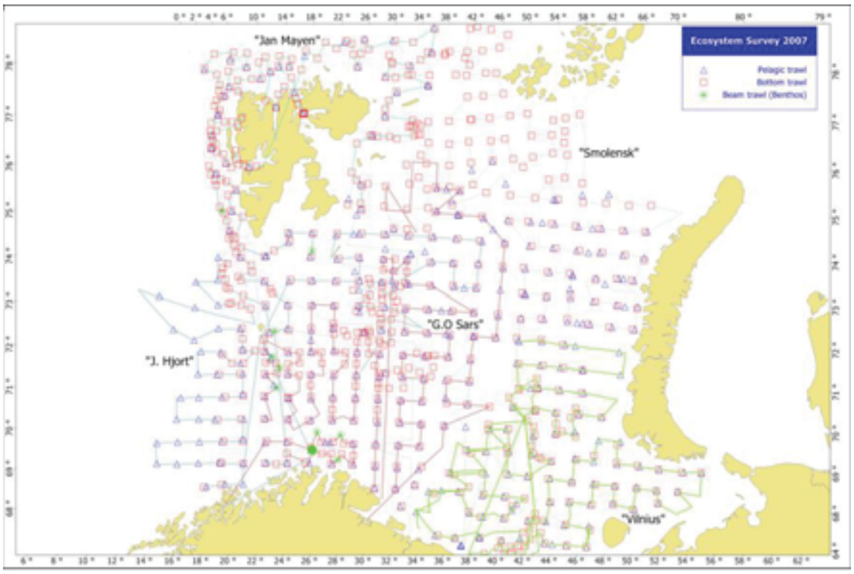

Figure 1. Cruise track from the BESS in 2007.

On the Norwegian side the BESS started in 2003 by combining five previous surveys into one single investigation (Table 1). These surveys included three joint IMR – PINRO surveys; the 0-group pelagic trawl survey (including hydrography) conducted since 1965, the joint acoustic capelin survey conducted since 1975, a demersal trawl survey for juvenile Greenland halibut and redfish covering the areas north and east of Svalbard, as well as two additional Norwegian demersal trawl surveys. Since 2005 also the Norwegian shrimp survey (demersal trawl survey) was included into the multipurpose survey as we refer to as the BESS.

On the Russian side the BESS started by combining two pelagic surveys (0-group fish and acoustic survey for pelagic fish), using standard trawls (the Harstad trawl) on both Norwegian and Russian vessels. Since 2004 the standard demersal trawl (the Campelen-1800 trawl) has been used on all participating vessels.

The planning of the surveys starts one year ahead, when ship-time is applied for, but the initial detailed planning starts in March. Here cruise lines, area coverage, timing, effort, gear specifications and data exchange are agreed upon (Figure 2). The survey is carried out from the beginning of August to the end of September. This time frame is determined by: the need to cover the 0-group cod and haddock before it settles at the bottom, to carry out a capelin assessment and give an assessment report to the ACOM by the first week of October and to utilize the period of the year with the least ice-coverage. To achieve this, the participating vessels often start their investigations at the beginning of August but in different areas of the Barents Sea. During the survey data is exchanged and preliminary results discussed.

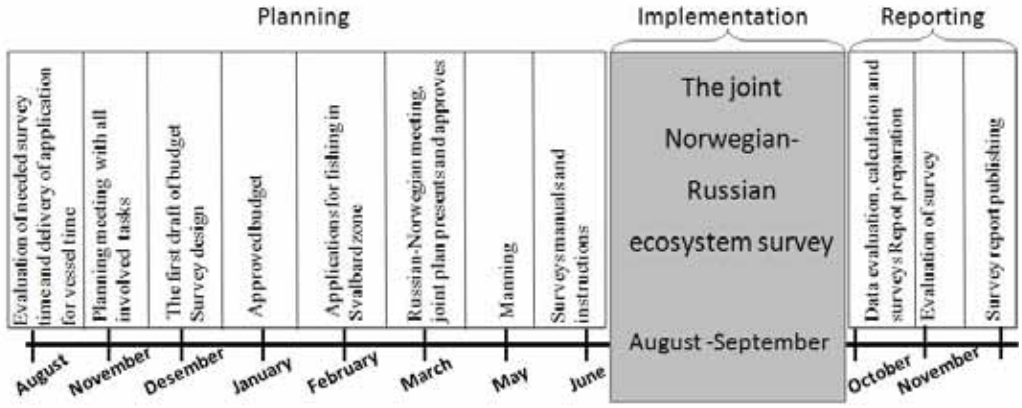

Figure 2. Overview of the tasks involved in the organization of the joint Norwegian-Russian ecosystem survey.

The area covered, distance sailed, effort (days at sea) and number of samples has varied among years. The BESS has covered an area between 1.1 -1.5 million square km, however from 2007 to 2009, the sailing distance was reduced from 2.6 thousand to 1.6 thousand nautical miles, and from 201 to 129 ships days (Table 2). Most aspects of the ecosystem are covered, from physical and chemical oceanography, pollution, phytoplankton and zooplankton, fish (both young and adult stages), sea mammals, benthic invertebrates and birds (Table 3). A range of methods and gears are applied, from water sampling using a CTD equipped with a water bottle rosette sampler, to plankton nets, pelagic and demersal trawls, grabs and sledges, echo sounders and direct visual observations (Table 3).

Table 1. Overview of previous surveys conducted in the Barents Sea in summer and autumn.

Survey	Main goals	Spatial coverage	Start year	Main method	Target component
Hydrographic sections (Norw/Rus)	Obtain vertical profiles of temperature and salinity	Fugløya–Bear Island, Vardø –North, Bear Island–West/ Kola, North Cape–Bear Island, Kanin–North	*	CTD	Temperature and salinity
0-group (Joint)	Abundance estimation, used in assessment (capelin and herring) and recruitment studies	Most of the Barents Sea	1965/1980	Pelagic trawl on predetermined positions	0-group of main commercial and some non commercial fish species. Occasional by-catch of invertebrates registered
Acoustic survey (Joint)	Abundance estimation, using in assessment, and TAC recommendation	Most of Barents Sea, extended northwards in 1986	1975	Acoustic survey Pelagic trawling on acoustic registration	Capelin, from 1986 polar cod and juvenile herring
Shrimp (Norw)	Abundance estimation, using in assessment, and TAC recommendation	Hopen deep (central area of Barents Sea), west of Svalbard	1981	Demersal trawl (Campelen) Stratified sampling design 10-15 nm between stations	Deep-water shrimp *(Pandalus borealis)*
Demersal (Norw)	Abundance estimation, using in assessment, and TAC recommendation	West of Svalbard From 1996 also in central Barents Sea	1981/1996	Demersal trawl (Campelen), variable coverage and sampling intensity	Cod and Haddock
Young haddock and saithe (partly) (RUS)	Abundance estimation, used in assessment, and TAC recommendation	South part of Barents sea	1982	Demersal trawl (Campelen), on acoustic registration	Young haddock
Young haddock and saithe (partly) (RUS)	Abundance estimation, used in assessment, and TAC recommendation	South part of Barents sea	1982	Demersal trawl (Campelen), on acoustic registration	Young haddock
Shrimp (Rus)	Abundance estimation, used in assessment, and TAC recommendation	Central and south area of Barents Sea, Grumant area, Goose Bank	1984	Demersal trawl (Campelen), Stratified sampling design 5-10 nm between stations	Shrimp
Flat fish survey (partly Rus)	Abundance estimation, used in assessment, and TAC recommendation	South part of REZ	1989	Demersal trawl (Campelen), at predetermined positions	Flat fish
Red fish survey (Rus)	Abundance estimation, used in assessment, and TAC recommendation	NEZ and Spitsbergen area	1992	Demersal trawl (Campelen). on acoustic registration	Red fish
Juvenile redfish (Nor), Greenland halibut (Joint from 1999)	Abundance estimation, used in assessment, and TAC recommendation	Around Svalbard	1996/1999	Demersal trawl (Campelen). Depth stratified sampling design	Juvenile redfish and Greenland halibut

*Detailed timing of each of the standard sections is given in Stiansen et al. (2009), page 146.

Table 2. The total effort carried out during the joint ecosystem survey in the Barents Sea Total from both Norwegian and Russian vessels). Numbers are taken from the annual survey reports ((Anon 2004, 2005, 2006, 2007, 2008 and 2010a, 2010b).

Investigation	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Days at sea (ship)	169	215	208	205	201	141	127	134
Days at sea (aircraft)	22	18	10					
Area covered (million km^2)*	1.178	1.439	1.416	1.289	1.463	1.331	1.538	1.470
Distance sailed (km)	11644	29765	23402	21365	26808	14216	16396	16725
Distance covered with marine mammals/sea birds**	3971/3397	2529/4361	6363/5076	8154/6197	7859/5314	6738/5126	3731/4065	6714/4191
Number of ctd stations	783	1144	1028	1052	610	776	428	462
Number of algae net hauls**	0	34	58	75	55	43	68	0
Number of WP2 hauls**	354	**345**	288	262	201	373	363	354
Number of Juday hauls**	203	329	158	356	181	241	263	203
Number of MOCNESS hauls**	35	42	46	61	24	0	28	35
Total number of Macroplankton trawl**	0	0	0	0	0	0	16	0
Number of trawl stations (pelagic/demersal)	605/379	650/473	650/358	608/365	452/383	387/367	605/379	650/473
No of stomach sampled (polar cod/capelin)	*872/1276*	*2220/1888*	563/807	1675/2022	1308/3115	1061/1822	909/1915	1204/1396
No of stomach sampled (cod)	*1419*	*2681*	2493	2794	3167	2828	3173	3155

*Area covered by the survey is calculated by drawing a polygon around the survey track and estimate the total areal for all vessels involved.

** Effort from Norwegian vessels only

Note: In 2005 21 WP2 hauls taken by PINRO are included in the Table

Note: In 2007, in addition 19 hauls of double net (Wp2 and Juday) were taken, not included in the table

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Table 3. Overview of the scientific investigations carried out during the joint ecosystem survey in the Barents Sea. Component monitored, gear used, samples taken, variable measured and application for these are given.

