Oceanography Committee **ICES CM 1998/C:14**

REPORT OF THE

ICES/GLOBEC WORKSHOP ON PREDICTION AND DECADAL-SCALE OCEAN CLIMATE FLUCTUATIONS OF THE NORTH ATLANTIC

European Environment Agency, Denmark
8–10 September 1997

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

Palægade 2–4 DK-1261 Copenhagen K Denmark

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1 TERMS OF REFERENCE

ICES Council resolution 1996

An ICES/GLOBEC Workshop on Prediction and Decadal-Scale Ocean Climate Fluctuations of the North Atlantic will be held at ICES Headquarters, 8–10 September 1997, under the chairmanship of Dr S. Sundby (Norway) to:

a) *study the decadal-scale ocean climate fluctuations of the North Atlantic, particularly:*

i) *consider the role of the large-scale pressure anomalies (e.g., the North Atlantic Oscillation),*

ii) *study the causal relationship between temperature signal and other physical processes,*

iii) *evaluate the scientific basis for long-term (decadal-scale) ocean climate predictions,*

iv) *study the links between decadal-scale climate fluctuations and growth and recruitment in cod stocks of the North Atlantic.*

Justification

The decadal-scale climate fluctuations of the North Atlantic have been shown to be correlated with fluctuations on growth, recruitment and distribution of some of the North Atlantic cod stocks. Efforts are now made on predicting the decadal-scale ocean climate fluctuation. It is therefore important to summarise the state of the art on the scientific background and to evaluate predictions.

2 INTRODUCTION

The workshop was hosted by the ICES Secretariat and took place at the neighbour institution European Environmental Agency (EEA), 8 - 10 September 1997. 18 scientists (Appendix 3) from 10 countries (Canada, Faroe Islands, Germany, Iceland, Norway, Russia, Spain, Sweden, UK and USA) participated during the workshop. General Secretary Chris Hopkins welcomed the workshop participants and pointed out that the GLOBEC activities were given high attention in ICES. The ICES/GLOBEC Secretary Keith Brander outlined the status of ICES/GLOBEC Programme, its relation GLOBEC-International and some of the future activities and developments of the programme. The convenor of the workshop, Svein Sundby presented the objectives of the workshop, and pointed out that the outcome of the workshop would be an important basis for future Cod and Climate Change work, particularly on applying environmental data in the assessment of recruitment and growth in fish stocks and generally on the development of marine resources management from an ecosystem point of view. The Cod and Climate initiative within ICES focused from the start in 1990 on the importance of understanding the physical processes causing interannual fluctuations in cod stocks, and the effects of basin-scale climate phenomenon was brought into the discussion already at that time. The convenor was glad that it had been possible to gather such an interdisciplinary group of people. Particularly, it was welcomed that atmospheric climatologists Professor Peter Lamb and Dr Mojib Latif participated. They represented professions, which usually are not present in the ICES community. It was emphasised that ICES needs to establish stronger links to the communities working in atmosphere sciences in order to address properly the problems of how the living resources of the ocean respond to climate fluctuations and change. Presently, the World Climate Research Programme on Climate Variability and Predictability (CLIVAR) is an important initiative, which ICES should make closer connections to. Co-chair of CLIVAR SSG, Dr Allyn Clarke, had planned to participate but was unfortunately not able to come due to other commitments. However, the CLIVAR Secretariat kindly supplied the workshop with the latest Draft Implementation Plan of CLIVAR. The workshop was organised in three sessions (Appendix 1):

Session 1). Observations of and Mechanisms behind Seasonal to Decadal-scale variations of Ocean climate.

Session 2). Predictions on Ocean Climate in the North Atlantic.

Session 3). Ecosystem Responses to Ocean Climate Fluctuations.

In Session 1) there were nine contributions. Six of them (Bill Turrell, Agusta Flosadottir, Yuri Bochkov, Svein-Åge Malmberg, Bogi Hansen and Johan Blindheim) were focusing on processes in the Nordic Seas, one (Ken Drinkwater) was addressing processes of the Labrador Sea, and two of the contributions (Peter Lamb and Mojib Latif) were on basin-scale and global-scale processes. Session 2) had two contributions. The first (Sergei Rodionov) was presenting an expert system for climate prediction. In the second presentation Geir Ottersen presented experiences with present methods for ENSO predictions and the relevance it would have to NAO predictions. In the Session 3) the six presentation considered ecosystem responses to the NAO. One of the presentations focused on phytoplankton (Andrea Belgrano), one focused on zooplankton (Doug Beare) and four of the presentations were on various fish stocks (Jürgen Alheit, Alicia Lavin, Bogi Hansen and Svein Sundby).

3 SUMMARY REPORT OF PRESENTATIONS AND DISCUSSIONS

Basin-scale features of NAO and comparisons with ENSO.

Presentations in the first two sessions gave overviews of the nature of the North Atlantic Oscillation (NAO) and its seasonal to interannual behaviour. The NAO is the most dominant mode of atmospheric variation in the North Atlantic, particularly during wintertime. It appears as an alteration in the two large-scale pressure systems of the Icelandic Low and the Azores High. Presently, the most often used quantification of the NAO is an index defined by Rogers (1984): the difference in the normalised sea level pressure anomaly between Ponta Delgado in the Azores and Akureyri in Iceland. A high NAO index represents a deep Icelandic Low with strong mid-latitude westerly winds, while a low NAO index represents a stronger Azores High compared to the Icelandic Low resulting in a weakening of the westerly winds. Professor Peter Lamb gave an overview of the general features and the behaviour of NAO. The NAO index is calculated all through the year with various averaging intervals. The most often used index in oceanic climate context, however, is the winter mean from December to March, since the NAO is strongest during winter. It is very seldom that there is a positive anomaly or a negative pressure anomaly at the same time in both the Azores High and in the Icelandic Low. One example is in 1963. Then the pressure anomaly in the Azores High was lower than in the Icelandic Low, and this event resulted in some particular weather pattern.

The seasonal behaviour of the NAO is very different from the El Niño Southern Oscillation (ENSO). The month-to-month persistence of the NAO is very low. The autocorrelation from one month to the next is 0.2. For more than 2 months delay there is no correlation at all. Even from week to week, and at times from day to day, the NAO may show large variations. In contrast the ENSO shows a high autocorrelation through the season from its appearance in June-July till it ceases in February-March. From month-to-month the autocorrelation is 0.8 and decays to 0 after 12 months. This persistence of the El Niño event is an important factor of the statistical prediction of the phenomenon. On an interannual basis, however, there seems to be a basic different in the pattern of the NAO and SO indices. SO is not a periodic phenomenon on interannual basis; it comes in bursts, and La Niña, the opposite phase of the Southern Oscillation often comes in response to the El Niño the following year. The NAO, however, seems to be of a more periodic nature at all time scales. Among the largest recurrent circulation modes worldwide, the NAO is the only one which is clearly present in all months of the year. Power spectrum analysis also shows clear periods of about 2, 8, 24 and about 70 years. Particularly, over the last 3 decades the NAO displays strong decadal-scale oscillations.

Presently, the mechanisms behind the El Niño phenomenon are principally well understood, as it is linked to slackening in the equatorial trade winds which extends the warm surface water eastwards leading to warmer than normal water at the American coast. This heavily reduces the upwelling, which normally occurs at the coast. The area of main atmospheric convection, which normally is located in the western Pacific, moves eastward following the area of high sea surface temperature. In turn it leads to higher rainfall in the eastern parts and drought in the west. For the NAO, however, we still do not understand the mechanisms behind it, even though its periodicity is well explored. Together with the fact that very large resources, both with respect to field measurements and computation, are used to forecast El Niño, we have to realise that such kind of prediction of the NAO lies into future. Several investigators have indicated that there are links between ENSO and NAO, while others have come to the opposite conclusion. It seems that ENSO shows stronger links to other equatorial weather phenomenon than to weather phenomenon at higher latitudes. Here we need more investigations on the generation and distribution of storm tracks, how individual storms affect seasonal patterns and knowledge of the interannual variability. We should focus on extreme episodes that might give more insight into the mechanisms. For example, for the most extreme years of El Niño, the NAO index appears to be most often positive.

The NAO results in a dipole structure in air temperature between the northeast coast of Canada and Northern Europe. This has been well documented and the earliest observation dates back to 1776 when Hans Egede Saabye pointed out that the mild winters in Greenland often occurred when the winter in Denmark was cold and vice versa. However, also as a result of the NAO, there is observed a dipole structure between the southeast coast of US and North Africa. The dipole temperature structure is also clearly present in the ocean. In the 1960s Russian scientists (Elizarov and Ishevskii) showed that there was an inverse relationship between the sea temperature in the Barents Sea and in the Labrador Sea.

