Workshop on Ecosystem Modelling of Faroese Waters
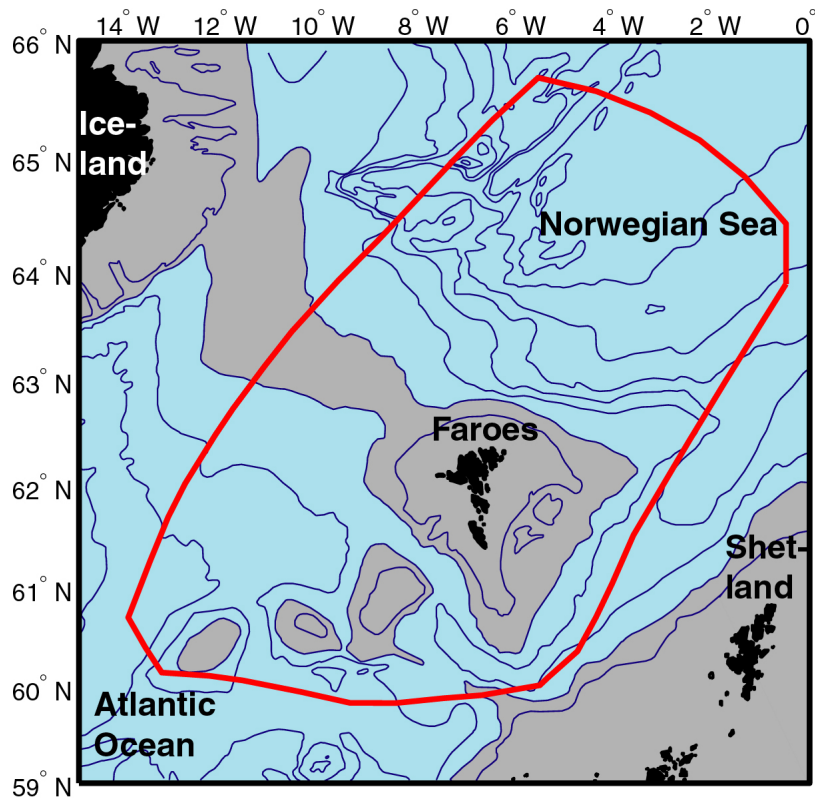## Tórshavn 24-26 September 2002

FRS 2003

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Summary

This report documents the results of a workshop on ecosystem modelling of Faroese waters, held in Tórshavn from the 24th to the 26th September 2002, organized by the Faroese Fisheries Laboratory (FFL), and financed by the Faroese Oil Industry Group (FOÍB). The aim of the workshop was to help the FFL and the rest of the Faroese research community strengthen the background for a coordinated attempt to model the Faroese marine ecosystem. As in other areas, most of the research in Faroese waters has focused on specific topics or species. Through these efforts, large data sets have been accumulated, which address many different components of the ecosystem, biotic as well as abiotic. Attempts have also been made to link biological variations to one another and to environmental factors. So far, most of the established links are, however, qualitative and hypothetical and we lack a consistent and quantitative understanding of, how variations in the abiotic environment or parts of the ecosystem affect the rest of the system. In other regions, mathematical models have been developed and have had some success in describing variations in smaller or larger parts of marine ecosystems. The FFL has therefore initiated an effort towards developing a mathematical model for the Faroese marine ecosystem. This work is at a very initial stage and the main purpose of the workshop was to help plan how to progress in it. What kind of models would it be appropriate to attempt for the Faroe region? What information is necessary as input to these models? Are there some key components or parameters for which we lack the necessary observational evidence? These were some of the questions that the workshop was aimed at clarifying.

To provide the best possible background for these questions, a number of foreign experts were invited together with Faroese researchers working with different components of the Faroese marine ecosystem. On the first day of the workshop, the participants from the FFL and the rest of the Faroese research community presented what was intended to be an overview of what is known about Faroese waters, what data sets are available, and what are the largest gaps in knowledge. On the second day, the invited experts gave presentations based on their work. Extended abstracts from the talks given on these two days form the main part of this report.

The last part of the workshop was a discussion on how to proceed. During a plenum session, a number of key questions were raised and three subgroups were formed. Reports from the discussions within these subgroups are included in this document and were presented in a final plenum discussion. The main conclusions and recommendations from the workshop may be summarised as follows:

- The Faroese Marine ecosystem – especially in the regions close to the Faroe Plateau - seems to be a fairly tightly coupled system with coherent variations from the primary producers to high trophical levels, including some of the commercially most important demersal fish stocks.

- Large inter-annual variations have been observed in primary production on the Faroe shelf. Understanding the causes for these will be essential for rational management of the demersal fisheries on the Faroe Plateau.

- Some investigations indicate that exchanges of water and zooplankton, especially *Calanus finmarchicus*, between on-shelf and off-shelf waters determine the annual primary production on the shelf. The work started in developing the MEMFIS plankton production model seems to have the potential to clarify this relationship and development of this model should be continued. Purely hydrodynamical models should also be used to investigate the dynamics of these exchanges.

- To constrain uncertainties in production models, more observations need to be carried out on some key parameters. Monitoring of the Photosynthetically Active Radiation (PAR) should be initiated and field experiments, using in-situ and satellite sensors, should be carried out to measure the magnitude and variability of on-shelf/off-shelf exchange.

- An alternative hypothesis for variations in shelf primary production is top-down control through predation. This type of relationship is well suited for ecosystem modelling, but lack of information on some key species, such as sandeel, may introduce large uncertainties into the models. Efforts should be taken to acquire more information on these species.

- A key question is, to what extent, grazing by zooplankton affects primary production on the Faroe shelf. In addition to the modelling studies, in-situ and/or laboratory experiments need to be carried out to clarify this question.

- Increased understanding of ecosystem links can be obtained by studying episodic or extreme events. One example is the period 1990-91, which exhibited many abnormal features in Faroese waters. Hindcast studies of these periods should be carried out, where biological events are compared to output from large scale ocean models with realistic atmospheric forcing.

- The relatively small geographical extent and the tight couplings of the Faroese marine ecosystem seems to make ecological links more visible than in systems that are more complex. This makes the Faroese system a natural laboratory for marine ecological studies. At the same time, the similarity to other well studied areas, such as Georges Bank, indicates that comparison to these areas might give useful information on the Faroese marine ecosystem.

Introduction

Hjalti í Jákupsstovu
Faroese Fisheries Laboratory

Why a workshop on ecosystem modelling of the Faroese waters? Do we in this small country have the necessary data? Do we have qualified persons to undertake such a great task? And finally will such a model be of any practical use? I will in a circumstantial way try to answer these questions.

The Faroe Islands emerging out of the Iceland - Scotland Ridge are situated 180 nm from its closest neighbours - Shetland, also a group of islands, 240 nm from Iceland and 360 nm from Norway (Figure 1.). The climate, dominated by the sea is wet and cold, and the production on land is consequently sparse, and in order to live on the Faroes for 1100 years the Faroese people have been totally dependent on the sea. With the currents comes driftwood up to a few decades ago an invaluable resource in a country with no natural woodland. The fish in the sea provided food, and the salty air combined with in general low temperatures makes wind drying a possible and absolutely necessary method for conservation of food. Through centuries pilot whales have provided a main staple of food for the Faroese people. From the pilot whale catch statistics we know the availability to have varied both over longer periods in addition to annually. And from the history we know of both annual and periodic variation in availability of fish and driftwood. The general apprehension has been that this variability has been linked to variations in the oceanic climate. The strong tidal currents have also created a strong awareness of the effects the environment has on the life in the sea. E.g. some fishing places were only used with rising tides and other with low tide.
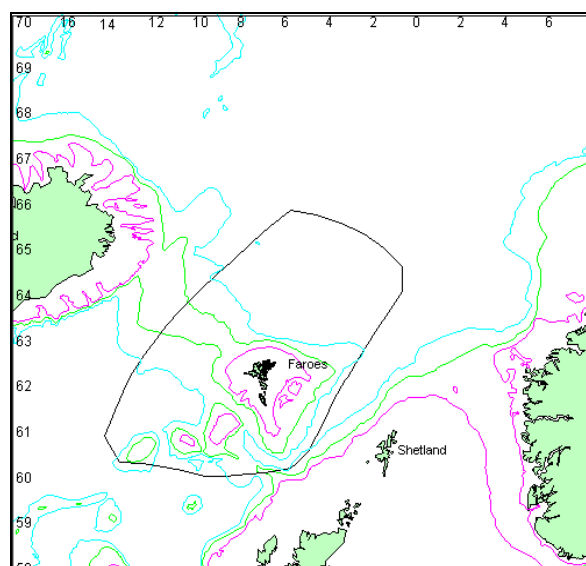
Fig. 1. The Faroese area.

The Faroese economy is still almost totally dependent of the sea and the production in the sea. And this, naturally, has created a great interest in the variability in the surrounding sea, and how this effects the resources.

The high dependency of the marine resources requires proper management. The advice on management has so far been based solely on fisheries and fishery independent survey data. However, the great variability in individual growth and recruitment to the fish stocks in the area makes an ecosystem input as well a must.

It was therefore a natural thing in our research along with fisheries research to give priority to oceanographic research. This possibility arrived in 1982 when we got our research vessel Magnus

Heinason, and in 1990 when we had the necessary laboratory facilities similarly to include biological oceanography.

We have now access to a number of time series of data relevant for the Faroese area. Several of them show clear indications on linkages between environment and availability to fisheries, other synchronically variations between primary growth and productivity in higher trophic levels.

During the workshop we will present these time series, and some of the links we have found so far. However, in order to understand these links, and to use them in the advisory process, we need models.

We, therefore, very much look forward to the workshop, which we trust will guide us in our future research, and thus be an important milestone in the history on fisheries and marine research in Faroese waters.

Acknowledgement

The Faroese Fisheries Laboratory is greatly indebted to FOÍB for funding the workshop, and to all the international experts who participated. All the Faroese experts, who presented their work and participated actively are also acknowledged.

Karina Nattestad compiled the report and together with Dagunn Olsen created the final printed version. Both are acknowledged for their work.

Faroese waters in a global perspective

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The Faroe Islands are situated in the warm Atlantic current floating northward toward the Arctic. Beneath this warm surface layer cold and dense water are floating southward toward the North Atlantic. These currents are the northern limbs of the global thermohaline circulation, figure 1.
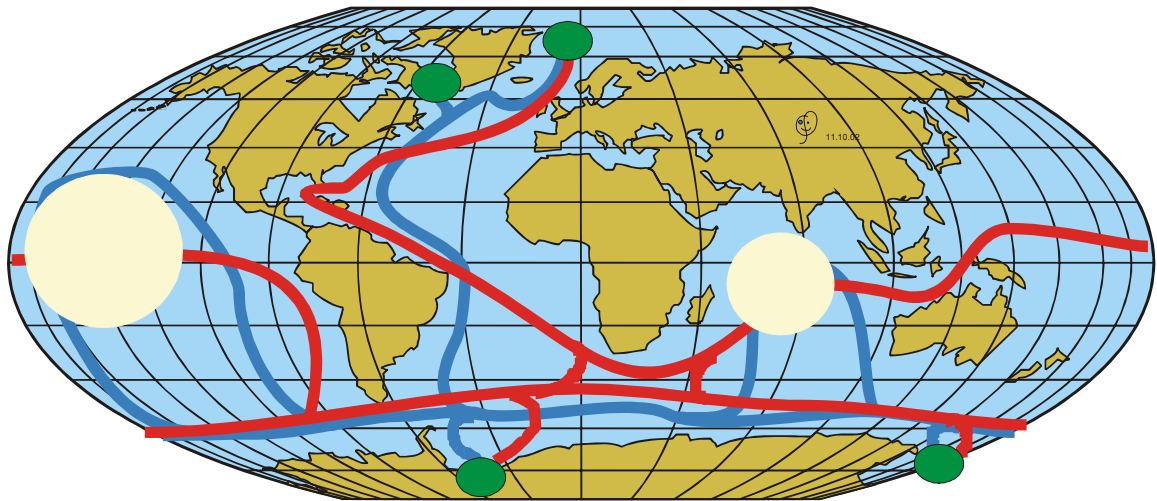

Fig. 1. Global Perspective.

Early in the history of modern oceanography one realised that the bottom water occupying the abyss of the world oceans was renewed from sources at high latitudes. In the north these sources were located in the Nordic Seas and in the south they were traced back to the Weddell Sea. The first observations of the deep water was carried out by Henry Ellis, captain of the British slavetrader "Earl of Halifax" in 1751. He discovered that the deep water in the Atlantic Ocean was cold. He was happy finding a way to cool his wine and didn't speculate on why it was so. It was natural to draw the conclusion that the origin of this cold water was at high latitudes, but it was not obvious that the deep water had to be cold.

The densest sub-surface water in the Atlantic is the water emerging from the Mediterranean Sea. This water has a high temperature but it is the high salt content that makes it dense. Increasing temperature reduces the density but high salinity increase the density. But in the end it is the relative high compressibility of cold water compared to warm water that determent which water will fill the abyss of the world ocean.

Some deep-water formation in the Pacific and Indian Ocean but most of the deep-water formation takes place in the bi-polar Atlantic Ocean. The Greenland/Iceland Sea, Labrador Sea and Weddell Sea cover only 5% of the total area but produce about 75% of the total deep and bottom water.

The bottom layer in the Atlantic Ocean is filled with water from Antarctica, figure 2. This water is called Antarctic Bottom water. Above this layer the North Atlantic Deep Water flow southwards. The most important processes in the formation of the coldest and heaviest bottom water, the Antarctic Deep Water, are connected with the Filchner-Ronne Ice shelf in the southern Weddell Sea. Then seawater interacts with the ice shelf it will be cooled down to its in situ freezing point temperature, which decrease with the depth. The dense water sinking down to the deep southern ocean may therefore have an initial temperature as low as –2.2°C. In Arctic great ice shelf don't exist and cooling of the seawater take place at the surface and the lowest possible temperature is the sea
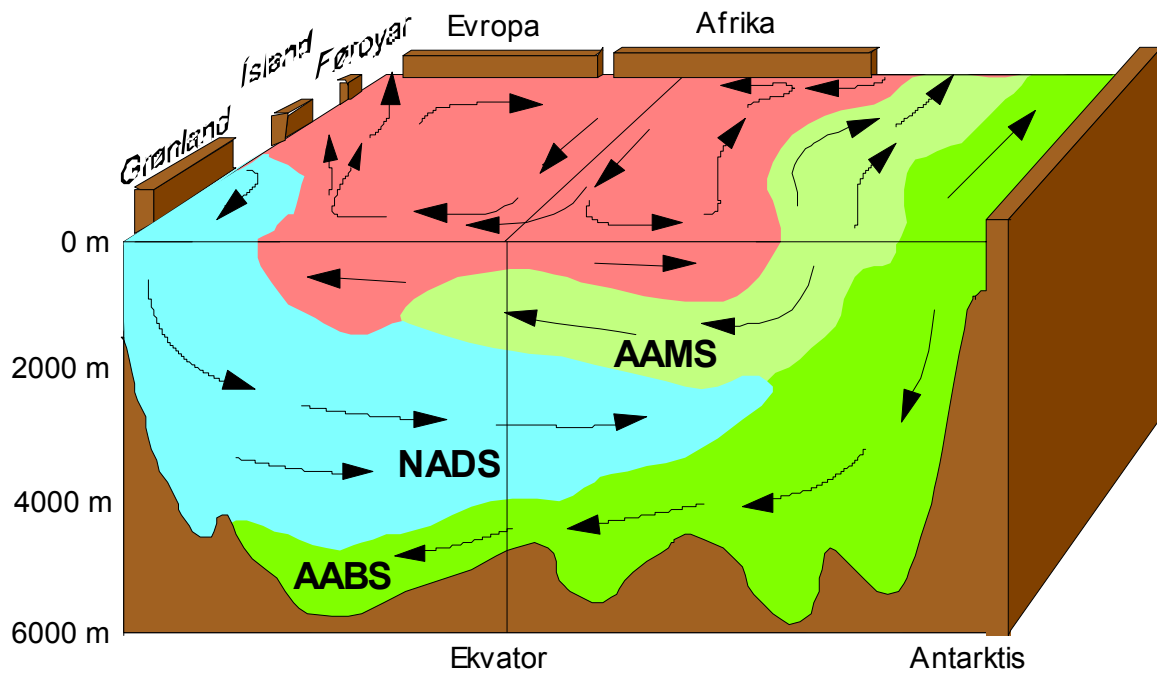
Fig. 3. BT figure.

surface freezing point (-1.9). In Arctic the main sources of deep water are the Labrador Sea and the Greenland/Iceland Seas.

If we make a simple drawing of the Nordic Seas exchange with the Atlantic Ocean it may look like the cartoon in figure 3. The communication between the North Atlantic and the Nordic Seas results in the most dramatic water mass conversions in the World Ocean. The influx of warm and saline Atlantic water in to the Nordic seas is separated by cooling and freezing into shallow fresh water (and ice) and saline deep waters. Witch provides the initial driving of the global thermohaline circulation cell by returning into the North Atlantic.
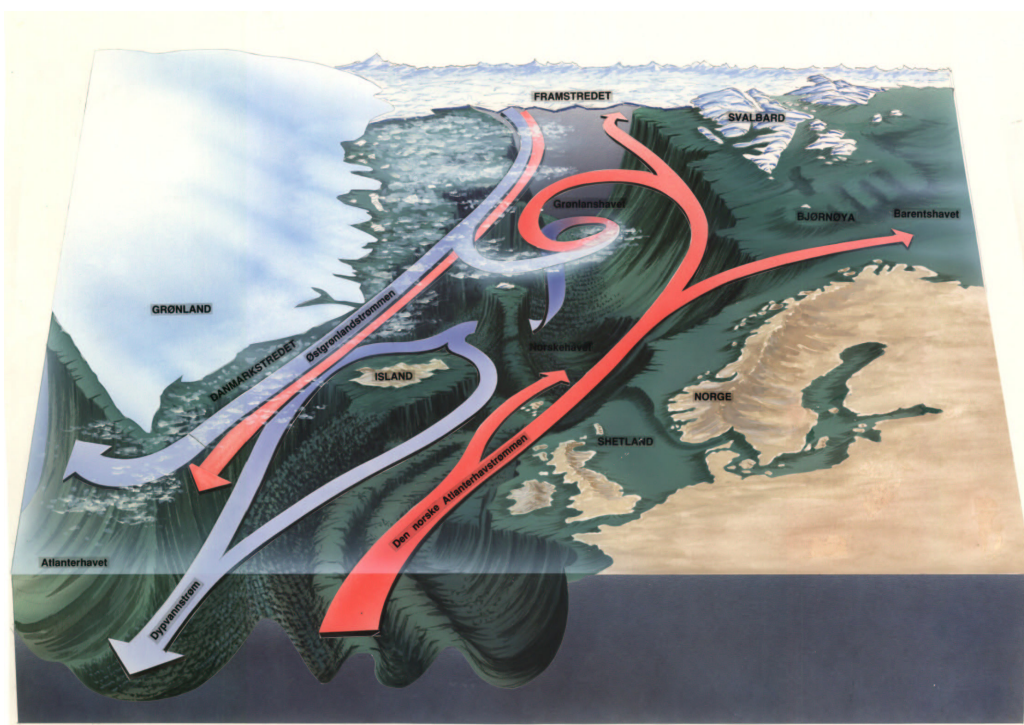
Fig. 2. Atlantic Ocean longitudinal section.

Faroese Waters

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Faroese waters are split into two parts by a series of ridges that are part of the Greenland-Scotland Ridge (Fig. 1). On both sides of the ridge, bottom depths exceed 1500m while the ridge itself has typical sill depths around 500m. The Atlantic sector, south-west of the ridge, includes a number of banks. North-east of the ridge, the Norwegian Sea extends to depths more than 3000m in the Faroese area.

In the surface, most of the area is covered by warm, saline Atlantic waters that flow past the Faroes into the Norwegian Sea. Only in the northernmost part are Faroese surface waters affected by cold, less saline, Arctic water masses that are carried into the area by the East Icelandic Current (Fig.2).
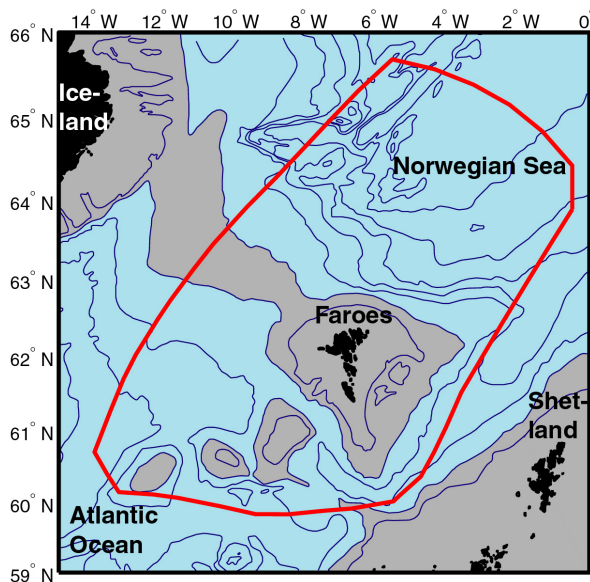
Fig. 1. Faroese waters may be defined as the ocean area within the Faroese economical zone, shown by the red curve. Gray areas are shallower than 500m.
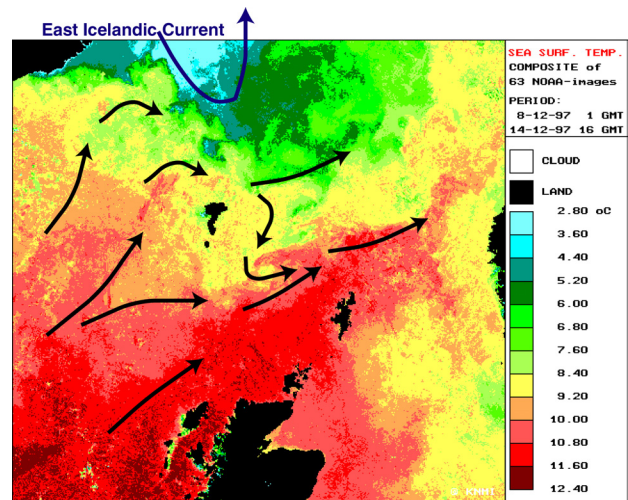
Fig. 2. Surface temperature in Faroese waters, 8.-14. December 1997 based on infrared satellite images (courtesy of the Royal Netherlands Meteorological Institute, KNMI). Arrows indicate main flow patterns.

The relatively homogeneous character of the surface waters disappears when going to larger depths. In the Atlantic sector, south-west of the ridge, warm (and saline) water extends to large depths while the north-eastern sector is dominated by cold (<0°C) and less saline water from around sill level and down to the bottom. At depths below the sill, the two regions therefore exhibit quite different characteristics (Fig. 3).

In mostly all directions out from the Faroes, we therefore find warm, saline Atlantic water in the upper layers and cold, less saline water at depth. Inbetween, water from the East Icelandic Current may often be identified as a salinity minimum, especially on the eastern side of the Faroe Plateau. This introduces an east-west asymmetry, especially at intermediate depths. The interface between the warm upper layers and the colder layers below is typically found at some 400-600m depth, but may vary considerably which introduces large variations of the bottom temperature at these depths (Fig. 4).
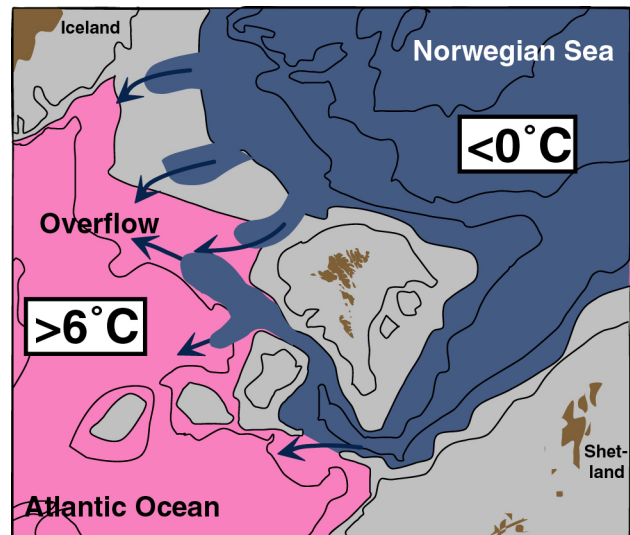
Fig. 3. At depths about 600-800 m, there is a large difference in temperature (and salinity) between the two regimes on either side of the ridge. There is, however, an overflow of cold water across the ridge that influences conditions in the Atlantic sector.
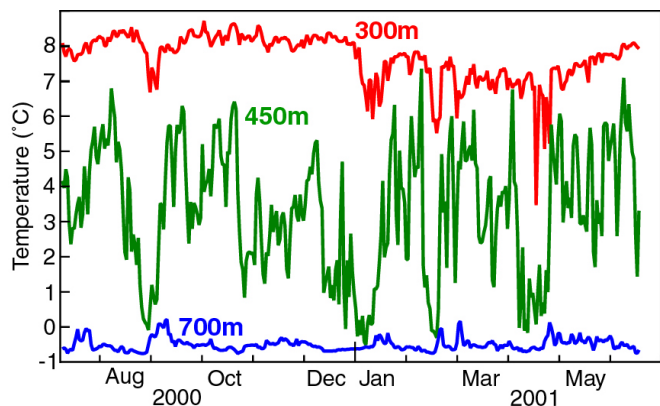
Fig. 4. Daily averaged bottom temperature at three sites north of the Faroes at different depths during a period, slightly shorter than one year.

As a whole, Faroese waters exhibit a fairly diverse and fairly variable character. Both the characteristics and the flow patterns, in the surface, as well as at depth, are determined by the thermohaline ventilation processes, occurring farther north in the Arctic Mediterranean. These processes generate the cold waters that flow past the Faroes at depth and the compensating inflow of warm Atlantic water in the surface. How these processes will change with global climate change, will determine how Faroese waters will be in the future.

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The Hydrography on the Faroe Shelf

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Faroese Fisheries Laboratory

The Faroe Islands are situated at 62°N 7°W and are surrounded by a shelf, which is approximately described by its 150 m bottom contour. The 200 m bottom contour occupies about 21000 km^2, and the width of the shelf is greatly varying around the islands (Fig. 1). It is only about 12 km wide east of the southernmost island and approxi-mately 50 km wide in the northwest direction. In some areas the topography is smooth with a well-defined shelf break, and in others it is irregular or continuously sloping without a shelf break.
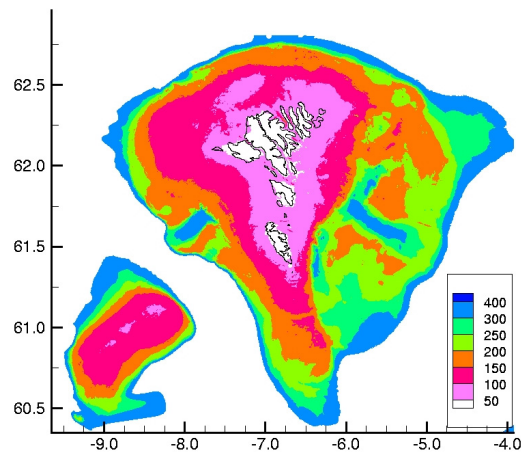
Fig. 1. The Faroe Plateau and the Faroe Bank. Courtesy of Knud Simonsen.

Because of strong tides, the on-shelf water is well mixed throughout the year, while the off-shelf water can be stratified in the summer season. In winter the cooling is on the other hand more efficient on the shelf (Fig. 2). This creates a temperature front, not only in the summer season, but also almost throughout the year, except for the period October/November. The temperature front is most pronounced in the spring before the onset of off-shelf stratification and least pronounced or non-existing in the autumn, when the stratification is broken down. The location of the front is analysed using SST measurements from R/V Magnus Heinason and it is found, that the frontal theory by Soulsby (1983), which includes the rotation of the tidal ellipses, best fits the observed location. But here, the influence of the wind is not taken into account.
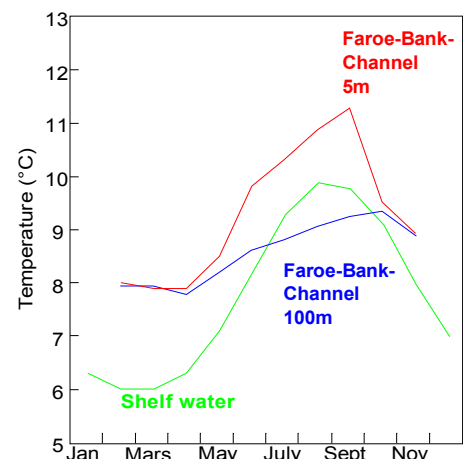
Fig. 2. Monthly mean temperature (°C) on the shelf (green) and in the Faroe Bank Channel at 5 m depth (red) and 100 m depth (blue) representing off-shelf water. The temperature on the shelf is based on measurements at Mykineshólm 1914-69, while the temperatures in the Faroe Bank Channel are based on mea-surements from R/V Magnus Heinason 1982-97. Adapted from Hansen (2000).

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The water inside the front occupies a special role in the Faroese marine ecosystem (Gaard *et al*., 2002) and is an important nursery area for larvae of many commercially important fish stocks. The primary production, the cod and haddock recruitment etc. are seen (Fig. 3) to have a decadal variation. Since the tides and the winds also have variations with timescales of decades it is believed that the exchanges of water and various properties across the front are very important from the biological point of view. Acquiring more detailed knowledge about the front aiming to find a relation ship between the physical processes in the front and the Shelf production is therefore a high priority.
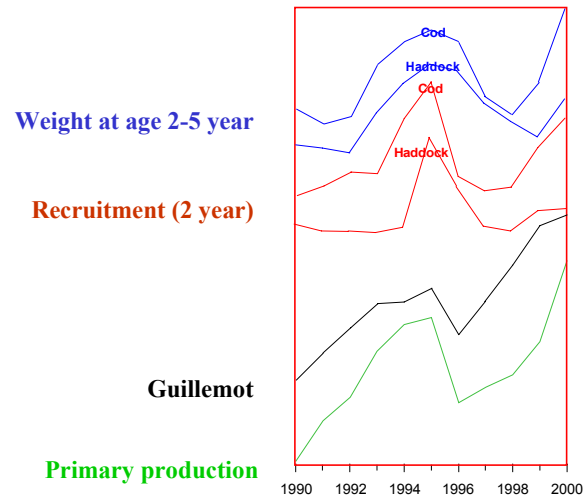
Fig. 3. Relative variability in calculated new primary production on the shelf, number of attending guillemots, re-cruitment of 2 years old cod and haddock, and mean weight of 2-5 years old cod and haddock during 1990-2000. Adapted from Gaard et al. 2002.

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Validation of a 3-D Ocean model in Faroese waters

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Warm and saline Atlantic water is transported over the Greenland Scotland ridge and into the Nordic Seas in two main branches. One branch goes between Iceland and the Faroe Islands and these water masses converge to the north of the Faroes were the flow is termed the "Faroe Current". The other branch is the Continental Shelf Current flowing between the Faroes and Shetland. From the mid nineties to present, these two branches have been monitored by regular CTD-cruises and by semi-permanent ADCP current measurements along the two standard sections, N and S, as showed in Figure 1.
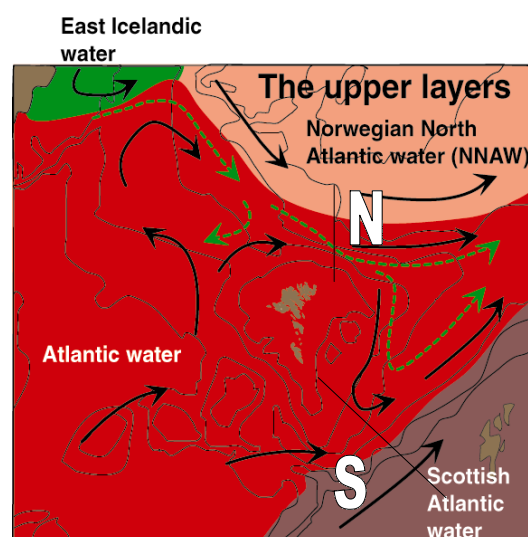
Fig. 1. The upper layer main flow pattern and the standard sections N and S.