Component monitored		Sampling gear	Samples taken	Variable measured	Application
Currents	at stations and between stations	ADCP	-	Current vectors	Current fields, model input
Water masses	at stations	CTD, water sampler	water	Temperature, Salinity, Depth, Oxygen, Fluorescence, Light	Distribution of water masses, input to models
Nutrients	at stations	Rosette Waterbottle System	nitrate, phosphate, silicate, nitrite in water	Nutrient levels	Mapping of nutrient levels
Pollution	Inorganic, organic and radioactive	Water sampler, box-corer, Demersal (campelen 1800) and pelagic trawl (Harstad)	Water, sediment, tissue samples (fish)	Pollution levels	Mapping of pollution levels in the BS. Advice to Ministry of Environment/Fisheries
Phytoplankton	at stations and over sections	Algae net, water bottle samples, in situ fluorometer (on CTD, not on all ships). Termosalinograph with fluorometer (not on all ships)	-	Species composition and abundance, chlorophyll a, fluorescence,	Mapping of distribution, research, input to management plan
Zooplankton	at stations and over sections	Plankton net (WP2), MOCNESS	Plankton, dry and preserved (formalin)	Biomass, species composition and abundance	Mapping of distribution, research, input to management plan
Target fish species					
Cod		Sensor 1: Demersal trawl (Campelen 1800) Sensor 2: Echosounder (EK60)	Otoliths, Stomachs Acoustic recordings	Numbers, biomass, length, sex, maturity status, diet composition. Vertical distribution, SA, TS	Assessment –ICES advice, internal IMR reports, predation mortality on capelin and shrimp
Haddock		Sensor 1: Demersal trawl (Campelen 1800) Sensor 2: Echosounder (EK60)	Otoliths Acoustic recordings	Numbers, biomass, length, sex, maturity status, Vertical distribution, SA, TS	Assessment –ICES advice, internal IMR reports,
Greenland halibut		Sensor1: Demersal trawl (Campelen 1800)	Otoliths	Numbers, biomass, length, sex, maturity status,	Assessment –ICES advice, internal IMR reports,
Redfish		Sensor 1: Demersal trawl (Campelen 1800) Sensor 2: Echosounder (EK60)	Otoliths Acoustic recordings	Numbers, biomass, length, sex, maturity status, Vertical distribution, SA, TS	Assessment –ICES advice, internal IMR reports
Herring	Juveniles	Sensor 1: Pelagic trawl (Harstad) Sensor 2: Echosounder (EK60)	Otoliths Acoustic recordings	Numbers, biomass, length, Vertical distribution, SA, TS	Assessment –ICES advice, internal IMR reports
Capelin		Sensor 1: Pelagic trawl (Harstad) Sensor 2: Demersal trawl (Campelen 1800) Sensor 3: Echosounder (EK60)	Otoliths Otoliths Acoustic recordings	Numbers, biomass, length, sex, maturity status, Numbers, biomass, length, sex, maturity status, Vertical distribution, SA, TS	Assessment –ICES advice, internal IMR reports,
Blue whiting		Sensor 1: Pelagic trawl (harstad) Sensor 2: Echosounder (EK60)	Otoliths Acoustic recordings	Numbers, biomass, length, sex, maturity status Vertical distribution, SA, TS	Assessment –ICES advice, internal IMR reports,

Table 3 cont.

Component monitored	Sampling gear	Samples taken	Variable measured	Application
Target fish species cont.				
0-group	Sensor 1: Pelagic trawl (Harstad)	Otoliths	Numbers, length	Assessment –ICES advice, internal IMR reports,
	Sensor 2: Echosounder (EK60)	Acoustic recordings	Vertical distribution, SA, TS	
Polar cod	Sensor 1: Pelagic trawl (Harstad)	Otoliths, stomachs some years	numbers, biomass, length, sex, maturity status	Assessment –ICES advice, internal IMR reports,
	Sensor 2: Echosounder (EK60)	Acoustic recordings	Vertical distribution, SA, TS	
Fish pathology research				
All species	Sensor 1: Demersal trawl (Campelen 1800) Sensor 2: Pelagic trawl (Harstad)	Individuals	Numbers, species	Monitoring, research, input to management plan
Other fish species monitored				
All pelagic and demersal fish species sampled	Sensor 1: Demersal trawl (Campelen 1800)		Length distribution, biomass	Ecosystem status reports (ICES and joint IMR /PINRO), input to management plan, monitoring by-catch
	Sensor 2: Pelagic trawl (Harstad)		Length distribution, biomass	
	Sensor 3: Echosounder (EK60)	Acoustic recordings	Vertical distribution, SA, TS	
Benthic decapods				
Deep-sea shrimp	Demersal trawl (Campelen 1800)		stage and length measurements	Assesment –ICES advice, internal IMR reports,
King crab	Demersal trawl (Campelen 1800)		Carapax width, sex	Monitoring, assessment (minor) internal reports
Snow crab	Demersal trawl (Campelen 1800)	Whole individuals	Carapax width, sex	Monitoring, assessment (minor) internal reports
Other benthos All	Demersal trawl (Campelen 1800) Grab, beam trawl, cam-pod (video), epibenthic sledge	Formalin fixed samples to be analyzed in lab on land	Species, numbers, biomass	Habitat mapping, starting time-series, monitoring by-catch
Marine mammals				
All species	Observers	Visual observations	Numbers, species, calves/adults	Monitoring distribution, research, input to management plan
Seabirds				
All species	Observers	Visual observations	Numbers, species, juvenile/adults	Monitoring distribution, research, input to management plan

The findings of the survey are reported in two or three steps: 1) Just after the cruises, a meeting is held and the first draft of the joint survey report is prepared. These reports are published in the "IMR - PINRO report series. These reports describe how the survey has been conducted and present preliminary data from the investigations. The level of detail varies for different investigations. The investigations carried out by other institutions than IMR (Norway) and PINRO (Russia), for instance the contaminants are mainly reported elsewhere. 2) At the end of the meeting, the main findings from the survey are released to the media in Norway and Russia. 3) During the years 2003-2008 also a second volume of the cruise report, containing results from lab-analysis on land (i.e. age structure of fish stocks, species and stage determination of zooplankton, benthos analysis, stomach analyses etc), were made. Volume 2 of the cruise report was presented no later than at a joint meeting held in March, the following year. A detailed description of how to conduct the survey is found in the survey manual (e.g. Anon. 2008), as well as in the annual survey reports (Anon 2003, 2004, 2005, 2006, 2007, 2008, 2010a and 2010b).

Survey design and sampling gears

The survey design of the BESS has been a compromise between the designs serving the aims of the previous surveys, the available ship time and the time needed to cover the Barents Sea. This has resulted in a regular grid with 30-40 nautical miles between "ecosystem stations" consisting of CTD probes, pelagic and demersal trawls and plankton nets. The exception has been a denser and depth stratified sampling of bottom trawls along the Svalbard archipelago (2004-2008), and a denser stations grid as part of a flatfish survey in eastern BS, employed in 2006. In 2005-2008 the distance between bottom trawl hauls was 15-20 nm in the deep central area previously covered by a shrimp survey. Also, pelagic trawling has been conducted on registrations of pelagic fish for allocation of acoustic signals to species and biological samples of capelin and polar cod, and in some cases, demersal trawling was conducted in response to aggregations of demersal fish close to the bottom.

A CTD is used to obtain vertical profiles of temperature and salinity on every pre-determined ecosystem station, and on standard oceanographic sections. The Norwegian sections are Fugløya – Bear Island, Vardø – North, Bear Island – West (overlaps with a Russian section), and the Russian sections are Kola, North Cape – Bear Island, and Kanin – North. Horizontal distribution of temperature and salinity at standard depths (0, 50, 100, 200 m and near the bottom) and vertical distribution of the same parameters along sections are prepared for the joint report after completion of data processing on the leading vessel.

Monitoring the radioactive pollution is done by measurements of Caesium in seawater, sediments and biota. Measurements of Plutonium, Strontium and Technetium are also done. Radioactive pollution is analysed on a few stations every year, and every third year a more extensive sampling is done. Biota samples were preferably taken from cod, haddock, capelin, Greenland halibut and long rough dab. Sediment samples were collected with sediment sampler "Smøgen Boxcorer", which takes an undisturbed sample of the seabed. The upper 1-2cm was analysed. Sediment- and biota samples are frozen onboard the vessel and freeze-dried prior to analysis. Water samples are collected from the surface seawater intake on the vessel. 50 sediment- and water samples distributed in the Barents Sea are normally taken. Samples of biota are collected from selected stations in the eastern, middle and western, southern and northern parts of the Barents Sea.

Plankton sampling is carried out at the location of most of the ecosystem stations and on the standard oceanographic sections. Water samples are obtained just after the retrieval of the seawater CTD rosette sampler, for chlorophyll and nutrient analysis. In addition, Norwegian vessels, samples obtained by a10 μ simple ring plankton net are taken for analysis of phytoplankton species compositions. On Russian vessels, phytoplankton samples are also taken at the oceanographic stations using seawater rosette sampler, but at three different depths. The formalin preserved samples are later analyzed at the laboratory for qualitative and quantitative analysis of phytoplankton.

On the Norwegian vessels, zoo plankton samples are obtained by using plankton net WP2 and the MOCNESS. In practice this mean 2-3 WP2 stations and 1 MOCNESS station per day. The sampling layers in the Barents Sea for the WP2 nets are from the bottom to the surface and from 100 m to the surface. At most stations the MOCNESS nets are towed in oblique hauls from 300-200, 200-150, 150-100, 100-50, 50-25, and 25-0 m. The number of nets varies from 3 to 8, depending on the bottom depth. The Russian vessels carries out similar sampling using Juday nets in the layers from the bottom to the surface, 100 m – surface and 50 m – surface. By taking into account the volume of water filtered through the net and the sampling depth interval, the results are expressed as wet or dry weight biomass per m^3 of seawater, or m^2 of water column. A factor of 5 is used to convert dry weight to wet weight (Skjoldal et al. 2004).