Mojib Latif outlined the principal mechanisms which could cause decadal-scale climatic variability:

1) External effects, for example sun spot activity and solar variability

2) Internal non-linear interactions of which there are 3 main groups: a) chaotic behaviour of the atmosphere b) chaotic behaviour of the ocean c) chaotic coupling between the atmosphere and the ocean.

3) Stochastic forcing of the slow climate subsystems by a fast varying component, for example the El Niño.

In order to explore these mechanisms Dr Latif presented results of a Climate GCM model which was run for 1000 years. The spectra for the model displayed peaks of 35 years and 15 years both in the sea surface temperature and in the sea level pressure. The 35-year period seems to be related to variations in the thermohaline circulation and the 15-year-period seem to be related to variations in the subtropical gyre circulation. The model reproduced well the NAO. The heat flux across the sea surface acts as a positive feedback. The model also displayed propagation of a temperature anomaly in the North Atlantic, and showed good inverse relationship between the NAO and temperature in the Labrador Sea. In the model the decadal-scale fluctuations are limited to heat exchange across the sea surface; it was not a result of flux variations in the ocean currents.

Mojib Latif's Climate GCM show that the signal to noise ratio is small at the interface between the ocean and the atmosphere and increases both downwards through the ocean and upward through the atmosphere. This has implication for prediction purposes in that the predictability must be lower at the sea surface. The Climate GCM also indicates that the ocean climate changes induced by the NAO are mainly a result of the heat exchange through the air-sea interface. The influence of variation in advection of water masses is small. The current measurements from the Nordic WOCE programme and the present VEINS programme can not presently confirm or reject whether the volume flux variations are important or not for the ocean climate variations in the Nordic Seas. In the Labrador Sea, however, a relationship was found between NAO and the baroclinic transport of the Labrador Current, but the influence of heat exchange by air-sea interaction is probably more important for the temperature variations. On the other hand, it is evident that both current meter measurements and shelf sea models for the North Sea and the Barents Sea do indicate that volume flux variations of Atlantic water is important for the fluctuations in the ocean climate.

Regional climate effects of NAO

Most of the contributions on regional ocean climate effects of the NAO considered the north-eastern part of the Subarctic Gyre of the North Atlantic, i.e., the Nordic Seas (Bill Turrell, Agusta Flosadottir, Yuri Bochkov, Bogi Hansen, and Johan Blindheim). One contribution (Ken Drinkwater) was on the western part of the Subarctic Gyre, i.e., the Labrador Sea, and one contribution (Sven-Åge Malmberg) considered mainly the middle region of the Subarctic Gyre, i.e., the Icelandic sector.

For the ocean climate of the Nordic Seas it was pointed out that there are three branches of inflowing Atlantic water to the region. In addition to the branch that has been most investigated, Scottish Atlantic Current flowing in between the Faroe Island and Shetland, there are the Faroese Atlantic Current flowing into the Norwegian Sea to the north of the Faroe Islands and the Icelandic Atlantic Current flowing into the Icelandic Sea around the northern coast of Iceland. It is important to consider these branches separately because they vary on different time scales. During high NAO there is a weakening of the Icelandic branch compared to the Scottish branch. The Faroese branch is strongest in summer, while it is considered that the Scottish branch is strongest in winter. On the other hand, the recent large effort on current meter measurements across the region between Shetland and Faroe Island can not confirm interannual or seasonal variations in the volume flux of this branch. A large proportion of the Atlantic inflow might be driven by convection/deep water formation, probably more than 50%. This is particularly valid for the Faroese branch and probably not so much for the Scottish branch.

Over the last 30 years of increasing long-term trend of NAO index the salinity in the central Norwegian Sea has steadily decreased. This seems to be caused by the strengthening of the Scottish branch and inflow along the Norwegian shelf break. In this way the whole water system of the Nordic Seas is displaced eastwards including the fresher Arctic water in the western parts of the system. Similarly in the deeper water (1000 - 1500 m) there has been a decrease in salinity from 34.92 in 1960 to 34.90 in 1995. Below these depths, in the Norwegian Sea Deep Water, there is no detectable change of salinity. The temperature of the Atlantic water in the Norwegian Sea does not correlate with the salinity. For example, the Great Salinity Anomaly of the 1970s did not have a low temperature.

There is a good correlation between the salinity decline in Shetland-Faroe Channel Deep Water and the wind stress. In the Barents Sea there has been a good correlation between high temperatures and high wind speeds indicating that high westerly wind results in a wind-driven influx of warm Atlantic water from the Norwegian Sea to the Barents Sea. However, over the last few years the temperature has decreased but not the wind speed. This might be due to higher frequencies of polar lows, which are often more abundant in cold years. Similarly, we know from measurements and model result of the North Sea that the influx of Atlantic water is very much dependent of wind stress.

In the western part of the Subarctic Gyre the NAO accounts for about 50% of the temperature variance. It was discussed whether the varying sea temperature in the Labrador Sea is a result of ocean-atmosphere heat exchange or advection. It was pointed out that the heat exchange across ocean-atmosphere is a very important factor in this region, but it was believed that advection is effective as well. In the Newfoundland region and over the adjacent shelf the number of icebergs originating from northern Labrador Sea is higher in cold years of high NAO. However, the baroclinic southward flow of the Labrador Current is clearly higher in warm years of low NAO.

In the middle region of the Subarctic Gyre the response to NAO is less clear due to its location between the two inversely oscillating regions. However, temperature of the Kola section in the Barents Sea lags the temperature of the Icelandic water with 2 years. In North Icelandic waters periods of three different main hydrographic regimes have been defined: Periods of *Atlantic conditions* are characterised by high temperatures with strengthening of the stratification. Periods of *Polar conditions* are characterised by cold and fresh surface water with the low salinity strengthening the stratification. During *Arctic conditions* the intermediate salinity maximum is less pronounced and the stratification is poor.

Climate predictions in the North Atlantic

Efforts on developing predictions of the ocean climate of the North Atlantic have been undertaken by Russian scientists already from the early 1960s. Initially, important elements in the predictions were statistical analysis of climate time series with emphasis on predominant periods of about 2, 7–8, 10–15 and 17–20 years and the dipole structure of the temperatures between the Barents Sea and the Labrador Sea. Also the 11-year period of solar activity was a factor in the predictions. It was pointed out that even very rough forecasts for one year in advance with a precision like «warmer than normal», «colder than normal» and «around average» should be of importance to fisheries management and stock assessment for purposes of predicting growth rates in fish stocks. Such rough forecasts on the ocean climate, issued in The Annual Environmental Report of Institute of Marine Research, Bergen, have been tried in the Norwegian fishery sector for one year ahead over the last years. As for the Russian efforts the main component of the forecast is statistical analysis of time series. It was said that in the Barents Sea and in Norwegian coastal waters there is a high autocorrelation in subsurface sea temperatures from March to September, but the autocorrelation breaks down during the autumn.

For Icelandic waters ocean climate forecasts for three-month periods are made. Forecast of one year is considered to be unrealistic in Icelandic waters. As Iceland is located near the inflection point of the temperature seesaw between the Barents Sea and the Labrador Sea it is a very difficult region to make forecasts based on NAO forcing. The NAO has definitely highest influence in the north-eastern and north-western region of the Subarctic Atlantic region.

Sergei Rodionov presented a new approach in long-term climate forecasting with an expert system (Climatic Expert System for the North Atlantic, CESNA) developed at the Computer Science Dept. of the University of Colorado at Boulder (Rodionov and Martin, 1996). The approach is different from currently existing dynamical and statistical methods. It is based on concepts and techniques from artificial intelligence and expert systems in general. The system is designed to predict mean seasonal climatic characteristics one to several years in advance. The current version of CESNA is focused on the winter climate and forecasts with a lead time of one year. In CESNA, the climate system is represented as a set of macroclimatic objects or conceptual features, such as centres of action, upper ridges and troughs, jet streams, temperature anomalies in key regions, extension of polar ice cover, precipitation patterns, etc. An evolution of the system is described as a sequence of events that involve large-scale interactions between these macroclimatic objects. While mechanisms of these interactions are still poorly understood, they may reveal themselves through statistical relationships or empirical rules-of-thumb. Key principles in the CESNA forecasts are to utilise the information in 1) cycles, 2) persistence and 3) time lags. The system can include qualitative as well as quantitative information. An example of predicting sea temperature in the Barents Sea based on the Kola section data show that the CESNA model fairly well reproduces the three large decadal-scale temperature waves over the last 30 years. The correlation between the observed and the modelled values was 0.63.