Data from these two sections are used to validate a regional version of the MICOM (Miami Isopycnal Ocean Model) model that is presently being run at Nansen Environmental and Remote Sensing Centre, (NERSC) in Bergen. This work is a part of the "West Nordic Ocean Climate program", which is funded by the Nordic Council of Ministries.

The modelled surface flow pattern and temperature were first qualitatively compared to data measured by satellite (Figure 2), finding that the model produced certain mesoscale features found in the data.
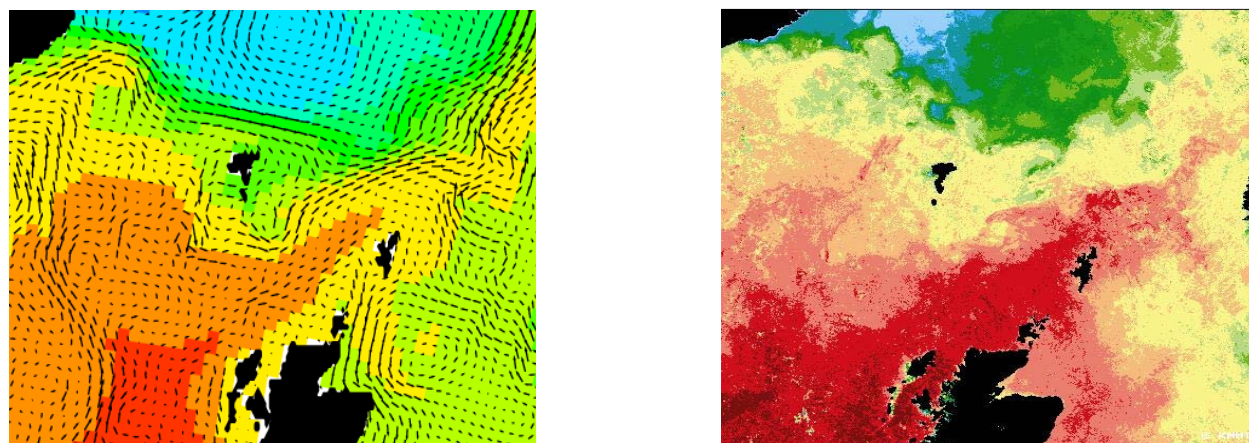
Fig. 2. The regional version of the MICOM model. Left panel: Averaged simulated flow pattern and temperature in the mixed layer. The right panel shows measured sea surface temperature.

Then modelled cross-sections (i.e. temperature as a function of vertical and horizontal coordinates) were picked out from the locations where the standard sections are. These sections were then compared to the measurements. A spatial comparison of the temperature in section N is shown in Figure 3 as an example, and the temporal development of the averaged temperature in this same section is shown in Figure 4.
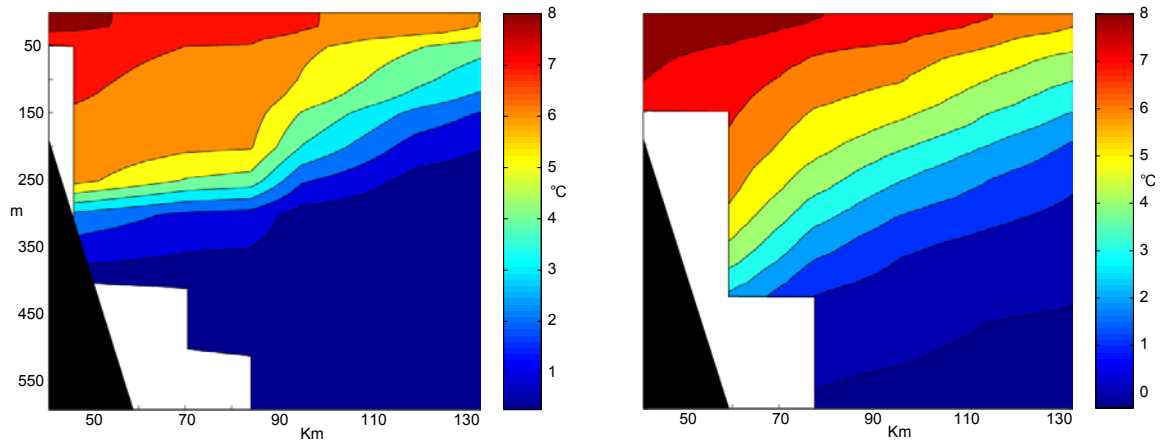
Fig. 3. The averaged temperature field in section N. Left panel shows the simulated field and the right panel shows the measured field.
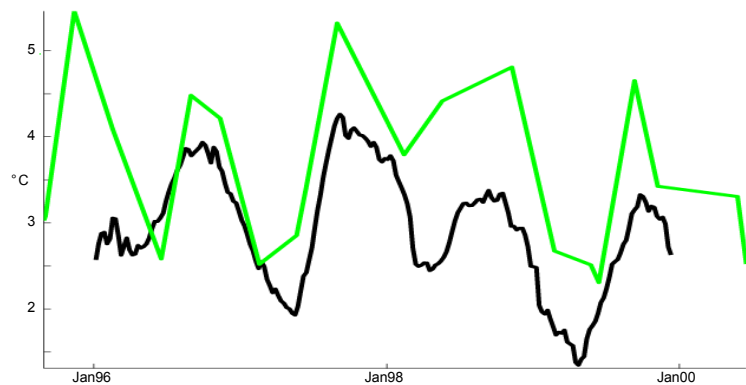
Fig. 4. The spatially averaged temperature at section N. Green is measured temperature and black is simulated temperature.

Conclusions
- Fairly realistic surface flow pattern
- Section N: a) Variations in the temperature are well simulated (both annually and inter-annually), but the field is generally too cold (ca. 0.5 °C); b) The modelled field is too fresh; c) Annual (and maybe shorter period) variations in the volume transport are well produced, but the simulated velocity is too weak, making the simulated transport too low.
- Section S: a) Variations and the average in the temperature is well simulated; b) The modelled current is too dispersed and the velocities are too low, but the integrated transport is comparable to data (1.5 Sv Vs. 1.4 Sv); c) The salinity is generally to low

Further validation the Micom model will be made in the future.

Numerical simulation of the circulation on the Faroe Shelf

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The water on the Faroe Shelf is well mixed and the circulation is barotropic, which implies that a accurate presentation of the circulation is provided by a 2D numerical simulation model. On the shelf the tidal currents are of major important and our efforts so far have mainly been concentrated on modeling the tides.

The characteristics of the tides on the Faroe Shelf is dominated by a semi-amphidromy for the semi diurnal tide on the east side of the islands (Figure 1). This implies a relatively large change in sea elevation amplitudes across the archipelagoes from 10 cm and 5 cm at Tórshavn on the east side to 70 cm and 30 cm at Sørvág at 30 km distance to west for the major semidiurnal tides, M2 (Figure 1) and S2, respectively. These large gradients are responsible for the relatively strong currents on the shelf. Between the islands the maximum currents are of order 2-5 knots, but at some locations they may exceed 10 knots.
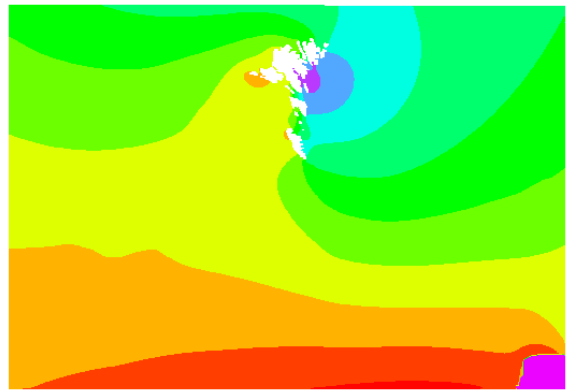
Fig. 1. The elevation amplitude of the M2 constituent. Each color code represents intervals of 10 cm, starting with 10 cm on the eastern central region on the Faroe Islands.

The amplitude of the diurnal tidal elevation is of order 10 cm over the entire Shelf, and generally the currents in the diurnal band are much weaker than the semi diurnal tidal current. However, on the southwestern shelf and on the banks to the west there are indications of enhanced currents in the diurnal frequency domain. The strong currents are responsible for the generally well mixed waters on the shelf.

On behalf of FGEM the Nansen Center in Bergen conducted a tidal simulation for the Faroe Shelf and surrounding areas including the Faroe Bank and Baily Bank to the west and the Faroe Shetland Current to the south with a resolution of half nautical mile. This model provided a fairly representative simulation of the circulation on the self. In addition it demonstrated that non-linearity may be a driving force of the anti-cyclonic circulation on the Shelf as well on the Banks to the west.

The results from the half nautical mile resolution model are used to force 100 m resolution models for the coastal areas (Figure 2). The purpose of these simulations was to generate
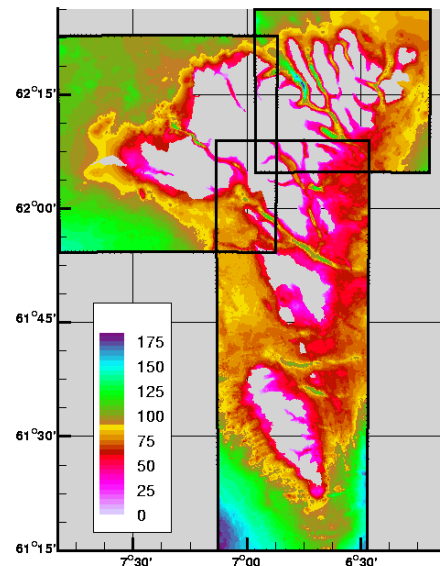
Fig. 2. Bathymetry in the three model domains used for 100 m reso-lution simulation of the tides in costal areas.

fairly accurate maps of the relatively complex tidal currents patterns near the coast for the ship traffic, for planning marine constructions and for the increasing fish farming industry. In these simulations it is found that higher harmonics due to non-linear effects may represents more than 25% of the tidal current strength at several locations. In addition residual currents due to non-linear effects are also appearing in the simulations, and they are crucial in determining drifting patterns on the shelf.

Over the last three decades the Fishery Laboratory and the Office for Public Works, which is responsible for the road system and harbours on the Faroes, has conduced a relative large number of sea elevation and current meter measurements in coastal areas as well on the shelf. The stations used in validation of the 100 m resolution models are shown on Figure 3.
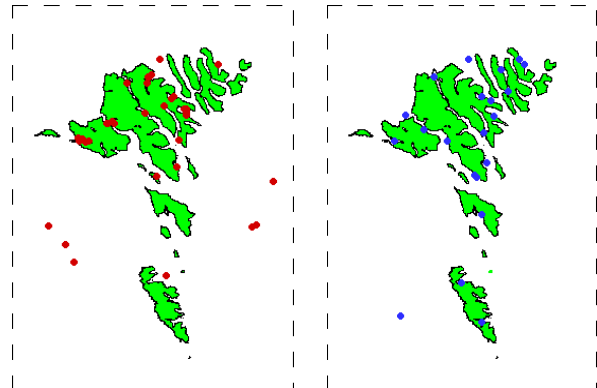
Fig. 3. Current meter (left) and water level stations, where data from measurements are used for validation of the 100 m resolution simulation.

Brief investigations of current measurements indicate that wind and changing sea level pressure does not have a significant effect on the current circulation on the shelf. However, fishermen have reported about significant changes in the current strength at some locations on the shelf slope, and salmon farmers have reported about currents of order 1-1.5 knot at a specific location due to passing storms. Studies of the effect of passing low pressures using a barotropic model are in preparation.

Some additional information about oceanographic research at the University is available from the web-pages www.streymkort.fo and www.sleipnir.fo/setur/nvd/havfrodi.

Zooplankton in Faroese waters

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The Faroese waters contain a vide variety of zooplankton species, but the most important is the large oceanic copepod *Calanus finmarchicus*.

C. finmarchicus overwinters in the deep waters of the Norwegian Sea and in the Faroe-Shetland Channel. They descend in late summer mostly as stage V-copepodites and reduce their metabolic rate living on stored lipids for several months in these deep cold water layers.

In these deep water masses *C. finmarchicus* is transported south-west through the Faroe-Shetland Channel and up through the Faroe-Bank Channel and into the Atlantic Ocean. The total transport of overwintered *C. finmarchicus* in these waters is estimated to be around 1000-2000 tonnes DW per day.

In late winter the *C. finmarchicus* population starts to ascend towards the surface again (Fig. 1), and in late April the entire population is situated in the warmer surface layers where they mate and spawn. *C. finmarchicus* shows some pre-bloom spawning but the intensive spawning activity doesn't occur until the start of the spring bloom.
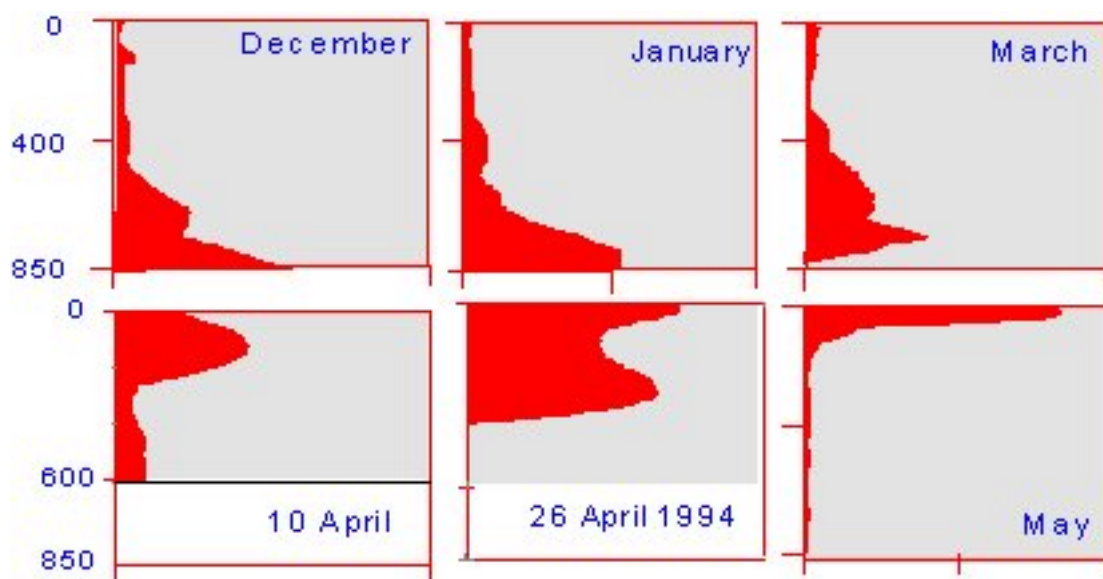
Fig.1. The ascent migration *of Calanus finmarchicus* in the Faroe-Shetland Channel and the Faroe-Bank Channel.

A recent and on going research on macrozooplankton where samples have been taken at 3 fixed station across the Faroe-Shetland Channel (FSC), has shown that the dominant macrozooplankton was krill. Especially the two krill species *Meganyctiphanes norvegica* and *Thysanoessa longicaudata* were dominant but the amphipod *Parathemisto sp*. was also present in relatively large amounts throughout the year.

The abundance maximum for krill was in winter at all 3 stations (Fig. 2), while *Parathemisto sp.* had abundance maximum in winter as well as in summer.

About 20% of the krill population was mature already in late February and some sporadic spawning took place at this early time as well, but the main spawning period seems to be later in April or May.

Fig. 2. Abundance of krill at all 3 stations combined in the FSC from May-2001 until Feb.-2002.
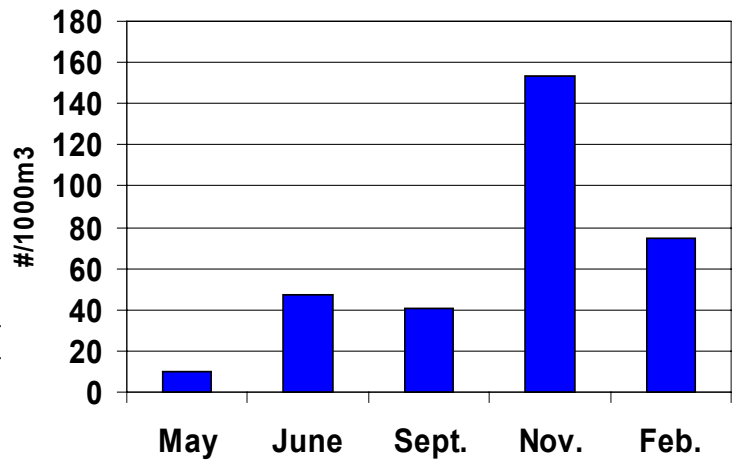
In the May samples the majority of the population was mature and krill eggs were found in most of the samples.

According to the length frequency histograms (Fig. 3) the krill 0-groups appear earlier (in mid June) in the population at the southern most station than at the other two stations.

Possible explanation for this could be earlier favorable conditions for growth or a possible higher growth rate for the krill, caused by the significant higher temperatures throughout the water column on the Scottish side of the channel.

Fig. 3. Length-frequency histogram of *T. longicaudata* at the southern most station in June showing the appearance of the 0-group.
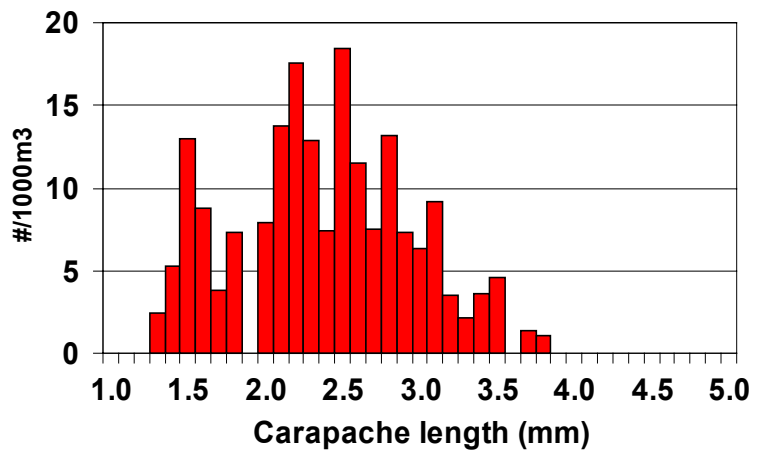
Plankton on the Faroe shelf

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The Faroe shelf essentially has its own plankton community, which is relatively well isolated from those in the surrounding oceanic environment. On the shelf, the hydrographic conditions, nutrient concentrations, and the phyto- and zooplankton species composition, production and abundance usually are markedly different from those in the oceanic environment outside the Shelf.

The water mass is turbulent and since the pool of nutrients in the Shelf water is limited, the nutrient concentrations may decrease much during spring and summer. During spring, diatoms dominate among the phytoplankton. During summers with high nutrient concentrations, diatoms continued to dominate throughout the productive season. However, in years with low nutrient concentrations in summer diatoms usually are outcompeted by smaller flagellates.

Primary production usually increases earlier in spring on the shelf than offshore. However, the timing of the spring bloom development, as well as the phytoplankton biomass and primary production, may fluctuate considerably between years. An index of the calculated mean potential new primary production in the shelf ecosystem during spring and early summer, based on nitrate loss, showed variability by a factor of five, from very low productivity at the beginning of the 1990s and in 2002 to the highest level in the mid 1990s and in 2000 and 2001 (Figure 1).
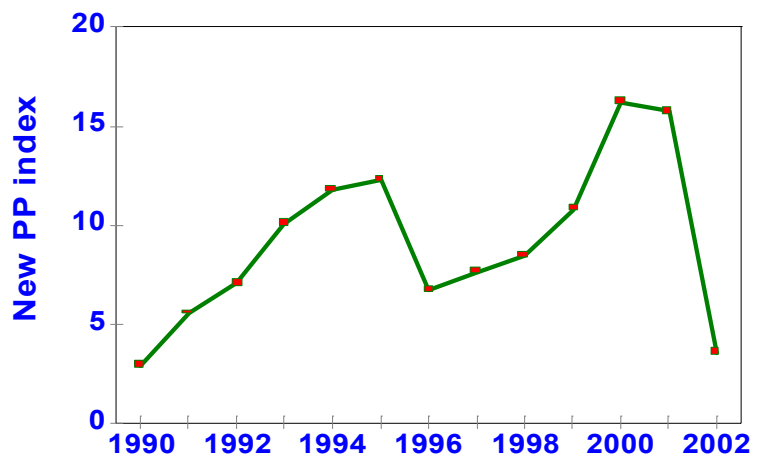
Fig. 1. Calculated index of the potential new primary production on the Faroe shelf, 1990-2002.

The zooplankton community is basically neritic. During spring and summer, while the zooplankton in the surrounding oceanic environment is dominated by the copepod *Calanus finmarchicus*, the zooplankton in the Shelf water is largely dominated by neritic copepods, mainly *Acartia longiremis* and *Temora longicornis* (Figure 2). *C. finmarchicus* occurs in interannually, highly variable abundance in the shelf water. Meroplanktonic larvae, mainly barnacle larvae, may also be abundant, and decapod
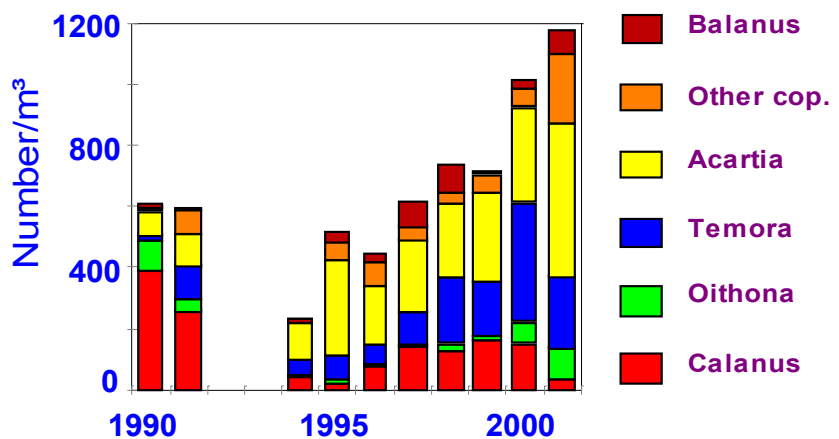
Fig. 2. Abundance of the dominant copepod species and barnacle larvae in the upper 50 m of the water column on the central shelf in June 1989-2000.

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larvae and ichthyoplankton are common on the Shelf during spring and summer. The summer abundance of *C. finmarchicus* (which originally is advected onto the shelf from the open ocean) has fluctuated very much (between ~ 400 copepods m^{-3} in 1989 and ~1 copepod m^{-3} in 2001. During the same time period, the neritic copepods increased much (Figure 2). Hence, the system gradually has fluctuated from a highly oceanic influence to a much more neritic ecosystem in regards to zooplankton species composition. Consequently, the midsummer zooplankton biomass on the Shelf fluctuated by a factor of ~15 during the same period. Although variable predation on the zooplankton undoubtedly has affected the observed zooplankton variability a variable inflow rates (largely induced by wind) is likely a major explanation for the variable abundance of *C. finmarchicus*. The main advective area is considered to be on the western and north-western shelf regions but other advective areas have also been observed.

Years with early spring bloom development and high potential new primary production (and *vice versa*) co-occur. There is also a clear inverse relationship between the nitrate loss in the shelf water during spring and summer (new primary production) and the zooplankton biomass (Figure 3), and it is hypothesised that the observed variations in timing of the spring bloom development and the calculated new, primary productivity are most likely due to variable grazing. It is hypothesised, moreover, that this effect occurs mainly during the pre-bloom period, when grazing by overwintered *C. finmarchicus* may prolong the lag phase.
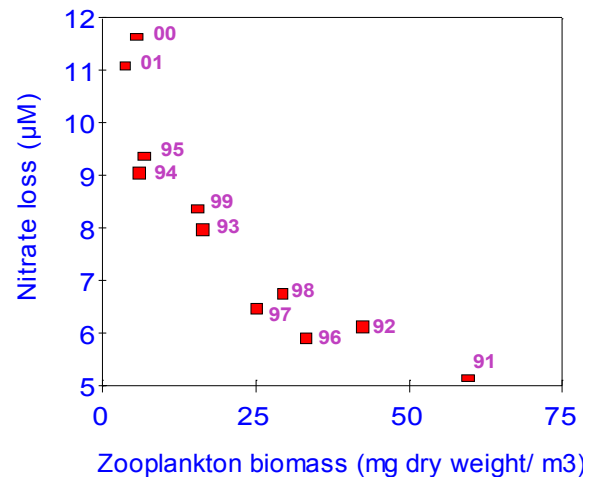
Fig. 3. relationship between zooplankton biomass and nitrate loss from winter levels to 26 June from 1990 to 2002.

First-feeding cod larvae on the Faroe shelf predate mainly on copepod eggs, of which *C. finmarchicus* eggs are considered to be the main food source. In large part, these larvae occur prior to the phytoplankton spring bloom. Seasonal copepod production on the central shelf region depends largely on the development of phytoplankton production. However, on the western and north-western shelf and slope regions, *C. finmarchicus* shows significant egg production prior to the spring bloom. This is roughly the same area that is considered to be the key advective area of *C. finmarchicus* onto the shelf in most years. The spawning grounds of Faroe Plateau cod are in the same region also, but are restricted to the area just inside the tidal front that surrounds the shelf water. Hence during early spring, cod eggs and larvae are advected along the same route as spawning *C. finmarchicus* and their offspring. During spring and summer, as cod and haddock larvae and pelagic juveniles grow, they progressively consume larger prey. First consuming copepod nauplii and small copepodites, followed by larger copepods, they finally add decapod larvae and occasionally also fish larvae to their diet.

There is a good correlation between the calculated potential new primary production and production in higher trophic levels of the shelf, including the major demersal fish stocks, seabirds and their food. Variability in primary production seems to affect production in the entire ecosystem.

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Fishes in Faroese Waters – a brief overview

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The fish fauna in Faroese waters is very composite mainly due to the special bottom typography and the very different water masses in the area. The fish fauna is mainly boreal but occurrence of arctic as well as of Mediterranean species illustrate the composite nature of the area. About 18 fish species have their north-westerly boundary at the Faroes. In total, about 170 different fish species have been recorded for the area.
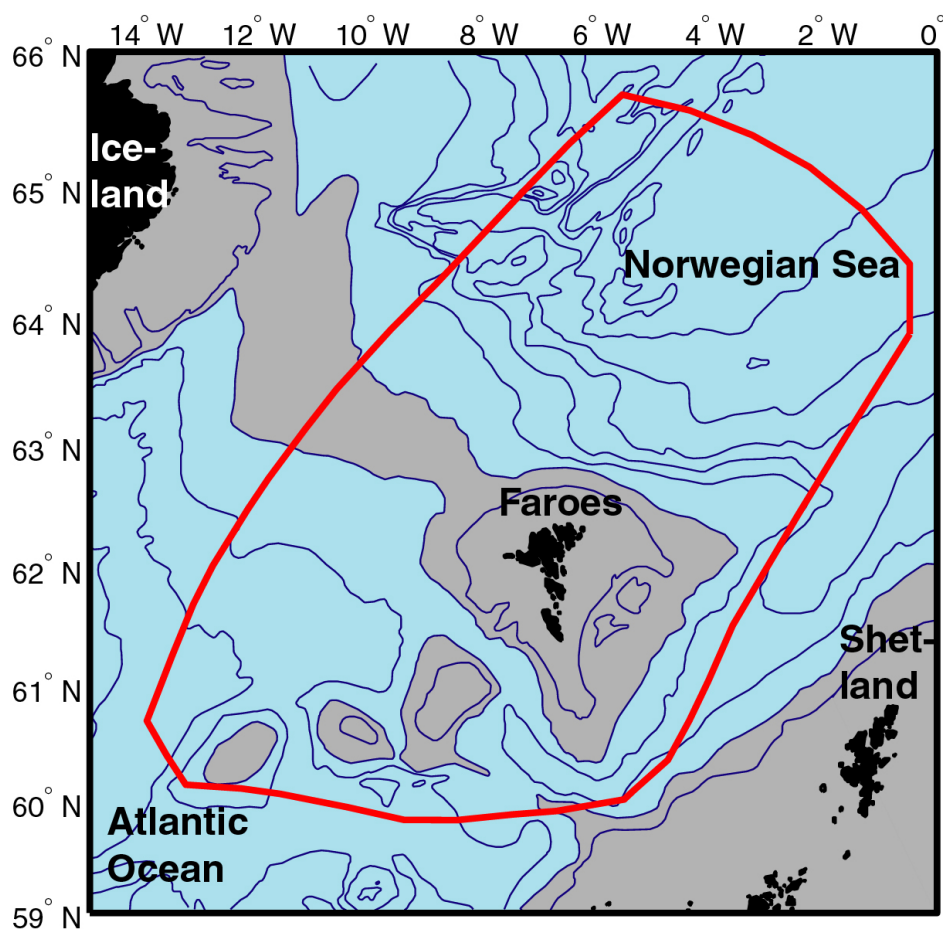
Fig. 1. The Faroese Waters showing the 200 nm EEZ and the topography of the area.

There exist several local self-sustained stocks in the area (Faroe Plateau cod, Faroe Bank cod, Faroe haddock, Norway Pout, small redfish etc.); others perform limited migrations in and out of the area but are in assessments/management regarded as local stocks (saithe, halibut, ling, tusk etc.) while many others are belonging to stocks with a wider distribution area (golden redfish, deep-sea redfish, blue ling, Greenland halbut etc.) or are stocks migrating to and/or through Faroese waters (herring, blue whiting, mackerel, horse mackerel, salmon, blue-fin tuna etc.).

With regard to the occurrence and distribution of the different species in Faroese Waters it is convenient to divide the area within the 200 nm EEZ as shown below:

I.   Fresh waters: Trout, salmon, char, three-spined stickleback, eel and flounder

II.   The Sea

A. The sea bed areas, the benthic Division

1. *The coastal areas in fjords and coves (the littoral zone)*: Very important as nursery areas for the young of many species, especially cod and saithe. Many other species, also adult specimen like dab, plaice, sand eel, flounder, butter fish, lemon sole, goby's, cottids, eel etc.

2. *The deeper zone in the fjords and sounds with a muddy sea bed*: Several species, especially dab, long rough dab, plaice, haddock, lemon sole, witch, halibut and whiting

3. *The banks around the islands, depths between about 50 m and 200 m (the sub-littoral zone)*: These areas are the most important fishing grounds for a large part of the fleet. The most abundant species are Norway pout, cod, haddock, small redfish, lemon sole, sand eel, dab, long rough dab and monkfish.

4. *The slopes towards the deep sea, depths between about 200 m and 500 m*: Very important fishing grounds with several species. Slopes to the west are different from those in other directions mainly due to exposure to different water masses, especially the deeper parts of the slopes have very different species compositions. The most abundant species are small redfish, Norway pout, golden redfish, blue whiting saithe, haddock, cod, tusk, ling, blue ling, halibut, catfish etc.

5. *The deep sea towards the Norwegian Sea and the Faroe Shetland Channel*: Area with typical cold water fauna and species like *Raja hyperborea*, Greenland halibut, jelly cat and several species of the genera *Lycenchelys* and *Lycodes*. North of the Faroes the special fish fauna belonging to the ice-cold deep is found, f.ex. *Paraliparis bathybius*, *Rhodichthys regina* and *Lycodes frigidus*.