The distribution and abundance of 0-group fish are estimated based on the in the pelagic trawl and converted to number of fish per square nautical mile. The trawling procedure, standardized on all vessels since 1980, consists of hauls with a pelagic mid-water trawl with a mouth opening of 20x20 m. Trawling is carried out at 3 depths, each over a distance of 0.5 nautical miles, with the headline of the trawl located at 0, 20 and 40 m, respectively, and with trawling speed of 3 knots. Additional steps with the headline at 60, 80 and 100 m, are made when the 0-group fish layer is recorded deeper than 60 m on the echo-sounder. All 0-group fish are carefully collected from the trawl, weighed, counted, and measured before abundance indices of the target species are calculated. The history of the development of the 0-group fish investigations, assessment methods and calculation of abundance indices is described in detail in and in Dragesund et al. (2008), and in Eriksen *et al*. 2009.

Both Norwegian and Russian vessels are equipped with calibrated EK-60 echo sounders, and acoustic s_A-values are collected from the total water column, avoiding the fields close to the transducer and the bottom. The values are carefully scrutinized to exclude noise, to compensate for the "dead zone" near the bottom and for ping losses typical for rough weather. Acoustic data from the frequencies 18, 38, 120 and 200 kHz, with 1 nautical mile horizontal resolution and 10 m vertical resolutions in the pelagic layers and 1 m vertical resolution in the bottom channels, is stored in the acoustic databases. A minimum acoustic threshold of –83dB is applied to detect smaller organisms such as juvenile fish and zooplankton. The allocation of acoustic values is carried out on the basis of the acoustic character of species and trawl samples at a resolution of 5 or 1 nm (from 2008 on). Thereafter a post processing system like BEI, BI500, LSS or FAMAS is applied, which facilitates the exclusion of noise and the allocation to species. Pelagic trawling is performed in response to potential changes in the echo sounder registrations for validation and support of the allocation of acoustic values to target species. To identify fish in the bottom channel only bottom trawl catches are used, but for the pelagic channels it is in most of the area necessary to include bottom hauls in addition to pelagic hauls as several demersal fish species also move quite high up in the water column. All pelagic s_A-values selected for target fish species (capelin, polar cod, young herring and blue whiting) together with the corresponding biological data (age, length and weight of fish aggregated by squares and areas) are used for stock assessment of these fishes. The s_A-values distributed to demersal species are also stored in the databases, but up till now, these data have not been processed further due to prioritising of pelagic acoustics in the survey. This may be done in the future.

The trawl used in this survey is a Campelen 1800 shrimp trawl with rockhopper ground gear. The standard towing time is 15 min at 3 knots, equivalent to a towing distance of 0.75 nautical miles. The pelagic trawl gear used is a Harstad trawl with a 20*20m mouth opening. The trawl is towed for 20 min at the surface, at 20m and at 40m. All bottom fish are sampled for individual length measurement, weight, maturity stage, stomach fullness and food composition. Catch per nautical mile from the fixed bottom trawl stations generates the basis for estimates of indices of abundance (swept-area estimates) for each year class (or length group) of the demersal fish species. In addition, an acoustic index of redfish is estimated. The distribution and relative abundance of the benthic fauna are investigated from the by-catch in the bottom trawl. Some samples are also taken for analysis of pollutants, genetics and other things.

Biological data were previously stored in different data formats on Norwegian and Russian vessels (in the SPD file format and in the BioFox format, respectively). The difference in data formats are now more or less overcome by development of a conversion programs (by PINRO). This has allowed IMR and PINRO to enter all data in a complete and joint data base. Marine mammal and seabird observers have participated on the survey on selected Norwegian and Russian vessels since 2003 (Table 2). On the Norwegian vessels, the seabird observers are from the Norwegian Institute of Nature Research (NINA). Two marine mammal observers and one seabird observer participated on the Norwegian vessels. The marine mammal observer's covers a sector from straight forward to 45^{o} on either ship side, and from the ship to the horizon (i.e., distance sampling). The seabird observer covers a 90^{o} sector to one ship side, and within 300 m from the ship (i.e. strip transect). Seabirds typically following ships, such as gulls and fulmars, are counted every hour. On the Russian vessels, one observer recorded both seabirds and marine mammals, covering a sector of 360^{o} and distances from the ship to the horizon. Due to the different observing methods, data from Norwegian and Russian vessels cannot easily be combined.

An airborne survey for marine mammals and seabirds accompanied the ecosystem survey in 2003-2005. During this survey, 2-4 observers recorded sightings from both sides simultaneously. A standard coverage sector is 45°, and mean flight altitude along transects is 200 m. An observer carried out counting usually under the angle of 90°, but has also an opportunity to observe partly front and back sectors in dependence on conditions of the flight vision, that increases the accuracy of counting.

Lessons learned

Aim

The main aim of the BESS has been to conduct synoptic sampling of the ecosystem components, by maintaining the old time series while at the same time start monitoring new components. The focus on the survey has varied between years (see discussion below) but has mainly been on the distribution and abundance of the young and adult stages of several pelagic- and demersal fish species, in addition to gather information about environmental features, functional groups important for ecosystem processes and biodiversity. The current survey design is thus a compromise between economic constraints, required data quality for assessment and consistency of long-term time series. This may in some years have resulted in suboptimal sampling of various parts or processes in the ecosystem. The planning of the survey on the Norwegian side has, moreover, been complicated by a constant pressure to cut ship time and costs, and the projects involved have been forced to struggle for the survey resources. On the other hand, this has kept the planning committee on a constantly search for new solutions, which might not have taken place if there was no competition for resources. Lessons learned, and suggestions for further improvements, are suggested in the following paragraphs. Pros and cons of the BESS compared to single species surveys is also summarized in Table 4.

Table 4. Summary of pros and cons with the Barents Sea ecosystem survey compared to single species surveys.

Parameter	Gains	Drawbacks
Aim		
Multipurpose	Ecosystem studies, processes, synoptic	Not optimal for all purposes
National and International cooperation		
Standardisation of equipment (Change of demersal trawl on the Russian side)	Comparable results between Russian & Norwegian vessels	End of nation specific time series/investigations
Joint survey manual	Comparable results between Russian & Norwegian vessels	Reduced flexibility
Transfer of knowledge and experience	Increased focus on taxonomic skills on Norwegian side	Time consuming
Data format adjusted on both sides	Common Data base	Time consuming
Data exchange formalized	More extensive use of data collected on the cruise	Time consuming
Structure on survey report	Easier to compare results between years, more assessable for people not attending the survey	Time consuming, less flexibility, everything written in English
Scientific publications	Several per review publications and notes in the public press, all with joint authorship between scientist from Russia and Norway scientific	no loss/ time consuming
Survey design		
Grid density and design uniform sampling intensity in the general, but higher sampling intensity in areas with high densities of shrimps, and a random depth stratified sampling around the Spitsbergen archipelago	A compromise in achieving a various range of goals. Avoid to break old time series.	Not optimal design for all purposes. Changes from year to year may add some unintended effects of the results. Demands a lot of resources (vessels, manpower and equipment)
Large area coverage	Cover the total distribution area for most species. Early observation of invading species	More time needed
Practical implementation		
Resources available	Reduced from prior to the onset of the survey	Reduced precision
Timing of the survey	Time optimised for capelin and 0-group	Not optimal for e.g. plankton
Number of parameters collected	Increased , more components covered	Time consuming
Number of ecosystem stations	Ecosystem survey stations allow synoptic spatial data of several ecosystem components	Ecosystem stations time consuming, less synoptic coverage of e.g. capelin

Table 4. cont.

Parameter	Gains	Drawbacks
Time/Distance between stations	Increased, reduction in time spent sampling, more tiem available for e.g. area coverage	Increase variance
Area coverage	Increased better spatial coverage	Time consuming
Time for trawl stations at high acoustic recordings	Reduced, more time for other purposes	Reduced: reduction in precision
Time for calibration of equipment	Reduced, more time for other purposes	Reduced: reduction in precision
Data quality/data description		
0-group data	Expansion of the study area (northwards)	Reduced study area in the west of sea often timing too late, settling of 0-groups fish
Pelagic fish	Increased study of bottom component distribution	Less dense grid of acoustic observations, fewer trawls to identify the acoustic registrations, increased uncertainty about horizontal migration
Hydrographic data	The expanded study area to the north	observations are lost on some standard ctd-sections
Demersal fish	New time series and numbers assessment of commercial species and information on non-commercial species. Area covers whole distributions of most species, also the arctic	Closing of previous bottom surveys (Russia). Variable sampling effort between years
Benthos community investigation and invertebrates data	New method developed by analysing benthos in demersal fish trawl in time and space. Time efficient because trawl only catch large species from the sediment surface (mega epifauna) and all identification made onboard the vessel.	Only gross estimates of abundance and biomass, and only a fraction of the collective benthic species composition (infauna and small epi/hyper fauna).
Plankton community investigation	Significantly increased the water area of research and volume of data collected	Fewer stations
Shrimp investigation	Increased area coverage, more samples taken.	lost long-term data sets and fewer observations. Lack of biological measurements
Birds and mammals observation	New information not collected at this time of year	No loss, Russian and Norwegian sampling methods differ?
Other investigation (pollution, fish health data, weather sampling, grabs, genetic sampling and etc.)	New data, better use the ship time	no loss

National and International cooperation

One of the great accomplishments with the BESS is the expansion of the cooperation between scientists and technicians in Norway and Russia. The joint effort in planning, implementation and reporting of a survey of this size is rare internationally. The cooperation has led to improvements like standardization of sampling equipment (demersal trawling) and comparable gears are used for plankton. Data exchange is formalized and transferee of data, experience and knowledge function well A common survey manual is developed and a joint structure of the survey reports is established (content, design and format of figures). The recent years, there have also been an increased number of joint publications in per review journals. All this planning has taken a considerable amount of time. Nevertheless, the time spent on conducting the suite of surveys now included in the BESS were considerably greater than the time currently used on the BESS. However, standardized methods across Norwegian and Russian vessels are still not used for zooplankton, marine mammals and seabirds, thus making integrated studies on these species across the Barents Sea less strait forward.

Conducting surveys in more than one national EEZ (economic exclusive zone) involve extra administrative challenges. Permissions to enter foreign countries EEZ have to be applied for long time in advance, and restrictions or a rejection of the application could come at short notice. To reduce the consequences of these unforeseen complications, it was decided that each nation should cover only own EEZ in the future. However, this may have lead to other complications, as for example systematic vessel effects through differences in technical or personnel qualifications.