Ecological responses to climate fluctuations in the North Atlantic

The presentations on ecological responses to the climate fluctuations ranged from effects on the primary production and the abundance of copepods to the effects on recruitment and year-class strength of cod, herring, capelin, sardine and albacore. It appeared that the NAO has a profound influence all through the marine ecosystems of the North Atlantic and at all trophic levels from primary producers to fish. However, it is remarkable that we have a rather poor knowledge of the causal mechanisms between the NAO and the variations in abundance of populations. There is obviously a strong link between NAO and temperature fluctuations, and although a high temperature in itself would increase growth rates in most boreal populations, the NAO might influence marine populations in a multitude of physical and biological ways, as it also influences wind pattern, advection, turbulence, light conditions, salinity, upwelling, frontal systems and vertical stratification. In addition, the understanding of the causal mechanisms to the final output to fish stocks is obscured by the fact that the various physical processes mentioned above partly act directly on a population and partly through trophic relationships. For example, the presentation of the spring phytoplankton production in Gullmar Fjord, Sweden, was strongly correlated with a high winter temperature and a high NAO.

In the presentations in Session 3) a wide range of hypotheses was proposed as causal mechanisms. The poor recruitment of the Faroese cod stocks (the Faroe Bank cod and the Faroe Plateau cod) since the 1980s has been related to the increasing wind speed of south-westerly direction. One proposed mechanism is that the eggs and larvae have been increasingly swept off from its natural habitats and lost for recruitment. Another proposed mechanism is a change in the general ocean circulation, which might increase larval loss. A third proposed mechanism is linked through lower trophic levels in the way that the proportion of Calanus overwintering in the shelf waters may vary by one order of magnitude. This in turn may be able to suppress and delay the primary production in spring by adult Calanus grazing resulting in poor conditions for the new generation of *nauplii* which constitutes the food for the cod larvae. However, it was emphasised that there are too many missing links to draw firm conclusions on the cause of the decline of the Faroese cod stocks.

The Arcto-Norwegian cod shows strong recruitment and growth in periods of warm years, which are associated with high NAO indices, particularly over the last three periods of strong decadal-scale oscillations. Here the proposed causal mechanisms is more directly linked to temperature effects: 1) in warm years increased growth of the gonads will give a higher egg production from the spawning stock; 2) in warm years the zooplankton production is higher which will give more food for the larvae and juveniles; 3) in warm years there is a better synchrony between the nauplii production and the first-feeding stage of cod larvae; 4) warm years have been observed to give higher growth rates of larvae and juveniles which also, according to the «bigger is better» hypothesis gives higher survival; 5) extreme cold winters during 1- and 2 group stage in the eastern parts of the Barents Sea result in juvenile mass mortality. Advection has also been put forward as influencing recruitment in the Arcto-Norwegian cod.

In the Greenland cod stocks import of larvae and juvenile cod from Icelandic waters, induced by a strengthening of the Irminger Current, has been observed to be an important factor to improve the cod stock. However, it is also assumed that high temperature improves growth and survival in this region. The cause of the breakdown of the Newfoundland cod stocks at the end of the 1980s is still being disputed. Overfishing has been proposed as one factor. However, the decline did coincide with a period of decreasing sea temperature, and the combined effect of high catch rates and lower growth due to low temperature might explain the breakdown. But, it should be mentioned that also here there might be a multitude of environmental factor associated with low sea temperature, which might cause poor growth and survival of cod.

The migration pattern of the herring is considered to be strongly influenced by environmental factors. Low primary production and zooplankton production in North Icelandic waters in the late 1960s was considered to have changed the migration pathways of Atlanto-Scandian herring towards east in the Norwegian Sea. The periods of abundance of Båhuslän herring all seem to coincide with periods of low frequency of south-westerly winds on a decadal scale. It was speculated whether this is linked to changes in the outflow of Baltic water, to a reduction in upwelling along the Norwegian Skagerrak coast or to larger scale mechanisms. At the Iberian coast the environmental factors influencing the fish stocks seems to be more related to processes influencing upwelling and rainfall. Here there is a correlation between the occurrence of westerly winds and the precipitation. These two factors are in turn inversely correlated with temperature and latitudinal position of the Gulf Stream. There is also an inverse correlation between the NAO and sea level along the Iberian coast. The recruitment of albacore is inversely correlated with the NAO index.

The workshop demonstrated that there is presently a large amount of material on correlations between the NAO index, ocean climate parameters and ecosystem responses. However, to be able to predict effects of climate variations on ecosystems, the limiting factor is not only the climate predictions itself, but the understanding of the causal mechanisms between the ocean climate parameters and the recruitment and growth of marine organisms.

APPENDIX 1 – AGENDA

Introductions

Welcome by General Secretary Chris Hopkins

The ICES/GLOBEC Programme by GLOBEC Secretary Keith Brander

Introduction to the theme of the workshop by Svein Sundby

Session 1. Observations of and Mechanisms behind Seasonal to Decadal-scale variations of Ocean climate.

Peter Lamb: Variability of North Atlantic Oscillation.

Bill Turrell: Decadal changes from standard ICES hydrographic sections.

Agusta Flosadottir: Subsurface temperature along a cable route between Iceland and the Faroe Islands, 1906–1962.

Yu.A. Bochkov: Appearance, possible genesis and the role of NAO in the North Atlantic and the Nordic Seas.

Sven-Åge Malmberg: Decadal-scale climate variations in the ice extent and hydrographic parameters in the water around Iceland.

Kenneth Drinkwater: Climate Variability in the Labrador Sea Region and its relationship to the NAO.

Bogi Hansen: Flux variations of the Atlantic inflow to the Nordic Seas

Johan Blindheim: Water mass characteristics in the Norwegian Sea in relation to variations in MSLP.

Mojib Latif: NAO and Global-Scale Variations.

General discussion on Session 1.

Session 2. Predictions on Ocean Climate in the North Atlantic

Sergei Rodionov: Climatic expert system for the North Atlantic (CESNA): learning to predict interannual to decadal climatic variations.

Geir Ottersen: Experiences with ENSO monitoring and prediction of relevance to prediction in the North Atlantic.

General discussion Session 2.

Session 3. Ecosystem Responses to Ocean Climate Fluctuations.

Jürgen Alheit and **Eberhard Hagen**: Long-term climate forcing upon European herring and sardine populations.

Andrea Belgrano, Björn A. Malmgren and **Odd Lindahl**: North Atlantic Oscillation (NAO) and primary production in the Gullmarfjord, Sweden (1985–1996).

Doug Beare: Interpretation of CPR zooplankton data series and the North Atlantic Oscillation.

Alicia M. Lavín: Common signals between physical, atmospheric variables and sardine recruitment at the North Iberian Coast.

Bogi Hansen: Climate influence on the Faroese cod stocks.

Svein Sundby: The North Atlantic Oscillation, the temperature seesaw and the effects on cod recruitment in the North Atlantic.

General discussion on Session3.

Recommendations and final remarks.

APPENDIX 2

SUMMARY OF PRESENTATIONS

VARIABILITY OF NORTH ATLANTIC OSCILLATION

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This paper will provide a comprehensive review of the variability of the North Atlantic Oscillation from 1875-present. The time-scales treated will range from the intraseasonal to multidecadal, with some separate analyses being presented for individual calendar months during October-April. Where they are informative, comparisons will be made with the Southern Oscillation. The treatment of the annual cycle will include the long-term mean, variance, inter-node coherence, month-to-month persistence, and signal-to-noise ratio for the NAO and its nodes. Pronounced multi-decadal trends will be identified using an 11-year Lanczos filter. For the intraseasonal and interannual time-scales, emphasis will be placed on a recently discovered August-November-January oscillation of the NAO. The increased occurrence of this oscillation since the early 1960s will be suggested to be responsible for the upward winter NAO trend during that period despite the extremely weak NAO serial correlation. Finally, the possibility of reconstructing the behaviour of the NAO for the last 1000 years will be discussed. This would exploit recently identified relationships between the NAO, Moroccan precipitation, and Moroccan tree-rings.