6. *The Iceland-Faroe Ridge*: This is a very special area where the warm Atlantic watermasses meet the colder watermasses from the north. The area is of considerable importance as fishing grounds. Abundant species are deep-sea redfish, cod, Greenland halibut, halibut, tusk, blue ling, blue whiting, Argentine, skate and others.

7. *The deep sea towards the Atlantic*: Here the typical Atlantic deep-sea fish fauna is met with. The number of species is high. Important species are Argentine, deep-sea redfish, blue whiting, ratfish, black scabbard fish, grenadiers, blue ling, tusk, *Mora*, several skates and sharks like skate, starry ray, shagreen skate, bird-beak dogfish, black-mouthed dogfish, black dogfish, leaf-scale gulper shark, Portuguese dogfish, long-nose velvet dogfish, and many others.

8. *The banks south-west of the Faroes including the slopes*: Important fishing grounds, especially the Faroe Bank. The Faroe Bank shallower than about 200 m is a very interesting small ecosystem with slightly higher temperatures than other parts of the area and some species are not or very seldom met with in other parts of the Faroe area, f.ex. poor cod, hake, brill. Also the growth of fish here is faster than elsewhere in the area.

   Many fish species have been reported from this area. Most of the slope species are the same as the ones in the deep sea towards the Atlantic. Important species are cod, haddock, saithe, poor cod, silvery pout, small redfish, golden redfish, deep-sea redfish, blue-throat, ling, blue ling, tusk, blue whiting, Argentine, halibut, lemon sole, dab, monkfish and several species of skates and sharks.

B. The free water, the pelagic Division: Many benthic species dealt with above have, in some stages of there lives, periods where they are pelagic or partly pelagic. Eggs and larvae of many species are pelagic for several months, and adult feeding fishes are frequently found pelagic. The true pelagic fauna is mainly composed of migratory species. Some of these species perform regular annual migrations to or through Faroese waters, i.e. Atlanto-Scandian herring, blue whiting, mackerel, horse mackerel, salmon, basking shark, porbeagle and more recently blue fin

tuna. Other pelagic species must be regarded as guests, f.ex. king-fish, moon-fish, capelin and blue shark.

A poorly known group of fishes, although very abundant and rich on species, is the so-called meso-pelagic fishes, inhabiting the mesopelagic zone. Important fish families are called lanternfishes, hatchetfishes, deep-sea smelts, loosejaws, dragonfishes and lightfishes.

In general, emphasise has been put on investigations of the commercially most important species, of which landings data exist back to the beginning of 1900. Data on the benthic (demersal) fishes have been sampled through regular monitoring of the areas down to about 500 m by scientific trawl surveys and from commercial fisheries by biological sampling of the landings and information on the vessels catch and effort data (logbooks, landing slips). The most important species, i.e. cod, haddock and saithe, are so well known, that analytical assessments can be performed. Others are not so well known, but main traits of the life history of many of them can be described, f.ex. ling, tusk, blue ling, redfishes, halibut, Greenland halibut, Norway pout, and time series with abundance estimates are available. Of the pelagic species, herring and blue whiting have been monitored by pelagic trawl-acoustic surveys and by analysis of the commercial fisheries, and the amount of information allow analytical assessment. The biological knowledge of salmon is also on a high level. Regarding other pelagic species, the knowledge is more sparse.

Relationship between primary production, food abundance and fish production on Faroe Plateau

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The landings of commercially important fish species, e.g. cod and haddock, went through a historically low level during the late 1980s that caused a severe economical crisis for the fish industry and the whole Faroese society. The landings recovered rapidly during mid 1990s and the common view on the Faroe Islands has ever since been that the fish (especially cod) had emigrated from other other areas.

This study investigates the link between primary production, food abundance and fish production on Faroe Plateau during the 1990s. The primary production was, roughly speaking, measured as the nitrate decrease from winter to summer. Fish production, that corresponded to the primary production, was calculated as weight increase of the fish population (cod, haddock or saithe) from mid year same year to mid year next year. The weight increase of e.g. the cod population was calculated as individual weight increase multiplied by the average number of individuals during the period, and summed up for all ages.

The results showed that there was only a weak negative correlation between e.g. individual growth and cod abundance, and no relationship between cod production and individual growth or cod abundance. There was, however, a high correlation between primary production and fish production (individual growth times fish abundance) as shown in Fig. 1. Generally, young fish (the period from 1.5 years to 2.5 years) had the highest proportion of the total production of the species. The abundance of young and fish recruiting to the fishery seemed to be constricted to years with high primary production.
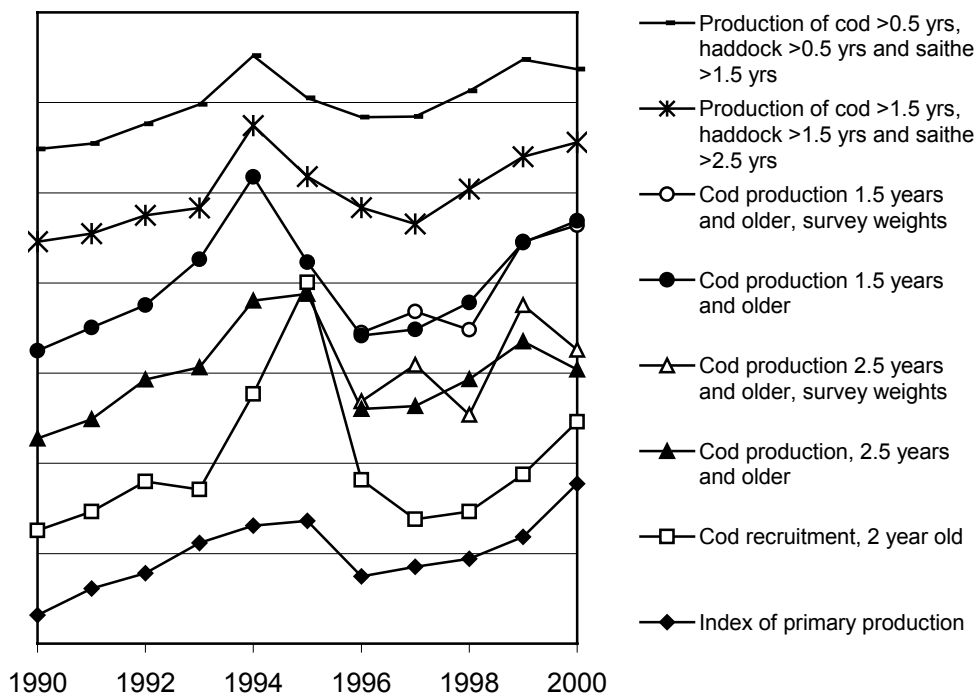
Fig. 1. Index of primary production and fish population parameters during the period 1990-2000. The values are standardized to own mean for the whole period and placed one unit apart. Cod production based on individual weights from the summer groundfish survey (in contrast to individual weigths from the commercial catch) are shown.

The link between primary production and fish production is believed to be food organisms for fish, that include (ordered by increasing depth): sandeels (< 200 m), Polychaeta (< 200 m), bentic crustaceans (< 200 m), Norway pout (100-300 m), Munida sp. (200-400 m), Euphausiaceans (200-400 m) and Blue whiting (200-500 m). Cod (< c. 50 cm) prey mainly on sandeels, Norway pout and bentic crustaceans whereas larger cod in addition feed on Munida and Blue whiting. Haddock feed mainly on Polychaetans, and saithe on Norway pout, Blue whiting and Euphausiaceans.

When primary production during the spring bloom in April has been high, the abundance of e.g. sandeels also seems to be high during the summer and following winter, and most likely the abundance of other prey organisms for fish. The fish older than e.g. two years take their share of the food abundance, but younger fish take, those years, a considerable part of the prey organisms. When primary production is poor, the food left for young fish is limited and causes a weak year class. This study suggests that the age when year class strength of cod is determined is somewhere between 0.5 years and 2.5 years, and that year class strength depends on the primary production and the density of older cod.

Cod showed the same variation as the combined production of cod, haddock and saithe, probably because the majority of the cod population normally is found within the Faroe Shelf area (less than c. 130 m depth), where the index of primary production applies. On the other hand, since the combined production of cod, haddock and saithe corresponded well to the primary production in the Faroe Shelf area, there seemed to be close links between the Faroe Shelf area and the rest of the Faroe Plateau. This link could be Norway pout, that was a very important prey item both in the Faroe Shelf area and outside. A high correlation between condition factors of fish inside and outside the Faroe Shelf area suggests that the food abundance in these areas are linked.

Most food items eaten by cod, haddock and saithe are present on the Faroe Plateau during the whole life cycle. Blue whiting, however, is an exception and may, in principle, disturb the relationship between primary production and fish production. Blue whiting is mainly found deeper than 300 m and is considered to be a part of the large Blue whiting stock in the North Atlantic ocean. The abundance of 0-group Blue whiting on Faroe Plateau seems to correspond well to the general abundance of Blue Whiting in the North Atlantic ocean. The abundance of older Blue whiting in Faroese waters, as measured by the median catch per station caught by bottom trawl in the summer groundfish survey, seems not to follow the stock size of Blue whiting, but probably more the index of primary production on Faroe Shelf. It should be noted that survey bottom trawl may not give the correct abundance estimate of Blue whiting on the Faroe Plateau. Also, the year span is short (1996-2001) making firm conclusions impossible. The fact that Blue whiting is only eaten by large fish (cod and saithe), that represent a small part of the total production of the species, may be the main reason why Blue whiting is not ruining the relationship between primary production and fish production.

Pelagic stocks in the Faroese area

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Three major pelagic fish stocks, blue whiting, mackerel and Norwegian Spring Spawning Herring feed in the Norwegian Sea, and are thus dependent on the zooplankton production in this area for their growth and survival. The feeding biology, annual migration cycle, i.e. spawning areas, larval drift, nursery areas and growth, however differ from one stock to the other, and large variation in distribution, migration and recruitment has been observed in the last 30-50 years. Although, the stocks feed in the Norwegian Sea, their life cycle and annual migration extends into the neighbouring areas to the west of the British Isles, the North Sea and the Barents Sea, as briefly described in the text table below. These stocks are thus, in addition to being part of the ecosystem in the Norwegian Sea, also integral parts of the ecosystems in these neighbouring areas, and the large-scale migrations have great implications for the management in all areas.

Stock	Spawning area	Nursery area	Feeding area	Catches 2001
Blue whiting	Porcupine Bank and West of the British Isles	Offshore west of the British Isles, The Faroes, In the Norwegian Deep, Off the Norwegian Plateau and Southeast Iceland	Norwegian Sea	1.7 mill t.
Norwegian Spring-spawning herring	On the banks off Western Norway	Along the West coast of Norway, Norwegian fjords and in the Barents Sea	Norwegian Sea	0.85 mill t.
Mackerel	West and south of the British Isles, and Bay of Biscay	On the Plateau West of the British Isles, in the North Sea	Norwegian Sea and northern North Sea	0.67 mill t.

The nursery areas for all three pelagic stocks are upstream from the spawning areas, however, the feeding behaviour of the larvae and 0-group differ both with area and depth. Assuming that the immediate post spawning migration to some extent is governed by the prevailing current systems, these will govern the total area occupied during feeding. Similarly the egg and larval drift will be governed by the current systems. The circulation in the Nordic Seas is both driven by the wind stress and thermal and freshwater exchange with the atmosphere within the Nordic Seas, but also through distance forcing through water exchange with the Atlantic Ocean to the south and the Arctic Ocean to the north. Thus, the water exchange with the neighbouring areas largely determines the seawater composition in the Nordic Seas.

Norwegian spring spawning herring

In the period since 1950 great fluctuations have been observed in the stock size and distribution of the Norwegian spring spawning herring. The stock migrated west into the Norwegian Sea after spawning on the banks off western and mid Norway in spring, here it fed during summer and migrated to the deep wintering area between Faroes and Iceland, north off the FA-IC ridge. Part of this stock entered the Faroese area and spawned on the banks east of the isles, however the much greater part migrated towards the west coast of Norway to spawn. The changes in stock size (collapse)

in the late 60'ties can be attributed either to excessive fishing mortality or changes in the environment or both. Particularly it seemed as the rather warm waters east and north of Iceland disappeared in the late 60's and have never reappeared. After the collapse the wintering area changed from the open ocean to a deep and cold fjord in Lofoten area, Northern Norway. The herring stock again entered the Norwegian Sea during its summer feeding migrations in the early 90'ties, and in 1995-1997 they again entered the northern part of the Faroese EEZ in late spring, however they did not spawn in Faroese waters. An example of the herring distribution in May is given in Fig. 7.

North Sea herring: changing currents east of the Faroes affect fish migration

The occurrence of North Sea herring in the eastern part of the Faroese EEZ in some years (e.g. in 1990 and 1991, Jacobsen, 1990; 1991) were thought to be due to abnormal current situations in the Faroe-Shetland channel during that time, probably caused by cyclonic eddies in the channel enabling North Sea herring to cross the Faroe-Shetland channel. A task, which under normal conditions must be extremely difficult considering the strong slope current on the western shelf-edge.

Blue whiting

Blue whiting is distributed in a wide area in the NE Atlantic influenced by the NA Current (Fig. 1). After spawning off Porcupine Bank and west of the British Isles they migrate to the feeding areas in the Norwegian Sea. The post-spawning migration passes on either side of the Faroe Plateau, and the route taken apparently is influenced by the strength of the branch of the NA Current flowing clockwise around the shelf-edge on the south-eastern boundary between the Faroe-Shetland channel (Hansen & Jákupsstovu, 1992). If this branch is strong it acts as a barrier to the blue whiting and guides the fish to pass on the western side of the Faroe plateau in spring. In the Norwegian Sea blue whiting disperses over wide areas on the warmer side of the Atlantic front. The location and strength of this front thus affect the distribution during summer.
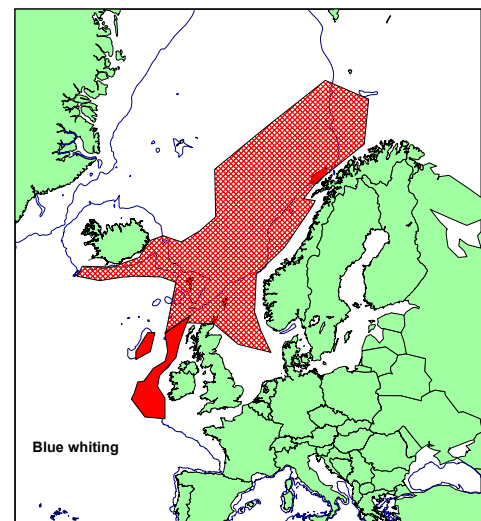
Blue whiting

Fig. 1. Main spawning areas (dark red) and distribution of blue whiting in the Northeast Atlantic.

Atlantic mackerel

Since the nineteen sixties also great changes have been observed in the area distribution of mackerel in the NE-Atlantic. Following the decline and almost extinction of the "North Sea component" the "Western component" has been the main target of the commercial fisheries for many years. Judged from the distribution of the fisheries, tagging data and other investigations, there have been great changes in feeding and wintering areas with time, and also the spawning areas have changed with time. The fishery for mackerel in the Norwegian Sea has in the recent years been extended to the north, especially north into the Norwegian Sea during summer (Belikov et al., 1998; ICES, 2002b) (Fig. 2). It is not known to what extent this reflects a true shift to a wider
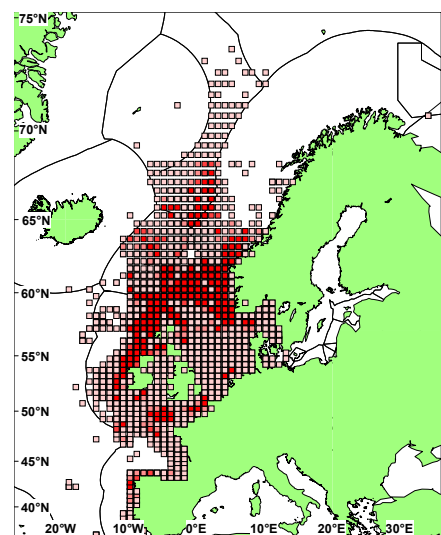
Fig. 2. Distribution of the fishery (1977-2000 data pooled) for Atlantic mackerel in the Northeast Atlantic. Note that some nations are not permitted access to some EEZs.

distribution or is reflecting a wider fishing activity and an increased survey intensity. In 2002 Faroes joined the international (Russia, Norway, Iceland and Faroes) combined aerial/research vessel surveys on mackerel in the Norwegian Sea (ICES, 2002a). In this project aircraft observations of schools of mackerel or herring on the sea surface have to be confirmed by research or commercial vessel in the area. The aircraft is equipped with a Light Detection Radar (LIDAR), which is capable of "seeing" 30-40m below sea surface, in a similar way as an echo sounder.

Plankton

There are large annual changes in the distribution and total biomass of plankton in the area north off the Faroes and in the Norwegian Sea. From 2001 to 2002 there was a large increase in zooplankton biomass in May (Fig. 3 and 4). This increase mainly occurred in the eastern region, although, higher biomass also was found in the colder water masses to the west. Russian cruises in June and July 2002 revealed an early production of *Calanus finmarchicus* in 2002 (Jacobsen *et al.*, 2002).
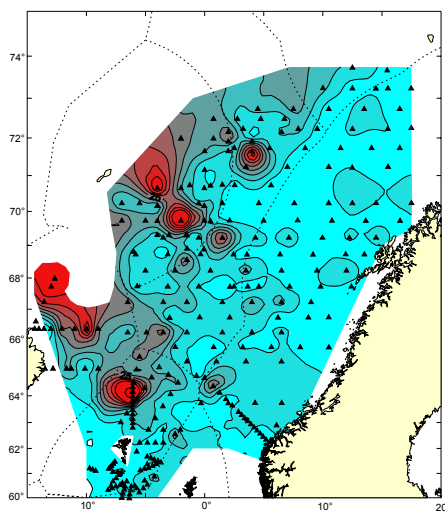
Fig. 3. Zooplankton biomass (g dw m^{-2}) (200-0m) in May 2001.
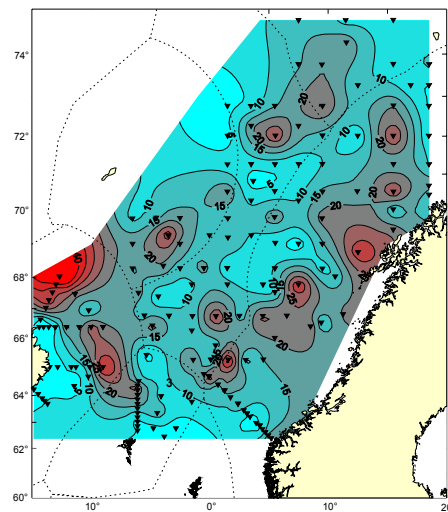
Fig. 4. Zooplankton biomass (g dw m^{-2}) (200-0m) in May 2002.

Hydrography

The winter NAO has increased in recent years, and was higher in 2002 compared with 2001. There has been a trend to a more easterly displacement of the Arctic front in the southern Norwegian Sea. Increased wind forcing gave also a larger Atlantic inflow into the Norwegian Sea in the eastern part at the Norwegian shelf edge. Observations of temperature show that the Norwegian Atlantic Current was about 2°C warmer in May-August, from the southern part of the Norwegian Sea to the Barents Sea, compared with 2001 and 1°C warmer compared to the long-term mean. Both the temperature and the volume of the Atlantic inflow into the Norwegian Sea, at least at the Norwegian shelf edge, increased in 2002 compared with 2001 (Jacobsen *et al.*, 2002).

Due to the seasonal warming a warm surface layer had developed in the Svinøy section in late July 2002 (Fig. 5). In some areas the SST was above 14°C. In the Atlantic layer, both the temperature and salinity were above the normal. Time series of the area in the Svinøy section that is occupied of Atlantic water and its averaged temperature for July/August from 1978 to 2002 is shown in Fig. 6. The vertical extent (area) decreases in the section while the temperature increases during. The averaged temperature in the section in 2002 was 8°C, which was the highest value ever since the systematic observations started in 1978 (1°C above the normal). There is an general trend of increasing temperatures in the North Atlantic water in the eastern part of the Norwegian Sea (Holst *et al.*, 2001; Jacobsen *et al.*, 2002).
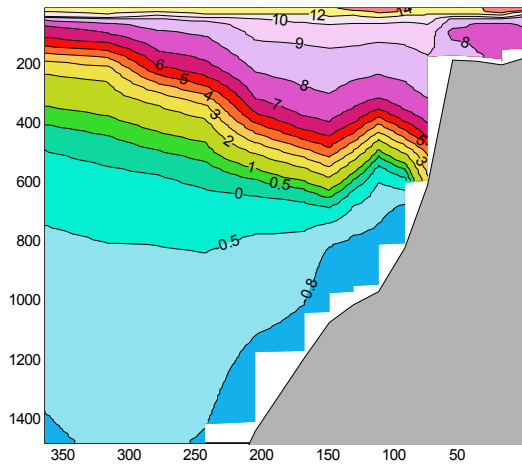
Fig. 5. Temperature in the Svinøy section (western Norway extending in a NW direction), 28-30 July 2002.
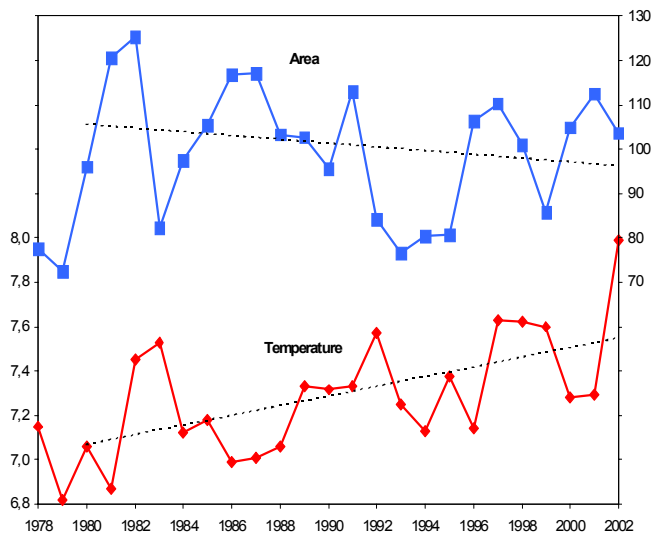
Fig. 6. Time series of area occupied by Atlantic water and its averaged temperature in the Svinøy section for July/August.

Q1: If the deepwater outflow is diminishing then the inflow should be reduced – but why has the summer temperature in the Atlantic water in the Norwegian Sea increased in recent years?

Changing summer migrations of herring

There has been an ongoing northward and eastward shift in the summer distribution of herring since 1995 to present (examples from 1995 and 2002, Fig. 7). This can be seen as a northeastward shift in the position of the centre of the acoustically mapped distribution of the herring (Fig. 8).
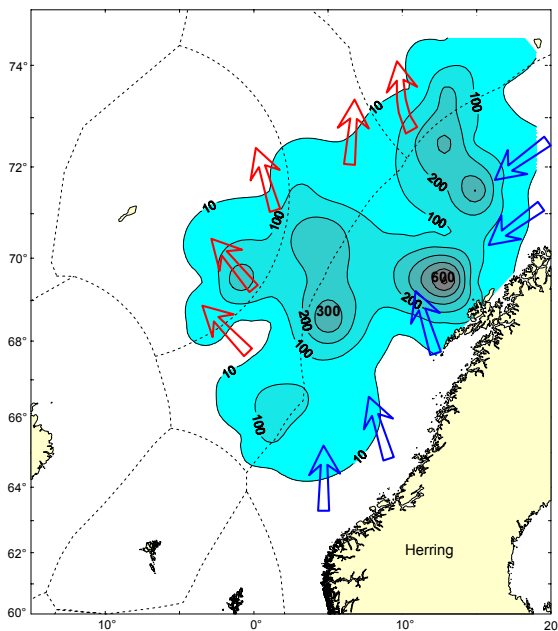
Fig. 7. Distribution of Norwegian spring spawning herring in May 2002. Arrows indicate general migration pattern in spring (blue arrows, near the coast) and early summer (red arrows, oceanic) in 2002. In August high concentrations of herring were found further north in the Svalbard area.
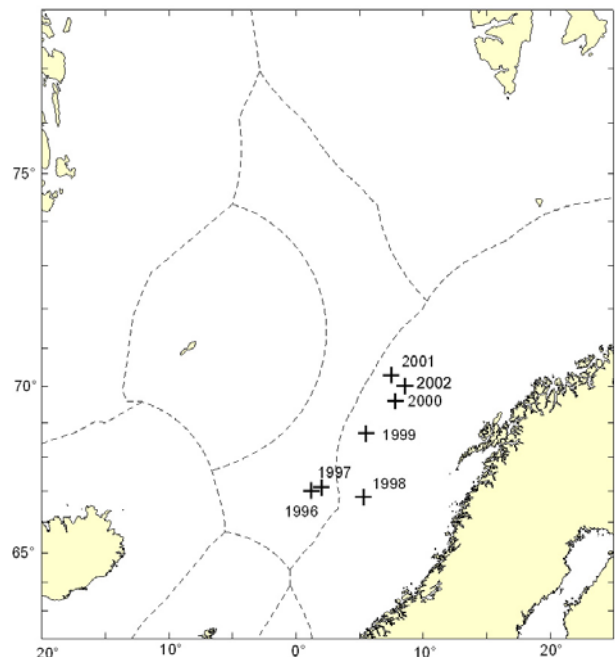
Fig. 8. Northward shift in the centre of gravity of the measured distribution (acoustics) of Norwegian spring spawning herring during May in the years 1996 to 2002. In 1995 the distribution centre (not shown) was probably even further south than in 1996.

Q2: Why is the herring migration changing, i.e. continuously shifting to the northeast during the period 1995-2002?

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Demersal fish assemblages of Faroe Bank

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The Faroe Bank area

The Faroe Bank is located approximately 75 km Southwest of the Faroe Islands (Fig. 1). Due to the small size of the Faroe Bank and its position as a geographically well-defined and self-contained ecosystem surrounded by an oceanic environment, it is a very suitable area for marine biological studies. Furthermore, comprehensive sampling programs can be made within a manageable time schedule. Inside the 200 m depth contour, the Faroe Bank covers an area of about 45 x 90 km (3,510 km^2) and its shallowest part is less than 100 m deep. Towards the northeast, it is separated from the Faroe shelf by the narrow (20 km) and deep (850 m) Faroe Bank Channel. Thereby, the Bank has many similarities with a seamount. Current measurements with satellite-tracked drogues on the Bank have shown that the water on the Bank is flowing in anticyclonic circulation with 1 circuit lasting about 1 month (Hansen et al. 1991). However, hydrographic, nutrient and plankton measurements have indicated that the isolation of the water masses on the Bank varies with time (Gaard and Mortensen 1993; Lastein 1992).
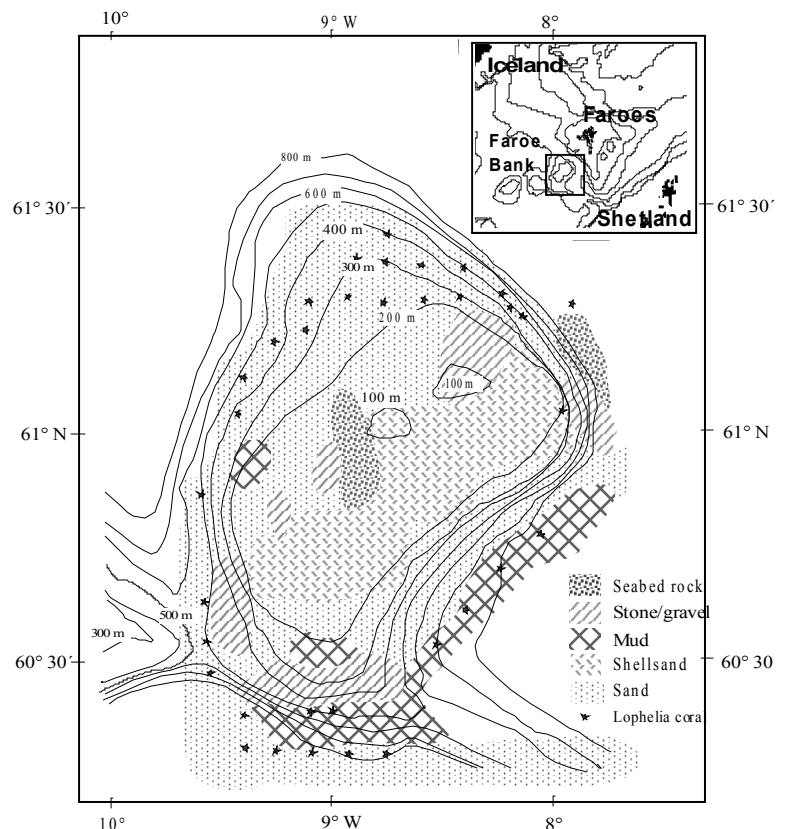
Fig. 1. Geographic location and sea-bed conditions of Faroe Bank

The topographic and hydrographic features on the Faroe Bank have led to the existence of a fairly isolated ecosystem. This isolation largely determines the character of the populations of fish and other organisms on the Bank. Tagging experiments with cod have demonstrated that migration between Faroe Bank and other areas is very low (Joensen 1956; Jones 1966; Strubberg 1916; Strubberg 1933; Tåning 1940) and morphological as well as biochemical differences have been confirmed for cod on the Bank (Love et al. 1974). Growth rate of cod on the Faroe Bank is higher than in most other areas (Ursin 1984; Fjallstein and Magnussen 1996) and genetic differences based

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on DNA (Dahle 1995) and fatty acids (Joensen et al. 2000) have been demonstrated. For this reason the Faroe Bank cod stock is considered as a separate stock, which for all practical purposes does not mix with the geographically closely located Faroe Plateau stock. Additionally, other fish species, e.g. haddock (Jones 1962), poor cod (Mattiangeli et al. 2000, 2001) and lemon sole (Rae 1939) are considered to be separate from those on the Faroe Plateau, while other species on the Bank are either not or rarely found on the Faroe Plateau (Joensen & Tåning 1970). Bottom trawl surveys around the Faroe Islands (unpubl. data) have also demonstrated that there are large differences in the distribution pattern for several of the species living on the Faroe Bank as compared to Faroe Plateau. For example, megrim only occurs on the Bank whereas squid and poor cod, which are common on the Bank, are scarce on the plateau. In contrast, plaice is common on the Faroe Plateau but rare on the Faroe Bank. This indicates that the Bank is a separate ecosystem for demersal fish as suggested by Jones (1966).