Also at a national level, sudden change in effort allocated to the survey has occurred (on the Norwegian side). These unforeseen circumstances have in some years led to a last minute re-evaluation of all cruise plans, resulting in inferior “synoptic coverage”. Furthermore, in some years the northern shrimp investigation and marine mammal observation were reduced. In addition, standard oceanographic sections and vertical plankton coverage by MOCNESS were not conducted.

During the BESS a wide variety on ecosystem data are collected. This means in practice that national and international experts must work together coordinating integrated synthesis of the information gathered during the survey. In this respect, the working environment associated with the BESS has proved a highly stimulating forum for scientific debates integrated across disciplines.

The various sampling programs conducted during such surveys should be deeply rooted in the institutes organizing the survey. In some cases, the part of the work that has to be done after the survey (like working up age samples or stomach samples in the lab, calculating acoustic estimates of demersal fish species, or undertaking an adequate quality assurance of all data recorded) has been lacking because sufficient manpower and money for this activity were not allocated.

Practical implementation

Compared to previous practice (before 2003) the number of days at sea is reduced, but a larger area is covered and in total, more samples are taken. The survey design and equipment have been more standardized, although additional improvements can be implemented. The survey design of BEES now consist of a uniform sampling intensity in the general survey area as well as a random bottom stratified sampling around the Spitsbergen archipelago (Anon. 2005). The sampling design is regular, although transects and stations are denser in some parts of the survey area. For instance in the area with high capelin densities, the sampling is denser than in other areas. A regular sampling is suitable for covering a large spatial area. However, the disadvantage is that the sampling resolution seldom or never is fully sufficient to capture the spatial gradients and patterns in the distributions. On the other hand, all the investigations involved in this survey have different spatial gradients and patterns. There is, for instance, an inherent conflict between those investigations that rely on sampling at specific, predetermined stations (trawl sampling for swept area or swept volume estimation of fish resources and for studies of species compositions etc., sampling of benthos, plankton, chemical and hydrographical characteristics of water masses), and those investigations that rely on data obtained when the ship is underway (acoustic investigations, trawl sampling of registered echo targets, counting of sea mammals and sea birds). Thus defining an irregular station grid suitable for all the investigations, and still cover the entire Barents Sea, is not straightforward.

Changes in survey design (e.g., survey area, distance between stations, sampling, and time at sea) from year to year due to economical and other circumstances may also add some unintended effects of the results when using the data without having detailed knowledge about the survey history.This challenges the data analyses for some specific needs, and post stratification must often be used for analysis purposes (Aanes and Vølstad 2009). Thus, one of the major challenges during survey planning is the contrast between optimizing the survey design for one species at the time, and optimizing the design for an assemblage of species or ecosystem processes. Further improvement of the survey should be based on identified spatial scales for all the involved investigations and components sampled. A survey design combining a regular and irregular sampling grid is likely to be the most feasible outcome. Below are some examples of trade-off between various tasks that are all considered important, and which cannot be completely solved.

In particular, this dilemma became obvious for the acoustic coverage of the capelin stock. Since this is the only result from the survey that is used directly in the management of a fishery, the capelin coverage has been given top priority. However, it was realized after a survey in 2008 that a) the design was clearly suboptimal for the capelin; b) not enough time had been set aside for capelin investigations, and 3) the tasks divided among the ships were inappropriate, all of which led to a non-synoptic coverage. Consequently, in the survey plans for 2009 and 2010 more effort was put into an optimal design for the acoustic survey, at the price of less work on plankton, benthos and demersal fish in the main distribution area of capelin. Probably, this improved the capelin stock size estimate somewhat, but still much less effort has been put into the acoustic survey during the period of BES than was done before.

Prior to 2003, the 0-group survey was conducted before mid September to avoid the bottom settlement of cod and haddock. Since the bottom settlement starts earlier in the southern area compared to the northern areas (Boitsov et al. 1996), the survey have started from the Norwegian and Murmansk coast and ended in the north. As the BESS has been conducted between August and October, bottom settlement has observed during the survey. This effect is difficult to account for since the spatial and temporal settlement is poorly known in the Barents Sea.

At the time of the year when BESS is conducted the geographic distribution of all age groups of cod and haddock is covered. This should make the indices of abundance from this survey useful for stock assessment purposes. However, a time series of at least 5 years is needed in order to include a survey index as a tuning series in an assessment model (ICES, 2007). Thus, after the 2008 survey a sufficient amount of data were collected and an evaluation was made (Aanes and Vølstad, 2009). The analysis of the data from the BESS revealed that the allocation of station varied over time and that the survey design employed each year was insufficiently documented. They had to force the data into a stratified design, using post-strata constructed to ensure that the inclusion probabilities of stations were approximately equal within each stratum. Their analyses showed that compared to the annual winter survey, the BESS produce less consistent estimates of temporal changes in cohorts of both cod and haddock. This suggests that BESS produce less reliable tuning series for VPA type stock assessments such as the XSA. They further pointed out that the underlying variability in density of cod (age 4-6) appears to be higher during winter compared to summer/fall, while the variation in haddock density appeared higher during summer than winter. In the last years both the Russian autumn and the BESS have showed higher abundance of cod than in previous years. The reasons for this are not fully explored, but a change in geographical distribution, with higher densities near the borders of the area covered has been observed. This also could indicate under-coverage of young cod during wintertime. In any case full area coverage of cod and haddock is important for long-term monitoring to track changes in abundance and the BESS could be used to “tune” the winter survey indices of cod and haddock (Johansen *et al*., subm to J. Mar. Biol.).

As survey costs also are considered when the efficiency of different surveys is discussed, several suggestions have been made on how minimize surveys. Godø *et al*. (2009) conclude that the most effective way of reducing the survey effort is to coordinate the trawl sampling with the sampling of the standard oceanographic sections. This procedure might reflect changes in abundance of cod, but would not give any information about changes in distribution of the same species, nor would it give valuable information for other components in the Barents Sea (plankton, benthos, other fish species or sea mammals). The BESS is the only survey that covers the whole area of distribution of cod during the feeding season. At this time cod feed most intensely on the edge of the distribution area and this aspect would be lost if only standard sections are sampled. Other studies have looked at the number of stomachs sampled or otoliths collected (Aanes and Vølstad, 2001; Nakken and Pennington, 2001) at each station and concluded that it is better to spread the samples over a larger geographical area, than to take many samples at the same station.

An alternative approach may be to choose every second (or third or fourth) of the stations taken at a full survey, or to pick randomly 50% (or 33% or 25%) of the stations, within strata's. However, a major challenge for the studies of species interactions is the coarse scaled data from the current survey, and obtaining data on an even coarser scale would reduce the usefulness of the data in such studies. Yet another approach to reduce survey effort could be to measure certain parameters every 2 or third year. This demands a long-term planning with predictable resources over a period of at least 5 years, and also a good understanding of the ecosystem and the life history of the species living there. The disadvantage is that the aim and sampling regime of the survey will change from year to year and make it difficult to compare results between years. Besides, species with a short life cycle, like the capelin or 0-group indices, must anyway be assessed every year to be able to give advice on the management of the fishery.

Effort has been made to measure as many parameters as possible during the BESS, but available time has put restrictions on what is possible to accomplish. Other measured components may therefore not have optimal coverage and thereby increased uncertainty, but will still give important information. Thus it is important at an early stage to identify the further usage of data and to use the available time, effort and resources according to a prioritized list. It is not be easy to make the prioritizing between various components or investigations. How should one choose between avoiding a break in a long time series of temperature or 0-group abundance and covering the whole survey area, reduce the number of trawl stations or the number of stomach sampled? The consequences of any reduction in effort should be made clear, i.e. by making an estimate of reduction in accuracy according to reduced effort.

The reduction of vessels days have also reduced the ability to account for bad weather conditions or stability of the sampling equipment, the time set available for intercalibration of equipment and replicate sampling in the same area, as well as trawling between stations for validation of acoustic data. For instance, it has been discovered that cod in the Russian EEZ have a higher consumption rate than cod in the Norwegian part. Due to lack of overlap in area coverage by both nations, it is difficult to evaluate whether these observations reflect real conditions or is due to differences in methods/routines of sampling and analysis between the two nations.

During the BESS several sampling gears are used and the sampling resolution varies widely. Examples are water samples with a resolution of cm^3, a bottom trawl sweeping a corridor several meters wide and several 100 meters length, and an ecosounder with a resolution of one ping, but a range of several km along the cruise line. Ecosystem studies demands improved attention to storage of data (metadata information, resolution) and methods for combining data from different sources. This is an area which demands further improvements in the near future.

Conclusions

The ecosystem approach to management is a challenging task, and some of the challenges concretizes when trying to adapt to this approach in monitoring by performing comprehensive ecosystem surveys. To obtain information on a range of different ecosystem components require different equipment and sampling strategies. There is, for instance an inherent antagonism between the sampling undertaken while the ship stops at a station and that undertaken while the ship is moving. The longer the ship stays at stations, the less area is covered each day, and the less synoptic is the total coverage of the area. It is also important to evaluate whether it is possible to extract more information from the existing surveys. More detailed species specific information from especially trawl catches e.g. jellyfish, krill and amphipods than current surveys provide, could bring additional valuable information for integrated ecosystem studies. Experimental process studies (shipboard or laboratory) such as egg production, grazing and oxygen rates are important inputs to ecosystem models and should be considered incorporated in future ecosystem monitoring programmes.

One way to address this is to conduct analyses of minimum effort required to provide observations on ecosystem state (e.g. stock size) or processes (e.g. migration, trophic interaction) of sufficient precision and coverage in time and space. Several aspects should be taken into consideration in these analyses. If the requirement to the precision level in measuring a certain process is reduced, one might increase the precision level in another. The spatial resolution of the observations should match the spatial scale on which the process in question varies. Temporal variation of a process will decide how frequent the process must be observed. Some processes may be surveyed several times a year, while others can be surveyed every second year. Furthermore, the data already collected should be used to assess the possibility of identifying areas of special importance, relative to physical processes, species diversity, species abundances, trophic transfer or other ecosystem processes. If such areas of importance are agreed upon across a multidisciplinary group of specialists, these areas can be used in survey stratification by increasing sampling intensity within these areas, and reduce sampling intensity outside these areas.