DECADAL CHANGES FROM STANDARD ICES HYDROGRAPHIC SECTIONS

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Two standard sections across the deep water channel separating the Faroese Plateau from the Scottish continental shelf have been surveyed regularly since the start of the 20th century (Figure 1). Observations along these sections have revealed significant decadal changes in the characteristics of surface, intermediate and deep water masses during this period. In addition, a standard section in the North Sea (JONSIS line) has been surveyed since 1970, and provides evidence of decadal change within the North Sea which appears strongly linked to the NAO.

Changes in the deep waters of the Faroe Shetland Channel (FSC) will be considered first.

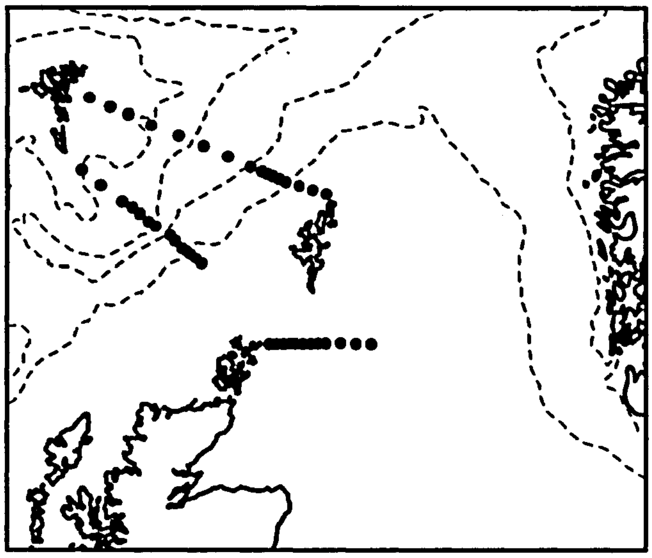

Figure 1 Map showing the location of the two standard hydrographic sections across the Faroe Shetland Channel (FSC), and the standard section in the North Sea

Faroe Shetland Channel Bottom Water

Changes in Faroe Shetland Channel Bottom Water (FSCBW) have been examined using temperature and salinity observed on the 800, 1000 and 1100 dbar pressure levels on the two FSC sections (Turrell *et al.*,, in press). The salinity of FSCBW has demonstrated a persistent and linear decline at a rate of O(0.01/decade) since 1975 (Figure 2).

The decline in salinity of the bottom water has been related to the cessation of the production of deep water in the Greenland Seas, which in turn appears linked to the overall atmospheric forcing. Meinke and Rudels (1995) demonstrated the link between the production of deep convection and wind stress curl over the Greenland Sea. They suggested this may control the supply of fresh water to the surface of the central gyre, which can modify the density of the winter surface water, and hence its ability to form deep convective water masses.

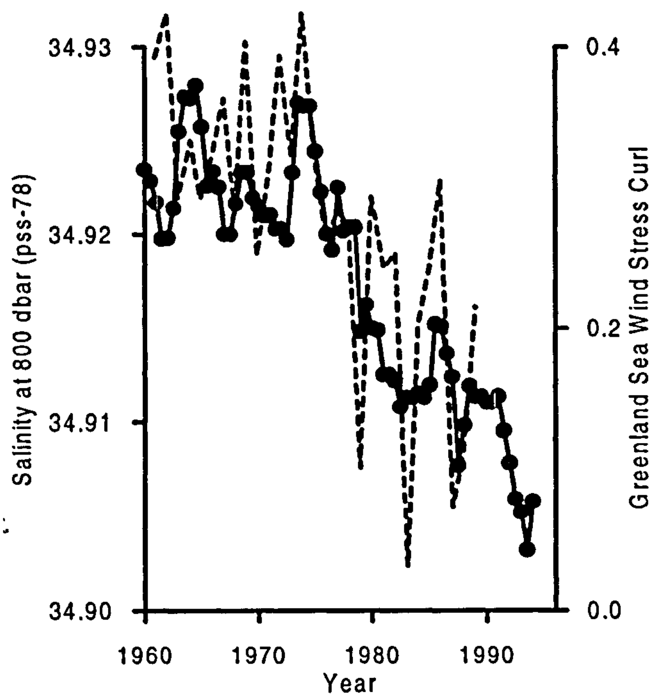

Figure 2 Salinity at 800 dbar in the Faroe Shetland Channel (solid line) compared to wind stress curl over the Greenland Sea, lagged by 2 years, from Meinke and Rudels (1995) (broken line)

The reduction in supply of deep water has resulted in the upper level of true NSDW becoming deeper outside the Channel, in the Norwegian Sea. This has resulted in a change in the composition of FSCBW, from being approximately 60% NSDW during the period 1960–1980, to 40% NSDW since 1990. The associated freshening of FSCBW has propagated out through the Channel into the North Atlantic and has resulted in fresher and less dense Iceland Scotland Overflow Water (ISOW).

There is a clear correlation between wind stress curl over the Greenland Sea and changes in salinity of the FSCBW (Figure 2). The wind stress curl itself may be related to the NAO, and hence the NAO is affecting deep water production and characteristics.

Ecological Link: There appears to be a direct link between the ecology of the surface waters in the North Sea, and the decadal change in the bottom waters. Overwintering *Calanus finmarchicus* may be advected south through the FSC, forming a source of plankton which rises and inundates the North Sea in spring. This inundation appears to have declined in the last 30 years, according to the CPR record, and this reduction may be associated with the reduced amount of NSDW in the FSCBW.

Intermediate Waters

While there have certainly been decadal change in intermediate water masses in the FSC, they are more difficult to interpret. It is clear that periods of salinity anomaly, such as the Great Salinity Anomaly (GSA) in the late 1970s, affect both surface and intermediate waters almost simultaneously, implying some other mechanism may be affecting the area rather than just the advection into the Channel of fresher types of surface water, as proposed by Dickson *et al* 1988. Further work is required before these changes may be understood.

Surface Waters

Two principal surface waters masses exist in the FSC; North Atlantic Water (NAW) and Modified North Atlantic Water (MNAW). NAW lies at the Scottish shelf edge. It arrives in the area within the Slope Current, probably originating in the Rockall Trough and Porcupine Bank areas. MNAW is the more dominant water mass in the FSC, and arrives in the area after circulating anticyclonically around the Faroese plateau.

NAW has been warming since 1987 at a rate of O(0.5°C/decade). This is a recent rapid warming imposed on a warming trend which commenced in 1966 and has continued at a rate of O(0.3°C/decade). Salinity of NAW has demonstrated great variability since the end of the low salinity anomaly (GSA) years in the late 1970s (Figure 3), and this recent

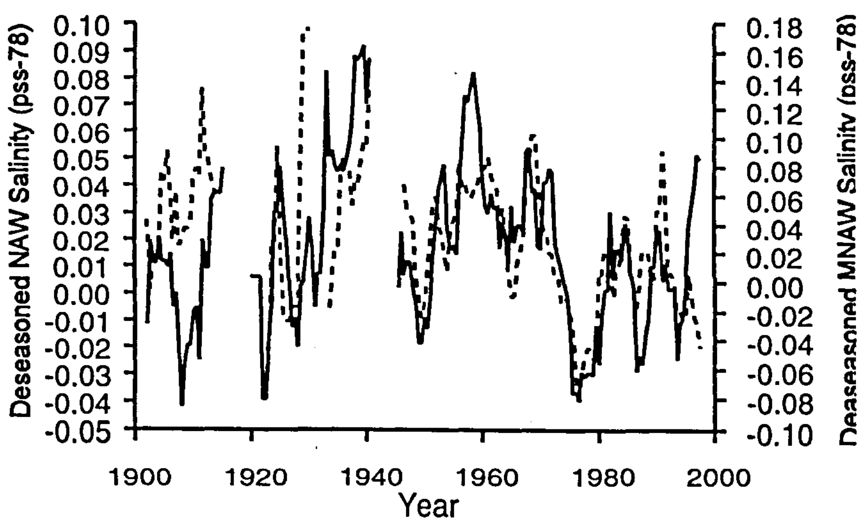

Figure 3 De-seasoned salinity in the two surface water masses of the FSC; North Atlantic Water (NAW) and Modified North Atlantic Water (MNAW).

variability may be more closely related to the North Atlantic Oscillation (NAO) index compared to the period prior to the arrival of the GSA. In addition to the shorter term variability, there has possibly also been a gradual overall salinity increase since the GSA period with salinities now approaching 1960 values. The most recent change is an increased rise at a rate of O(0.2/decade) since 1993.

MNAW has demonstrated somewhat different decadal changes compared to those of NAW.