Species composition

In the annually spring bottom surveys between 1983 and 1996, 61 fish species were caught in 303 trawl hauls. Of this, 30 species are characterized as common on the bank The fish assemblage on the Faroe Bank is mainly boreal, but the occurrence of Arctic as well as Mediterranean species bears witness to the composite nature of the area. Based on cluster analyses, the Faroe Bank fish fauna can be grouped into 3 assemblages: shallow, intermediate and deep assemblage. The fish species are distributed regularly across the depth range from 95 to 771 m (Fig. 2). The boundaries of these assemblages are strongly connected to depth whereas the relatively homogeneous oceanographic features have a relatively small influence.
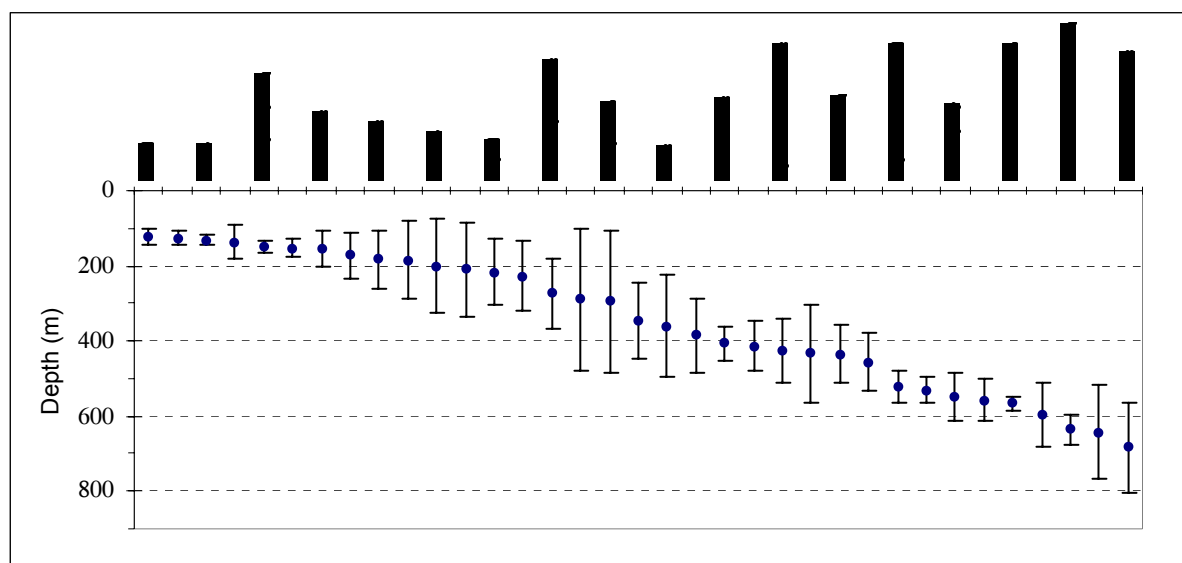
Fig. 2. Preferred depth for demersal fish on the Faroe Bank. Weighted average depth ± standard deviation. **S** refers to species of belonging shallow fauna, **I** of the intermediate fauna and **D** the deep fauna.

To carry out analyses Faroe Bank was grouped into 100 m depth inter intervals. The number of fish species in each of the 6 depth zones varies between 21 and 45. Of these, 4 of the most common species make up 61 to 88% of the total abundance and 67 to 94% of the total biomass (Fig. 3).

Fig. 3. K-dominance curves for the whole Faroe Bank, based on weight and number of fish caught in bottom surveys on the Faroe Bank during the period 1983–1996. In the box species with the highest rank are listed.
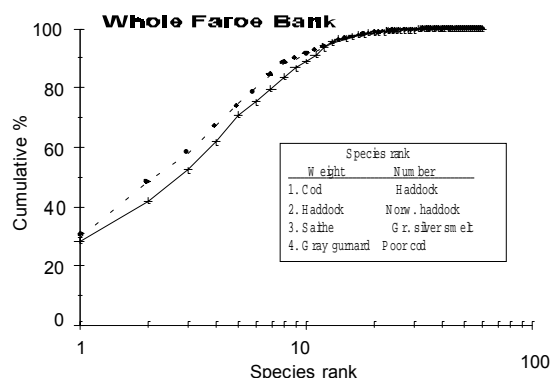
Fishery

The average annual commercial catch on the Bank during the period from 1983 to 1996 was 11,717 t. The commercially most important fish species were saithe, cod, ling and tusk. On average, 56% of the total catches were made up of these key species. However, in some years, the pelagic species blue whiting, herring and mackerel have been present in significant numbers and induced big fluctuations in the total catches. Thus, in 1995 and 1996, these 3 species made up 40 and 47% of the total catches, respectively.

Size spectra

The fish assemblages on the Faroe Bank are characterised by large fish. On the shallowest part of the Bank, the average size was 5079 g ($2^{12.31}$) and as we descended deeper, the average size of fish decreased (Fig. 4). This is a consequence of replacement of the dominant large and medium-sized cod and haddock by smaller species.

Fig. 4. Biomass spectra for different depth zone of the demersal fish assemblages on the Faroe Bank. The size classes correspond to the $\log_2$ of weight (number indicate the lower boundary of each class).
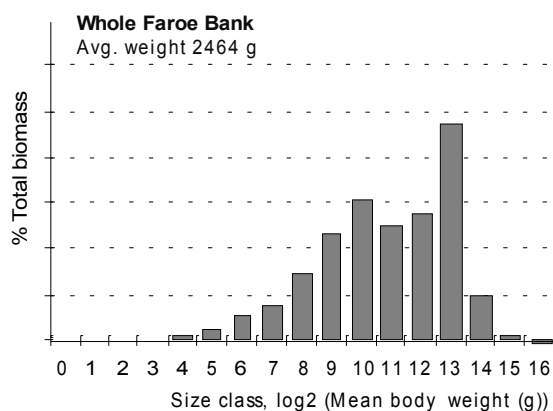
Growth conditions for fish

It is well known that cod on Faroe Banks are fast growing. To test if it is it a general fact that all fish species living on the Faroe Bank are fast-growing, or if the cod a special case, growth of 14 fish species living on the bank have been compared with growth-data described for this species in other areas. (Tab. 1). Of the 14 investigated species on the Faroe Bank, 13 have medium or higher growth rate compared to other areas. Of this growth is very high in two cases (cod, 1982 – 2000, 1985 and, poor cod). In 3 cases it is high to very high, in 2 cases it is high and in 3 cases the growth is characterize to be medium to high. Only for ling the growth is characterize to be low to very low on Faroe Bank compared to other areas. As general it must be conclude that growth of most fish species on Faroe Bank is high even not always higher than in other areas. A possibly explanation for this high growth could be that maturity age of fish on Faroe Banks seem to be relatively high. In 10 of the 14 species maturity age exist maturity age are medium higher.

Table 1. Relative growth (**G**) and age at maturity (A_{mat}) of some fish species living on the Faroe Bank compared to what have be found for this species in other geographic area.

Species	Number of areas compared		Maturity ranges (years)	Very low	Low	Medium	High	Very high
	Growth	Maturity						
Greater silver-smelt	13	8	3.4 – 8.5			**G**	A_{mat}	A_{mat}
Cod (Avg 1982-2000) (1985) (1989)	13	7	2.1 - 10.53					**G**
					A_{mat}			**G**
						A_{mat}	**G**	
Saithe (9428)	8	3	3.1 – 5.8			**G**	A_{mat}	
Tusk	7	4	5.6 – 9.6			A_{mat}	**G**	
Haddock (9428)	10	3	1.5 – 2.8			**G**	**G** A_{mat}	
Poor cod	6	2	2 – 2.0					**G**
Ling	6	2	6.8 – 7.1	**G**	**G**	A_{mat}		
Blue ling	4	3	6.2 – 7.3		A_{mat}	A_{mat}	**G**	**G**
Silvery pout	2	0				**G**	**G**	
Blue whiting	7	1	3.1			**G**	**G**	
Grey gurnard	4	2	3.0 – 4.5			**G**	A_{mat}	
Witch	8	1	4.5			**G**		
Dab	8	4	1.9 – 3.5			A_{mat}	**G** A_{mat}	**G**
Lemon sole	5	3	2.9 – 8.2				**G** A_{mat}	**G** A_{mat}

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Benthos in modelling the Faroe shelf ecosystem

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Several benthic investigations have been performed in Faroese waters since the late 19th century. Some of the more famous expeditions were Ingolf , Michael Sars (1902 & 1910), Deutsche Tieffsee, Triton, Lightning, Porcupine, and Knight Errant. In the late 1920s and early 1930s, Danish scientists made a great effort to describe Faroese fauna. Their complete work was published as the *Zoology of the Faroes*. In the sea, the main effort was concentrated in shallow waters, mostly between 0 – 100 m.

Recognising the fact that only a very limited amount of work was done in deeper waters and that great improvements in benthic sampling equipment have occurred since the *Zoology of the Faroes* was published, it was decided to undertake further investigations. The BIOFAR programme was initiated in 1988 and ran for three years. It was a joint inter-Nordic effort with participants from Norway, Denmark, Sweden and the Faroe Islands. The two main objectives were to generate a complete list of benthic invertebrate fauna for the Faroe Islands and to obtain a more complete picture of species distribution in relation to various physical parameters, such as current, temperature, salinity and depth. In 1995, the BIOFAR programme was extended to cover shallow waters from 0 – 100 m.
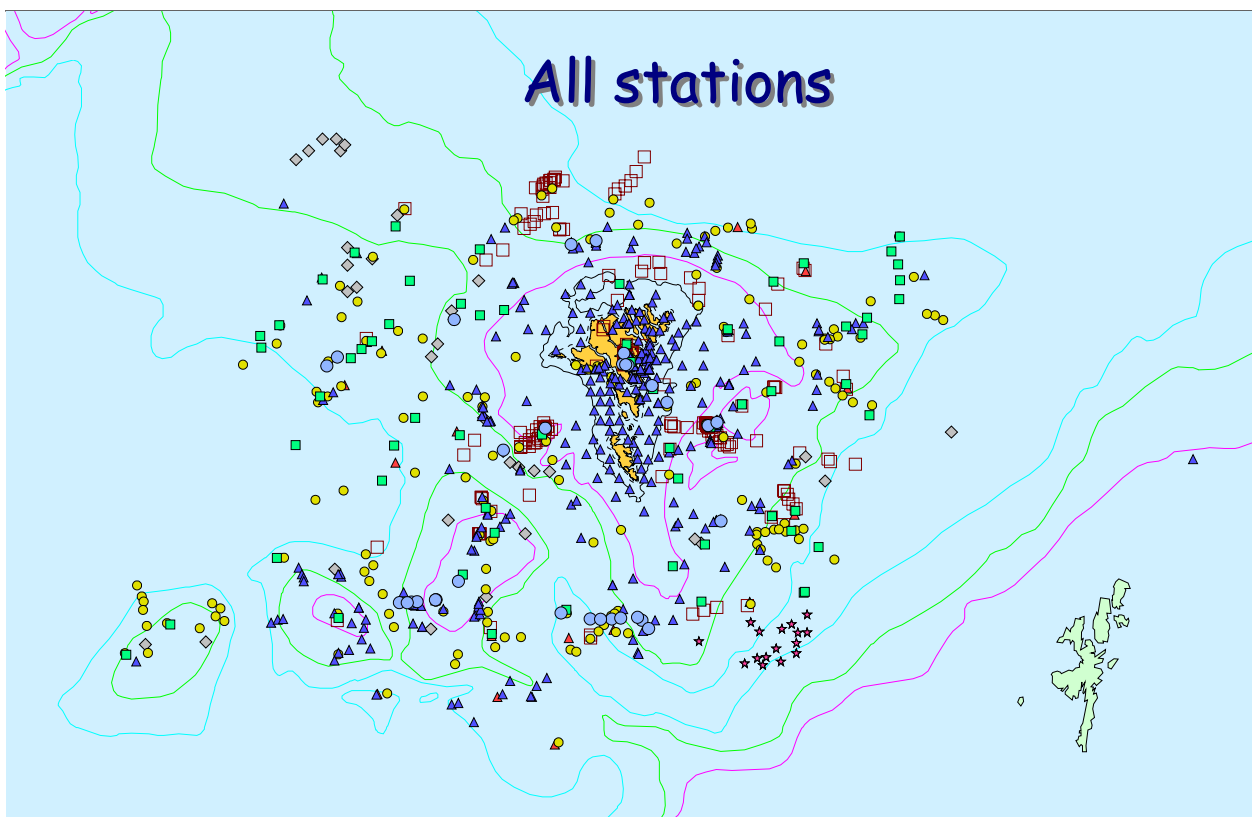
Benthic stations in the Kaldbak Lab. database

In addition to the *Zoology of the Faroes* and the BIOFAR programme, there have been a number of deep-sea investigations that also covered the Faroe Islands. Concurrent with the BIOFAR 2 programme, the Kaldbak Marine Biological Laboratory conducted a baseline study (FARCOS) of

the shallow waters of the Faroes. Additionally in 2001, the Faroese GEM project (a collaboration of various oil companies) conducted a baseline study in the first Faroese region licensed for oil exploration.

The majority of the samples provide information on species composition, but only relative abundance. Due to the stringent demand for exact species determination, most of the material was divided into taxonomic groups and then sent to specialists all over the world. Unfortunately, the advantage of high quality taxonomic determination was offset by the disadvantage of long processing times and the fact that some groups will never be finished. This was true for both BIOFAR and the *Zoology of the Faroes* project.

In total, there are approximately 1,500 benthic stations in the Faroe Islands. Several types of benthic samplers have been used and a tremendous amount of data has been gathered by the investigations. From a modelling point of view, only a few of these samples can be used directly in energy flow modelling because both the *Zoology of the Faroes* and the BIOFAR programmes were designed mainly to give information on species composition and, thus, only give relative species abundance. Valuable information, however, can be extracted from the samples and this information contributes to mapping the complex structure of the benthic systems. Information obtained from analysing the fauna in relation to different biotic and abiotic parameters is also valuable and can be used to map likely benthic communities that are essential parts of a benthic ecosystem.

Modelling the benthic ecosystem of the Faroe Shelf is a totally new scientific field in the Faroes. Considering the economic importance of cod and haddock, which both feed on food items found in the benthic system, it is fair to expect increased focus on studies of fish food sources. It is also reasonable to expect that future work on modelling will include:

- Estimations of energy input to the benthic system. The highest levels could be grouped as
    - Terrigenous, intertidal and sublittoral material
    - Large animal remains
    - Small remains of plankton
    - Plankton
- Studies of the structure of benthic biota and systems
- Studies of the factors controlling these systems
    - Energy input
    - Physical environment
        - Temperature
        - Currents
        - Salinity
        - Grain size
        - Organic content
    - Interspecies competition
    - Community structure
    - Fertility
    - Predation ……..

Seabird-data that can be used in modelling the ecosystem of Faroese waters

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Nearly 2 million pairs of seabirds breed in the Faroe Islands. As seabirds begins breeding only when 5-12 years of age there is also a very large number of subadult birds. In total there may be about 5 millions of Faroese seabirds with a total biomass around 3,000 t, consuming about 300,000 t / year. Four of the 21 species make up 95% of the total biomass. These are the fulmar (48%), puffin (21%), guillemot (17%) and kittiwake (9%). The fulmar is the most numerous and widespread species of seabird in the North Atlantic and numbers have increased dramatically over the last 250 years. It seems clear that the fulmar nested, really for the first time in the Faroes, some time between 1816 and 1839. Many of the seabirds migrate or disperse from the Faroese waters after the breeding season but the fulmar is in Faroese waters the year round.

The size of the fulmar and puffin breeding populations are estimates, while the guillemots and kittiwakes have been counted 3 times and 2 times respectively in their colonies. The seabirds at sea have been counted during the last 20 years. Survey coverage was greatest during summer and at least during the winter, when reduced day length, strong winds and increased swell heights restricted both ship speeds and the number of days suitable for surveying. Although the survey coverage was low it has been possible to make maps showing the distribution of the birds and to calculate the number of birds in the total area. The maps also show the seasonal distribution of the birds, which is importan in ecosystem modelling.

Seabirds have probably been hunted since people arrived on the islands, but we only have few hunting data. Feathers from hunted seabirds have been exporten from 1700 – 1900, and the export shows a maximum in the middle of each century. Late in the 1950s the guillemot population started to decline and this decline has continued. Since 1972 the guillemots on a study area on Skúvoy has been counted each year (Fig.1), and late in the 1980s the number dropped to its lowest level in 1990. Since then the number has increased to the level of the early 1980s. The drop and increase in the guillemot population is almost identical to that in the fish production and the recovery during the 1990s coicides with the increase of the calculated primary production index for the Faroe shelf. The harvest of puffins was low in the late 1980s and the early 1990s. Morover, in 1989, 1990 and 1991 a lot of dead chicks were found in the colonies around the islands and this has never been reported before. In 1991 an experiment with supplementay feeding of the young showed that they were
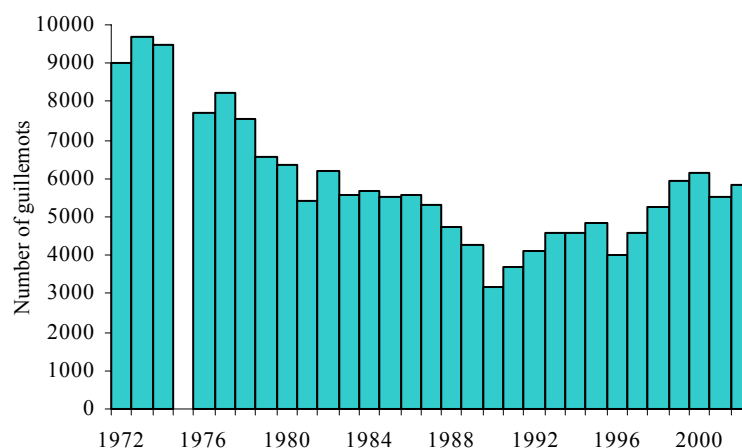
Fig. 1. The number of attending guillemots on Høvdin, Skúvoy 1972-2002. The census in 1975 is excluded.

starving. The food brought to the young also changed. The normal food is 0-group sandeel, but in 1991 0-group of Norway pout and capelin also was a substantial part of the food. The abundance of 0-group capelin, which is a more northern species, was higher in 1991 than usually found on the shelf. The caloric value of the food was low in 1991 and 1992 as the size of individual fishes was low, but as the size of individual fishes increased and the food consisted of a higher proportion of sandeels, the situation improved to normal chick weights and survival. Sandeel therefore plays a central role in the seabird diet, and for many seabirds, it is the most important food source during the chick-rearing period. The fact that the seabirds had problems finding sandeels in sufficient amounts and size during the end of the 1980s and the beginning of 1990s strongly indicates that the recruitment of sandeels failed during that period. The presented data indicate interannual coincidence between primay production and some seabird abundance and reproduction despite several intervening trophic levels. Although the production on the Faroe shelf was low for a period, not all seabird species were negatively affecte. This is not conflicting, however, as the seabirds use different feeding strategies.

The food brought to the chicks is not necessarily the same as that which the adults themselves eat. As seabirds still are hunted in the Faroes we have good opportunety to systematic analysing of stomack contence of seabirds. A pilot project is started on stomack contens of puffins that are hunted in the breeding season. The preliminary results indicate that sandeel and Norway pout is the main food and that the relative occurence fluctuate during the season and differs between years.

Present Knowledge of Marine Mammals in Faroese Waters

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During the last two centuries 27 marine mammal species have been recorded in Faroese waters (Bloch 1998): seven pinnipeds and 20 cetaceans. Grey Seal (Halichoerus grypus) and Harbour Porpoise (Phocoena phocoena) are the only species occurring permanently inshore in Faroese waters, while the following species are observed offshore year round as well as migratory: Fin Whale (Balaenoptera physalus), Minke Whale (B. acutorostrata), Sperm Whale (Physeter macrocephalus), Bottlenose Whale (Hyperoodon ampullatus), Long-Finned Pilot Globicephala melas), Killer Whale (Orcinus orca), and White-Sided Dolphin (Lagenorhynchus acutus). Of the remain 18 species some migrates into and stay only temporary in Faroese waters: (Harp Seal (Phoca groenlandicaWhale (), Hooded Seal (Cystophora cristata), Blue Whale (B. musculus), Sei Whale (B. borealis), Humback Whale (Megaptera novaeangliae), Bottlenose Dolphin (Tursiops truncatus), and White-Beaked Dolphin (L. albirostris)). The last 11 species are all only occasionally observed.

Grey Seal is the only pinniped species breeding in the Faroes (Mikkelsen et al., in print), the other species may be considered incidental visitors. However, more resently it is found that the Hooded Seal, quite frequently, may use the Faroese area as feeding ground, mainly in spring and late autumn/winter (Folkow and Blix, 1995; Bloch et al., 2001). This may be correlated with the migration of Blue Whiting (Micromesistius poutassou) in the area. Also, Harp Seal has been noted as by-catch in the Faroese pelagic long-line fishery (Bloch et al., 2001). However, the extent of a potential Harp Seal feeding migration into Faroese waters is unknown. It may not be an annual event, but could, however, be correlated with the irregular Harp Seal invasions in Norway, i.e. when seals in high numbers from the East Ice stock migrate southward, in search of food.

Among the 20 whale species, Fin and Minke Whales are the most frequently observed baleen whales. Among toothed whales, six species commonly occurs: Sperm Whale, Northern Bottlenose Whale, Killer Whale, Long-Finned Pilot Whale, White-Sided Dolphin, and Harbour Porpoise (Bloch 1998; Bloch et al., 2001). The most numerous cetaceans in Faroese waters most likely are Long-Finned Pilot Whale and White-Sided Dolphin.

When evaluating the role of marine mammals in the Faroese marine ecosystem, for most species several obvious lack of knowledge and uncertainties can be identified, among others: 1) the period each species spend inside the area, 2) the number of animals of each species in the area, 3) the prey species taken by each marine mammal species, and 4) the quantity of prey species eaten (Bloch and Mikkelsen, 2000).

The Faroese long-term whaling statistics on Long-Finned Pilot Whale and Bottlenose Whale give an account of the regularity of their cyclic occurrence in Faroese waters, since 1584, and seems to be correlated with the occurrence of their main prey species and climatic variations (Desportes and Mouritsen, 1993; Hoydal and Lastein, 1993; Zachariassen, 1993; Bloch, 1994; Bloch and Lastein, 1995).

Data from the Faroese baleen whaling, running 1894-1984, combined with special studies and occasional observations, may provide a applicable picture of the time frame the various marine mammals spent in Faroese waters (Skov et al., 1995; Bloch, 1998; Bloch and Mikkelsen, 2000; Bloch and Ofstad, 2000; Skov and Bloch, in print).

The North Atlantic Sightings Surveys (NASS), with the purpose to determinate whale abundances, have been protruded in 1987, 1989, 1995, and 2001. Abundance estimates have been made of the most frequently occurring marine mammal species in Faroese and adjacent waters. The surveys have been constructed to count the species with special interest inside participating countries, i.e. Fin Whale, Sei Whale, Humback Whale, Minke Whale, Bottlenose Whale and Long-Finned Pilot

Whale. In order to estimate the abundance of smaller cetacean species, sightings surveys have to be protruded different, which not have been possible so far (Sigurjónsson et al., 1989; 1996; Gunnlaugsson and Sigurjónsson, 1990; Sigurjónsson and Gunnlaugsson, 1990; Joyce et al., 1991; Buckland et al., 1992; 1993; Catanach et al., 1993; NAMMCO, 1997). A small cetaceans survey (SCANS) was executed in the North Sea in 1994 (Hammond et. al., 2002)

From the baleen whaling, and from various later examinations, information excists concerning sex distribution, sexual status and stomach content from most of the baleen whale species (Degerbøl, 1940; Sigurjónsson and Víkingsson, 1995; Bloch et al., 1996; Bloch and Mikkelsen, 2000; Desportes and Mouritsen, 1993; Desportes and Bloch, ms; Mikkelsen et al., in print).

The NAMMCO Scientific Committee Working Group on Economic Aspects of Marine Mammal – Fisheries Interactions has been established to determine the role of the marine mammals in the North Atlantic. In this context, preliminary calculations of the comsumtion by marine mammasls in the Faroe area have been performed, see Table 1 (Bloch and Mikkelsen, 2000; NAMMCO, 2001).

From the work estimating marine mammal consumtions, presented in Table 1 (Bloch and Mikkelsen, 2000), the general experience was that most of the knowledge on marine mammals excists on the species being target in the hunt through time in the Faroes, i.e. the baleen whales and Sperm whale in the offshore commercial whaling, and the Long-Finned Pilot Whale and Bottlenose Whale from the old traditional drive fishery. Smaller cetaceans have also been hunted in the drive fishery i.e. Bottlenose and White-Sided Dolphins, and even though a study is running at the moment on these species, still little is known about their occurrence, abundance and feeding habits in Faroes waters. Nevertheless, it is known that the smaller cetacean species are mainly fish-eaters, and from Table 1 they are calculated to eat close to one third (27%) of all the fish biomass eaten by marine mammals in Faroese waters. Therefore, it is an essential gab in our knowledge that so little is know about their abundance and occurrence of small cetaceans, a knowledge gap hopefully partly fullfilled by the coming Small Cetacean Abundance in Northern Sea Survey (SCANS II) in 2004/5.

Table 1. Preliminary estimation of consumption by marine mammals in Faroese waters. The annual consumption for whales is calculated following the method B by Sigurjónsson and Víkingsson (1998) as explained in the text. The values of daily consumtion for seals are calculated following Hammill and Stenson (ms) and Folkow and Blix (1995). Taken from Bloch and Mikkelsen (2000).

Annual consumption, tonnes					
Species	**Fish**	**Cephalopods**	**Crustaceans**	**Total**	**%**
Fin Whale	7.260		328.126	335.386	15,3
Minke Whale	167.975		163.168	331.143	14,9
Bottlenose Whale		6.653		6.653	0,3
White-sided dolphin	133.366	7.019		140.385	6,3
Bottlenose dolphin	20.251	1.066		21.317	1,0
Killer Whale	25.241			25.241	1,1
Pilot Whale	198.476	1.157.000		1.355.476	61,0
Harbour Porpoise	**4.801**	**253**		**5.054**	**0,2**
Total	**557.370**	**1.171.991**	**491.295**	**2.220.655**	**100,0**
Hooded Seal	22.654				
Grey Seal	8.640				
Total	**31.304**				
Grand total	**588.664**			**2.251.959**	

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Tides and Tidal Fronts, their dynamics and biological implications:
A comparison between Georges Bank and the Faroes Shelf

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The tides play an important role in shaping the physical oceanography on the Faroe Plateau. The strong tidal currents result in large tidal excursions, tidally well-mixed waters over much of the plateau due to bottom generated turbulence, the development of a tidal front separating these mixed waters from the stratified waters further offshore, and the anticyclonic residual current around the plateau generated through bottom friction and non-linear processes (Gaard et al., 2002). These in turn greatly influence the biological components of the marine ecosystem and how they function (Gaard et al., 2002). The strong mixing leads to high nutrient concentrations, which in turn produces high primary production. In the vicinity of the tidal front one finds the highest egg production of the important zooplankton species *Calanus finmarchicus* and also the main spawning grounds for cod. Cod eggs and larvae often appear in the strong horizontal gradients of the hydrographic properties that define the tidal front. The similarity in several of these features with those on Georges Bank is striking, including the importance of *C. finmarchicus* and the commercial species of cod, haddock, herring, mackerel and scallops. Georges Bank, which is approximately 3 times larger than the Faroes Plateau, has been the focus of several important studies during the last two decades. These include the Georges Bank Frontal Study undertaken by Canada in the late 1980s and the GLOBEC studies carried out by the United States in the 1990s to present. These have provided valuable information on the relative importance of various processes controlling the marine ecosystem on Georges Bank from physics to fish.

Several of the tide-related features on Georges Bank may also be operating around the Faroes. Although the tidal currents dominate the current variability over Georges Bank and on the Faroe Plateau (both typically 0.5-1 ms^{-1}), it is important to recognize that horizontal movement (e.g. drift of eggs and larvae) are dominated by the residual current whereas the vertical transfer of properties through the water column is dominated by short term turbulent process with times scales of minutes or less (Fig. 1).
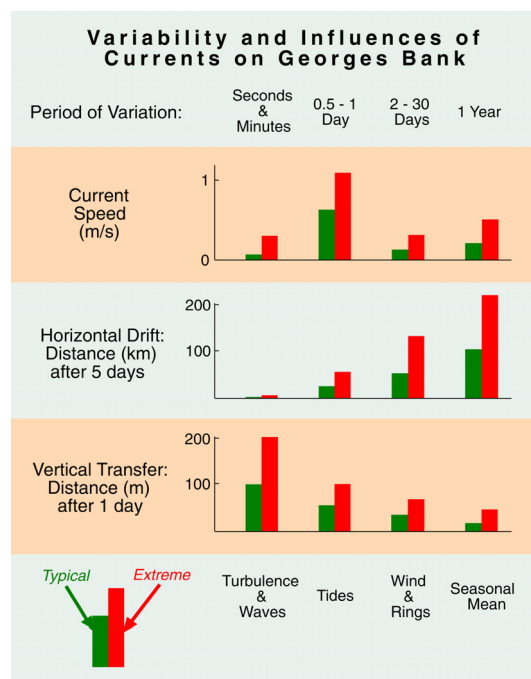
Fig.1. Relative importance of processes to the current speeds, horizontal drift and vertical transfers on Georges Bank.

Convergence at tidal fronts has been suggested by the collection of debris along surface fronts. On Georges Bank, Drinkwater and Loder (2001) measured convergence using surface ARGOS and 10-m drogued LORAN-C drifting buoys. The buoys were deployed in the vicinity of the tidal front over 2 years during the late 1980s. Buoys located within approximately 10-20 km of the front often converged and hydrographic data collected at deployment and recovery indicated movement towards higher stratification if they were deployed on the mixed side of the front and towards reduced stratification if deployed on the stratified side of the front. Estimates of the horizontal diffusivities indicated that at length scales of <20 km, they often were negative, indicative of convergence (Fig. 2). At the 10-20 km length scales, the diffusivities tended to be lower than those observed by Okubo (1971, 1974) in the open ocean, where as at larger length scales they were higher. The higher dispersion at the larger length scales on Georges Bank compared to other areas is believed due to the strong tidal currents and the large-scale divergence of the residual currents in the area where the buoys were deployed.

Fig. 2. The effective horizontal eddy diffusivity, K_e, as a function of the average length scale. The top panel shows the results from the full range of length scales encountered and the bottom panel is expanded for length scales < 20 km (from Drinkwater and Loder, 2001).
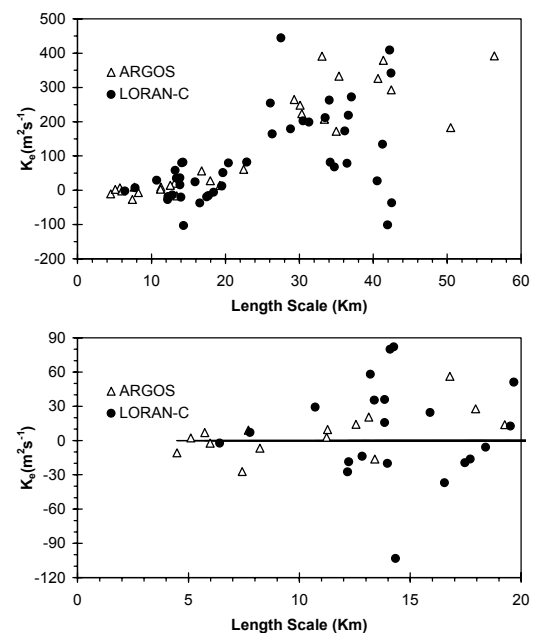
Convergence does not only occur at the tidal front on Georges Bank. Time depend convergence within the mixed waters during two separate strong windstorms has also been documented (Drinkwater and Loder, 2001). This is possibly a result of topographic effects. Also, there is periodic convergence and divergence of buoys located on and off the bank during flood (northward) and ebb (southward) flows, respectively (Drinkwater and Loder, 2001). This is due to the difference in the strength of the tidal flows between on- and off-bank. During a flood tide the higher currents over the Bank deliver more water to the northern edge of Georges Bank than can be carried away by the weaker horizontal currents off the Bank. This excess water forms a depression at the Bank edge every tidal cycle, i.e. an internal tide is generated (Loder et al., 1993). This also results in increased turbulence at the edge of the bank. The wave propagates away from the Bank into deeper waters but it can not propagate back onto the bank until the speed of the internal wave exceeds the opposing current speed on the Bank. Once the wave begins to propagate back onto the Bank, it must break somewhere before it reaches the well-mixed waters. This breaking provides a mechanism for increased turbulent mixing at mid-depths. This process may also occur in some locations on the Faroes Plateau, although it may not be as important as on Georges Bank because the on-off bank tidal currents are generally much larger on the northern edge of Georges Bank than they are on the Faroes.