The limitations posed by available personnel, survey vessels, survey time and economy constrain the outcome of the BESS, i.e. leave no time for development or implementation of new sampling methods. The planning of an efficient monitoring system should therefore aim towards optimal allocation of effort between different ecosystem processes, combination of methods, and simultaneous observations. However, to be adaptive, the monitoring system should also be flexible to meet current and future demands. Lack of long term funding and the associated low effort that has been put into developing the survey design also reduces the flexibility in performing the BESS.

Another aspect that deserves increased focus is how research vessels are being built and used. The deployment of traditional scientific gear from the research vessels on station proceeds normally one at the time. The time spent at a station could be reduced if several types of gear could be deployed simultaneously (temperature sensors on trawls, multiple trawling i.e.). Advanced research vessels are currently and will in the future be the primary platform for large scale near “synoptic” investigations. No other advanced instrumentation can replace these platforms in any foreseeable way, particularly when it comes to obtaining quality measurements at the species level. Over the years many new sophisticated sampling techniques have been developed (i.e. krill trawl, OPR, AUV, acoustic investigations of zooplankton). New, multipurpose and time consuming sampling equipment/techniques should therefore be considered in the future. This will also prepare us for obligations in new areas like for instance in the Polar Sea.

Reduction of survey effort for the BESS resulted either in a reduction in number of samples taken (for oceanography, bottom fish and plankton) or a cancellation of further research (shrimps). To keep the size of the covered area and number of investigations at the same level as in 2005-2007, and to allow for some flexibility due to changing weather conditions, calibration of equipment and trawling at acoustic recordings, an effort of at least 200 vessel days is required.

Multipurpose research surveys provide information on the spatial and temporal patterns of environmental and biological variables, which has enhanced our understanding of ecosystem interactions, assessment and management. The ecosystem approach to management is putting greater demands on the amount of information needed for adequate scientific advice, and multipurpose surveys will obviously be of major importance in the future. Such surveys will require enhanced planning, including increased focus on vessel configuration and survey design. This will be further discussed in Michalsen et al. 2012 (submitted to J. Mar. Biol.).

Based on the experience we now have, we recommend for the coming years an identification of a clear aim of the survey, calculations of survey effort versus precision obtained, and development of a new standard survey design. We also recommend establishing a long-term perspective of the survey to ensure continuity in 1) the identified aim, 2) the resources needed to perform a survey with that aim, and 3) the structure of organisation of the survey.

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3.7 Simulation of changes in the harvesting strategy of Northeast Arctic cod as response to climate change

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Introduction

There is a high certainty that global warming is a reality. Future climate change scenarios from Global Circulation Models indicate a rise in temperature and a decline in ice coverage in the Barents Sea. Coupled biological-physical models project an increase in the plankton production as a response to climate change in the area (Ellingsen et al., 2008). Available studies show that the stock size of cod in the Barents Sea is expected to increase with temperature rise of 1-2°C due to extended distribution and positive changes in reproduction (Drinkwater, 2005).

The fishery, along with climate, is the main driving force of cod stock dynamics in the Barents Sea. Climate change mainly influences cod recruitment, but mortality of adult fish is regulated by fisheries to a larger extent than by natural factors. Therefore, if we want to get a realistic picture on cod stock dynamics in the future we have to consider the likely alterations in cod fishery that will be related to the expected climate change.

The harvest strategy is determined by fisheries techniques and gears, conceptual basis (theoretical approach) and management aims. The current harvest strategy of the NEA cod is related mainly to trawl and long line fisheries, based on the precautionary approach and aimed at achievement of the maximum sustainable yield (MSY). In our study we assumed that the fundamental points of the current cod harvest strategy will be kept also in the near future. In this case we can expect that:

- the future NEA cod stock should correspond to the one that produces the MSY;
- F_{msy} is the most realistic candidate for the future F_{target} for the NEA cod.

Therefore, to make projections of cod stock and yield in the Barents Sea under this assumption, the adjustment of F_{msy} to the climate-induced changes in cod stock is needed.

Material and methods

In our study the potential changes in F_{msy} for the NEA cod under different warming scenarios were explored through the use of the STOCOBAR model that was developed in PINRO (Filin 2005; 2007). This model simulates the stock dynamics of cod in the Barents Sea, taking fisheries, trophic interactions and environmental influence into account. It is an age-structured, single-area and single-fleet model with a one-year time step. It is designed as a tool for prediction and exploration of the cod stock development as well as for testing harvest strategies under different ecosystem scenarios. STOCOBAR is a process simulation model. The cod stock dynamics are described through the imitation of cod growth, feeding, maturation, recruitment, cannibalism and fishing mortality (Figure 1). Development of the

STOCOBAR model has been done partly within the EU project UNCOVER (2006-2010) and the joint PINRO-IMR project (2004-2013) on optimal long-term harvest in the Barents Sea.

The model parameters are estimated by fitting the model outputs to the observed data on cod weight, length, maturation, condition and diet. Minimization of the square of discrepancies between simulated and observed data through the use of the Solver in Excel spreadsheets is applied. Sources of the data that are used in the model adjustment are the following:

- report of ICES AFWG;
- joint Russian-Norwegian database on cod stomachs in the Barents Sea (Dolgov et al., 2007);
- results of trawl and acoustic surveys in the Barents Sea;
- PINRO database on cod hepatosomatic index;
- PINRO database on the water temperature on the Kola section.

The temperature scenarios, which are produced by the STOCOBAR model, were used to evaluate influence of temperature increase on estimation of F_{msy} for cod stock in the Barents Sea. These scenarios are based on the historical data of annual water temperature at the Kola section. The cyclic climate variability was imitated by alternation of the cold, moderate and warm years in the temperature scenarios. This was implemented by random selection of temperature values from the historical data aggregated by cold, moderate and warm years. In our study the cold periods include temperature less than 3,6 C°, the warm periods have temperature more than 4,2 C° and for the moderate periods temperature ranged from 3,6 C° to 4,2 C°. The duration of each of these periods equal to 3±2 year were established. Three future temperature scenarios were used in the simulations: current temperature regime, temperature increase of 1ºC and temperature increase of 2ºC.

Unlike the cod, the capelin stock projections in our model are based only on a statistical approach. These projections include both deterministic and stochastic components. Stochastic component reflects uncertainties associated with natural variability in capelin stock size and this is imitated by random selection of values from the aggregated historical data. Deterministic component reflects impact of cod on capelin stock dynamics as well as the relationship between successive capelin stocks in the historical time-series. Previous observations have shown that if the cod spawning stock biomass (SSB) is less than 400 thousand tons, the probability that capelin stock size will be large is much higher than in a situation where cod SSB is more than 400 thousand tons. On the other hand, historical data show that the probability of appearance of a large capelin stock is much higher if the capelin stock was large also in the previous year.

The procedure of setting the capelin stock biomass for each modeled year includes 3 steps (Figure 2). Firstly, the value of the capelin stock biomass is randomly selected from the historical data, aggregated depending on cod stock size (more or less than 400 thousand tons). At the second step the values of the capelin stock biomass are selected randomly from the historical data, which are now aggregated depending on capelin stock size in the year before (more or less than 3 million tons). Subsequently, the arithmetic average for these two randomly selected values of capelin stock biomass is calculated and put into the projection. This procedure is repeated for each modeled year.

The Ricker recruitment equation was used to couple cod spawning stock biomass and recruitment at age 1. Uncertainties associated with the recruitment were introduced by including residuals in the simulated data. The variability in recruitment is derived from the relationship between historical spawning stock biomass and the number of recruits at age 1 for the period 1984-2007.

A simplified version of the current control harvest rule for cod was used in the simulations. If the SSB is equal or higher than B_{pa} (460 000 tons), the fishing mortality rate is set equal to F_{target}. If spawning stock falls below B_{pa}, the fishing mortality rate is linearly reduced from F_{target} to zero according to the decrease in SSB. The series of successive model runs were performed for each temperature scenarios using steps in F_{target} increment equal to 0,05. For each F value 5 replicates of the 200-years projections were made.

Data on capelin stock assessments on 1 January as well as on cod maturity, mean weight-at-age, abundance, fishery mortality coefficients and the fishing selection pattern were taken from ICES AFWG report 2009. Annual temperature data averaged for 0-200 m depths on the Kola section for the period since 1951 to 2010 were used for development of the temperature scenarios for the simulations.

Results and discussion

The simulations demonstrate that the temperature rise will lead to increase in cod stock production due to faster growth and maturation of cod (Figure 3). On the other hand, cannibalism will also increase caused by increment in cod consumption. This will produce a negative impact on survival of young cod.

According to the model the expected warming in the Barents Sea will lead to the ability of the cod stock to sustain a larger fisheries pressure without risk of depletion. This will provide an increase in potential total allowable c atch. From the simulations negative fishery effect on the cod stock size is apparent from $F_{target} = 0.30$ under the current temperature regime, and from $F_{target} = 0.40$ and $F_{target} = 0.50$ under warming scenarios of 1ºC and 2 ºC, respectively (Figure 4). The yield of cod is increasing with a positive shift in the temperature regime. The trend lines in the graphs of yield indicate that the warming scenario of 2°C supports the largest relative growth of catch within high rates of F_{target} (Figure 4).

The projections show that cod SSB falls below B_{pa} more often under the current temperature regime than in the case of warming scenarios (Figure 5). The maximum acceptable level of probability of drop in SSB beyond the B_{pa}, which supports sustainable fishery, is not determined in the existing harvest control rules for NEA cod. According to our simulations the 20-25% rate of mean long-term probability of drop in SSB below B_{pa} may be considered as a candidate for this. If long-term simulations show that this level is exceeded this may be considered as evidence that the tested harvesting strategy does not meet the requirements of sustainable management. Based on this assumption we found that F_{target} values of 0.65 and 0.90 correspond to F_{ms}y under 1ºC and 2 ºC warming scenarios, respectively.