There has been a general cooling of MNAW since 1960 at a rate of O(0.3°C/decade). Salinity has also decreased since 1960 at a rate of O(0.02/decade), with a more rapid decrease evident since 1991. Salinities are beginning to approach those values observed during the GSA period. These changes appear to be closely correlated with those in the Norwegian Sea, rather than with changes in the NAW.

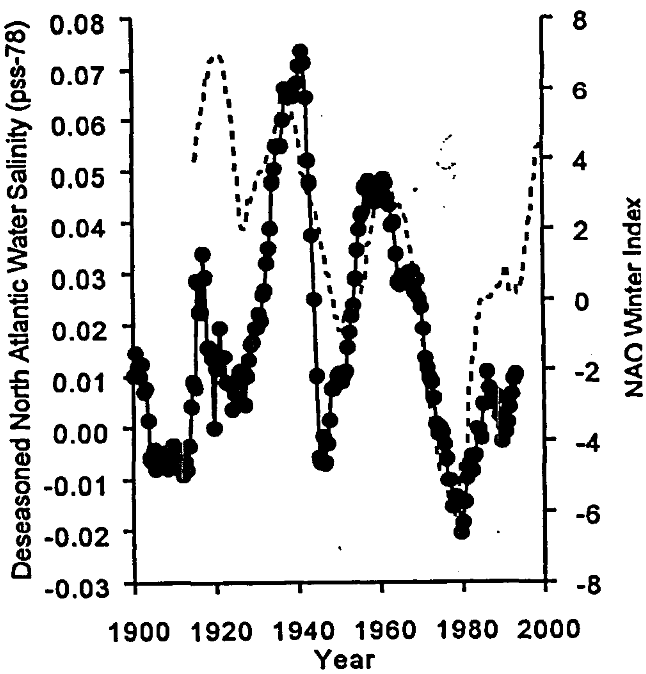

Figure 4 Salinity of Atlantic Water lying at the Scottish shelf edge north of Shetland (solid line) compared to the winter NAO index from Hurrell (1995) (broken line). Both time series have been filtered using a 10 year running mean

The long-term trends in the salinity of NAW has been examined by filtering the data with a 10 year running mean (Figure 4). When this filter is also applied to the winter NAO index of Hurrell (1995) there appears to be a correlation, with the inverse of the NAO index leading the salinity of NAW by 12 years. This may imply an indirect link between salinity of surface waters in the FSC, and the creation of low salinity anomalies by wind forcing controlled by the NAO in more western parts of the sub-polar gyre which subsequently arrive in the FSC by advection within the gyre. A strong NAO results in the export from polar regions of increased amounts of low salinity water, which enters the gyre to reappear in the FSC after circulating within the gyre.

North Sea

In the North Sea the salinity variability in the past has been well correlated with that of NAW, with a possible 1 year lag. However, unlike NAW, the salinity of Fair Isle Current Water (FICW) has more recently demonstrated a differing trend, with FICW salinity decreasing since 1973, while NAW salinity is generally increasing. Also unlike NAW, FICW demonstrated a cool episode in the mid 1990s which has now ended with a rapid warming, resulting in an increase in temperature of 1°C since 1994.

The properties of Cooled Atlantic Water (CAW), which typifies water lying within the central northern North Sea below the seasonal thermocline, are more closely tied to those of NAW. Hence CAW does demonstrate the gradual warming seen in NAW since 1970, and the more recent salinity variability seen in NAW is reflected in that of CAW. One difference noted is that while the salinity of NAW has risen since 1993, CAW salinity has declined. This may imply reduced oceanic inflow to the North Sea during the last 3–4 years.

Since the low salinity GSA period, the salinity of CAW shows a clear correlation with the NAO index (Figure 5). This may partly be due to the changes within the source NAW water, but also to changes in the inflow of NAW into the North Sea, itself determined to some extent by wind forcing and hence a possible link with NAO variability.

North Sea Cod Recruitment: There appears that the may well be a subsequent correlation between the NAO and cod recruitment in the North Sea (Figure 6). The mechanisms behind this correlation are not yet known, but a link with changes in oceanic inflow and the internal North Sea wind-driven circulation must be strong candidates.

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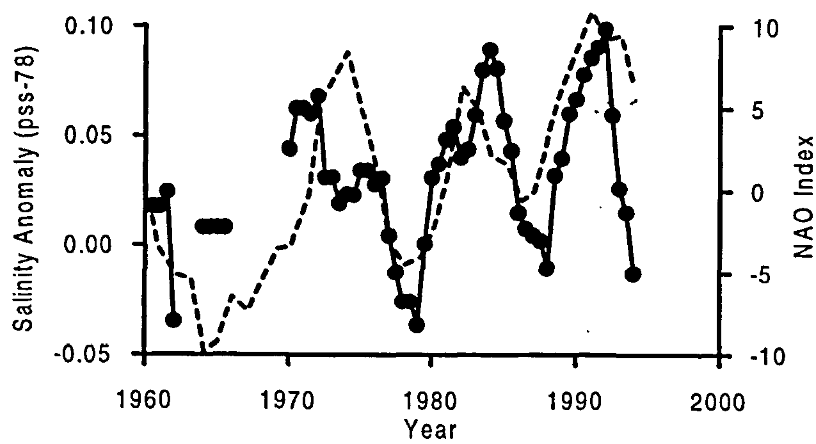

Figure 5 Salinity of the bottom water in the central northern North Sea (solid line) compared to the winter NAO Index from Hurrell (1995) (broken line)

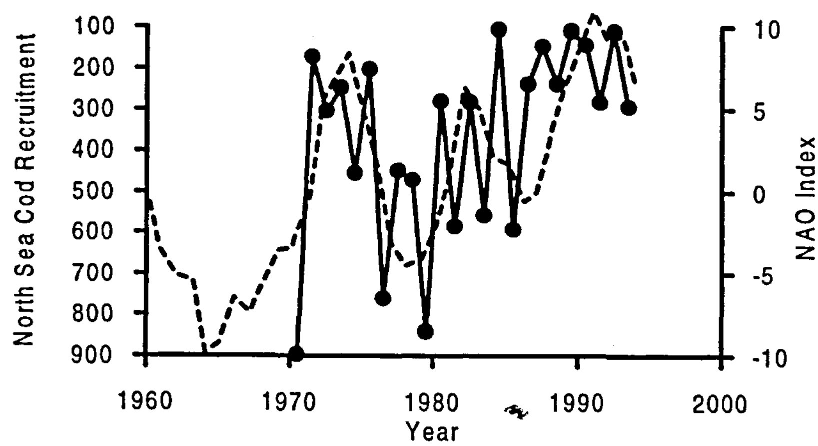

Figure 6 The winter NAO index from Hurrell (1995) compared to North Sea cod stock recruitment as given in the 1997 ICES Demersal Fish Working Group

SUBSURFACE TEMPERATURE ALONG A CABLE ROUTE BETWEEN ICELAND AND THE FAROE ISLANDS, 1906–1962.

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Over the last few years, evidence has been accumulating on the varied and far-reaching climate effects that appear to be related to the North Atlantic Oscillation (NAO). Evidence relevant to understanding the ocean's role is largely based on a handful of long time series in the ocean, in combination with large-scale analyses of atmospheric and sea surface patterns. However, most of the ocean time series stations started only in the post-WWII period, and analyses based on the large ship-observation based data sets have difficulties bridging the mid-century for reasons that include differences in patterns of shipping and observation methods at sea. Many data analyses and most data-based model runs therefore confine themselves to the post-war period, usually the 1950s onward. This period does include the NAO low of the 1960s-70s and a subsequent evolution to highs in the 1990s. However, to cover a full cycle from the previous NAO high we would need to go back to the early decades of the century, a task for which only limited data exist. A possible contribution is provided by the long-term variations observed in a 1906–1962 time series reflecting a line average of sea floor temperature along the Iceland-Faeroes Ridge. This 56-year record overlaps with post-war time series started in the 1950s by approximately a decade. We consider whether the cable record may provide an additional fragment of information on the history of subsurface ocean temperature over the Iceland-Faeroes Ridge during the earlier half of the current NAO cycle.

The Iceland-Faroes Ridge is a complex region where water masses of Atlantic, Norwegian Sea and Arctic origin meet. In comparison with the rest of the World Ocean, the surrounding region possesses a number of long oceanographic time series. However, none of these directly reflect the possibly changing conditions over the ridge. While there is a considerable body of observations data from nearby shipping, interpretation of ship observations is complicated by questions of temporal and spatial sampling of the rich spatial and temporal variability in the area, which includes meanders of the Iceland-Faeroes Front and both cyclonic and anticyclonic eddies. A long, well-resolved time series of a spatially averaged quantity may present a usefully contrasting sampling strategy.