Results from dye experiments in the vicinity of the tidal fronts on both the northern and southern sides of Georges Bank have provided evidence of strong on-bank flow (Houghton, 2002). Large quantities of dye were injected at the base of the tidal front on three separate occasions, 2 on the southern side and one on the north. In all three cases, the dye moved in an on-bank direction relative to the front. This provides the best direct evidence yet of on-bank flow onto Georges Bank. If similar mechanisms are operating on the Faroe Plateau, such on-bank flow may be important for
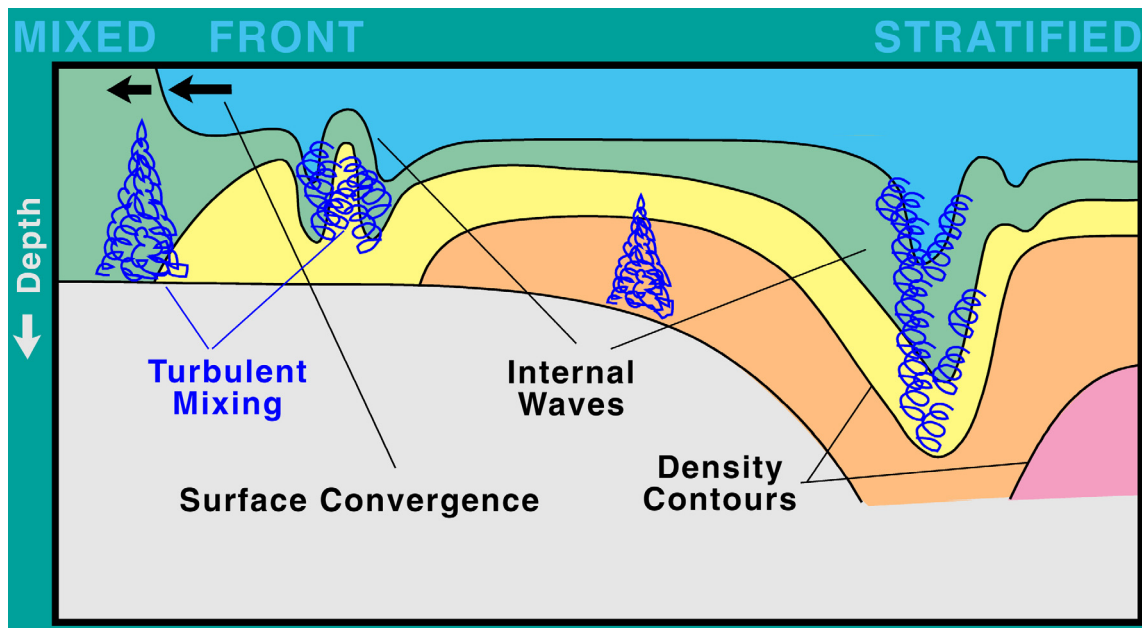
Fig. 3. A schematic diagram of the internal wave at the northern edge of Georges Bank (after Loder et al., 1992).

retention of eggs and larvae of fish and zooplankton on the Plateau and also might provide another way to transport *C. finmarchicus* onto the shelf from offshore.

Finally, although not related to tidal fronts or Georges Bank, the idea was presented that cod larvae may be transported from Iceland to the Faroes. Studies by Begg and Marteinsdottir (2002) indicate large concentrations of mature cod at the southeast corner of Iceland in all years from 1985-1999. If they spawn there, the residual currents would suggest that they might be carried along the Iceland-Faroes front towards the Faroe Plateau.

In summary, there are several similarities between Georges Bank and the Faroe Plateau, most notably the importance of the tidal currents and tidal fronts. The large number of studies of the former may provide insights into processes operating on the Faroes. Physical and biological models applied to Georges may be applicable to the Faroes.

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Primary Production and marine climate in the Nordic and Arctic Seas

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Marine bioproduction in the Arctic and Subarctic is based primarily on microscopic unicellular algae (phytoplankton) in the water column and microalgae associated with ice. Algae utilise light to produce organic matter by photosynthesis, thereby reducing CO_2 while releasing O_2 and producing carbohydrates which, according to the needs of the algae, can be converted into essential compounds such as proteins and nucleic acids by incorporating nitrogen, phosphorus, sulphur, and other elements.

The produced organic matter is eaten by herbivorous grazers, mainly zooplankton, which in turn may be eaten by fish, ultimately ending in top carnivores, with a loss of 75–80 % of the organic matter from one trophic level to the next. The main losses are associated with respiration within the organisms themselves, microbial degradation of dissolved organic matter, sinking cellular remains and faecal pellets, thereby releasing CO_2 and nutrients. Thus only a small fraction of the organic matter reaches the seabed – the deeper the water column, the smaller the fraction.

This summary deals with phytoplankton dynamics and the primary production of the arctic seas. Much information has been compiled in the last 30 years (Zenkevitch1963; Walsh et al. 1989; Smith 1990; Sakshaug et al. 1991; Sakshaug et al. 1994; Carmack et al. 1997; Macdonald et al. 1997; Kassens et al.1999; Wheeler et al. 1997; Loughlin and Ohtani1999). Importantly, recent investigations have shown that the primary production in the deep Arctic Ocean is considerably higher than assumed earlier. Moreover, there is an increasing recognition that arctic and subarctic ecosystems and population variability are closely associated with marine climate variability, making the term "ecological balance" not very meaningful in the polar context (Melnikov1997; Niebauer et al.1999, Ottersen et al. 2000; Stabeno et al. 2001; Olsen et al. 2001).

Phytoplankton and ice algae, the main primary producers in arctic and subarctic seas, are unicellular and predominantly multiply by binary fission. Diatoms, chrysophytes, dinophytes (dinoflagellates), prymnesiophytes, and green flagellates, are the predominant groups (Sukhanova et al. 1999). Most phytoplankton are of 5–20 mm size yet a few species can reach 500-750 mm. All photosynthetic algae possess chlorophyll *a* and a group-dependent variety of auxiliary pigments (fat-soluble chlorophylls *b,c,d* and carotenoids and in some cryptophytes, cyanobacteria and red algae, water-soluble phyco-bilins (Jeffrey et al. 1997). Some diatoms can form thick mats on the underside of the ice whereas other diatoms form dense blooms in the upper water column, as does the jelly-like prymnesiophyte, *Phaeocystis pouchetii* (Booth and Horner1997; Hasle and Heimdal 1998; Gradinger1999; Wassmann 2001. *Emiliania huxleyi* and a number of other calcifying prymnesiophytes (coccolithophorids), are important in late summer in the southern fringes of the Subarctic, as are cyanobacteria (Paasche 1960; Sakshaug et al. 1981).

Around 300 phytoplankton species have been registered in the Arctic, and at least this many species in sea ice, where diatoms and dinophytes are predominant. Some species live both in the water column and in the ice. The western Barents Sea and the Sea of Okhotsk are the most speciesrich areas in terms of phytoplankton (Loughlin et al. 1999) and the deep Arctic Ocean the poorest (Horner 1984; Booth and Horner1997) albeit. The number of heterotrophic species is presumably large, comprising about 35 % of the flagellate taxa (Ikävalko and Gradinger1997).

Because protein represents 30–50 % of healthy algal cells and carbohydrate 40-60 %, microalgae resemble legumes in bulk nutritional value. Fat content is <10 % in most species but higher in some large-celled species, and a significant fraction is made up by polyunsaturated fatty acids (PUFAs; Falk-Petersen et al 1998). Nutrient-starved algae are poor in protein (Sakshaug et al. 1983). The predominant carbohydrate in the sea is the water-soluble b-1,3 glucan (chrysolaminarin), which is produced especially by diatoms and prymnesiophytes (Myklestad 1974; Børsheim 2000). Moreover,

chrysophytes, prymnesiophytes and dinophytes, especially *Phaeocystis, Emiliania,* and ice algae, produce copious amounts of dimethylsulphopropionate (DMSP) and dimethyl sulphide (DMS), which can act as osmolytes, cryoprotectants and antioxidants (Kirst and Wiencke 1995; Sunda et al. 2002). DMS can enter the lower atmosphere where it can play a role in generating sulphuric aerosols and, thus, clouds. The latter, however, has not been unequivocally substantiated (Groene 1995).

Limitation and control of primary production

The growth rate and production of microalgae is usually limited by nitrogen or phosphorus (for diatoms, also silicate limitation occurs) unless light is limiting. The degree of limitation is affected by controlling factors that modify the nutrient supply and light, such as vertical mixing and grazing (Thingstad and Sakshaug 1990). In the Northeast Pacific and the eastern deep Bering Sea, iron generally controls nitrate uptake (Frost and Kishi 1999). This can also happen temporally between blooms, as shown for the Trondheimsfjord (Öztürk et al. 2002). Paradoxically, oligotrophic communities are usually not very nutrient-deficient because the predominant species seem to "fit" the nutrient flux. In fact, strongly starved populations are in the main restricted to transient situations when the algal biomass grows beyond what the nutrient flux can support, e.g. during the conclusion of a bloom. Very starved cells are presumably not viable, but some species can undergo sexual reproduction when starved cells are supplied the missing nutrients (Sakshaug and Holm-Hansen 1977).

Arctic light ranges from midnight sun to winter darkness. Solar elevation is generally low and does not reach $>23.45°°$ at the North Pole and $>55.5°°$ at $60°°$ latitude, corresponding to maximum (clear-sky) visible irradiance of 1200 and 1700 mmol m^{-2} s^{-1}, respectively. Besides, phytoplankton are subject to the vertical light gradient in the water column as they move with vertical water movements. Attenuation can be further amplified by sea ice, especially if it is covered by snow. In fact, ice and snow together can transform the light field in the water immediately beneath the ice into that typical for 30–100 m depth in ice-free water.

Low clouds associated with low-pressure fronts can attenuate light by 80–90 % (Sakshaug and Slagstad 1991). In the clearest arctic water, the 1% of surface irradiance, often taken as the lower limit for net photosynthesis, is situated around 65 m depth, but common Chl*a* concentrations (0.5–10 mg m^{-3}), can reduce it to 57–15 m. Extreme Chl*a* concentrations (>60 mg m^{-3}) in the Bering Sea can reduce the 1 % light depth to <3.5 m. Dense silt suspensions, typical for glacier-fed estuaries, can reduce it from 35 m to a fraction of a metre.

Deep layers are permanently rich in plant nutrients, but the surface layer exhibits high concentrations only in winter, when consumption by algae is minimal. After the spring bloom has consumed the winter nutrients, primary production is dependent on the day-to-day nutrient supply from below. The maximum winter surface concentration is dependent on the extent of admixture of deep water and its nutrient concentration. The latter is relatively low in the Atlantic sector and the Eurasian Arctic Ocean because these areas are "Mediterranean-type" seas that receive north-flowing Atlantic water that is "biologically spent. The most nutrient-rich deep waters are found in the North Pacific and the oceanic Bering Sea (Shiomoto 1999). Advection of this water cause nutrient concentrations to be about twice higher in the Bering Sea than on the Atlantic side (Codispoti 1979; Coachman and Walsh 1981). Following the conclusion of the spring bloom, surface concentrations of nitrate, phosphate and silicate approach the detection limit, except for the iron-limited parts of the pacific sector.

Seasonality and productivity

The spring bloom, which initiates the growth season, is triggered by the seasonal increase in light and stratification of the upper layers. In the eastern subarctic Pacific and in the shelfbreak area near the Atlantic Current north of Svalbard, grazing can suppress the phytoplankton biomass, thus effectively hindering a bloom from developing (Banse and English 1999; Wassmann 2001).

In principle, a phytoplankton bloom begins when the integrated gross photosynthetic rate in the mixed part of the water column becomes larger than the losses (respiration, sinking, grazing, release of dissolved organic carbon; Sverdrup 1953). Thus the bloom may begin 4–6 weeks earlier if the vertical mixing reaches 20 m depth instead of 100 m depth (Sakshaug and Slagstad 1991). In permanently ice-free areas – the eastern Nordic Seas and parts of the Barents Sea and the Bering Sea – stratification is late and thermally induced, thus the bloom commences in late May–early June (Stabeno et al. 1999; Olsen et al. 2001). In subarctic waters north of Iceland, the spring bloom culminates in late March–late April, as in Norwegian fjords (Sakshaug 1972; Gislason and Astthorsson 1998).

In areas with first-year ice, the growth season begins with an ice-edge bloom that establishes a 20–100 km wide belt off the ice edge (Braarud 1935; Alexander and Niebauer 1981; Sakshaug and Skjoldal 1989; Head et al. 2000). Such blooms develop rapidly when the ice breaks up because nutrient-rich water is exposed to light while the water from the melting ice establishes an upper mixed layer of only 15–35 m depth. As the sea ice continues breaking up, the bloom will follow the retracting ice edge. The ice-edge bloom makes the ice-edge zone the most important habitat for life in seasonally ice-covered waters.

Because it is dependent on the timing of the melting of sea ice, the ice-edge bloom begins in mid April–early May at the southernmost fringes of the first-year ice. Close to the multiyear ice in the Arctic Ocean, it is likely to begin in July (Alexander and Niebauer et al. 1991; Strass and Nöthig 1996; Niebauer et al. 1999). Consequently the growth season lasts for 180–200 days in the southernmost ice-covered parts and for only 70–100 days close to the multiyear ice. In the Greenland Sea, however, southward transport of ice and late melting causes a late ice edge bloom, in May as far south as Denmark Strait (Braarud 1935).

If waters are not too stratified, secondary blooms can arise in the summer and autumn on the basis of episodic supply of nutrients. These episodes can occur more or less regularly in connection with enhanced vertical mixing when atmospheric fronts pass (Sakshaug and Slagstad 1992). In shelf seas, hydrodynamics in combination with topography (banks, islands) or upwelling along shelf-breaks can keep primary production locally high by bringing nutrients to the euphotic zone fairly continually (near Svalbard, Bjørnøya, the Barents Sea, the Bering shelf, the Aleutian Arc).

Annual primary production (particulate matter) is smallest in the Central Arctic Basin and highest on the Bering Shelf, 11 and 50–900 g C m^{-2} yr^{-1}, respectively (Springer et al. 1996; Gosselin et al. 1997). Siberian shelf seas on average produce about 30 g C m^{-2} yr^{-1}, and the Nordic Seas about 100 g C m^{-2} yr^{-1} (Romankevich and Vetrov 2001; Sakshaug 2002). The primary production in the Central Arctic Basin is the lowest of all seas whereas high-productive stretches on the Bering Shelf are among the highest.

Phytoplankton is grazed in the upper layers or it sinks towards the bottom while being broken down by microorganisms. When phytoplankton blooms and large zooplankton stocks coincide in space and time, the grazing efficiency is large (match) and sedimentation small. The relatively late phytoplankton blooms in Atlantic Water represent good match with the development of the copepod, *Calanus finmarchicus* (Skjoldal et al. 1987; Dalpadado and Skjoldal 1991; Kosobokova 1999). In the high Arctic, the very flexible copepod species, *C. glacialis*, ensures good match by adjusting the egg production to the timing of the phytoplankton bloom whether it begins early or late. The opposite phenomenon, mismatch, is in the case of *C. finmarchicus* most pronounced when the spring bloom is early, which can follow cold winters when the sea ice reaches so far south into relatively warm water that it melts early from below. Mismatch occurred in the Atlantic Barents Sea in 1979, 1981, 1992, 1996, 1998, 1999 and 2001, when the phytoplankton happened 4–6 weeks earlier than normal (Olsen et al. 2001). Presumably mismatch is likely in Atlantic Water when the depth of mixing is <40 m depth and match when it is >40 m depth. Extreme mismatch is observed in Norwegian fjords where the bloom occurs in February–March, long before mesozooplankton stocks grow large (Wassmann 1991). Thus virtually the whole bloom sinks.

Interannual variations

Overall, the arctic ice cover has decreased about 50 % since the 1880s (Vinje et al. 1996). Yet multidecadal, decadal and shorter quasiperiodic climate cycles have been predominant. This, and the different response times of different organisms, has caused continual fluctuations and imbalances in the marine ecosystem. More precisely, variation in the marine climate in the Arctic is closely associated with variation in the position and intensity of the storm track (westerlies) because of the effect of wind on ocean currents and the depth and intensity of vertical mixing. The storm track, which is associated with the polar vortex, usually passes over Iceland and the Aleutian Arc. Not very accurately, the Arctic and North Atlantic Oscillations (AO and NAO) are used as proxies – the latter for the Atlantic sector only (McCartney 1997; Thompson and Wallace 1998). For the North Pacific sector, the Pacific Decadal Oscillation (PDO) is often used. Moreover, the Southern Oscillation (SO), which is associated with El Niños and La Niñas, is important there (Hare and Mantua 2000).

During positive AO, the polar vortex is accelerated. If the low pressures in addition move from Iceland toward the Barents Sea, they are particularly efficient in pushing Atlantic Water into the Arctic Ocean as far as the Laptev Sea. Moreover, lows in the Barents Sea can be efficient in pushing ice-filled water out of the Arctic Ocean and southwards along the East Greenland coast (Guay et al. 2001; Proshutinsky et al. 2001; Cavalieri 2002). Freshwater from Lena in the Laptev Sea is pushed westwards; thus the sea ice melts quickly from below there. This can reduce the sea-ice volume in the Arctic Ocean by 25 % compared to negative AO (Hilmer and Jung 2000). In the Barents Sea, the maximum ice cover is 40 % smaller during positive than during negative AO (Vinje et al. 1998). NAO has not shown any trend in the last 200 years, but it was strongly positive in the 1800s, 1900–1920 and in 1989–1995 and outstandingly negative in the 1960s and in the winters 1996, 1998, and 2001.

In the Barents Sea, primary production was 30 % higher in the warm period 1989–1995 than in the cold 1960s, mainly because of a 4–5-fold increase in primary production in the extra area that was ice-free (Slagstad and Wassmann 1996). Moreover, the Barents Sea stock of *Calanus finmarchicus* was up to 10 times larger than during negative AO, mainly because of efficient import from the Norwegian Sea (Skjoldal and Rey 1989). In the same period, warming of the Beaufort Sea impoverished the ice fauna as the ice melted (Melnikov 2001). Strongly positive AO also shifted warm-tolerant copepods in the Northeast Atlantic more than 10 ° latitude northwards while cold-tolerant copepods were shifted southwards in the Northwest Atlantic (Beaugrand et al. 2002).

A positive PDO index implies high sea surface temperature (SST) anomalies in the Northeast Pacific and cold anomalies in the Northwest Pacific, and a negative index, *vice versa* (Francis et al. 1998). Following a large climate shift in 1976, PDO went from negative to positive in association with a period with predominance of El Niños. This resulted in warm winter anomalies in the Southeast Bering Sea, a deepening of the Aleutian Low, and smaller than normal ice cover (Overland et al. 2001; Stabeno et al. 2001). However, a shift towards negative PDO in the late 1980s weakened the Aleutian Low in combination with La Niña-type climate. This brought northerly winds and extensive ice cover to the Bering Sea in the period 1989–1998 (Niebauer et al. 1999; Stabeno et al. 2001). Warmer summers, however, has brought a 10-fold increase in gelatinous zooplankton biomass since 1989, especially on the Middle Bering Shelf (Brodeur et al. 1999). In the very warm and bright summers of 1997 and 1998, blooms of *Emiliania huxleyi* were observed for the first time on the northeast Bering shelf (Stockwell et al. 2001).

The Arctic marine climate exhibits primarily cycles of 2.6-9, 11, 13.0 and 18.6 years. The latter two resemble the Wolf sunspot and lunar node cycles, respectively (Yndestad 1999; Ottersen et al. 2000). These cycles are known from mediaeval cod fisheries off England and France and globally from a large number of natural phenomena (Currie et al. 1994). AO and NAO exhibit prominent multidecadal cycles that are known as the Low-frequency Oscillation (LFO) and the Atlantic Multidecadal Oscillation (AMO), respectively (Polyakov and Johnson 2000; Enfield et al. 2001). They average 60–65 years (Schlesinger and Ramankutty 1994; Appenzeller et al. 1998) and can be

associated with warming in the 1860–1880s and the 1970–1990s, and cooling in 1905–1925 and in the 1960s.

The future

Nearly all scenarios predict warming and smaller areal ice cover in the next 100 years. Some scenarios also indicate a strengthened polar vortex – consistent with positive AO (Macdonald et al. 2002). Yet climate oscillations are also likely to exist in the future because the positive phase can bear the seed of negative phases due to the large amount of freshwater that positive AO brings into the Arctic. Freshening of the Greenland Sea has been very noticeable in the last two decades (Hansen 2001; Dickson 2002). LFO and AMO indicate that cooling could return around 2020. PDO shifted to negative PDO in 1999 but has, like AO and NAO, behaved erratically since then. If persistent, however, this can imply less frequent El Niños and more ice in the Bering Sea. Possibly, these oscillations will be superimposed on a long-term warming trend. So far, however, warming in the Arctic has been associated with import of warm air and water rather than local warming.

Less sea ice should increase areal primary production in the Arctic Ocean, especially on the Eurasian side and in the Beaufort Sea. Moreover, earlier melting in spring will enhance annual primary production by extending the growth season. The actual outcome, however, is highly dependent on regional and local changes in upwelling, wind-driven vertical mixing, and freshwater supply from sea ice and rivers – it takes only a small decrease in salinity to counteract the impact on vertical mixing of an increase in the wind intensity.

Sea ice is likely to disappear first in the arctic part of the Barents Sea and on the Bering shelf. Given today's wind field, the annual particulate primary production in the arctic part of the Barents Sea can possibly increase by a factor of 3–5. This would be a consequence of less sea ice and increased supply of Atlantic nutrients through deepened vertical mixing (increased salinity of Arctic Water). Moreover, deeper mixing will create a late and protracted spring bloom along the southern fringes of the sea ice (match with zooplankton) whereas the bloom can arise as early as in late April near the multiyear ice pack. A permanently ice-free Bering shelf is likely to yield higher annual primary production because the growth season will be extended. There is a possibility that an increase in aeolian transport of continental dust can relieve iron limitation in the Northeast Pacific and the eastern oceanic Bering Sea.

On the Siberian shelves, where primary production is restricted today because vertical mixing merely reshuffles nutrient-poor shelf waters, primary production presumably will not increase much until the ice over the shelfbreak will vanish so that wind-driven upwelling of nutrient-rich water can be initiated. In the central (deep) Arctic Ocean, areal primary production will increase as the number and size of open leads in the multiyear ice increase. However, primary production is not likely to increase beyond the level typical for the Siberian shelf seas today because stratification caused by melting of the winter sea ice will restrict nutrient supply during the growth season.

Depths of mixing <40 m, typical for areas where sea ice melts, is likely to favour diatom blooms whereas mixing to 60–80 m depth is likely to favour *Phaeocystis*. Thus, given a stronger wind field, *Phaeocystis* is likely to be more common than today, e.g. in Atlantic Water, unless there is an increase in freshwater input that causes strong stratification. Moreover, if the mixing reaches >100 m depth, also possible in Atlantic Water, a low-productive community dominated by nanoflagellates can be favoured, as in the off-shelf parts of the Southern Ocean (Hewes et al. 1990). This implies little transfer of carbon to herbivores and little export production because the grazers would largely be ciliates (Sakshaug and Walsh 2000).

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Modelling zooplankton dynamics to represent the trophic matter flows to higher levels

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Introduction

Energy fixed by phytoplankton is transferred up the marine food web to zooplankton, potentially harvestable fish resources, and top predators. However, the relationship between primary production and the productivity of the higher trophic levels is obscure. This is because food web structure varies in space and time, but also because the efficiencies of the predator-prey linkages are critically dependent on the taxonomy and demography of the components, and on the physical environment.

During the last decades, numerous biogeochemical models have been developed to simulate budget matter in regional seas. Generally these models do not pay much attention to the highest trophic levels, i.e. zooplankton and their predators. In fishery, modelling of fish populations has a long tradition but does not take into consideration the environment.

Biogeochemical models have concentrated on the physics-nutrient-phytoplankton systems; they subdivide the ecosystem in large functional units (e.g. limiting nutrient, phytoplankton, zooplankton) and simulate energy flows through these units. In a very recent step (last decade) biogeochemical models have been coupled with 3D physical models and simulated results have been compared with satellite pictures and field data. A major consequence of this research effort (comprising modelling) has been to show that the main productive areas are characterised by hydrographic features at the mesoscale (eddies, fronts, up-wellings). Thus, the link between physical processes and biological production appears to be the base of the food-web.

In comparison to the development of biogeochemical models, food-web models have been rarely produced during the last decades. A major contribution to design of model food webs was made by Steele (1974). The GLOBEC program (Global Ocean Ecosystem Dynamics; web site: http://www.pml.ac.uk/globec/main.htm) wishes to concentrate in particular on dynamics of critical zooplankton populations and on their responses to physical forcing. In doing so, it bridges the gap between phytoplankton studies and predator related research. Models of zooplanktonic population dynamics related to physical forcing at mesocale, and models of zooplankton dynamics related to phytoplankton and to their predators are required to fill the gaps concerning the high trophic levels in ecosystem models.

Several GLOBEC studies on zooplanktonic species have shown the link between species' life cycle and physical structures: many of the dominant herbivorous zooplankton live for a few months, about the duration of mesoscale physical structures. A major problem for zooplankton modelling is that these organisms go through different developmental stages, change in forms, behaviour and functions and that their body size varies by at least 2 orders of magnitude during their life time, with associated allometric scaling of physiological rates.

Modelling zooplankton population dynamics

The purpose of zooplankton population models is to describe and eventually predict the changes in abundance, distribution, and production of targeted species populations under forcing of the abiotic environment, food conditions and predation. The typical questions addressed are:

- What controls population dynamics of a species?
- How might environmental changes affect recruitment?

There are 3 basic approaches to single species population modelling.

1) Bulk-biomass entity model (BM) model
2) Structured population models (SPM) using an Eulerian approach (concentration based)
3) Lagrangian models (LM): the individual based model approach.

Fundamentally different approaches are required to model higher trophic levels compared to nutrients and phytoplankton. These differences arise from the sophistication of behavioural responses of higher organisms to the environment, and from the wide range (orders of magnitude) of changes in body size of individuals within the life cycle. Both structured population, and individual based models may be appropriate under different circumstances.

Bulk-biomass entity (BM) are used in NPZD model and interpret the Z variable as the zooplankton species of interest. They have a weak capacity to understand zooplankton dynamics.

Structured population models (SPM). Structured population models (SPM) are required to simulate seasonal and annual dynamics of successive cohorts of targeted species with multistage development. By coupling with spatially resolved ecosystem models, they provide an Eulerian approach to the stage distributions of the studied populations. The generalization of these models are referred to as the McKendrick - von Foerster equation (see Carlotti et al., 2000, for details). This approach is particularly convenient to develop for studying the trophic link between lower trophic levels and the targeted species at mesoscale.

Stage- and weight-structured population models are a way to represent realistic growth and development of zooplanktonic populations, and then their role in the ecosystem dynamics. Steele and Mullin (1977) showed the necessity to use numbers of individuals rather than biomass to support a good description of the population dynamics. Recent development of structured representations of population dynamics integrate both biomass and number by taking into account the processes involved in individual growth and by linking bioenergetical processes to demographic processes. A major point in building realistic models of zooplankton population dynamics is that numerous data concerning aspects of growth and reproduction have to be known.

Attempts to couple structured population models with biomass based ecosystem models have been made (Carlotti & Radach, 1996; Heath et al., 1997) but simulations yield time series disregarding spatial dimension. These first attempts on modelling population dynamics outlined the difficulty of obtaining adequate data for testing complex models of zooplankton response to short term spatio-temporal variations in physical forcing. This requires vertically resolved data on stage abundances of the main species. Very few studies emphasise this information. FLEX'76 experiments (Sundermann & Lenz, 1983) to study the North Sea dynamics provided such data sets which are still currently used in models.

Structured population models are problematic for incorporation in 3-D resolved models as age and/or size resolved representation of particular species requires a high number of variables to simulate. For this reason, few simulations of structured population models deal with spatial distribution in time (Slagstad & Tande, 1996; Bryant et al., 1997). Further development will need to simplify the structured population model whilst retaining its essential dynamics properties to an extent that inclusion in a three dimensionally resolved scheme becomes feasible (see Fennel, 2001).

In these models, mortality remains a major process of population dynamics to be determined. Critical developmental stages (i.e. with high mortality rates or particular behaviour) should be represented as single variables whereas other less critical stages should be aggregated. SPM of zooplankton also should deliver prey field of IBM of fish larvae.

Individual based models (zooplankton/fish larvae) are required to focus on species' specific response to physically induced variability. The role of individual variability in bioenergetical and behavioural processes in the demographic processes is essential to understand how a population can answer to natural variability of the environment. A key feature of the population dynamics of higher metazoaans (eg. mesozooplankton, early life stages of fish) is that the survivors at any stage

in the life cycle rarely seem to be drawn at random from the initial population. Individual survival probability can often be related to for example, parental origin, growth rate, or spatial and temporal characteristics. As a result, the average properties of the population over a period of time do not necessarily reflect the average properties of the survivors. The consequences for modelling are that approaches which are formulated in terms of the development of a population of average individuals will fail to capture an important element of the dynamics. One solution is to formulate Individual Based Models (IBM) which incorporate the essential aspects of individual variability in the exposure of animals to the environment and the responses of individuals to exposure. The approach is to track individuals through time, modelling their growth and survival probability in terms of their exposure to forcing environmental conditions. Individual based modelling is most applicable to modelling the early life history dynamics of ichthyoplankton since the methodology exists to determine the individual growth histories of animals sampled in the field from otolith microstructure. Thus, it is possible to parameterise and test the models in a field setting. New models should parameterize the subjacent physical/biological processes which are ultimately most pertinent to population and community processes (emergent function at upper scales).

More sophisticated approach with detailed biology and coupling with the physical and biological environment is becoming more common. The most advanced method, the Lagrangian ensemble (e.g. Carlotti and Wolf 1998) is still in the developmental stage.

Attempts to create individual-based models (IBM) coupled with flow fields derived from hydrodynamical models are strongly increasing (e.g. Miller et al., 1998). These schemes could integrate easily more elaborated biology (e.g. Hinckley et al. 1996 for fish larvae; Carlotti & Hirche, 1997, for copepods). The value of models that incorporate IBM and physical habitat modelling techniques consists not only in increasing our understanding of the link between spatial and temporal dynamics of zooplankton/fish populations but also in allowing exploration of potential environmental variations in this habitat on these populations.

Closing remarks

Expected results of these new models will permit to understand how changes in the global environment will affect the abundance, diversity and production of animal populations, and consequently the biomass of many fish stocks. In return, the improved representation of highest trophic levels will yield a much improved understanding of the world ocean ecosystem dynamics related to physical variability.

A major point to be developed concerns the **representation of the entire zooplankton community**: zooplankton population models deal with one copepod species as the herbivore in the food chain, whereas there is usually seasonal a succession of species. Multi-species models may be constructed from combinations of bulk-biomass representations, structured population models, and Individual Based Models. These may operate on different spatial and temporal scales, presenting particular technical challenges.

It is not possible to simulate the dynamics of all the species or to model the entire zooplankton community, but generally 5 to 8 populations dominating the mesozooplanktonic community may be sufficient to simulate the community dynamics. From the stand point of studying the bioenergetics and survival of larval fish, it is necessary to include models of several zooplankton species.