However, one should keep in mind that estimates of allowed shifts in cod fishery rate, as a response to the expected warming in the Barents Sea, were obtained under various assumptions. This indicates their uncertainty and requires careful interpretation. The highest uncertainties are most likely caused by the following factors: Firstly, it is associated with likely changes in fishing selectivity by age groups. Increased growth rate is assumed to result in changes of the suitability of young cod for fisheries. It should be expected that young cod may reach a fishable size at age 2, and not at age 3 as it does at present. Since increased fisheries impact on the young age groups of cod was not taken into account in our simulations, underestimation of the fisheries impact may be the result. Secondly, we did not consider the influence of water temperature on the state of the capelin stock in the Barents Sea. And thirdly, simulation of cod recruitment was made regardless of expected changes in the plankton production in the Barents Sea due to future warming. Recruitment is a key process, which determines the stock abundance. The effect of climate change on the NEA cod recruitment is rather indirect; it is a response to changes in prey or predators. The mechanism of this influence is complicated, and it is difficult to identify contribution of the different drivers to the recruitment success.

Conclusions

Changes in the harvesting strategy of NEA cod in response to the expected warming in the Barents Sea will be determined by:

- F_{msy} increase due to stock productivity growth;
- shift of fishing selectivity to the younger fish due to acceleration of growth rate;
- changes in the fishing pattern caused by climate-induced changes in natural mortality rate, including cannibalism.

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Filin A.A. 2005. STOCOBAR model for simulation of the cod stock dynamics in the Barents Sea considering the influence of ecosystem factors.// Ecosystem dynamics and optimal long-term harvest in the Barents Sea fisheries. - Proceedings of the 11-th Russian-Norwegian symposium Murmansk, 15-17 August 2005 / PINRO Press Murmansk, 2005 / Pp. 236-247.

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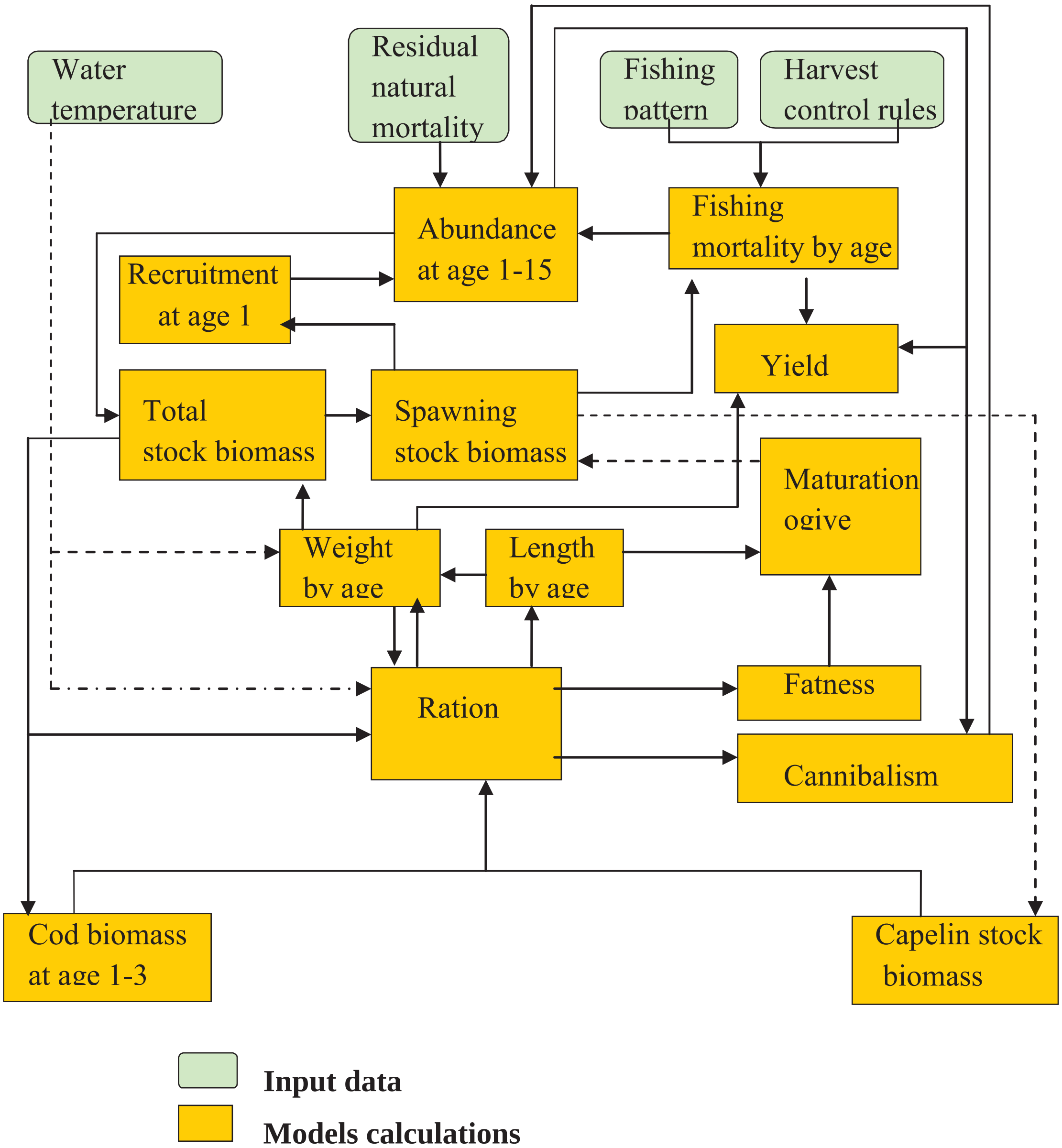
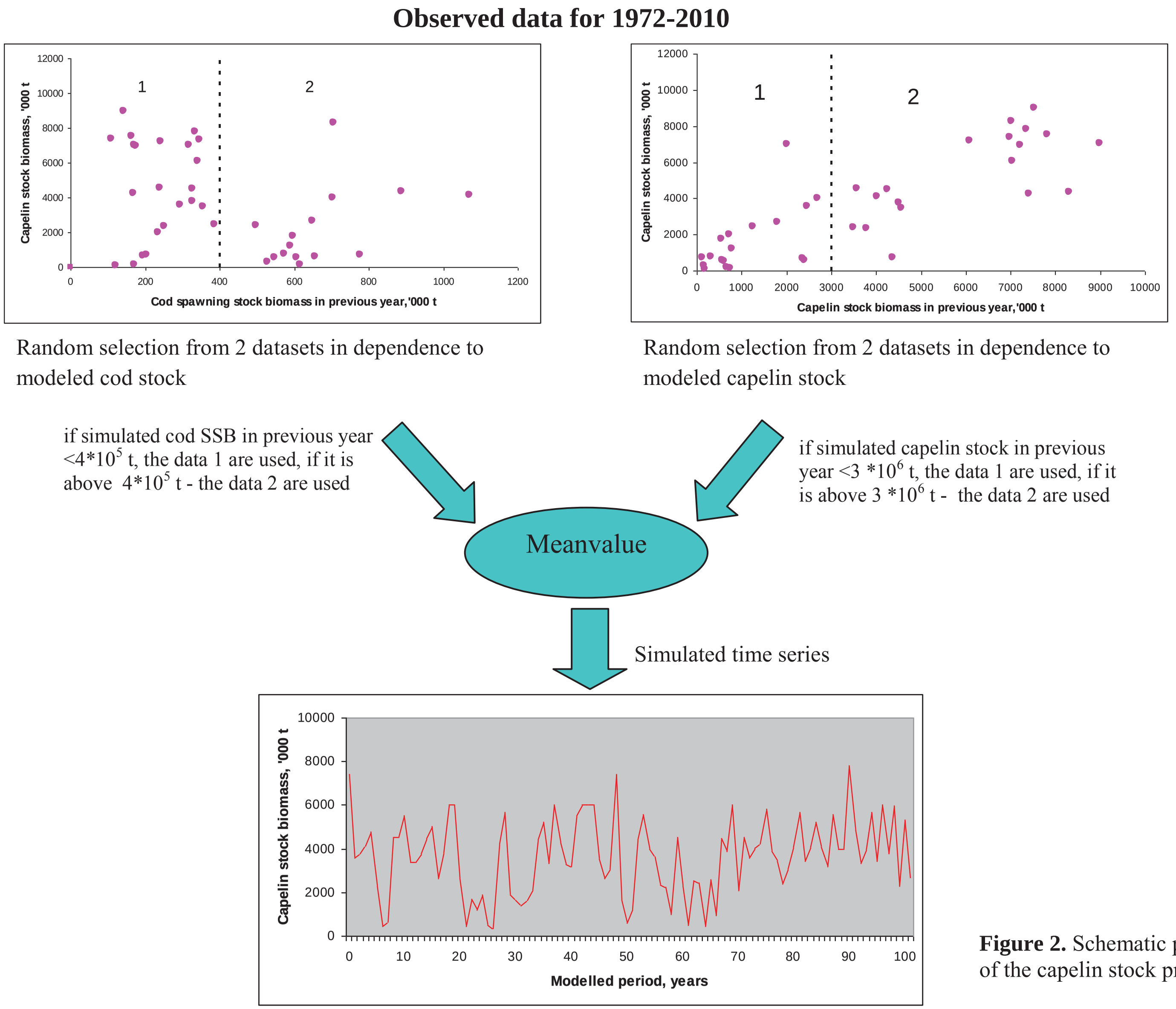


Figure 1. A schematic description of functional links used for the cod stock simulations in the STOCOBAR model.


Observed data for 1972-2010

Random selection from 2 datasets in dependence to modeled cod stock

Random selection from 2 datasets in dependence to modeled capelin stock

if simulated cod SSB in previous year $<4*10^5$ t, the data 1 are used, if it is above $4*10^5$ t - the data 2 are used

if simulated capelin stock in previous year $<3*10^6$ t, the data 1 are used, if it is above $3*10^6$ t - the data 2 are used

Meanvalue

Simulated time series

Figure 2. Schematic presentation of the capelin stock projections.