The Iceland-Faroes telegraph cable was operated by the Great Northern Telegraph Company between 1906 and 1962. It ran from Seydisfjordur, in the east of Iceland, to the Faroes Islands, along the Iceland-Faroes Ridge. Regular electrical tests were carried out as a routine part of submarine telegraph cable operation. One of these was to measure the cable's resistance in situ by letting the cable serve as one of the resistors in a Wheatstone bridge. Cable resistance was known to vary with sea temperature, and an effort was made to resolve the seasonal cycle, with cable tests made on the first Sunday of each month from September 1906 through 1942, and thereafter quarterly on the first Sundays of February, May, August, and November. Within the range of sea floor temperatures, the resistance of the copper conductor varied sufficiently linearly with temperature for the cable resistance to interpreted in terms of an average bottom temperature along the cable path, provided the resistance of the same piece of cable was known at a reference temperature. This reference resistance was determined at the cable factories, and subsequently updated by reports from the cable ships as sections of cable were replaced during repairs. The data presented here were obtained from the Icelandic `Journal of Electrical Measurements', supplemented by measurements made at times of cable repair and recorded in the `Cable House Service Journal'. The conversion to temperature has been recalculated based on formulas from handbooks of the time (Fisher and Darby, 1905; Gulstad and Albertus, 1915). Measurements were also made in the Faeroes with the Iceland end grounded. These have been discussed by Michelsen (1994) and Hansen *et al.* (1994).

The `cable temperature' shows very little noise or variability on month-to-month time scales. It does not appear to be affected by the fluctuations of the much noisier outdoor air temperatures, or by the occasionally extreme variations in the cable house temperature, both of which were recorded in the journals. The mean cable temperature appears to be consistent with climatological averages over the ridge. There is, furthermore, a very clear annual cycle, which has been discussed by Michelsen (1994) and Hansen *et al.* (1994). The phase of this cycle indicate that the cable is indeed reflecting subsurface ocean temperatures, rather than either land or sea surface temperature.

Internal consistency checks we have made include comparisons of the Wheatstone bridge measurements made in Iceland with those made in the Faeroes, and comparisons of the in-situ resistance measurements with the ship-reported time history of reference resistance. Apart from some discrepancies due to low measurement resolution in the first few years, the internal consistency of all three data sets is good, encouraging reasonable confidence in both the short and long-term variations seen in the data.

Over the 56 years of the time series, a smoothly varying long-term oscillation is seen. This does not resemble the type of errors to be expected in case of corrupt reference resistance, which would be associated with cable repairs and should occur abruptly. Further supporting the interpretation of the long-term variation as a real ocean feature, a time series from the (poorly resolved) vicinity of the Iceland-Faeroes Ridge in a numerical simulation driven by COADS (Woodruff *et al.,* 1987) wind and sea surface temperature (SST) data (T. Ezer, personal communication), shows a qualitatively similar type of temperature variation over the 1950s-1990s, and of similar phase during the period of overlap with the cable data in the 1950s. The cable time series as a whole shows some similarities with the NAO-related second EOF of North Atlantic cold-season SST as constructed by Deser and Blackmon (1993) from COADS sea surface temperatures, and there is a good match between the cable temperature and the `warm' and `cold' periods identified in Kushnir's (1994) analysis of zonally averaged COADS SST. We discuss some possibilities for the physical mechanism of the seasonal and long-term variations seen in the cable data, and their relationship to the NAO.

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APPEARANCE, POSSIBLE GENESIS AND THE ROLE OF NAO IN THE NORTH ATLANTIC AND THE NORDIC SEAS

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The paper concerns the investigations into regularities of appearance and conjugation of hydrometeorological process large-scale fluctuations in the North Atlantic and the Nordic Seas, as well as determining the role of North Atlantic Oscillation (NAO) in the formation of these fluctuations.

Based on the current data (1951–1996) numerous facts of close statistically significant feedback of the main parameters of climate in the Barents and Labrador Seas have been established. It was noted, that this teleconnection was of synchronous character. It couldn't be by accident. New data, verified, that NAO is one of the main factors of the formation of fluctuations in climatic systems of the North Atlantic and adjacent seas, large-scale in time and space, are presented.

In this connection, the regularities of seasonal and interannual link of atmosphere effect main centres in the Atlantic Ocean (the Icelandic minimum and the Azores maximum) are analysed in some detail. Peculiarities of the frequency structure of atmosphere pressure long-term (1951–1996) alterations in the specified centres of the effect of atmosphere and NAO, as well as the main parameters of marine climate in the North Atlantic and the Nordic Seas, which are characterised by a number of dominant cycles: 2–3, 5, 7–8, 10–15, 17–20 years and trend (climatic) component, are considered. "Decadal cycles" play an important role in the formation of long-term changes of hydrometeorological processes. The period large-scale varies in the range of 7–20 years and they approximate up to 40–50% of long-term changes. Frequency structure of perennial changes of the main parameters of marine climate in the North Atlantic and the Nordic Seas, as well as the structure of NAO, on the whole, correspond to the present-day scientific concepts concerning the character of long-term variability of natural processes on the Earth and general reasons of their formation.

Obtained spectra of climate parameters in the studied area of the World Ocean indicate the regularities of long-term changes of climate on the whole for the period considered (1951–1996) (long-term mean model) and are usually used as a basis for a number of prediction models of natural processes. Nevertheless, the assessment of stability of separate dominant variations in time using NAO index and water temperature on the "Kola Meridian" (KM) Section as an example, carried out applying gliding spectral analysis, shows the instability of these variations appearance within the period considered. For instance, against the background of systematic decrease in the influence of quasi-two-year components of studied climate parameters from 1951 to 1996, in 70–80s the impact of "decadal" cycles sharply increases. In nineties fluctuations, close to 7–8 years, started to make the most significant contribution to the long-term changes of both NAO and water temperature in the Barents Sea.

The preliminary results indicate enough close time conformity in appearing the variations, close in duration, in the most informative climate parameter of the North Atlantic - NAO index, as well as in the most informative heat index of marine climate in the Barents Sea - water temperature on the "Kola Meridian" Section. Undoubtedly, found out instability of different cyclic components and conformity of their appearance for NAO and KM should be taken into account in future when developing diagnostic and prediction models of marine climate in investigated areas of the World Ocean.

Along with the instability of the cyclic component appearance in time their spatial heterogeneity has been brought out. In this paper a distinct geographic localisation of appearance power of prevailing cycles of water surface temperature in the North Atlantic is presented as an example. So, variations of 7–8 year duration are the most typical of the eastern North Atlantic, where they reach 30–40% of long-term changes. Variations with the duration close to 10 years, by contrast, dominate (about 30%) in the North-West Atlantic and the central North Atlantic, at the latitude of 40–50°N. Long-term fluctuations of water temperature with a duration of 17–20 years are the most distinctly (25–30% of dispersion) pronounced in the North Atlantic Current area. This is well-conformed to their advective nature - 19-year cycle of tide-forming forces.

Facts of increase in parameters of natural process changes are of particular concern in studying the large-scale changes of natural processes in the North Atlantic and the Nordic Seas and when assessed these changes in ecological modelling and predicting. This becomes apparent visually in increasing a number of anomalous and extreme phenomena observed in the ocean and atmosphere of the Earth. In the Barents Sea the progressive increase in changes of the main parameters of its climate is registered during the last century. In that period significant decrease in the time of delay of the Barents Sea marine climate regarding the appearance of the solar activity "11-year" cycle was recorded. In the paper it is shown that the possible reason of that nature phenomenon is strengthening long-term accentuation of the main effect centres in the North Atlantic and their integral index - NAO.

Established above frequency structure regularities of the long-term changes of the main parameters of marine climate in the North Atlantic and the Nordic Seas, the instability of its appearance in time and space, increase in the unsteadiness of climatic systems are a possible basis for developing a new type of the prediction model of the marine climate in the Barents Sea.