Such community models should integrate interaction processes between demographic models of selected zooplanktonic species. To build these models, understanding of interactions involving lower trophic levels (phytoplankton, microzooplankton), higher trophic levels (fish larvae), physical and chemical conditions is critical.

Complex models of interactions are not easily tractable in hydrodynamical models. It will be necessary to extract from complex interactions, those processes which are the most relevant for the population dynamics of the selected species and for the ecosystem dynamics. Evaluating the results of such models will also be carried on in a variety of scales from laboratory cultures and mesocosms, to regional scale assessments.

Finally, the inclusion of zooplankton community models in whole ecosystem models should end with regional models of zooplankton production and fish recruitment. These models should be a tool to study regional differences.

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Three dimensional ecosystem modelling with stage resolving description of zooplankton

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Modelling of marine ecosystems involves coupling of physical and biological processes. Advanced model systems integrate eddy resolving three dimensional circulation models and chemical biological models of the lower trophic levels. Zooplankton is often introduced as a bulk-variable, lumping together the biomass of all zooplankton stages.

Regarding more detailed descriptions of the higher tropic levels there are several models concentrating in particular on zooplankton developments by resolving stages. Here we present a coupled model for the Baltic Sea, which was originally constructed to simulate the nitrogen cycles, see Figure 1, in which the bulk zooplankton variable was replaced by a stage resolving model component for copepods. The biogeochemical model developed further early versions of Fennel (1996) and Fennel and Neumann (1996), and is described in detail in Neumann (2000) and Neumann, Fennel, and Kremp (2002).

An important achievement is the capability to compute the distribution patterns of early stage (nauplii) and their changes with time. A series of snapshots of the model nauplii for different times is shown in Figure 2. A more detailed description of this simulation is given in Fennel and Neumann (2002). This potential provides a link to recruitment studies by addressing the match-mismatch problem. Survival of larvae requires the availability of food, in particular nauplii, at the right time and place. Investigations on trajectories of fish eggs and larvae require prey fields to estimate survival rates.

The simulation shown in Figure 2 indicate areas of aggregation and retention of nauplii which roughly coincide with known nursery areas of some fish species. An important problem to validate the model is the lack of sufficient field data resolving stage of copepods. Thus, modelling / theory is ahead of observations. This issue is addressed in the German GLOBEC programme where through a close interaction between observations in field campaigns and experiments as well as modelling the required data sets and process descriptions will be provided. The data serve to assess the skill of the models and to improve the parameterizations and equations in the biological model.

Bio-chemical model for the Baltic Sea

Fig. 1. Biogeochemical model for the Baltic Sea according to Neumann (2000). The model involve three nutrients (ammonium, nitrate and phosphate), three functional groups for phytoplankton (diatoms, flagellates and blue-greens), bulk zooplankton and detritus, as well as oxygen as state variables. The bulk zooplankton can also be replaced by a stage resolving copepod model component, developed in Fennel (2001).
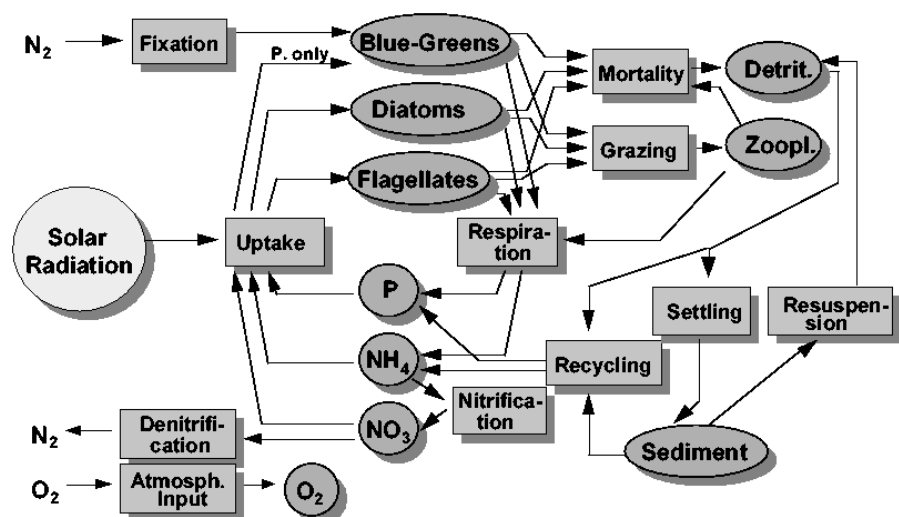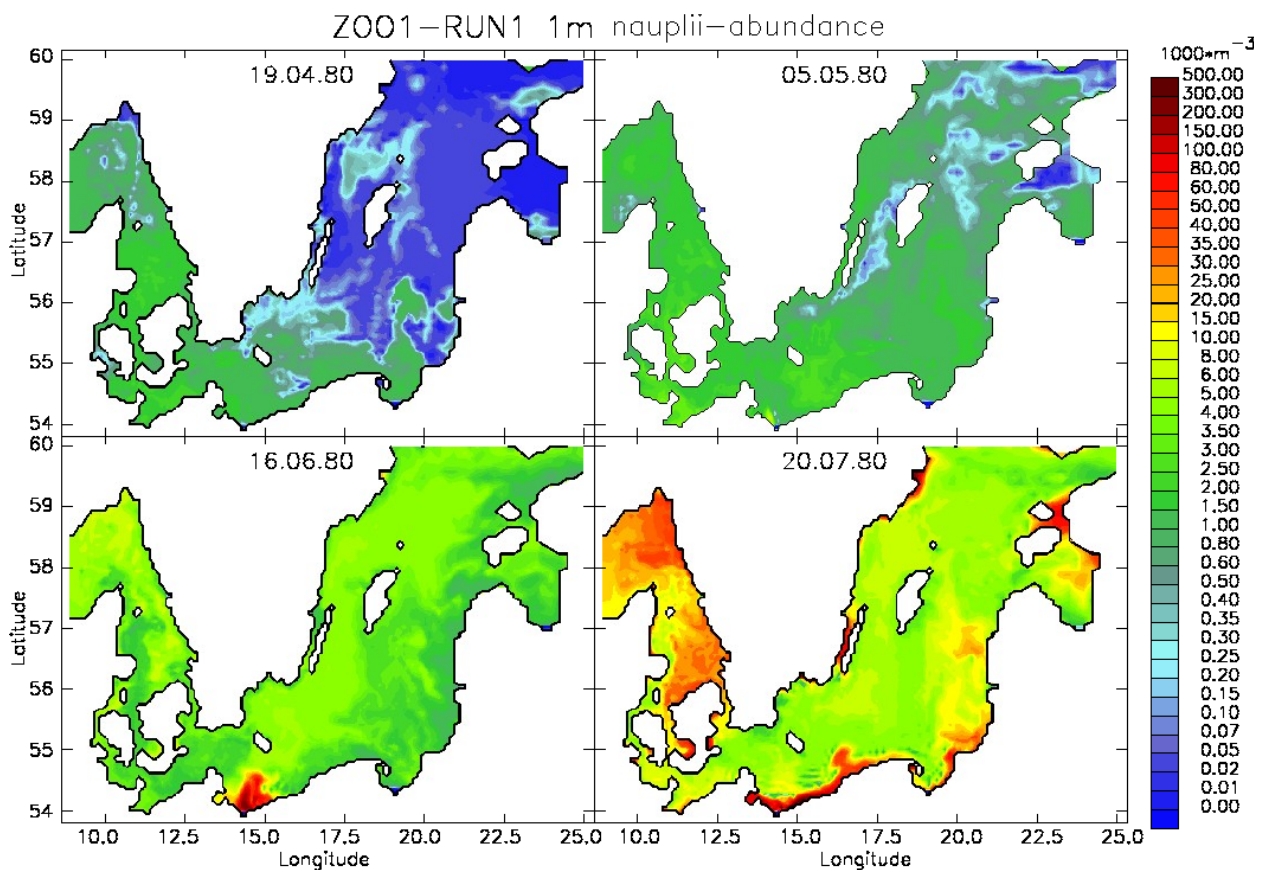
Fig. 2. Series of snapshots of distribution patterns of model nauplii in the upper mixed layer, simulated with a coupled model, Fennel and Neumann (2002).

The presented coupled biogeochemical model with stage resolving zooplankton was developed for the Baltic and the stage resolving component was guided by dynamical signatures of the *Pseudocalanus* in the Baltic. Therefore, the physical features and the species of interest differs from those around the Faroe Islands. However, such a model contains both site specific and universal dynamical aspects, which allow to apply such a model also to other systems after appropriate modifications.

For the planning of the model building one possibility could be to follow the road we used for our Baltic Sea ecosystem model, by starting with simple box models as in Fennel (1995) and inserting this in relative simple circulation model as in Fennel and Neumann (1996). Later both the biological model and the circulation model can be developed further, as for example in Neumann (2000), Fennel (2001), and Fennel and Neumann (2002).

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Climate and climate change in the Atlantic-Arctic region

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Motivation and introduction

The climate system is characterized by variations on a variety of spatial and temporal scales. These variability modes are either caused by variations in the external forcing of or internal processes within the climate system, or a combination of both. Examples of external forcing factors are variations in the solar irradiance and the composition of gasses and particles in the atmosphere, the latter caused by e.g. volcanic activity or human-induced emissions of greenhouse gasses and aerosol particles. Internal processes include restructuring of heat, fresh water or momentum within or between the atmosphere-sea ice-land-ocean systems.

Some natural variability modes are documented by instrumental records covering the last 50-150 years, and are consequently fairly well known. The two most pronounced of these variability modes are the El Niño-Southern Oscillation with centre of action in the equatorial Pacific and with a characteristic time scale of 3-5 years, and the North Atlantic Oscillation/Arctic Oscillation with centre of action in the North Atlantic and Arctic region and with a characteristic time scale of 10-20 years. Both of these variability modes lead to significant changes in the regional, and in some cases also the global, climate system on the indicated time scales.

A consequence of the limited time span covered by the instrumental records, variability modes occurring on multi-decadal and longer time scales are generally poorly known. To identify such modes, proxy observations (e.g., tree rings, and sediment and ice cores), together with e.g. written historical sources, can be used. For instance, historic sources and paleoclimate records show that the climate system has experienced variabilities on a variety of temporal scales not covered by the instrumental records, and that extreme short events unprecedented in the observational record have occurred. Two recent anomalous climate periods are the "Medieval Warm Period" between the 10th and 14th centuries when Northern Hemisphere temperatures were about 1.0 °C warmer than in modern time, and the "Little Ice Age" between the 15th and 19th centuries when Northern Hemisphere temperatures may have been between 1.0 and 2.0 °C below the modern values. It is likely that none of these two anomalies were monotonously cold or warm, and there were large temporal and spatial differences.

It is therefore of importance to keep in mind that the climate system is characterised by variability in both time and space. This is of particular importance when the climate system of the following decades to centuries are assessed: How large – if any at all – are the human induced changes to the climate system compared to a system unperturbed by human activities?

The Intergovernmental Panel on Climate Change (IPCC) states that instrumental and paleo proxy records from the atmosphere, the oceans and land indicate that human activities is about to change the climate system of the Earth. The direct reason for this is the observed increase in the concentration of atmospheric greenhouse gasses and aerosol-like particles since the beginning of the industrial era. As an example, carbon dioxide, the principal human-induced greenhouse gas, has increased from about 280 parts per million (ppm) (or 0.028 %) at 1750 to about 370 ppm today. This increase is mainly caused by burning of oil, coal and gas, and by changes in the use of land. The current atmospheric concentration of CO_2 is likely higher than over the last 400.000 years, and possibly higher than over the last 15 million years. It is therefore not a surprise *if* the climate system is changing as a result of human activities.

It is extremely difficult to predict regional changes in the climate system as a consequence of human activities. The main reason for this difficulty is linked to the interplay between the natural variability modes of the climate system and a gradual (human-induced) change of the climate forcing (see also below). Key questions in climate change research are therefore devoted to whether the natural variability modes might be damped, strengthen or change temporal-spatial characters as the global warming continues.

In the following, a discussion of possible changes in the Atlantic-Arctic climate system is given. Possible consequences on the marine biota are not considered here. However, as the marine biota is generally dependent on the marine climate, changes in the biota, including changes in the marine biodiversity, can not be excluded.

Climate models using the moderate IPCC (2001) B2 scenario predict in average an increase in the global mean temperatures of 0.7°C by the year 2020, 1.4°C by the year 2050 and 2.1°C by the year 2080 (Figure 1). The different climate models using this scenario predicts a temperature increase by the year 2100 ranging from 1.9°C to 3.4°C, illustrating the uncertainties in the predictions.

Fig. 1. Future changes in global mean temperature different emission scenarios using several different climate models. The bars show the range of simple model results in 2100 (Figure 9.14 in IPCC TAR: The Scientific Basis).
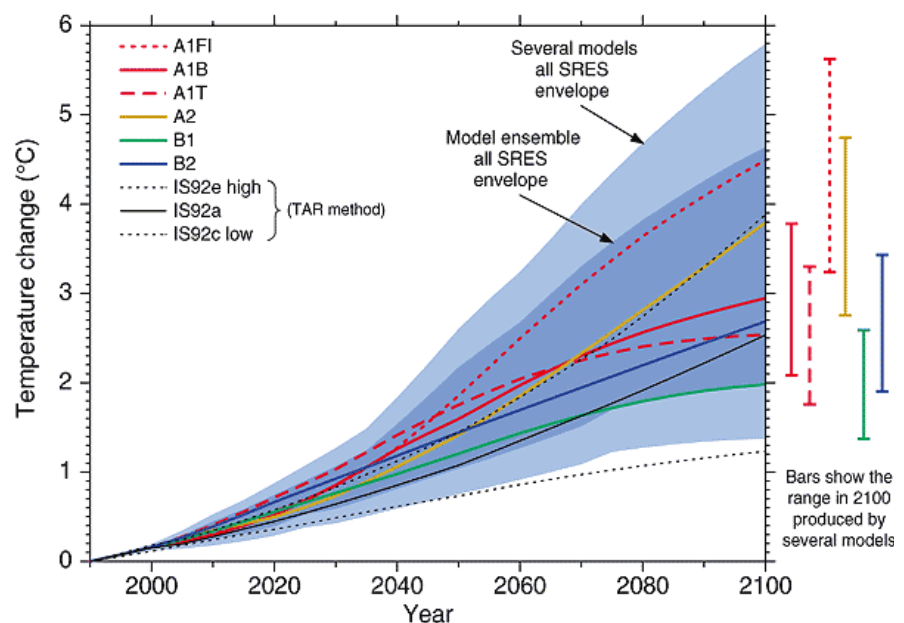
In the climate model inter-comparison project (CMIP), control-integration and a perturbation-integration with a 1 percent increase in CO_2 have been compared for a range of different climate models. The change in the global mean temperature for 18 of the models is shown in the left panel of Figure 2. After 80 years (at doubled CO_2 concentration), the average global mean temperature increase for the models is 2°C, or 0.25°C/decade, or in the lower range of the values found from the B2 scenario integrations. For four models forced with the B2 scenario (Figure 2, right panel), the average temperature increase averaged over the region north of 60°N is 0.4°C/decade, or almost twice the global trend.

Turning from global to regional scale climate change, the uncertainties are generally much larger. There are at least three reasons for this: 1) The natural variability in the local climate may many places be of an order of magnitude larger than the variability in the global mean state of the climate, so the signal to noise ratio becomes small; 2) we do not know all physics behind the variability; and 3) parameterisations of unresolved topography and physics may be inaccurate.

As the climate models have typically been too coarse to resolve local or regional topography (typical grid size has been 200 and 400 km), the usual approach to get high resolution climate scenarios has been to take the results from a global model and use it as input to a regional atmospheric model. As there are large discrepancies between the climate scenarios from the coarse models, output from several models should be dynamically downscaled in this way to provide a best possible statistical significance of the results.
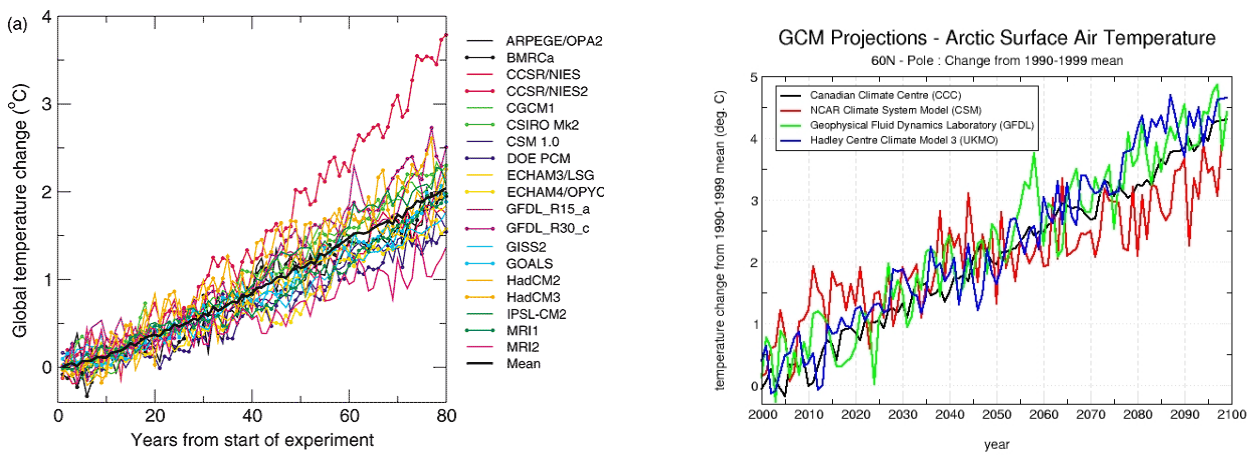
Fig. 2. Left: Future changes in global mean temperatures for 18 different models participating in the coupled model inter-comparison project second phase (CMIP2). The only change from the control runs is a 1 percent increase in CO_2 per year from ca 1990 values (Figure 9.3 in IPCC TAR: The Scientific Basis). Right: Future changes in Arctic mean temperatures for 4 models using the B2 scenario (ACIA web pages, http://zubov.atmos.uiuc.edu/ACIA/).

The atmosphere temperatures and wind systems

Observations

During the last decades, there has been a significant warming trend over the Arctic, corresponding in average to approximately 5°C/century. The warming has not been uniformly distributed, as there has been a slight cooling over the eastern Canada, northwest Atlantic and Greenland area, and a stronger warming over Siberia.

The observed temperature pattern is related to the large-scale North Atlantic or Arctic Oscillation (NAO/AO) pattern, an atmospheric sea-saw in pressure between the low-pressure region in the north, and the sub-tropical high in the south. The strongest pattern is found in the North Atlantic, where the Icelandic low and the Azorean high are close to the centers of action. A much-cited index for the NAO is the pressure difference between Lisbon or Gibraltar to the south, and southwestern Iceland to the north. The NAO index resembles the global temperature pattern, with a preferred positive state during the 1930s and 40s, a steadily decrease to a minima in the 1960s, and then a steady increase towards record highs in the 1990s. The trend is a manifestation of a strengthening of the North Atlantic westerlies, with increased heat and moisture transport responsible for a row of warm and wet winters experienced in the North-East Europe at the end of the last century.

Predictions

Figure 3 shows the predicted temperature increase from the 1961 to 1990 period to the last three decades in this century, as a mean over all models using the B2 scenario. A general warming of typically 1-2°C over the oceans and 2-3°C over the continents are seen. There is a strong increase in the temperature trends towards the Arctic, with a temperature increase over Norway ranging from 3°C in the south to 5°C in the north, and temperature increase over northern part of Canada and Siberia reaching 6°C.

For the Nordic Seas area, the predicted temperature increase is ranging from 3°C in the south to 6°C in the Fram Strait and eastern part of the Barents Sea region. In the Arctic Ocean, the warming is exceeding 8°C north of the Siberia, while north of Alaska, Canada, and Greenland it is 5°C.

The strongest temperature increase is evidently found in areas where there is sea ice in present day climate (in the models), and not ice in the future climate. Thus the strong warming found in the northern and eastern parts of the Nordic Seas could be a result of errors in simulating the present

Fig. 3. The multi-model ensemble annual mean change of the temperature (color shading), its range (thin blue isolines) (Unit: °C) and the multi-model mean change divided by the multi-model standard deviation (solid green isolines, absolute values) for the SRES scenario B2. The change represents the period 2071 to 2100 relative to the period 1961 to 1990 (Figure 9.10 in IPCC TAR: The Scientific Basis).
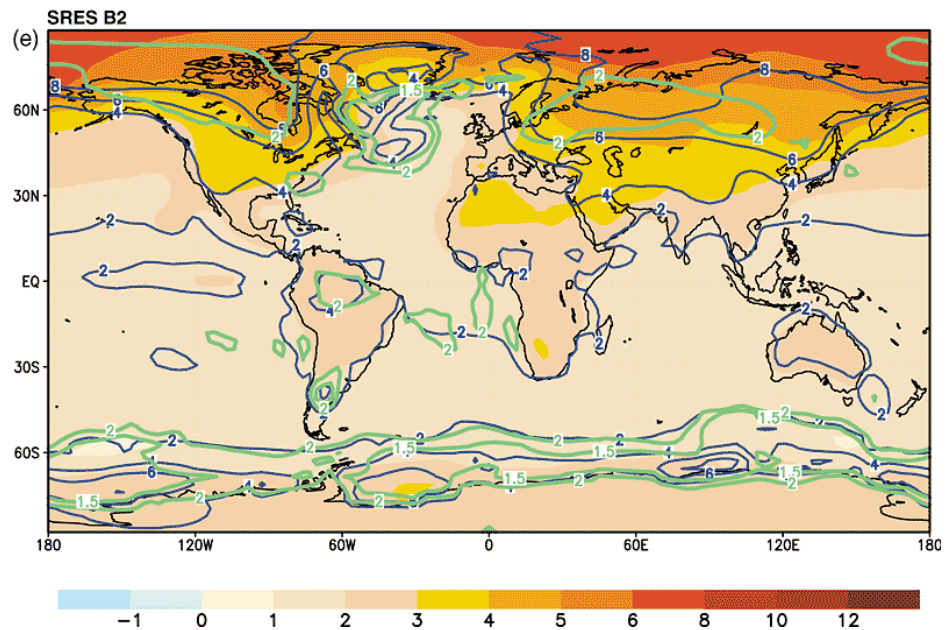
day climate, yielding too large ice cover, rather than a warming of the open sea areas, of the present day climate.

To give realistic scenarios for the atmosphere and ocean parameters in the Nordic Seas region, it is essential to know how the NAO/AO will behave in a world with higher concentrations of greenhouse gasses and aerosol particles. However, the physics leading to the variability and recent trend in the NAO/AO are still not fully known. Several recent simulations with a relatively high-resolution atmospheric model indicate that the NAO is forced from the tropics, and in particular from the equatorial Pacific and Indian Oceans. The exact mechanism is not clear, but it is apparently linked to changes in the precipitation pattern and to the release of latent heat. If this is correct, increased greenhouse gas forcing and warmer waters in the tropical regions might generate a continued trend towards stronger and more persistent westerlies, with especially warmer and wetter winters as the result.

Analysis of the model output from several different climate models (Benestad, Cicerone 6, 2000), show a large spread in the simulated development of the NAO. However, on average, the models yield no significant change in the NAO during the next 100 years. Too much confidence should not be put into this result, as the present day climate models are generally not able to capture the observed trend in the NAO. There may be several reasons for this, among the most cited are too coarse resolution in the ocean models (especially in the tropics), too low vertical resolution in the stratosphere, or simply that the observed low frequency variability and trend in the NAO is an accumulated result of high frequency noise (weather). While the two first problems may be solved with improved computer resources, the latter point gives bad prosperities, as in that case the NAO and a significant part of the development in atmospheric and oceanic climate in our region cannot be predicted.

In a recently finished CMIP2 integration with the Bergen Climate Model (BCM), there is a significant trend in the NAO during the 75 years of integration, representing and increase in the westerlies of approximately 2 %/decade. There is also a weak tendency to become more variability in the winter NAO, a feature that has been seen in observations during the last 50 years (Figure 4).

To summarize, it is probably that the low frequency variability in the westerlies (NAO) may be linked to the global warming, either as a direct feedback from the tropics, or as a result of stratospheric cooling, or as a combination of both. If this is the case, the possibility for a further strengthening of the westerlies is certainly realistic.
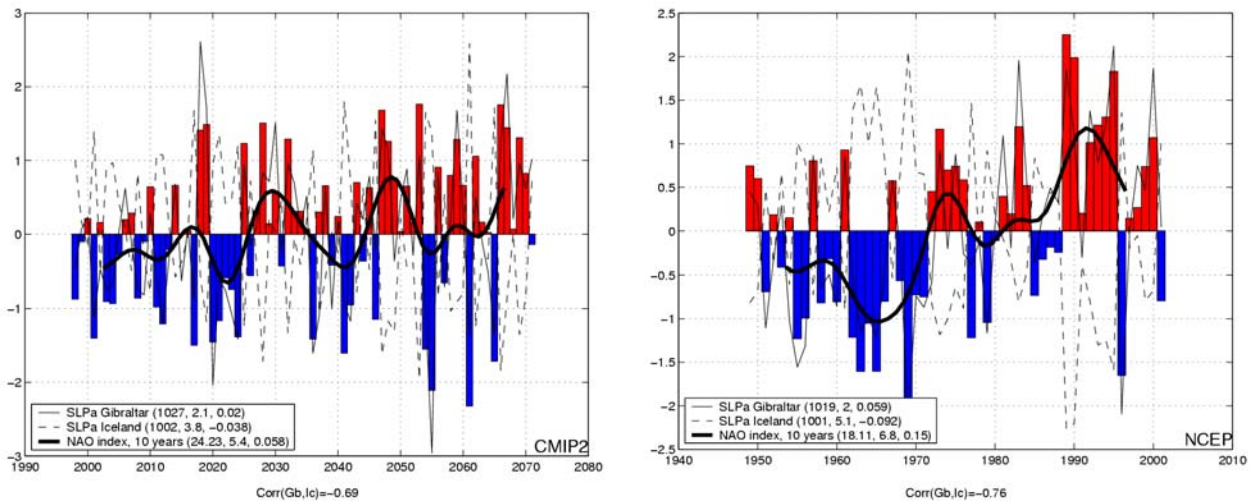
Fig. 4. The NAO index in the BCM CMIP2 integration (left) and the NCEP data (right). The bars show the unfiltered NAO index calculated using the grid points nearest to the positions 22ºW, 64ºN (Iceland) and 5ºW, 36ºN (Gibraltar). The thick line shows the 10 years low pass filtered index, and the thin lines the normalized pressure anomalies at Iceland and Gibraltar. Values in the legend box are means, standard deviations and trends in the unfiltered pressure and pressure difference time series.

Water mass distribution and currents

Observations

There has been a substantial change in the climate conditions in the Nordic Seas during the period with reliable instrumental records. Key observations are: large salinity anomalies, more polar water and eastward shift of the front between Atlantic Water (AW) and Polar Water (PW), a reduction in the deep water formation in the Greenland Sea, a warming of the deep waters and reversal of the deep currents in the Nordic Seas, and a reduced the Faroe Bank overflow.

Predictions

Due to the large thermal capacity of the water, the oceans will probably be less warmed than the atmosphere. Estimates for the Nordic Seas by the Hadley Center model give a temperature increase of the range 1-3ºC during the next 100 years, which is in agreement with other models (e.g. from the Max-Planck institute, Hamburg). However, due to lack of available ocean data from many of the community climate models, and to a common problem with the sea ice distribution in the models (see above), it is difficult to use the same set of models in discussions of the development of the regional marine climate as for the discussion of the surface air temperature and winds. We will therefore quote some numbers from a newly finished 80 years CMIP2 integration (1 percent/year increase in the CO_2 concentration) with the Bergen Climate Model (BCM). The evolutions of the temperature and salinity fields are shown in Figures 5 and 6.

From the experiment with the BCM, we have examined at the model years 1) 20-28 (ca. 2016-24), 2) 50-58 (ca. 2046-2054), and 3) 76-80 (ca. 2072-2076), thus the three. There are no significant differences between summer and winter temperature changes, so only March values are shown here.

From today and to 2020 there is a cooling of between 0 and -1ºC in most of the model area (Fig. 5). Largest drop in temperature is found along the marginal ice zone in the Barents Sea and off the east Greenland coast, with maximum of more than 1ºC in the Denmark Strait. Some of this cooling is probably associated with the weak westerlies in this period (see Figure 4). In the central Nordic Seas there is a warming of 0.5ºC compared to the start state. In 2050 the entire Nordic Seas has become warmer than the initial state, with the exception of a small spot in the Denmark Strait.

Fig. 5. Evolution of the temperature (SST) and sea-ice field in the BCM CMIP2 integration. Left column shows the March SST and sea ice distribution around the years 2020, 2050, and 2075, and right column changes from year 2000 to 2020, 2050 and 2075 respectively.

Largest warming is now found in the northeastern Barents Sea, in the Baltic Sea, and south of Iceland. By the time of a doubling of the CO_2 (year 2070), surface temperatures in the Nordic Seas have increased by 1-2°C, with highest values found in the Baltic Sea, the North Sea and the Barents Sea. Minimum warming (less than 0.5°C) is found in the Denmark Strait.