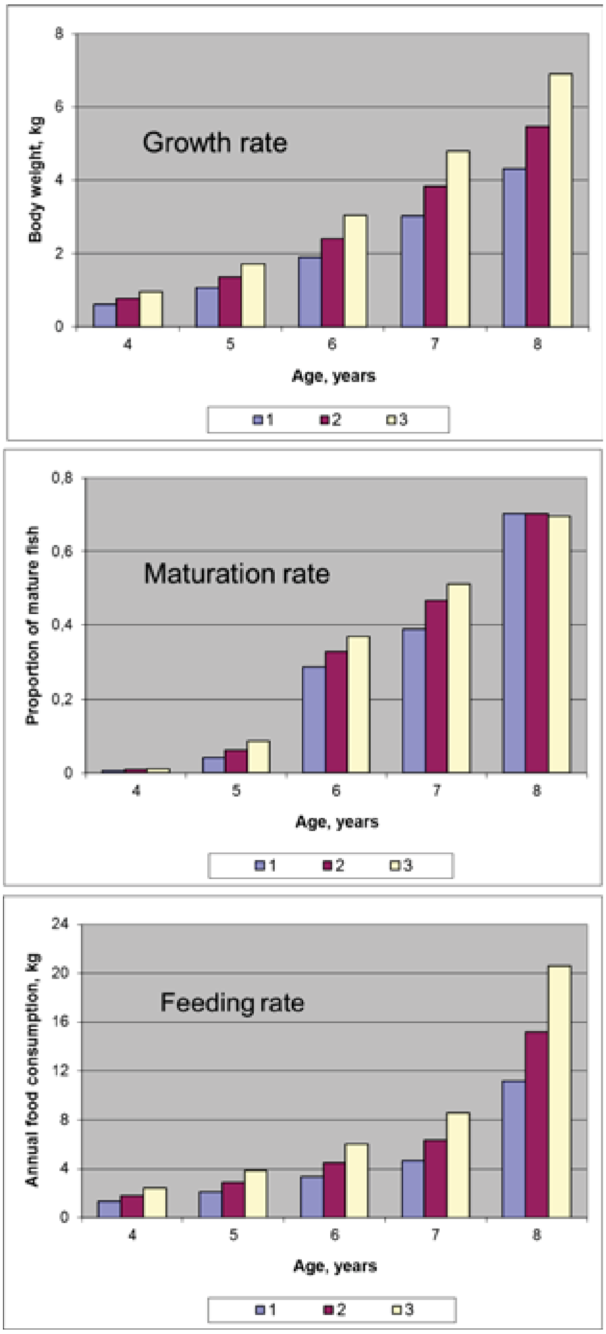


Figure 3. Comparison of simulated mean long-term cod stock parameters under the 3 scenarios of future temperature regime in the Barents Sea and the single fishery management (F_{pa}=0,50): 1 – current temperature regime; 2- warming scenarios of 1ºC.; 3 - warming scenarios of 2ºC.

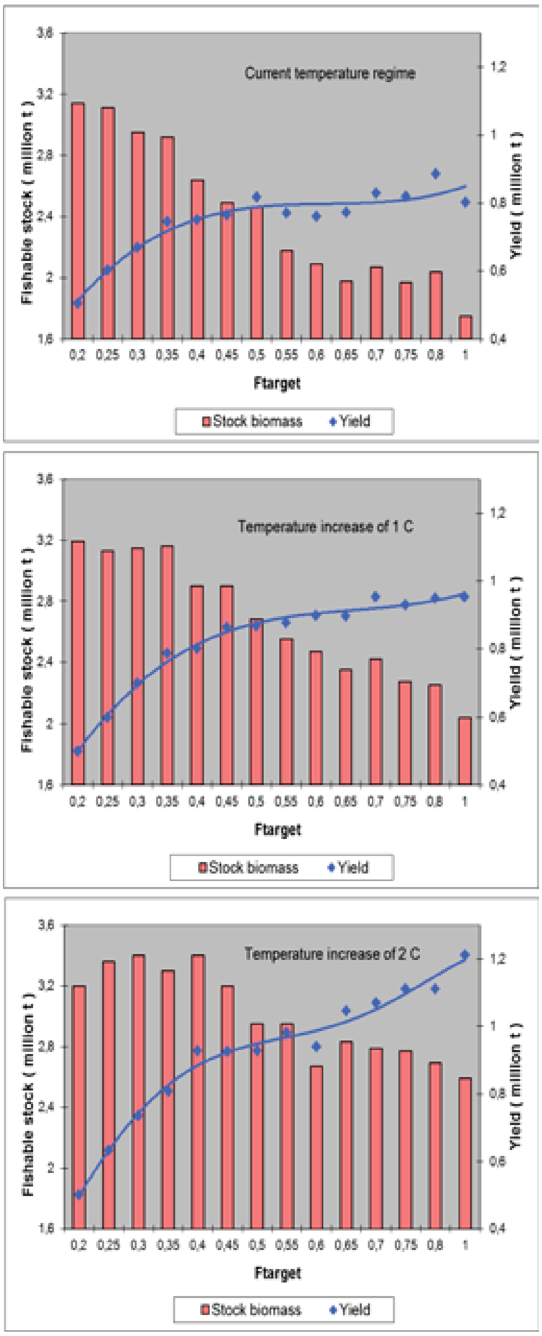


Figure 4. Simulated long-term mean annual stock size and yield of cod as a function of fishing mortality under the 3 scenarios of future temperature regime in the Barents Sea. The line denotes trend.

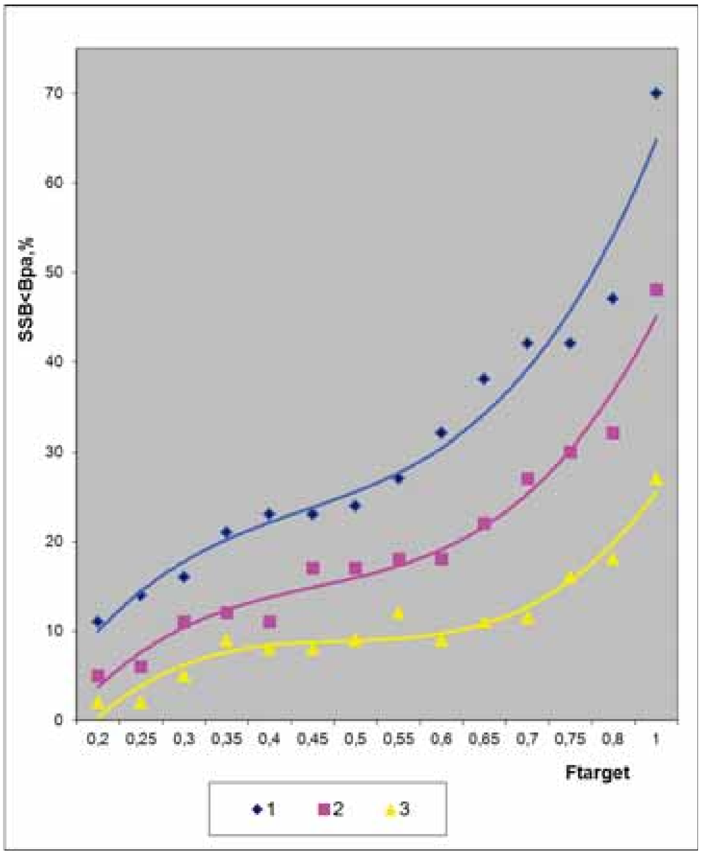


Figure 5. Simulated probability of mean long-term drop of cod SSB below B_{pa}=460*103 t as a function of fishing mortality under the 3 scenarios of future temperature regime in the Barents See: 1- current temperature regime; 2 – temperature increase of 1ºC; temperature increase of 2ºC. The lines denote trends.

Appendix 1: Symposium programme

The 15th Russian-Norwegian symposium on

Climate change and effects on the Barents Sea marine living resources

UNIS in Longyearbyen, Svalbard, Norway, 7-8 September 2011

Organized by the Institute of Marine Research (IMR), Norway
and Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Russia

Participation

The symposium addressed scientists, fishery managers and representatives of the fishing industry.

Scope

The long term climate changes imply increased temperatures, less ice and a warmer ocean in the Barents Sea area. However, a special challenge in analyzing the Barents Sea ecosystem is that the short-term trend (since 2006) shows decreasing temperatures and increasing sea ice cover. The Russian-Norwegian Symposium 2011 aims to address question related to these long and short term variations, and ask what these physical changes really are, and how they may protrude into the future. Furthermore, the question is raised as to how these assumed climate driven physical changes may change the ecosystems, and what implications and future challenges this represents for the management of the resources in the area.

Proceedings

The Proceedings of the symposium will be edited by an editorial board, including T. Haug, I. Røttingen and K. Sunnanå from IMR, and K. Drevetnyak, Y. Lepesevich and O. Titov from PINRO, and published in the IMR/PINRO Joint Report Series.

Symposium Programme Committee

From Norway:	From Russsia;
T. Haug, IMR	Y. Lepesevich, PINRO
O.J. Lønne, UNIS	O. Titov, PINRO
O.A. Misund, IMR	
I. Røttingen, IMR	
K. Sunnanå, IMR	

Local organizing committee:

Trond Broks and Vera H. Lund, Institute of Marine Research

Tuesday 6 September 2011

0800-0900 **Historical and cultural meeting with Longyearbyen**
Guided walk in Longyearbyen, starts from the main entrance of the Hotel.

1000-1030 **Icebreaker**
Joint refreshments in the Hotel Bar.

Wednesday 7 September 2011

0800-0845 **Registration**

0845-0915 **Opening adresses (Chair: T. Haug)**
O.J. Lønne, UNIS
O.A. Misund, IMR
Y. Lepesevich, PINRO

0915-1015 **Theme session I: What are the changes?**
(Chair I. Røttingen)
J.E. Overland (NOAA PMEL, Seattle, USA): Arctic surprises: Sea ice loss and increased Arctic/Sub-Arctic linkages **(keynote)**.

1015-1045 **Coffee & Posters**

1045-1240 **Theme session I (continued)**
S. Dahle: On drifting ice to the North Pole.