DECADAL-SCALE CLIMATE VARIATIONS IN THE ICE-EXTEND AND HYDROGRAPHIC PARAMETERS IN THE WATERS AROUND ICELAND

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Introduction

Iceland is situated at the meeting place or fronts of warm and cold ocean currents, which meet at this point because of the geographical position and the submarine ridges (Greenland-Scotland Ridge) which form a natural barrier against the main ocean currents around the country (Figure 1). To the south is the warm Irminger Current which is a branch of the North Atlantic Current (6–8°C) and to the north are the cold East-Greenland and East Icelandic Currents (÷ 1–2°C). There are also deep and bottom currents in the sea around Iceland, principally the overflow of deep cold water from the Nordic Seas and the Arctic Ocean south over the submarine ridges into the North Atlantic. The different hydrographic conditions in Icelandic waters are also reflected in the atmospheric or climatic conditions in and over the country and the surroundings seas, mainly through the Iceland Low and Greenland High. These conditions in sea and air have their impact on biological conditions, expressed through the food chain in the waters including recruitment and catches of commercial fish stocks.

Hydrographic conditions

North Icelandic waters 1924–1997

A selected hydrographic section in North Icelandic waters (Siglunes 3, Figure 1) has been used to characterise the hydrographic conditions in North Icelandic waters from year to year. At this station Atlantic water ($t > 4°C$. $s > 34.9$) dominated during the periods 1924–1964, 1972–1974 (climate reversal in the northern North Atlantic, Dickson *et al.* 1975), in 1980, 1984–1987, 1991–1994 and 1996–1997, periods which may more or less coincide with a positive NAO index (Figure 2a, b). The late sixties as well as shorter periods thereafter (1975–1979, 1982 and 1988) were predominantly characterised by Polar influence associated with an eastwards and southwards extension of the so-called "cold tongue" of the East Icelandic Current, frequently manifested by the appearance of sea ice and some biological consequences. These hydrographic conditions in the late sixties in North Icelandic waters again coincide with the most extreme negative NAO period in this century and conditions in the late seventies as well. The drift-ice conditions are bound to low-salinity (< 34.7) in the surface layers of the East Icelandic Current, preventing overturning by cooling or advection, thus favouring drift-ice conditions as well as ice-formation in North Icelandic waters. This relationship is of some prognostic value for the possibilities of drift-ice in North Icelandic waters. Ice indices in this century in Icelandic waters (Figure 2c) indeed reveal clearly the periods of severe ice conditions prior to 1920 and in the late sixties, which is to a certain degree in accordance with the overall NAO index during this period. The biological consequences of the hydrographic impact in the late sixties in North Icelandic waters are well documented in low primary production and zooplankton concentrations as well as changed feeding migration pathways of the Atlanto-Scandian herring towards the east in the Norwegian Sea.

Besides the Atlantic and Polar periods in North Icelandic waters a third condition has been observed, so-called Arctic conditions. Thus Polar conditions (Figure 3, 1979) are characterised by cold and fresh surface water, the low salinity strengthening the stratification. High maxima in temperature and salinity in intermediate and near-surface depths characterise Atlantic conditions (Figure 3, 1980) with the high temperatures strengthening the stratification. During Arctic conditions (Figure 3, 1981) the intermediate salinity maxima are less pronounced and the stratification is poor. During the so-called Arctic conditions ($t = 0$–$3°C$, $s \sim 34{,}8$–$34{,}9$) in the years 1981–1983, 1989–1990 and most severely in 1995 the hydro-biological conditions in North Icelandic waters were extremely unfavourable. These different hydrographic condition in North-Icelandic waters are reflected in conditions of the Icelandic capelin stock which feeds in the Iceland Sea as well as weight of cod in Icelandic waters, which feeds to a high degree on capelin (a.o. Malmberg and Blindheim 1994). Recruitment of Icelandic cod too seems to be depending on the hydrographic condition, being relatively higher during Atlantic conditions on the feeding grounds in North Icelandic water, especially it seems to rise just at the interface between Polar/Arctic and Atlantic conditions, but poor during the Polar/Arctic periods (Figure 4). The fishing stocks thus vary periodically depending, besides on biological conditions, on variations in the hydrographic conditions which again are reflected in the NAO index to a certain degree as mentioned above.

South Icelandic waters

In the warm waters south of Iceland periods of relatively high (> 35,15) and low (< 35,15) salinities occur. Noteworthy were the low salinities observed in the mid-seventies (Great Salinity Anomaly) and again at least in 1988 and 1992–1996 rising to 35.20 in 1997 (Figure 5). The latter periods may also be related to far-reaching conditions in the Sub-Polar Gyre (Malmberg *et al.* 1996, Belkin *et al.* 1997). Along with low salinities in the area low temperatures are also generally observed. Noteworthy is that in 1996–1997 the salinities in the East Icelandic Current were on the contrary relatively low (< 34,7) and the extension of the "cold tongue" northeast of Iceland was quite pronounced in 1995 and 1997, but less so in 1996. At the same time in the mid nineties the NAO seems to fall to negative indices after a period of positive indices since the eighties.

NAO, Rossby waves, GSA

The North Atlantic Oscillation (NAO) which denotes a mode of variability of the standing waves of the northern hemispheric tropospheric circulation is manifested by simultaneous strengthening/weakening of the intensities of the Iceland Low pressure centre and the Azores High pressure ridge as well as lateral movement of their locations. In the seventies these conditions were frequently explained by the so-called Rossby waves in the stratosphere with their ridges and troughs which vary in phase and amplitude from time to time. The response in the sea includes a.o. SST, pathway of storms, shifts of polar stratospheric circulation, altered pattern of eddy meridional heat transports by the atmosphere and changes in air-sea heat and water vapour exchanges. In the sixties-seventies during the period of negative NAO indices much attention was paid to these atmospheric conditions and its reflection in hydrographic conditions so clearly expressed for example. by the ice-years in North Icelandic waters in the late sixties. Positive vs. negative anomalous conditions in the atmosphere and hydrosphere were reported (a.o. Rodewald 1967) across the North Atlantic from the Labrador Sea to the Barents Sea. Conditions in Icelandic waters, located in between these two western and eastern seas, but also nearby the Polar and Arctic fronts, are more complex and very sensitive to the variability in sea and air. In the continuation to the Rossby waves or the NAO one must consider the advection of the GSA in the northern North Atlantic in the seventies (Dickson *et. al* 1988) originating in the waters north of Iceland in the sixties as well as a suggested new anomaly in the eighties (Belkin *et. al* 1997), possibly originating as well in the waters west of Greenland. These considerations may be of some prognostic value along with the trends of the NAO. The response in the different oceanographic regions may vary due to local conditions. Thus examples have been given on different timing of decrease of convection in the Iceland Sea (late sixties) and the Greenland Sea (seventies) in relation to wind stress curl over the two sea areas (Malmberg and Jónsson 1997).

At last some historical information can be given on the general conditions in sea and air in the northern North Atlantic as during the "warm" period from around 1920–1965 (Smed 1975) along with northwards shifted Rossby waves (polarfronts) of "small" amplitudes and zonal westerlies vs. a generally "cold" period during the past centuries ("the little ice-age"). This past cold period may be compared with the conditions after the present sixties with southwards shifted and meridional distribution of air-sea conditions. Also it may be of interest to point out the areas of the most extreme deviations or variations both during ice ages and in present times which follow similar lines bound to land-ocean distribution and the Coriolis parameter. Thus, the outlook into the future due to for example. influence of the so-called "Greenhouse effect" may still be a questionable impact compared with other "natural" variations in climate at least in the area of the northern North Atlantic and the Nordic Seas.

Fisheries and environment

Jakobsson (1992) gave an excellent overview of the variability of the fisheries in the North Atlantic in relation to environment (GSA). There are indications that the widespread cooling in the northern North Atlantic since about 1960 has entailed adverse effects on cod stocks in these waters as a whole. While this is most recorded for the West-Greenland stock and the northern cod stock off Newfoundland, there were decreases in other North Atlantic cod stocks over recent decades. This especially seems to be important for stocks which live near the lower limit of the temperature range for cod, e.g., off Labrador/Newfoundland, West-Greenland and even in North Icelandic waters. In these areas it seems that the environmental conditions had to improve before stocks and catches could be expected to be of the same strength as before the mid or late 1960's, just the time when the NAO went to its minimum. Here it is pertinent to ask to what extend the decrease in cod stocks is due to the deteriorating ocean climate or overfishing. It is difficult to say which of the factors, fishing or environment, is the more decisive in relation to decline in the cod stocks. The crucial difference between them is that while we are unable to do anything about environmental fluctuations, we should be able to manage the fishery. Careful regulations is particular important when a fish stock is weak as a result of unfavourable environmental conditions.