Salinity changes in the Nordic Seas are generally small, except for the areas influenced by coastal runoff and melting of sea ice (Fig. 6). By the year of 2020, there has been a freshening of typically 0.1 to 0.3 psu in the Baltic Sea, southeast in the Barents Sea and in the Kara Sea, and also a week freshening along the east Greenland coast. The freshening trend continues to the 2050s, with values in the Baltic Sea and north of Siberia in the range of 0.1 to 0.5 psu. There is also a significant freshening in the Polar Ocean (0.3 to 0.5 psu), which is evidently advected south with the East Greenland Current (EGC) into the Denmark Strait and East Icelandic Current (EIC). In the AW regime the waters have become slightly more saltine, but still without exceeding 0.1 psu. In the 2070s the model gives a 0.1 to 0.2 psu more saline water south of the inflowing area, and less than 0.1 psu more saline AW in the Nordic Seas. In the Baltic Sea, north of Siberia and in the Polar Ocean, salinities have decreased between 0.5 and 1 psu, and again the tongue of negative salinity change can be seen along the East Greenland Coast.
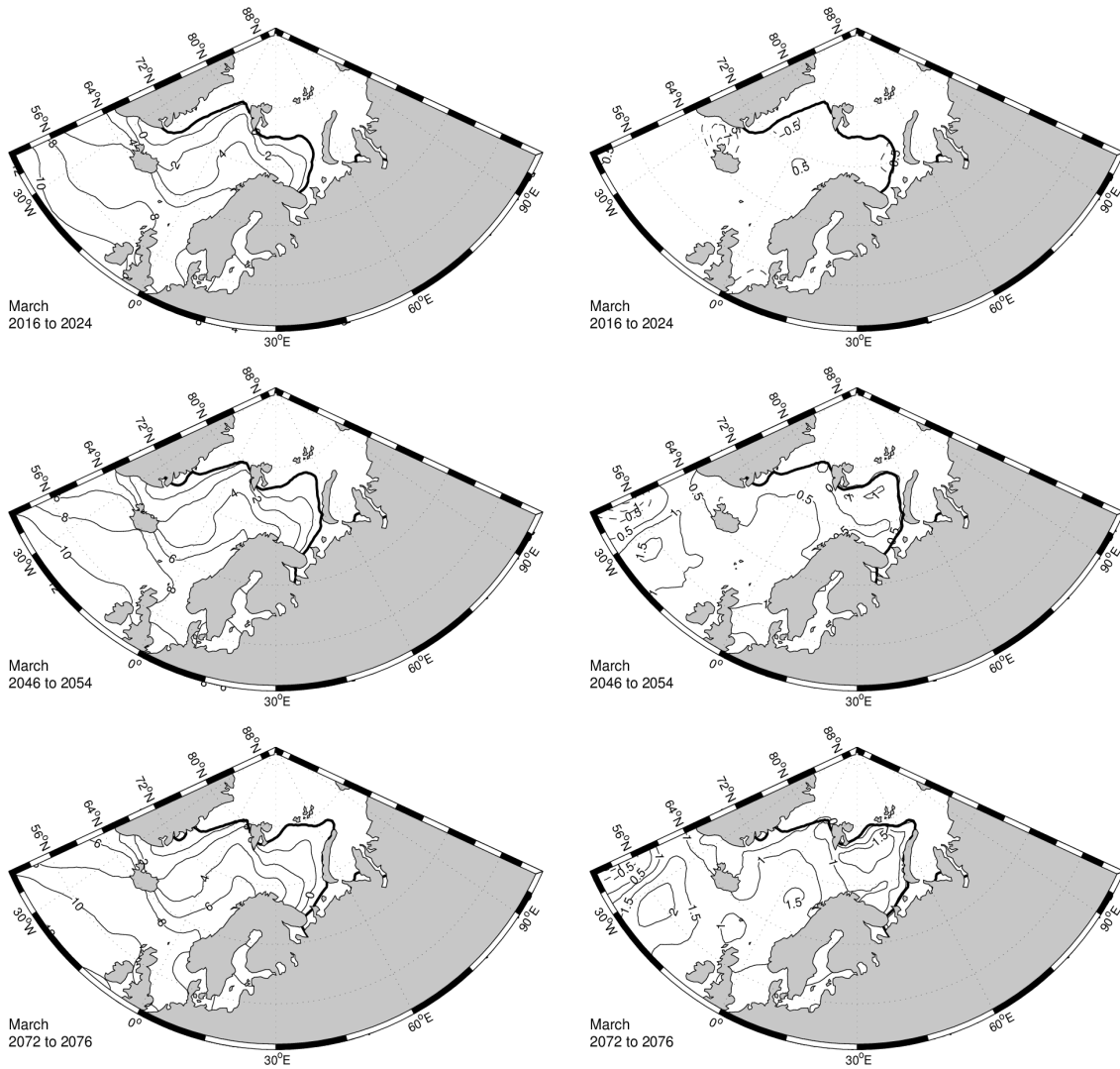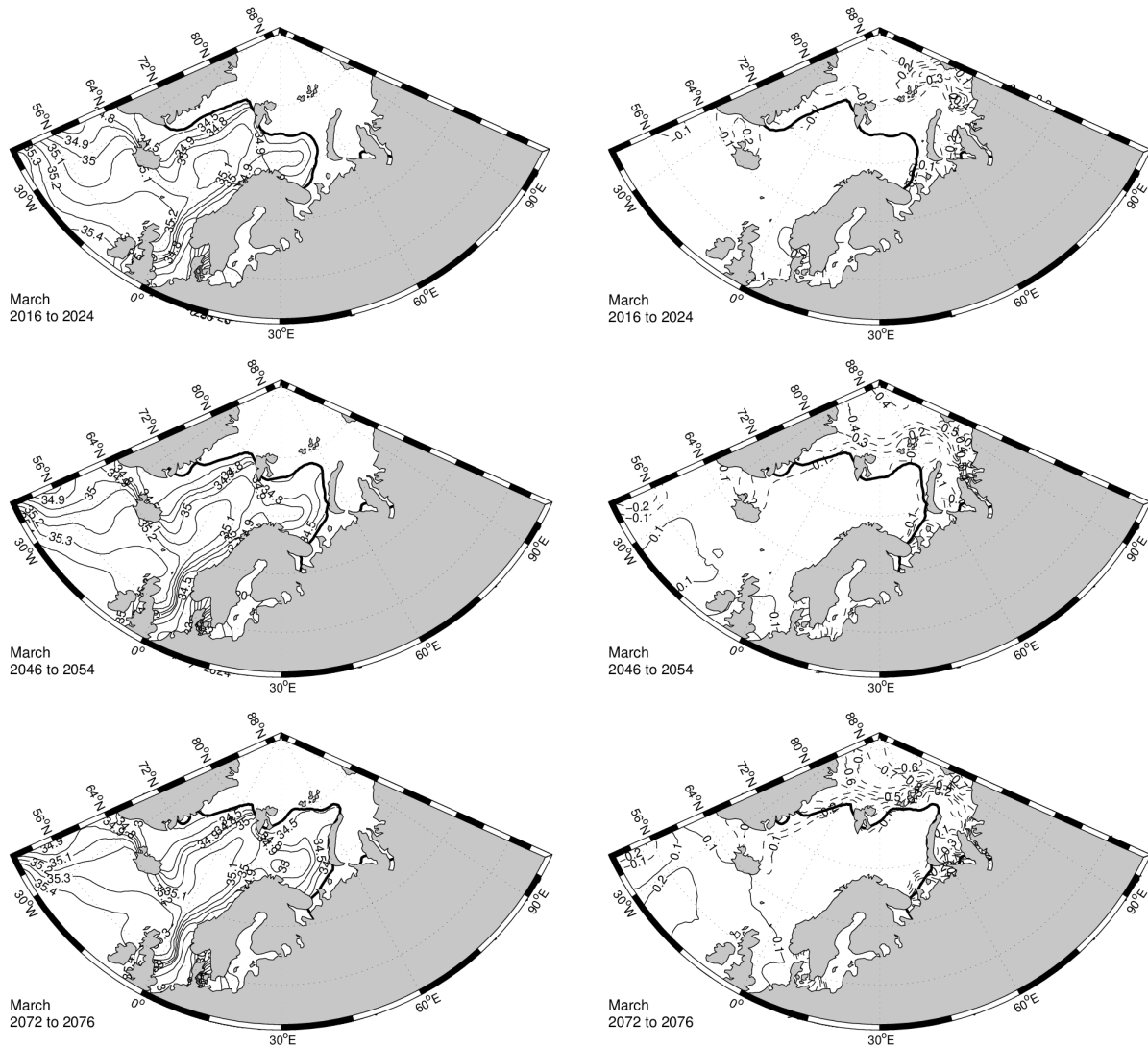
Fig. 6. Evolution of the salinity (SSS) and sea-ice field in the BCM CMIP2 integration. Left column shows the March SSS and sea ice distribution around the years 2020, 2050, and 2075, and right column changes from year 2000 to 2020, 2050 and 2075 respectively.

From 2000 to 2020 there is a small (<10%) increase in the net inflow through the Iceland-Scotland Gap, mainly near Iceland, and a corresponding increase in the Denmark Strait outflow. There is generally a weakening of the cyclonic gyre in the Nordic Seas of a few percent. By the year of 2050, the Nordic Seas gyre has weakened further more (10%). It is more inflow of AW in the eastern branch (east of the Faroe Island), and less in the western. No significant changes are seen in the Barents Sea. Towards the 2070s there is a further reduction in the internal cyclonic flow in the Nordic Seas. There seems to be a weak strengthening (~0.25SV) of the AW transport trough the Barents Sea, and a similar reduction of the flow through the Fram Strait.

Deep water formation

Observations
Since the 1960s when there was an active and deep-reaching convection in the Greenland Sea, there is evidence of a reduction in the deep-water formation in this area (Dickson et al, 1996, *Prog. Oceanogr.*). In addition, measurements from the Faroe-Shetland overflow indicate a reduction in the transport of dense water from the Nordic Seas toward the North Atlantic (Hansen et al, 2001,

Nature). It is still uncertain to what extent these findings influence the basin- to global-scale thermohaline circulation, and the heat transport towards our latitudes.

Predictions

There have been many warnings about an abrupt stop in the thermohaline circulation, and a possible rapid change towards a colder climate in the northern Europe, as a possible scenario under global warming.

These scenarios are all built on idealized experiments, or experiments with very coarse resolution models, not necessarily simulating the climate and physics realistically. From Figure 9 it is seen that many of the models in the IPCC (2001) report simulate a reduction in the overturning in the North Atlantic, but none of them an abrupt stop. In the German model, ECHAM4/OPYC, there is no reduction at all. This is explained by better resolution in the tropics, as more fresh water is transported from the tropical Atlantic to the Pacific, resulting of advection of more salty water into the sinking regions in the northern parts of the Atlantic.

In the CMIP2 integration with the BCM no significant reduction in the overturning is found (not shown). In the central Nordic Seas, there is a tendency for the mixed layer depth to become shallower as a response to slightly less density in the area, indicating more shallow convection here. There is a tendency for deeper mixing closer to the ice edge, as the mixed layer depth increases in the Barents Sea and in the western and northern parts of the Greenland Sea.

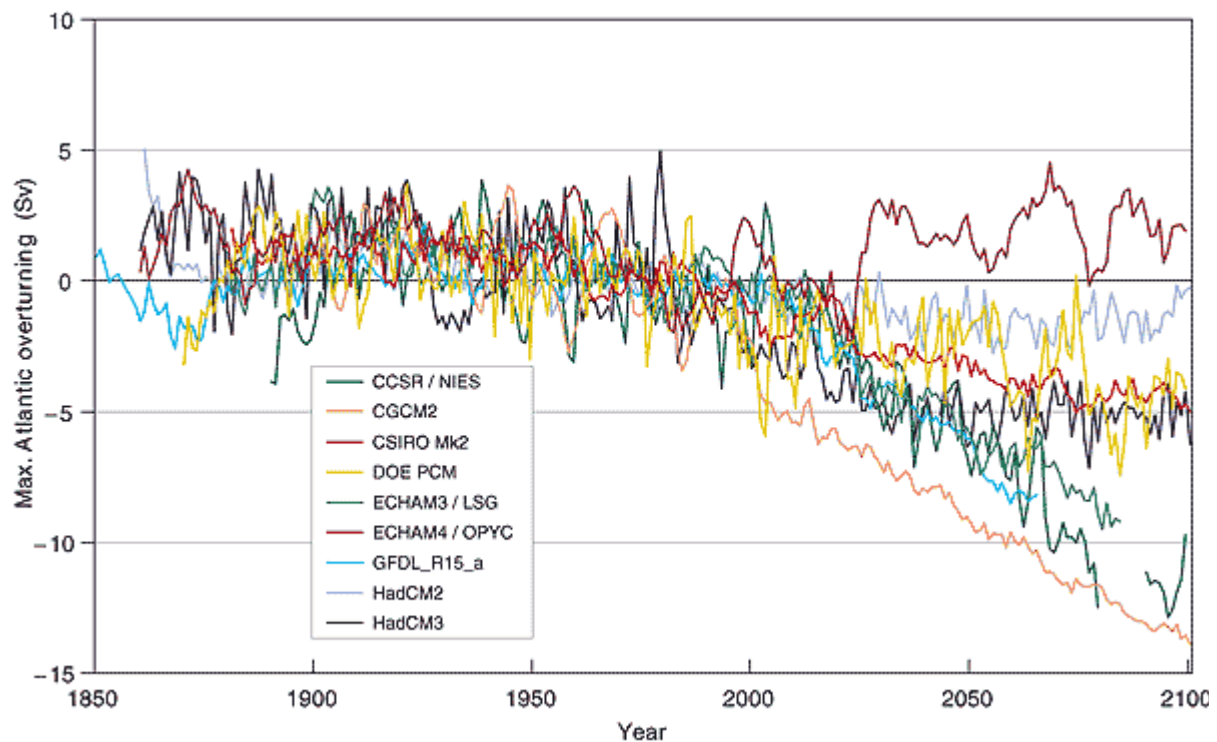Fig. 9. Simulated water-volume transport change of the Atlantic "conveyor belt" (Atlantic overturning) in a range of global warming scenarios computed by different climate research centers. Shown is the annual mean relative to the mean of the years (1961 to 1990) (Unit: SV, 10^6 m^{3}s^{-1}). The past forcing is only due to greenhouse gases and aerosols (Figure 9.21 in IPCC TAR: The Scientific Basis).

Summary

Due to large discrepancies between the different climate models, and the failures in many climate models to simulate the sea ice extent in the Norwegian and in particular the Barents Seas, it is difficult to give qualified predictions for the state of the Nordic Seas and Arctic region for the years 2020, 2050, and 2080. While the overall trends can be given with some confidence, the presence of the possible unpredictable North Atlantic/Arctic Oscillation can for periods of several years mask the trends in the data sets.

In Table 1, a summary of this draft is provided. While most results are objectively analyzed based on several models, some of the specific values may be biased towards the scenario given by the Bergen Climate Model. The reason for this is caused by the availability of the relevant data, and the fact that the BCM yields a more realistic ice cover in the Nordic Seas than most of the other models.

Table 1. Summary of the results.

	Observed variability/change in the Nordic Seas during the last 3 decades	2020	2050	2080
Atmospheric temperature	A warming trend in the eastern part, cooling in the western part, probably associated with the NAO	Ca 1°C warmer. Spatial differences due to NAO	Ca 2°C warmer. Spatial differences due to NAO	Ca 3°C warmer. Spatial differences due to NAO
Wind systems	Increased westerlies	Ca 5% (?) more westerlies. Depends on the state of the NAO.	Ca 10% (?) more westerlies. Depends on the state of the NAO.	Ca 15% (?) more westerlies. Depends on the state of the NAO.
Ocean currents	Probably increased NAC. More narrow NWAC, and possible increased flux to the Barents Sea and Arctic Ocean. Decreased flux out through FS channel.	Ca 5% weakening of the Nordic Seas Gyre. Less inflow of AW (?)	The Nordic Seas Gyre further reduced. The inflow of AW more in the eastern (Faroe-Shetland) branch.	AW distributed more East. Possibly a strengthened transport to the Barents Sea, and a reduced flow through the Fram Strait.
Water mass distribution	Increased influence of PW. Warmer water in the NWAC. More fresh intermediate water. Warming of the deep water.	The observed trends will probably continue. Possibly cooling in negative NAO years.	Ca 1°C warmer and 0-0.1 psu saltier in the AW domain. Fresher water along the coast.	1-2°C warmer, most in the Barents Sea. More continental runoff. More salty AW inflow.
Deep-water form.	Less convection in the Greenland Sea, and more convection in the Labrador Sea. The total overturning has probably been fairly constant.	Deeper mixed layer southwest of Iceland and in the central Nordic Seas. Possibly related to NAO state.	Generally a shallower mixed layer depth in the Nordic Seas, indicating less deep water formed.	Deeper mixed layer in the Barents Sea and western Nordic Seas. Elsewhere more shallow.

Using Ecopath with Ecosim for ecosystem based management of fisheries

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Ecopath with Ecosim (EwE) is an ecological modeling software for PC's that has been developing for more than a decade. Its development is now centered at the University of British Columbia's Fishery Centre. The software has more than 2400 registered users representing 125 countries, and more than 130 ecosystem models have been published (see www.ecopath.org). The approach is thoroughly documented in the scientific literature. EwE has three main components: Ecopath – a static, mass-balanced snapshot of the system; Ecosim – a time dynamic simulation module for policy exploration; and Ecospace – a spatial and temporal dynamic module designed for exploring protected area impacts and design. This approach can be used to:

- Address ecological questions;
- Evaluate ecosystem effects of fishing;
- Explore management policy options incorporating economic, social, and ecological considerations, and legal constraints;
- Evaluate impact and placement of marine protected areas;
- Evaluate effect of environmental changes;
- Quantify bioaccumulation patterns of persistent pollutants through the food web.

The foundation of the EwE suite is an Ecopath model, which creates a static mass-balanced snapshot of the resources in an ecosystem and their interactions, represented by trophically linked biomass 'pools'. The biomass pools consist of a single species, or species groups representing ecological guilds. Pools may be further split into linked ontogenetic (juvenile/adult) groups or multi-stage groups, (e.g., age groups). Ecopath data requirements are relatively simple, and generally already available from stock assessment, ecological studies, or the literature: biomass estimates, total mortality ecosystem model along with estimates of uncertainty based on a gradient estimates, consumption estimates, diet compositions, and fishery catches. If input data are specified with ranges an automated mass balance routine can be used to obtain a balanced descent optimization routine.

The time-dynamic simulation module, Ecosim provides a dynamic simulation capability at the ecosystem level, with key initial parameters inherited from the base Ecopath model. The key computational aspects are in summary form:

- Use of mass-balance results (from Ecopath) for parameter estimation;
- Variable speed splitting enables efficient modeling of the dynamics of both 'fast' (phytoplankton) and 'slow' groups (whales);
- Effects of micro-scale behaviors on macro-scale rates: top-down vs. bottom-up control incorporated explicitly.
- Includes biomass and size (or age) structure dynamics for key ecosystem groups

Ecosim uses a system of differential equations that express biomass flux rates among pools as a function of time varying biomass and harvest rates. Predator prey interactions are moderated by prey behavior to limit exposure to predation, such that biomass flux patterns can show either bottom-up or top down (trophic cascade) control. Conducting repeated simulations Ecosim simulations allows for the fitting of predicted biomasses to time series data, thereby providing more insights into the relative importance of ecological, fisheries and environmental factors in the observed trajectory of one or more species or functional groups.

Time series fitting in Ecosim: evaluating fisheries and environmental effects

Ecosim can thus incorporate (and indeed benefits from) time series data on:

- relative abundance indices, (e.g., survey data, catch per unit effort [CPUE] data);
- absolute abundance estimates;
- catches;
- fleet effort;
- fishing rates; and
- total mortality estimates.

For many of the groups to be incorporated in the model the time series data will be available from single species stock assessments. EwE thus builds on the more traditional stock assessment, using much of the information available from these, while integrating to the ecosystem level.

The time series fitting uses either fishing effort or fishing mortality data as driving factors for the Ecosim model runs. A statistical measure of goodness of fit to the time series data outlined above is generated each time Ecosim is run. This goodness of fit measure is a weighted sum of squared deviations (SS) of log biomasses from log predicted biomasses.

The model allows four types of analysis with the SS measure:
1. determine sensitivity of SS to the critical Ecosim vulnerability parameters by changing each one slightly (1%) then rerunning the model to see how much SS is changed, (i.e., how sensitive the time series predictions 'supported' by data are to the vulnerabilities);
2. search for vulnerability estimates that give better 'fits' of Ecosim to the time series data (lower SS), with vulnerabilities 'blocked' by the user into sets that are expected to be similar;
3. search for time series values of annual relative primary productivity that may represent historical productivity 'regime shifts' impacting biomasses throughout the ecosystem;
4. estimate a probability distribution for the null hypothesis that all of the deviations between model and predicted abundances are due to chance alone, i.e. under the hypothesis that there are no real productivity anomalies.

In addition to the nonlinear optimization routines described above the fit to data can also be improved in a feedback-process by examining some of the crucial ecological parameters in the EwE model (notably total mortality rates and the settings for top-down/bottom-up control). It is important to note here that such fitting does not include any 'fiddling-factors' internal to the model, instead the type of question that is addressed after each run is "which species parameters or ecological settings are not set such that the model captures the observed trends over time adequately?"

The inclusion of time series data in EwE facilitates its use for exploring policy options for ecosystem-based management of fisheries. The time series fitting has so far been conducted on only a few ecosystem models, (e.g., on models of French Frigate Shoals, Eastern Pacific, Strait of Georgia, Gulf of Thailand, North Sea, while a dozen or so applications are known to be in progress). Results from these studies indicate that the model is capable of producing very reasonable fits, (i.e. fits that can be compared to those obtained using single species models) for available time series related to the ecological resources of an ecosystem in one go. This indicates a capability or at least a potential to replicate the known history of the ecosystems. In turn this lends some confidence to how the model can be used for policy exploration.

The application to the Strait of Georgia and the French Frigate Shoals both indicate that after the models fit to observed time series had been optimized through the feed back process involving changes to the ecological interaction parameters, there were still considerable deviations between observed and estimated parameter estimates. The (third) nonlinear search type above was therefore used on both systems to search for time series anomalies that may indicate regime shifts. In both

cases it was found that the routine indicated changes in primary productivity patterns in line with observed changes at the decadal scale. An implication of this is that the fitting of time series in Ecosim may be used not just for identification of ecosystem effects of fishing but also to address questions of environmental impact at the ecosystem level (as well as for individual groups of course).

Practical ecosystem modelling: Matching models to uses

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Ecosystem models are built and used to:

> Consolidate knowledge,
> Increase knowledge, and
> Support better decision-making.

Although they can overlap, these uses are not identical, and no single modelling approach serves all of them equally well. Moreover, models differ in the cost and ease of development, as well as their suitability for the different functions. Therefore users should consider carefully the relative priority of each function, and choose wisely the type of model most appropriate for their interests.

If the goal of using a model is consolidate knowledge, then to the fullest extent possible the measurement in which you are most confident should have a dominant position in modelling. It is the least accurate measures in a series that determine the accuracy of the combined result. Usually monitoring time series provide a lot of very comparable data on some parts of the ecosystem, and little or nothing on other parts. Although this does mean that it is premature to try to build whole ecosystem models for consolidating understanding, there are many highly informative modelling activities that can be undertaken. Many of these analyses fall under the umbrella of "community ecology studies", which can environmental covariates included in the analyses. Such analyses can shed great light on the information contained in the data sets available for an area, even if they leave out parts of the ecosystem known to be important but which monitoring has not provided direct information.

Models can be used to build from the known to the unknown, on many scales from a few parameters to whole ecosystems. To use models to increase knowledge, it is first necessary to:

> specify and organise what you know,
> provide an inventory of the pieces that are available to be added to that knowledge, specify
> the tests that have to be passed as linkages are explored, and
> specify what a pass and a fail are on those tests.

The next step is to build two or more models, differing in known ways, compare both to the available observations, and to each other. There are several questions to ask of the results, including:

- ❑ Do they both fit equally well the data you have to constrain the model?
- ❑ If each model fails to fit some part of the data, how do the fits differ?
- ❑ Among models with comparable fits, do outputs of the models provide different patterns that cost-effective monitoring differentiate

Correspondingly, the contribution of neutral modelling to ecological theory is informative for such comparative use of models to increase knowledge. When single models are used to increase knowledge, it is not the median output of the model that is scientifically useful. Rather, single models, particularly if they are over-parameterized relative to constraining data, are informative when used to determine boundaries of critical failure, and otherwise quantify the range of uncertainty

that is actually present in the current knowledge and data available about the system. Resampling strategies for data and parameters are particularly important in developing such models.

When considering if and how to use ecosystem modelling in supporting management decision-making, it is a useful starting point that within government good decision-making is equivalent to good risk management. This perspective makes several imperatives clear:

❑ Know the management objectives, and have them expressed in operational terms
❑ Know the consequences that might arise from each option available, so one can estimate the costs if things go wrong.
❑ Know the uncertainties associated with the factors considered in the decision, so one can estimate the probabilities of various consequences of each option.

Ecosystem modelling can inform each of these steps, but it cannot replace any of them.

Some type of modelling is essential for the third step, in particular, since uncertainties are inherently mathematical estimates. What does it take for ecosystem models to be "reliable" enough to serve as a basis for management advice? Inputs should have high and known accuracy and precision. , It must be possible for incorrect formulations to be rejectable. These are problematic standards for models of competition and predation to meet, if applied to systems with many species or trophic levels. Use of statistical models and the neutral modelling approaches of ecology are helpful in these contexts, both for species-species and species-environment interactions.

As a constructive approach to determining the appropriate complexity of an ecosystem model used for supporting decision-making, the following steps are useful to follow:

❑ For was many stocks as data allow, consider the interannual coefficient of variation in factors such as cohort strengths, per capita productivity, natural mortality growth, etc;
❑ Rank the important biological factors by their CVs;
❑ Focus the ecosystem modelling on the most variable factors;
❑ Conduct data analysis that will bring out the key physical and biological factors than cause the observed variability;
❑ Build models that include the key forcing relationships and not all possible linkages.

This strategy is likely to result in complex ecosystem models being used for relatively few factors; perhaps natural mortality, whereas statistical models, for all their dangers, are still the more reliable option for supporting management.

Ecospace & The Faroe marine ecosystem

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The Faroe Islands utilize a spatial- and effort-based system of fisheries management, explicitly including ecosystem considerations in their policies. Given the importance of fishing to the Faroe economy and culture, considerable interest has been expressed in the evaluation of these new management measures at the ecosystem level. With the help and assistance of Jákup Reinert, I constructed a trophodynamic ecosystem model of Faroese waters (based on ICES Area Vb, ~ 190,200 km^2) using Ecospace, a routine of the Ecopath with Ecosim suite of modelling tools (documented and freely available at www.ecopath.org). The aim was to demonstrate some of the options available for spatial modelling. The input data sources for the 19 functional groups are summarized in Table 1, and illustrate areas for data improvements. Most data used for species of commercial importance were based on ICES Working Group stock assessments, or if not available for the present area, were taken from nearby or similar areas or models. An earlier version of the model is documented elsewhere (Zeller & Freire 2001). Thirteen gear types/fisheries were defined for the model, including foreign and domestic fisheries. Landings for 1997 by species in ICES area Vb were obtained from the ICES 'Statlant' database. No information on discards is currently incorporated into the model. All non-Faroese fleets (mainly Iceland, Norway, Russia, United Kingdom, Germany, France, Denmark and Estonia) were grouped into a single 'Foreign' category fishing mainly on pelagic species. For the spatial simulations, habitats were defined by four depth strata, and species preferences assigned to these habitat types based on their preferred depth distributions (Jákupsstovu & Reinert 1994; Zeller & Pauly 2001). Basic movement rates, which are not rates of directed migration, but rather basic relative population dispersal rates as a result of random movements (Christensen et al. 2000) were assumed to be of three relative magnitudes: 3, 30 and 300 km year^{-1} representing essentially non-dispersing, demersal and pelagic groups, respectively. The relative dispersal rate in 'bad' habitats (i.e., non-preferred habitats) was assumed to be 5 times the basic movement rate, and it was further assumed that groups were twice as vulnerable to predation in bad habitats than in preferred habitats (Christensen et al. 2000). I would like to stress that the present model should be considered preliminary and, until input data have been verified and improved, should not be considered sufficiently representative for actual policy evaluations or simulations. Spatially explicit simulations were carried out to examine potential management options for the Faroe Islands fisheries. The overriding consideration was long-term sustainability under conditions of high uncertainty within a precautionary framework (Pauly et al. 2002). Findings of these preliminary simulations are being published (Zeller & Reinert in press). Emphasis was placed on examining the present management system based on spatial gear restrictions (12 nm zone and additional seasonal trawl exclusion zones), as well as additional fully closed areas from which all gears were banned. Ecospace, as well as Ecosim can prove useful for modelling the marine ecosystem of the Faroe Islands.

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Table 1. Sources of data used for Ecopath model. B: biomass. P/B: production to biomass ratio. Q/B: consumption to biomass ratio. Sources in **green** are area or stock specific, while sources in **red** are generalized or less reliable or consist of expert opinion.

GROUP	B	P/B	Q/B	Diet
Baleen whales	Trites and Pauly, 1998 Pauly et al., 1998	**Mendy and Buchary, 2001 V.Christensen, pers. comm**.	Trites and Pauly, 1998 Pauly et al,. 1998	Trites and Pauly, 1998 Pauly et al., 1998
Toothed mammals	Trites and Pauly 1998 Pauly et al., 1998	**Mendy and Buchary, 2001 V.Christensen, pers. comm**.	Trites and Pauly, 1998 Pauly et al., 1998	Trites and Pauly, 1998 Pauly et al., 1998
Seabirds	**Mendy and Buchary, 2001** **Anon., 1998d, 1999e**	**Mendy and Buchary, 2001**; **Anon., 1998d, 1999e**	**Mendy and Buchary, 2001** **Anon., 1998d, 1999e**	**Mendy and Buchary, 2001**
Cod	**ICES single sp. VPA: Anon., 1998c, 1999b**	**ICES single sp. VPA: Anon., 1998c, 1999b**	**Mendy and Buchary, 2001**	Jákupsstovu and Reinert, 1994, **Mendy and Buchary, 2001**: adjusted with data from Du Buit 1989
Haddock	**ICES single sp. VPA: Anon., 1998c, 1999b**	**ICES single sp. VPA: Anon., 1998c, 1999b**	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**: adjusted with data from Du Buit 1989
Saithe	**ICES single sp. VPA: Anon., 1998c, 1999b**	**ICES single sp. VPA: Anon., 1998c, 1999b**	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**: adjusted with data from Du Buit ,1989
Redfish	**Mendy and Buchary, 2001**, **Anon., 1998e**	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**, **Anon., 1998e**
Other deep-water fish	-----	**V. Christensen, pers.comm.**	**V. Christensen, pers.comm.**	**V.Christensen, pers.comm**., Incl. cannibalism: **Anon., 1999d, Bjelland and Bergstad, 1998**
Greenland halibut	-----	**Anon., 1999b**	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**: adjusted for herring and blue whiting Michalsen and Nedreaas, 1998.
Other demersal fish	-----	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**
Herring	-----	VPA adjusted to Area Vb **Holst et al., 1998, Anon., 1999c**.	**Mendy and Buchary, 2001**	Christensen, 1995; **V. Christensen, pers.comm**.
Blue whiting	-----	**ICES VPA: Anon., 1999c**	www.fishbase.com	www.fishbase.com
Mackerel	-----	**VPA (western stock): Anon., 2000a**	www.fishbase.com	North Sea (Christensen, 1995); West Atlantic (Studhome et al., 1999)
Other pelagic fish	-----	**Mendy and Buchary, 2001** Christensen, 1995	**Mendy and Buchary, 2001** Christensen, 1995	**Mendy and Buchary, 2001**
Benthos	-----	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**	**V. Christensen, pers.comm.**
Squid	-----	**Mendy and Buchary, 2001**	**Mendy and Buchary, 2001**	**V. Christensen, pers.comm.**
Large zooplankton	Dry weight south-west Iceland (Gislason and Astthorson, 1995); DW=0.26*WW, Opitz, 1996	-----	**V.Christensen, pers. comm.**	**V.Christensen, pers. comm.**
Small zooplankton	? ? ?	**V. Christensen, pers. comm.**	**V. Christensen, pers. comm.**	**V. Christensen, pers. comm.**
Phytoplankton	P: Longhurst et al., 1995; Pauly and Christensen, 1995.	**Mendy and Buchary, 2001**	-----	NA

Possible environmental influences on the cod stocks at the Faroe Islands and a comparison with other North Atlantic stocks

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Population characteristics of the three major gadoid stocks at Faroe are shown in Table 1. Life expectancies for adult haddock and saithe are higher than for other areas and for cod only Norwegian coastal cod has lower mortality rates. The coefficients of variation of spawning stock biomass and recruitment are low and growth rates of adult fish are also low compared with other areas. Given the temperature regime at Faroe, the low growth rates are rather surprising and raise interesting questions about the level and nature of marine productivity around the Faroes. Also the low CV of biomass conceals an interesting difference between this and other cod stocks. There is much greater short term variability at Faroe, whereas other areas have bigger long term trends.

Table 1. Population characteristics.