V. S. Lien & A. G. Trofimov: The Barents Sea – Arctic Ocean gateway: Water mass characteristics and transformations.

R. Ingvaldsen, H. Loeng & S. Lind (IMR): Barents Sea climate variability during the last decade.

B. N. Kotenev, A. S. Krovnin & S.N. Rodionov (VNIRO, Russia): Climate trend forecast for the Norwegian and Barents Seas in 2012-2025.

B. Ådlandsvik, W. P. Budgell & A.B. Sandø (IMR): Regional climate scenarios for the Barents Sea.

I. Esau (Nansen Centre/Bjerknes Centre, Norway) & I.Repina (Obukhov Institute for Atmospheric Physics, Moscow, Russia): Observations and fine-resolution large-eddy simulations of the katabatic wind over Kongsvegen glacier, Kongsfjorden and Ny Ålesund.

1240-1400	**Lunch** Served at the symposium venue
1400-1810	**Theme session II: What effects can be expected on the ecosystem? (Chair: Y. Lepesevich)** O. Titov (PINRO): Fishery and oceanographic aspects of performance of the Barents Sea ecosystem and the experience with their application by the ICES AFWG (**keynote**). H. Loeng (IMR): From the Barents Sea to the Arctic Ocean. K. Drinkwater (IMR), S. Basedow (University of Nordland, Norway), Y. Børsheim (IMR), M. Carroll (Akvaplan-niva, Norway), S.R. Erga, I. Fer (University of Bergen, Norway), K. Hancke, E. Hovland (NTNU, Trondheim, Norway), V.Lien (IMR), S. Våge (University of Bergen, Norway) & B. Ådlandsvik (IMR): The Polar Front and its influence on the Barents Sea ecology. L. Buhl-Mortensen, P. Buhl-Mortensen, B. Holte, L.L. Jørgensen & A.H. Tandberg (IMR): Baseline mapping: a necessity for an assessment of effects on climate changes on benthic communities.
1600-1630	**Coffee & Posters**
1400-1810	**Theme session II (continued)** I. Manushin, N. Anisimova, and P.Lubin (PINRO): Long-term changes of macrozoobenthos in the southeastern Barents Sea. M. L. Carroll, W.G. Ambrose Jr. (Akvaplan-niva, Norway), B.S. Levin, G.A. Henkes (Bates College, Lewiston, Maine, USA), H. Hop (Norwegian Polar Institute), W. Locke (Bates College, Lewiston, Maine, USA) & P.E. Renaud (Akvaplan-niva, Norway): Pan-Svalbard growth rate variability and environmental regulation in the Arctic bivalve *Serripes groenlandicus*. P. Wassmann & M. Reigstad (University of Tromsø, Norway): Climate induced changes in primary production and pelagic-benthic coupling in the northern Barents Sea. J. E. Søreide (UNIS), M.L. Carroll (Akvaplan-niva, Norway), H. Hop (Norwegian Polar Institute), W.G. Ambrose Jr. (Bates College, Lewiston, USA), E. N. Hegseth (University of Tromsø, Norway) & S. Falk-Petersen

(Norwegian Polar Institute): Trophic structure and carbon flow in Arctic- and Atlantic regimes around Svalbard revealed by stable isotopes and fatty acid tracers.

Ø. Varpe (Norwegian Polar Institute), C. Jørgensen (Uni Research, Norway) and Ø. Fiksen (University of Bergen, Norway): Double menu for *Calanus* in the Arctic: what are the life history consequences in a changing climate?

1930 **Adventure in the wild – hiking tour (with dinner) in Adventdalen**
Starts from the main entrance of the Hotel.

Thursday 8 September 2011

0830-1010 **Theme session II: (continued; Chair K. Sunnanå)**

M. Daase, S.Falk-Petersen, E. Leu, A.Wold, Ø. Varpe (Norwegian Polar Institute), J.E. Søreide, J. Berge (UNIS), D. Martynova (Russian Academy of Science, St. Petersburg), D. Benoit (University of Quebec, Canada), G. Darnis, L. Fortier (Laval University Quebec, Canada) & K. Eiane (University of Nordland, Norway): Timing of the blooms determines the life strategy of Arctic *Calanus glacialis*.

A. Shadrin (Lomonosov Moscow State University, Russia), E. Eriksen (IMR), V. Makhotin (Lomonosov Moscow State University, Russia), H. Gjøsæter & S. Subbey (IMR): Embryological studies of capelin eggs under different temperature conditions.

R. Ingvaldsen & H. Gjøsæter (IMR): Impact of marine climate variability and stock size on the distribution area of Barents Sea capelin.

H. Hop (Norwegian Polar Institute) & H. Gjøsæter (IMR): Polar cod and capelin in relation to water masses and sea ice conditions.

O.S. Kjesbu, J.E. Skjæraasen, F. Rey (IMR) & C. Jørgensen (University of Bergen, Norway): The link between temperature, fish size, spawning time and reproductive success of Atlantic cod.

1010-1100 **Coffee & Posters**

1100-1300 **Theme session II (continued)**

B. Bogstad, G.E. Dingsør, H. Gjøsæter & R. Ingvaldsen (IMR): Changes in the relations between oceanographic conditions and recruitment of cod, haddock and herring in the Barents Sea.

G.O. Johansen, E. Johannesen & K. Michalsen (IMR): Size and age dependent geographic distribution of NEA cod in the Barents Sea - effects of physical conditions and abundance.

A.V. Dolgov & A.L. Karsakov (PINRO): Species-specific habitat conditions and possible changes in the distribution of fishes in the Barents Sea under climate change.

M.A. Wiedmann, M. Aschan & R. Primicerio (University of Tromsø, Norway): Vulnerable fish species in the Barents Sea.

K.V. Drevetnyak, M.Yu. Antsiferov & P.A. Murashko (PINRO): The effect of climate fluctuations on demersal fisheries in the Barents Sea and adjacent waters.

1300-1400 **Lunch** Served at the symposium venue

1400-1500 **Theme session II (continued)**

E.L. Orlova, A.V.Dolgov, I.P. Prokopchuk & A.P.Yakovlev (PINRO): Influence of climatic changes in the Barents Sea on functioning of trophic complex makroplankton-pelagic fishes-cod.

A.K. Frie, T. Haug, U.Lindstrøm, K.T. Nilssen & T.-A. Øigård (IMR):

Variability in population parameters of Northeast Atlantic harp seals;

responses to changes in sea temperature and ice cover?

E. Yakushev (NIVA, Norway): Modeling of the role of organic matter production and destruction on the carbonate system seasonal changes in the Barents Sea.

1500-1600 Theme session III: Management implications and challenges. (Chair O. Titov)

A.H. Hoel (IMR): Implications of climate change for the management of living marine resources (**keynote**).

E. Shamray & Y. Lepesevich (PINRO): If the management of living marine resources ought to be effected by climate changes? (**keynote**)

1600-1630 Coffee & Posters

1630-1800 Theme session III (continued)

I. Røttingen & S. Tjelmeland (IMR): The collapse of the Norwegian spring - spawning herring stock; Climate change or fishing effort?

V. M. Borisov, M.A. Bogdanov & I.V. Tarantova (VNIRO, Russia): Sea surface temperature dynamics and year class strength of capelin (*Mallotus villosus*) in the Barents Sea.

D. Howell (IMR), A. Filin (PINRO), B. Bogstad, J.E. Stiansen & E. Eriksen (IMR): Unquantifiable uncertainty in projecting stock response to climate change: Example from NEA cod.

K. Michalsen (IMR), D.D. Prozokevich (PINRO), P. Dalpadado, E. Eriksen, H.Gjøsæter, R. Ingvaldsen, E. Johannesen, L.L. Jørgensen, T. Knutsen & M. Mauritzen (IMR): Ecosystem surveys: lessons learned in the Barents Sea.

1930 Reception, followed by the conference dinner at the conference venue

Posters

Theme session I: What are the changes?

E.L.Vinogradova (P.P.Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia): Variability of hydrochemical structure at inner and outer boundaries of Eurasian Arctic estuaries.

Theme session II: What effects can be expected on the ecosystem?

B. Planque, E. Johannesen, K. Michalsen (IMR), R. Primicerio (University of Tromsø, Norway), M. Fossheim, R. Ingvaldsen (IMR) & M. Aschan (University of Tromsø, Norway): Barents Sea Ecosystem Resilience under global environmental change, BarEcoRe: 2010-2013.

E.L. Orlova, V.N. Nesterova, & O.V.Goncharova (PINRO, Russia): The implementation means of Calanus hyperboreus and Mallotus villosus reproductive strategies in the Barents Sea (2002-2009).

E. Eriksen, G.O. Johansen, R. Ingvaldsen & J.E. Stiansen (IMR): How is year class strength of 0-group cod in the Barents Sea influenced by its dynamics and geographical distribution?

L. Klyashtorin & V. Borisov (VNIRO, Russia): Climate changes impacts on the herring and cod stocks dynamics. The possibility of forecasting.

A.V. Dolgov (PINRO) & E. Johannesen (IMR): Structure of the Barents Sea fish community as result of climatic fluctuation.

B. Bogstad, P. Dalpadado (IMR), H. Hop (Norwegian Polar Institute), E. Orlova, G. Rudneva, I. Prokopchuk & V. Nesterova (PINRO): Feeding of polar cod in the Barents Sea related to food abundance and oceanographic conditions.

N.A. Yaragina & A.V. Dolgov (PINRO): Long-term variations in the importance of prey species for demersal fishes in the Barents Sea under climate change.

O. Svetocheva (MMBI, Russia), E. Eriksen & T. Haug (IMR): Barents Sea Ammodytidae and their ecological significance for the top predators during summer feeding.

T.A. Karaseva & T.V. Shamray (PINRO): Monitoring of external pathologies in fish as a method of integral estimation of changes in the ecosystem of the Barents Sea under the influence of nature and climate factors.

V. Zabavnikov & I. Shafikov (PINRO): Marine mammals and their possible influence on fishery under current state conditions in the Barents Sea.

C. Schrumm (University of Bergen, Norway) & E. Yakushev (NIVA, Norway): Modeling of PCB propagation in the Barents Sea.

Theme session III: Management implications and challenges.

A.A. Filin (PINRO): Simulation of changes in the harvesting strategy of the Northeast Arctic cod as response to the climate change

Appendix 2: List of participants

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