Species	Stock	Life expectancy (years) =1/(F+M)	Natural mortality (M)	Age span for average F	CV of spawning biomass	CV of recruits	Age of recruits	Auto-correlation of recruits lag 1 yr	Growth rate of mature fish (yr⁻¹)	Years of data
Blue whiting	ICES area	2.04	0.2	3-7	26	68	0			20
Cod	Baltic E	0.96	0.2	4-7	61	61	2	0.78	0.45	35
	Baltic W	0.77	0.2	3-6	35	58	1	0.32	0.49	31
	Celtic Sea	1.12	0.2	2-5	37	75	1	0.30	0.40	30
	Faroe	1.54	0.2	3-7	37	56	2	0.31	0.31	40
	Iceland	1.32	0.2	5-10	56	39	3	0.18	0.25	46
	Irish Sea	0.94	0.2	2-4	40	60	0	0.09	0.36	33
	Kattegat only	0.84	0.2	3-5	57	55	1	0.33		30
	N. Sea	1.05	0.22	2-8	46	61	1	0.10	0.35	38
	NE Arctic	1.28	0.2	5-10	79	62	3	0.47	0.26	55
	Norwegian coastal	1.83	0.2	4-7	22	47	2	0.51		16
	W. Scotland	1.04	0.2	2-5	48	60	1	0.01	0.62	35
Haddock	Faroe	2.08	0.2	3-7	36	82	2	0.37	0.22	40
	Iceland	1.27	0.2	4-7	25	73	2	0.10		22
	Irish Sea	0.73	0.2	2-4	61	90	0	-0.73		8
	N. Sea	0.86	0.26	2-6	71	148	0	0.03	0.33	38
	NE Arctic	1.41	0.2	4-7	42	124	3	0.04	0.19	51
	Rockall	1.41	0.2	2-5	41	78	1	0.04	0.19	16
	W. Scotland	1.18	0.2	2-6	59	127	1	-0.15	0.35	36
Saithe	Faroe	2.05	0.2	4-8	24	49	3	0.41	0.22	40
	Iceland	1.92	0.2	5-12	45	58	3	0.63	0.19	39
	N. Sea	1.42	0.2	3-6	57	54	1	0.25	0.29	29
	NE Arctic	1.74	0.2	3-6	58	45	2	0.13	0.29	41

A comparison of growth patterns for several cod stocks shows that while adult growth rates are low at Faroe, they grow rapidly during the first two years of life. This indicates particularly favourable growth conditions for these young fish, but a deterioration once they reach a size of between 1-2 kg.

There has been an underlying trend of increasing weight at age 2 for cod since 1960 but a decreasing trend for older ages. Weight at age is a cumulative measure which depends on the growth rates experienced over several years. The feeding conditions in a particular year (which may be influenced by phytoplankton and zooplankton production) will affect the growth rate during that year. Growth rate (G) can be estimated as **$G_{a-1,y-1}=\ln(W_{a,y} / W_{a-1,y-1})$** where a is age and y is year.

Since growth rate is a function of size it is necessary to standardise the rates to a particular size when making comparisons and this can be done by fitting an exponential model (in this case $G = 0.226 \times weight^{-0.42} - 0.074$). Interannual variability in growth rates is consistent across the age

pairs 3 to 4, 4 to 5 and 5 to 6, with high growth rates in 1966, 1972, 1983, 1992 and 1999. Saithe and haddock show somewhat similar fluctuations in growth rates. The causes of the growth fluctuations will be discussed at the workshop, but the causes are not obvious. Temperature has been proposed previously (Brander 2000), but it is difficult to specify the effective ambient temperature and the recent fluctuations in growth rate do not seem to match the overall temperature variability.
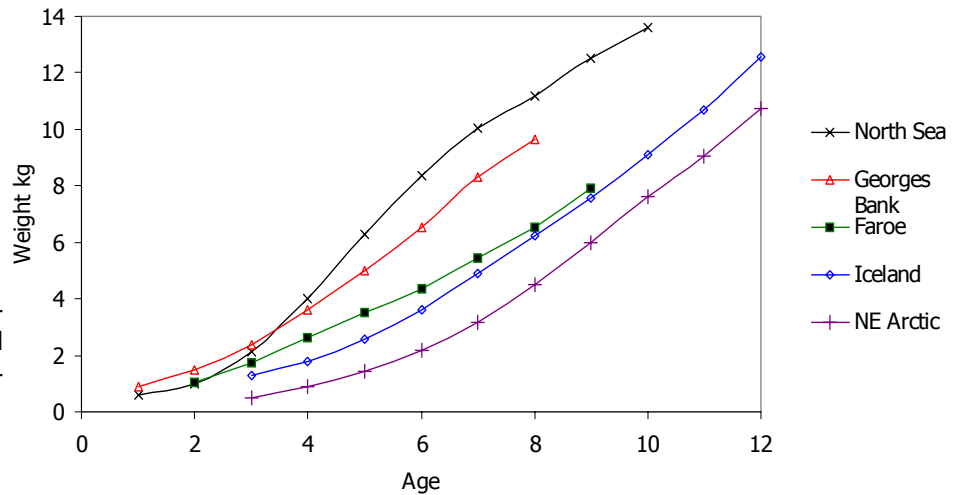

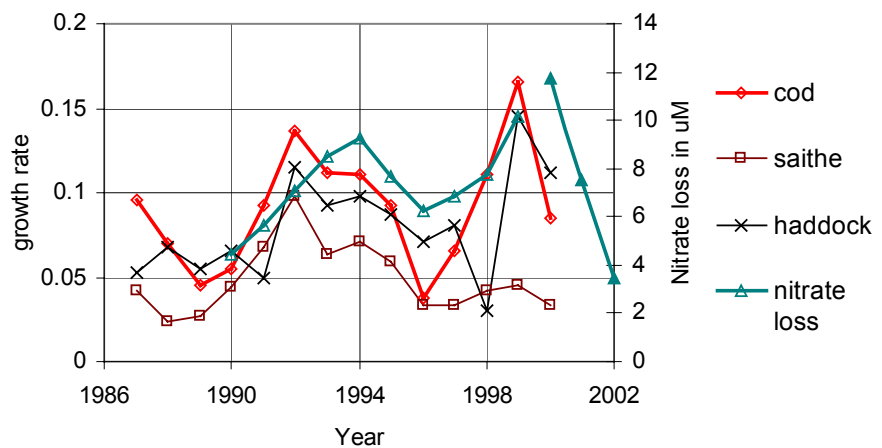Fig. 1. Weight-age relationships for different cod stocks in the North Atlantic.

Fig. 2. Growth rates of Faroe Plateau cod, saithe and haddock and nitrate loss on the Faroe shelf from spring to mid summer.

Variability in new primary production, as measured by nitrate drop, has been proposed as a "bottom up" cause of the observed fluctuations in growth, but the time series is short and the fit is not very convincing.

Conclusions:
- Growth rates of three main Faroe gadoids vary quite a lot (at least a factor of two) and this has a big effect on catches and management strategy
- Trends are common across (older) ages and across species – it's not just noise
- Factors in the physical and biological environment are probably involved
- The long time series of weight at age is worth exploring further, using improved estimates of environmental factors, such as ambient temperature
- Until the effects of ambient temperature are allowed for there seems little point in trying to fit other models, with food or density dependence.

Marine Ecosystem Model for the Faroe Islands (MEMFIS)

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The possibility to initiate the modelling activity was given by a grant to The Faroese Fisheries Laboratory (FFL) from The Faroes Partnership. The FFL has decided to use the first year financing to establish a project to implement a basic model. Since there is no experience with ecosystem modelling in Faroese waters, a number of fundamental questions have to be addressed. A main aim is also to clarify which further physical and biological investigations need to be conducted to establish a model.

Until now focus has been on the lowest trophical levels on the shallow parts of the Faroe Shelf and their dependence on the physical environment.

A main reason for this is the indication that the primary production on the shelf varies considerably between years and that these variations are transmitted throughout the ecosystem. It furthermore appears that oceanic zooplankton, especially *Calanus finmarchicus*, which are advected onto the shelf in spring, may control the primary production, see Figure 1.
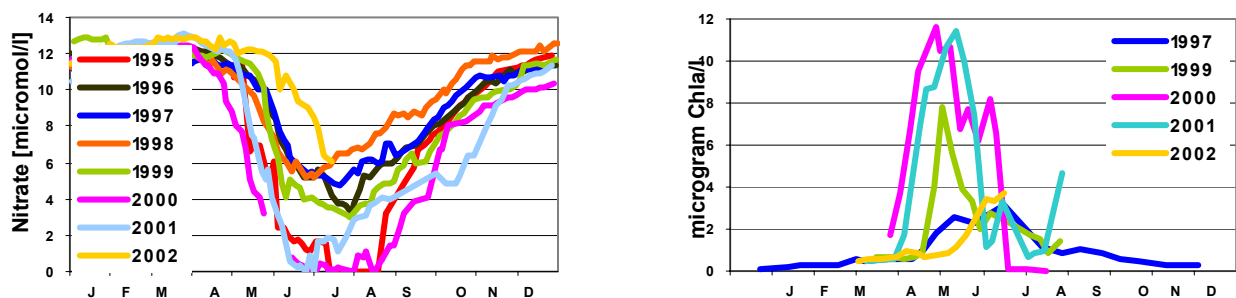

Fig. 1. Nutrients and growth on the Faroe Shelf.

The initial modelling effort was therefore aimed at illuminating this process and the living organisms in the model have been limited to a homogeneous phytoplankton population and a *Calanus* population that is imported into the system in spring. Except for this import, the system is assumed to be closed and without any spatial variation. This approximation is justified from the experience that the inner Faroe shelf is a rather homogeneous body that is kept well mixed by the strong tidal currents. With these assumptions a mathematical model of the phyto- and zooplankton dynamics on the inner Faroe shelf has been developed from basic principles and from literature.

The model ecosystem has four components, nutrients, phytoplankton, zooplankton, and detritus, see Figure 2.
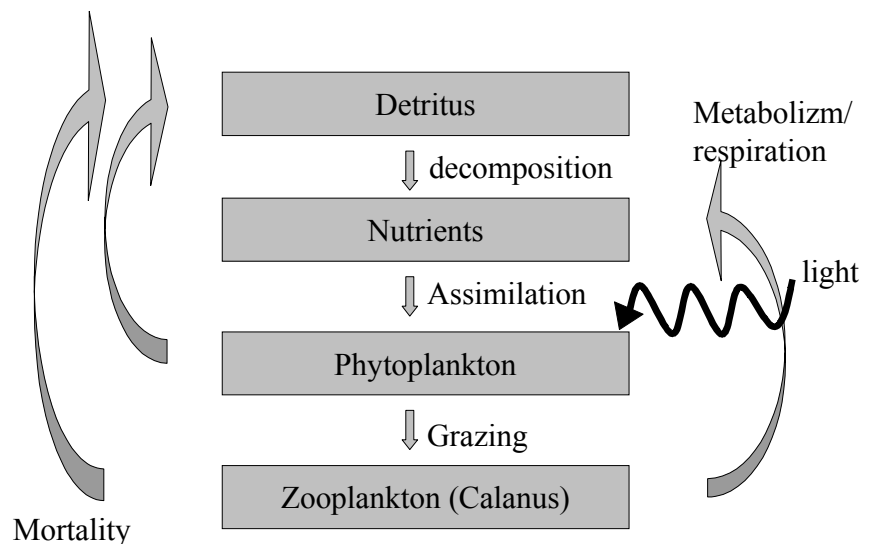

Fig. 2. Model ecosystem.

Results

Figure 3 shows a typical run of the model, with typical light values and typical zooplankton import. These model results can be compared to observed phytoplankton development and nutrient variation. The model results show the gross features of the spring bloom on the Faroe shelf as observed, but discrepancies are seen in details.The nutrients and phytoplankton concentrations behave as expected from the observations, except that the decrease in nutrient concentration is steeper than in the observations, and also it appears too early which also is the case with the phytoplankton maximum. Possible reasons for the discrepancies are discussed below.
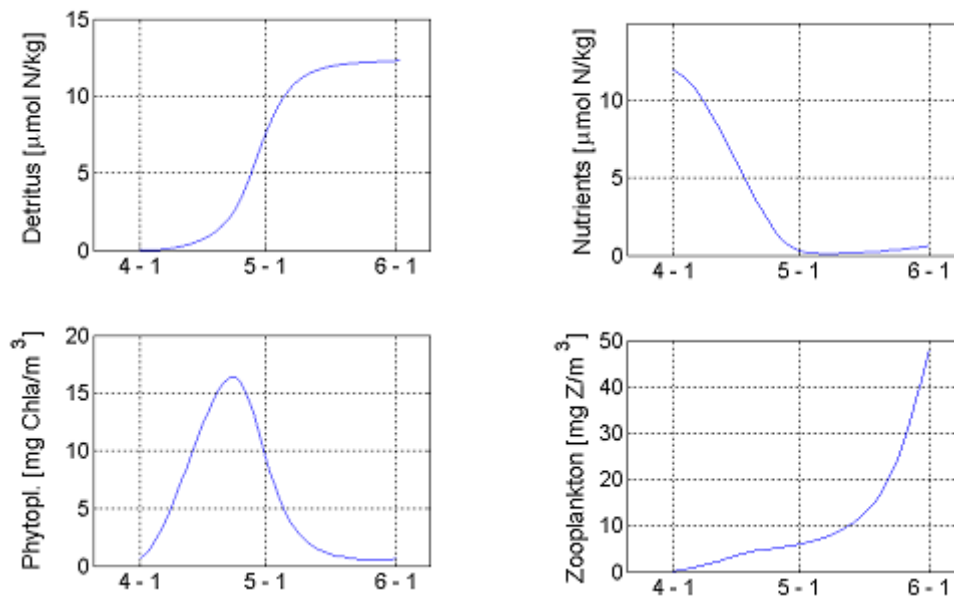

Fig. 3. Model results.

Constants in the model

Several constants are used in the formulas, and determining all of them precisely is complicated. Sometimes it is possible to estimate a value from FFL observations and FFL specialists but sometimes it is necessary to use values from other areas, e.g. Norway.

Grazing in the model

The grazing from zooplankton on phytoplankton computed by the model is very small and indicates an ecological efficiency from the first to the second trophical level much smaller than generally observed in nature. It seems as if phytoplankton is very insensitive to grazing from zooplankton. A large zooplankton import contra a small zooplankton import makes only a very slight difference in phytoplankton concentration, indicating that there is an insufficiency in the program in linking phytoplankton and zooplankton together.

Light in the model

In order to get a precise rate of photosynthesis it is necessary to know the amount of light available in the ocean. Some of the discrepancies seen may be due to inappropriate representation of light intensity in the model. Much effort has been spent in determining appropriate functions for typical light variation in Faroese waters in spring, but the available information on light conditions in the Faroes is very sparse and a satisfactory result has still not been reached.

Future developments

Future development of the model will first focus on clarification of the problems with light and grazing to reach better agreement with nature. When that goal has been reached, horizontal variation will be implemented into the model to study the change from the shallow to the deeper parts of the shelf and into the surrounding water.

Discussion

The final day of the workshop was dedicated to discussions in three subgroups.

One group specifically discussing the MEMFIS model manned with experts into this special field together with the Faroese scientists involved. The two other groups manned with the other participants in the workshop equally divided in number an expertise were presented with five specific issues to discuss. The questions were.

Q 1.   Questions related to the MEMFIS plankton production model.

Q 2.   The mean weight at age of cod has through the last 40 years varied significantly. This is a key parameter in the assessment and forecasts of the cod stock on the Faroe Plateau, and any deviations in the "true" value from the assumed one, may create significant biases in the forecasts. Correlating the primary production against the growth of cod on the Faroe Plateau indicate a significant relationship, and a vital question is to what extent this relationship can be used to improve the mean weights at age in the forecasts.

Q 3.   An overriding long term ambition for the Faroese Fisheries Laboratory is to collect data and time series of data, which could be used in modelling the ecosystem in Faroese waters. The subgroups were asked to identify the data needed in addition to shortcomings of data at hand and to attempt to prioritise new data collection to this end.

Q 4.   The Faroe Plateau encompasses a fairly isolated marine ecosystem with large annual and inter-annual variations. This could make the causal relationships behind the variations more easily observable on the Faroe Plateau than in the larger systems. The small geographic area, in addition, allows for a total surveying of the area within a very short period of time. The question, therefore, is; can the Faroe Plateau be used in a wider global perspective as a "laboratory", where specific ecosystem questions universal to all areas can be studied. If so, this would enhance, both the general knowledge on the dynamics of marine ecosystems, as well as the knowledge on the Faroese marine ecosystem.

Q 5.   The large variation observed both in the level of primary production on the Plateau as well as the variation in species composition in both the phyto and zoo plankton indicate that the stability of the inner water masses on the Plateau is a key parameter to this variation. And a very important question is how these variations are governed. How do the inner and outer gyre interact? Are the tidal forces the main and only driving force, or do variations in the outer Atlantic currents have significant impacts as well.

Q 6.   Future work.

Report from sub-group 1

Sub-group 1 was chaired by Helge Drange, reported by Bogi Hansen, and included in addition: Ken Drinkwater, Arne Myhrvold, Knud Simonsen, Jóhannis Danielsen, Karin M. H. Larsen, and Petur Steingrund.

The group spent most of its time discussing the exchanges between the on-shelf and the off-shelf waters, primarily of physical properties but not exclusively. This included discussion on processes, models, observations, and strategies for further studies.

Many processes may potentially contribute to the exchange of water and various properties between the shelf and the off-shelf regions. Tidal excursions on and off the shelf, combined with vertical and horizontal mixing, induce exchanges between shallower and deeper areas. Internal waves have in other areas been shown to impact shelf regions when they surge onto or even over shallow parts. Bottom topography, especially in the form of canyons can guide internal waves or more persistent flows. The Faroe shelf, furthermore, is located close to the very energetic overflow current through the Faroe Bank Channel. Under normal conditions, the overflow water is confined to much deeper levels, but large variations have been observed and the possibility of occasional surges onto the shelf should be investigated. This might be one process to transport *Calanus finmarchicus* onto the shelf.

Models to study the on-shelf/off-shelf exchanges could be of several different kinds. Simple analytical models might give some insight into the exchanges induced by tidal excursions. Numerical models would have to have a fairly high resolution to allow studies of exchange processes. High-resolution barotropic models have been very successful in describing the tidal characteristics on the Faroe shelf and their possibility for evaluating tidally-induced residual flow patterns and mass transport should be explored in more detail. Idealised 3-D or quasi 3-D numerical models with detailed topography of the Faroe Plateau and realistic hydrography could be used to study selected processes such as the impact of internal waves. Some processes, however, need to be driven by large- or even global-scale forcing. To study these, high-resolution regional 3-D models nested within coarser global models can be used, but they require large efforts in computer- as well as man-power and the only realistic strategy for the FFL is to pursue this option together with modelling environments abroad. A possible option along these lines would be to extend the successful co-operation with the Nansen Centre in Bergen.

Observations of the on-shelf/off-shelf exchanges and their variability are hampered both by the effects of fishing gear on moored equipment and by the inherent difficulty in measuring small cross-slope exchanges within a background of intensive along-slope flows. To study the propagation of internal waves or more persistent flows through canyons, ADCPs (Acoustic Doppler Current Profilers) could be moored within trawl-protected frames and could give information on currents as well as zooplankton fluxes. Another option would be to moor recording fluorometers to obtain time series of phytoplankton biomass for comparison with estimates of primary production from nutrient drawdown. Large-scale deployment of drifters would provide a Lagrangian method for studying residual currents and possibly exchange processes. They could also be used to test or confirm model accuracy and reliability. If deployed inside the shelf area, their dispersal into off-shelf waters would yield information on flushing rates. Deployments of drifters in the off-shelf waters might give more interesting information on the inflow of off-shelf waters onto the shelf, but would probably require a large number of deployments to allow estimates of spatial and temporal variability in this process. Dye injections and observations of other tracers were also discussed but, again, will usually require large efforts to elucidate exchange variability. An exception to this is salinity, which as a natural tracer has been used to evaluate flushing rates and their variation and which furthermore can be monitored with moored equipment. A data source that has not been utilised to its full potential is satellite imagery, both as regards information on sea surface temperature and phytoplankton biomass

through chlorophyll-a measurements. The cloudiness of Faroese waters is a serious drawback, but a more detailed study of these data sets could provide much information on both the physical and biological properties on and off the shelf and on the exchanges between these two regimes. Inspired by the group discussion, a new project, using a moored ADCP, a number of moored salinity recorders, and a towed thermistor/salinity chain has been proposed.

The strategies that the FFL could employ to study on-shelf/off-shelf exchanges were discussed in some detail and included both modelling and observation as discussed above. It was suggested that special emphasis might be put on the study of extreme events, such as the early nineties, 1995, and 2002. It was noted that some of these have also been found to be unusual in other areas. Thus, in 1995, conditions were exceptional in north Icelandic waters. As a way to focus the efforts in further studies, a new workshop, concentrating on the exchange problem, was suggested. Such a workshop need not include more than some 6 external experts, but should address both modelling and observations.

In addition to on-shelf/off-shelf exchanges, the group discussed ways in which future scenarios for Faroese waters could be evaluated. Since global coupled climate models are the only available tools, however uncertain, to evaluate future climate scenarios, these will have to be involved. This implies that estimates of future Faroese conditions will have to be based on cooperation with or at least input from foreign modelling communities. Again, the established contact with the Nansen Centre in Bergen could perhaps be extended to provide the necessary link. In addition to input from climate models, information will, however, also be necessary on links between local climate changes and the marine ecosystem. As an example, we need to study how extreme wind situations affect the productivity. Such process studies need to be carried out before the input from climate models can be of much utility. A special feature, worth noting, is the advective transport of North Atlantic Ocean characteristics found both in observations and models. This might in future allow increased predictability of Faroese waters.

The group briefly touched upon the question, how studies of the Faroese marine ecosystem could be used in a wider perspective and noted that this system appears to be simpler than many other marine ecosystems. This may perhaps explain the large effects that have been suggested to result from changes in the environmental conditions. In such a system, causal relationships could be more easily recognised than in more complicated systems and there is a potential for clarifying processes in such a simple system that can then be applied to other areas.

Finally, the group discussed what data needs are most pressing and should be filled. Most of these have already been touched upon in the above discussion but, additionally, the group noted the lack of information on some key components of the Faroese marine ecosystem such as sandeel, Norway pout, jellyfish, and benthos. Potentially, some of these species may be involved in top-down control of productivity. Thus, as an example, a system involving cod predation on sandeel, sandeel predation on *Calanus*, and *Calanus* predation on phytoplankton could perhaps explain some of the observed variability in primary production on the shelf. Simple budget estimates might clarify some of the components of such a system but the lack of data, in this case for sandeel, makes more.

Report from sub-group 2

Sub-group 2 was chaired by Jake Rice, reported by Jan Arge Jacobsen, and included in addition Keith Brander, François Carlotti (parttime), Villy Christensen, Wolfgang Fennel (parttime), Hjálmar Hátún, Eyðfinn Magnussen, Lise H. Ofstad, Bergur Olsen, Jákup Reinert, Jan Sørensen, Dirk Zeller and Svein Østerhus.

The group mainly discussed Q2 and Q5 but the other items were included as well, especially Q3 and Q6.

Q5: Taylor column forcing

It was stressed that the local on-shelf/off-shelf transport of the Faroe Plateau is not a single entity, and the forcing can come from very different sources such as the Atlantic Current, the East- Icelandic Current, tidal forcing, eddies, and wind stress. The transport across the boundary affects the advection of Calanus, the amount of nutrient input and regeneration on the shelf, import and export of recruitment products and the recruitment retention time on the Plateau. Further the migration routes of various pelagic species migrating through Faroese waters is affected by the strengths of the retroflected Faroe Current. A list of cross-front exchange processes, diagnostics, and consequences should be set up for the Faroe Plateau. The time scales of such processes should be indicated and their sources identified. One example was mentioned, eddies might come in with a spatial scale of 50 km and time scales of 4 days from the NW and are likely to bounce off the shelf. Smaller eddies may move onto the shelf and mix with the shelf water.

The group discussed to some length the possibility to look for episodic events as a key to study the ecosystem. Continuous vs. episodic exchanges should be separated in the study. What are examples of episodic events that provide a signal large enough to be reflected in the whole ecosystem in the Faroese area. Such major events may be used as case studies for the Faroes. We should test out the episodic events as causal factors and identify and analyse their consequences – both modelling and historic data analysis should be done. Examples of such events could be:

1990-91

Fluxes in Atlantic waters between Iceland and Faroes and between Faroes and Shetlands probably caused major shifts in the Faroese ecosystem, with exceptionally large quantities of O-group capelin over the entire shelf. Usually a few 0-group capelin are caught during the annual 0-group survey, but in 1991 they were the most numerous species in the survey. In 1990 and 1991 large quantities of North Sea herring migrated to the banks east of the Faroes across the Faroe-Shetland channel during summer, where a fishery developed. It was mentioned that in 1990 there was a minimum freshwater flux from the East-Icelandic current onto the shelf. An approach could be to look into the wind effects, which will require hindcasting of the winds, and trace back possible causes to the event. Some information on wind stress could be obtained from DNMI (Norway), DMI (Denmark) or other hindcast data sets, i.e. NCAR/NCEP. These could be checked (calibrated) against local land-based data.

1994-95

Great salinity anomaly occurred, with a maximum freshwater flux from the East-Icelandic current entering the Faroese waters in 1995.

The present year (2002) was also mentioned as a potential episodic year. Also the great salinity anomaly in the 1970s could be studied.

The group felt that many of the processes on the Faroe Plateau were comparable to Georges Bank, i.e. the degree of leakage on and off the shelf is comparable to Georges Bank. Although the latter is a bank and the former is a shelf, the forces and processes were considered to be analogous

for both systems, justifying a joint project. Could the results from a specific well-studied system (Georges Bank) be extrapolated to the Faroes?

Q2 Changes in mean weights at age

The group discussed various aspects of the observed changes in mean weight at age for Faroe Plateau cod, Faroe haddock and Faroe saithe. The observations are based on commercial sampling of cod, haddock and saithe. It was questioned how well the commercial sampling reflected the real weight at age for these species. Surveys might give more information on mean weights at length for these and many more species, which also should be looked at in order to determine the scale of the underlying force. Data are also available on local herring (fjord herring), which might give a clue to variation in productivity in the inner shelf areas.

The lipid content of livers should be measured both to account for energy reserves for growth and maturation, and egg quality should be determined. This might be a better indicator of variations in the productivity on the shelf than the signals form the mean weight at age.

Why the growth rate apparently being very high in first two years and then slower thereafter has to be answered. Slow growth is thought to be due to food limitations. It was also questioned by how much growth rate does vary, how synchronous is the variation and how the variation is partitioned among cohort effects and year effects. Once the variance is quantified and partitioned among cohorts and year effects, then comes the jobs of relating to factors that could cause the variation.

How can we improve the mean weight at age used in the forecasts models (predictions). In the short term there are ways to improve greatly on the methods of calculation. A note was provided describing ways to calculate the mean weight at age as a starting point in the predictions – the existing method (presently used by ICES) was the worst alternative. Instead an estimate of the instantaneous growth rate should be obtained, and then applied to weight at age in the most recent year, as a basis for the prediction. In such a model there is a potential to obtain independent predictors for instantaneous growth in the present year (1'st prediction year).

The Georges Bank experience to model where eggs and larvae may need to be in order to obtain maximum survival could be applied to the Plateau. Tests generality of Georges Bank as model of leaky gyre systems as in the Faroes.

A fine scale model of currents and temperatures might be feasible in such a relatively simple system, e.g. inject cod eggs where spawning takes place. The oil industry is already interested in fine-scale physical models and this might be a good use. Are interannual differences in physical models large enough to allow for the observed growth differences to occur?

Inverse modelling might be used, e.g. how big a temperature difference would have had to be in order to account for the differences observed. This kind of inverse modelling could also be used for other parameters such as wind stress and current strengths and directions.

What are the links from primary production to growth of cod. What is the time lag from a plankton bloom to variations in growth and recruitment? The relationship between primary production and cod growth rate may not be all that strong. *Is temperature a good proxy for variations in growth, but might be so for recruitment ???*.

From tagging experiments of Faroe Plateau cod it seems as there is a strong homing of individual cod in the spawning to feeding migration; they do not to leave the plateau. But, what about Icelandic cod migrating to the Faroes? Have they been tagged at the right time and the right spot (i.e. east off Iceland on the Faroe-Iceland ridge) where there is a chance that they might migrate south-eastwards to the Faroese waters?

Episodic events potential for closer study.
-    The disappearance of cod in the late 1980s and the reappearance in the mid 1990s. There is a need to come forward with plausible explanations for the rapid recovery of the cod stock

in the 1990s. Was it a release of top-down effects such as predation and other sources of mortality?
- Capelin – usually only a few 0-group capelin are caught in the 0-group survey, but in 1991 they were the most numerous fish species in the survey, and apparently produced no progeny. At the same time an invasion of North Sea herring was observed east of the isles.

Was there a change in the spatial distribution of cod preceding the rapid decline? Analyses of survey and logbook indices indicate a change in catchabilities during this period and thus the apparent change in abundance might not have been as dramatic as seen. What is the evidence from the surveys? What was the reason for the weak year-classes in the late 1980s – was it the strength of retention on the shelf – ocean physics transporting the reproductive products away – wind stress? For the 1992 and 1993 year classes of cod there must have been some major predators missing.

The group noted that there is a need for examination of predation in areas where juvenile fish are distributed.

MEMFIS Group

Participants: François Carlotti, Wolfgang Fennel, Egil Sakshaug, Sólva Káradóttir Eliasen and Eilif Gaard. Reporter: Eilif Gaard.

The group discussed the ongoing modelling of the lowest trophical levels on the Faroe shelf. This is the first modelling work under the task "Marine Ecosystem Model for the Faroe IslandS (MEMFIS and has been reported by Sólvá K. Eliasen, Eilif Gaard and Bogi Hansen (2002): "A mathematical model of the lowest trophical levels on the Faroese shelf". Technical Report 02-01.

The aim work is to simulate the seasonal development in irradiation, phytoplankton production and copepods (*Calanus finmarchicus*) on the Faroe Shelf. Although highly preliminary, the model simulates well the seasonal development of the phytoplankton, the corresponding decrease in nutrients and the seasonal development of the copepods. However, the timing of the simulated spring bloom is too early and intensity of the simulated primary production is too high. The group went through the model and the field data and discussed similarities and possible reasons for differences between the field measurements and the model simulations.

The main problem for the modelling work is the lack of high quality data on Photosynthetically Active Radiation (PAR). Unfortunately no such measurement data exist and as an attempt to get approximate information on PAR, calculations are made based on the angular height of the sun and compared with *in situ* measurements on wider spectra, operated by the Faroese Office of Public Works, Faroe Islands.

In modelling and field measurements of primary production continuous PAR data of high quality are essential. FRS therefore needs to start monitoring on PAR.

Light attenuation measurements started in 2000 and were intensified to all CTD stations operated by R/V Magnus Heinason since 2002, as a light sensor now has been interfaced to the CTD. Information on light penetration/attenuation is therefore rapidly improving and is at the moment probably sufficient to improve the theoretical attenuation values that are used in the preliminary model.

It was also suggested to include phytoplankton sinking rates into the model and to split grazing rates into *Calanus* copepodite stages, causing the copepodites to be more dependent on the phytoplankton concentration and also do depict the nature more correctly.

Drs. Fennel, Carlotti and Sakshaug presented their experience with plankton modelling and offered to send to the Faroese Fisheries Laboratory relevant material on plankton modelling. This material has arrived. Dr. Fennel has sent his plankton model (MATLAB files), and Drs. Carlotti and Sakshaug have sent relevant published material on plankton models and constants that are used in their work. Dr. Sakshaug also informed about an irradiance model, which is available.

Models need to be tested and validated against field measurements. In this respect field measurements of primary production and grazing rates are essential.

In conjunction of this it was suggested that a summer course for upper graduate students and Faroese students could be beneficial for the students as well as the Faroese scientific community. This course could be split into two parts: one part dealing with field measurements and another part dealing with modelling. Drs. Fennel, Carlotti and Sakshaug offered to educate in such a summer course.

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