Conclusions

Time series of oceanographic observations reveal variability in processes such as stratification and advection over regional and large ocean areas in connection with air-sea interaction. They contribute to a better understanding of the processes underlying the oceanic and biological variability. The author believes that a major factor concerning the variation in size and behaviour of fish stocks, at least along the Arctic and Polar fronts, is the maritime climate, which influences the living conditions including spawning, feeding, recruitment and maturation. The mechanisms behind this may not be well understood. Temperature may have a direct effect on fish stocks or be associated with variable current activities such as climatic events and turbulence and other physical parameters, which again affect the multiple living conditions. The overall view may be summarised as follows:

There has been a dramatic decline of cod stocks in the northern North Atlantic during recent decades (1960–1990). In parallel with climatic changes in the northern North Atlantic during the same period, the spawning, feeding and fishing grounds of cod in these waters have declined since the 1960' during a period of increased interannual variability of the NAO. Also, cold years in North Icelandic waters as well as in the waters off Labrador, West Greenland and in the Barents Sea seem generally to give weak year classes of cod.

Ecological oceanographers may have been aware of the trends in fisheries in relation to environmental variations in the past decades, but their physical understanding which was more or less only explained qualitatively, seemed not to reach the management community. The NAO index being a quantitative one again seems to be better understood being a rather simple but important parameter explaining large scale features. Though, at last it shall be emphasised that the location of the Icelandic Low (or the phase of the Rossby waves) and the variable tracks of storms is an important features as regards different oceanic regions and their hydro-biological conditions when considering decadal-scale climate variations in the northern North Atlantic.

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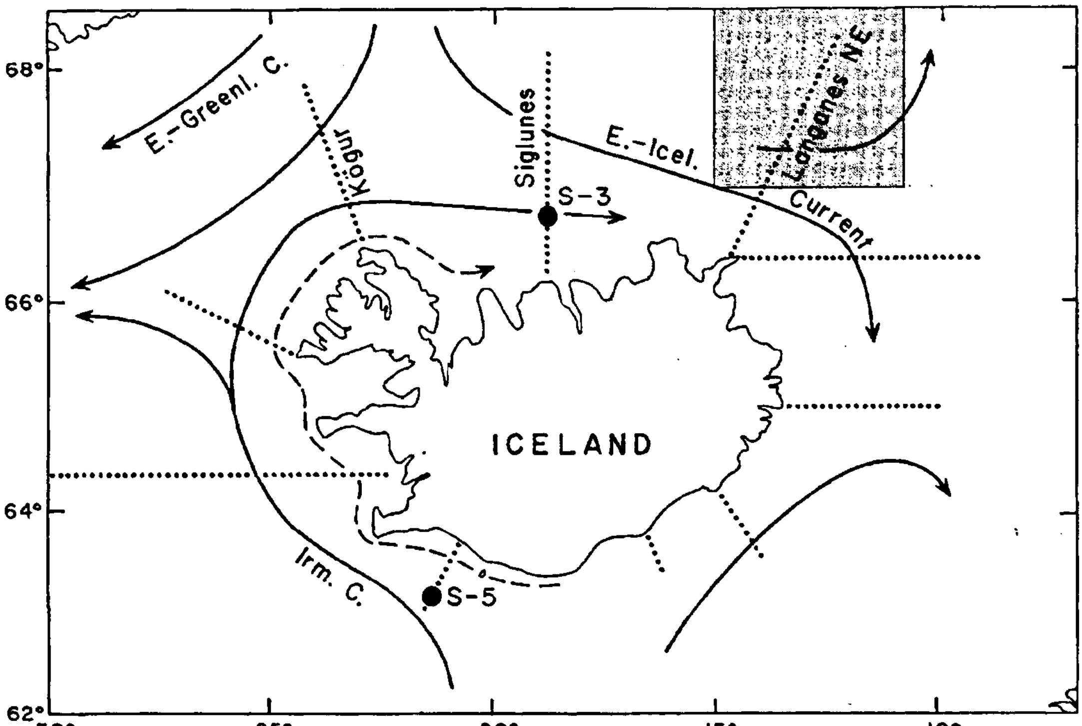

Figure 1 Main currents and locations of standard hydro-biological sections in Icelandic waters. Selected areas and stations dealt with in the paper are indicated.

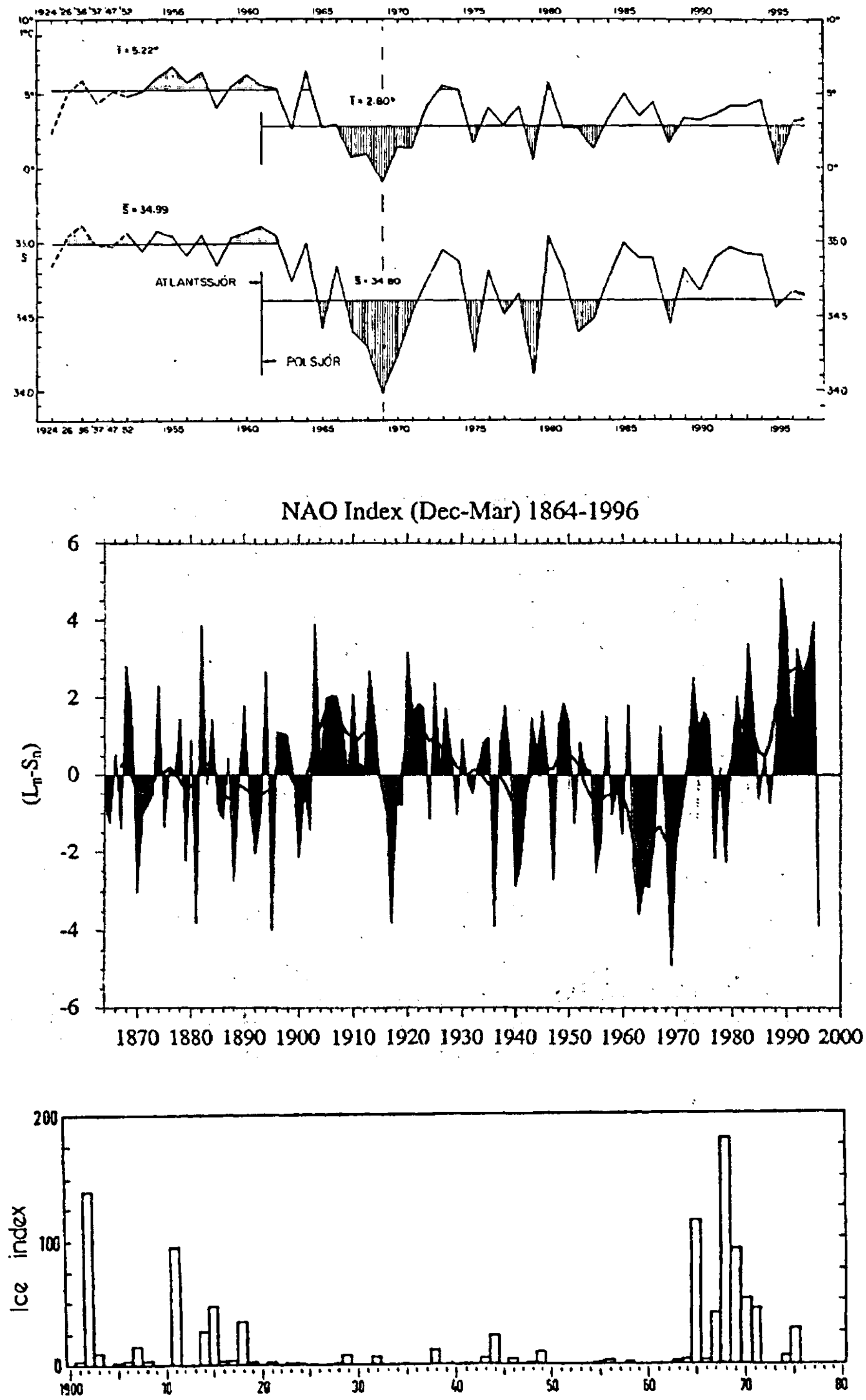

Figure 2 a) Temperature and salinity at 50 m depth at a hydrographic station in North Icelandic waters (S-3, for location see Fig, 1) in May/June 1924, 1926, 1936, 1937, 1947 and 1952–1997.

b) The winter NAO index (1866–1996) using normalised sea level pressure differences between Lisbon, Portugal and Stykkishólmur, Iceland (U.S WOCE Report 9, 1997).

c) Ice index for Icelandic waters 1901–1975. Product of weeks with ice per

year and the number of coastal areas near which it was observed (E. Sigurdsson, Icelandic Met. Off.)

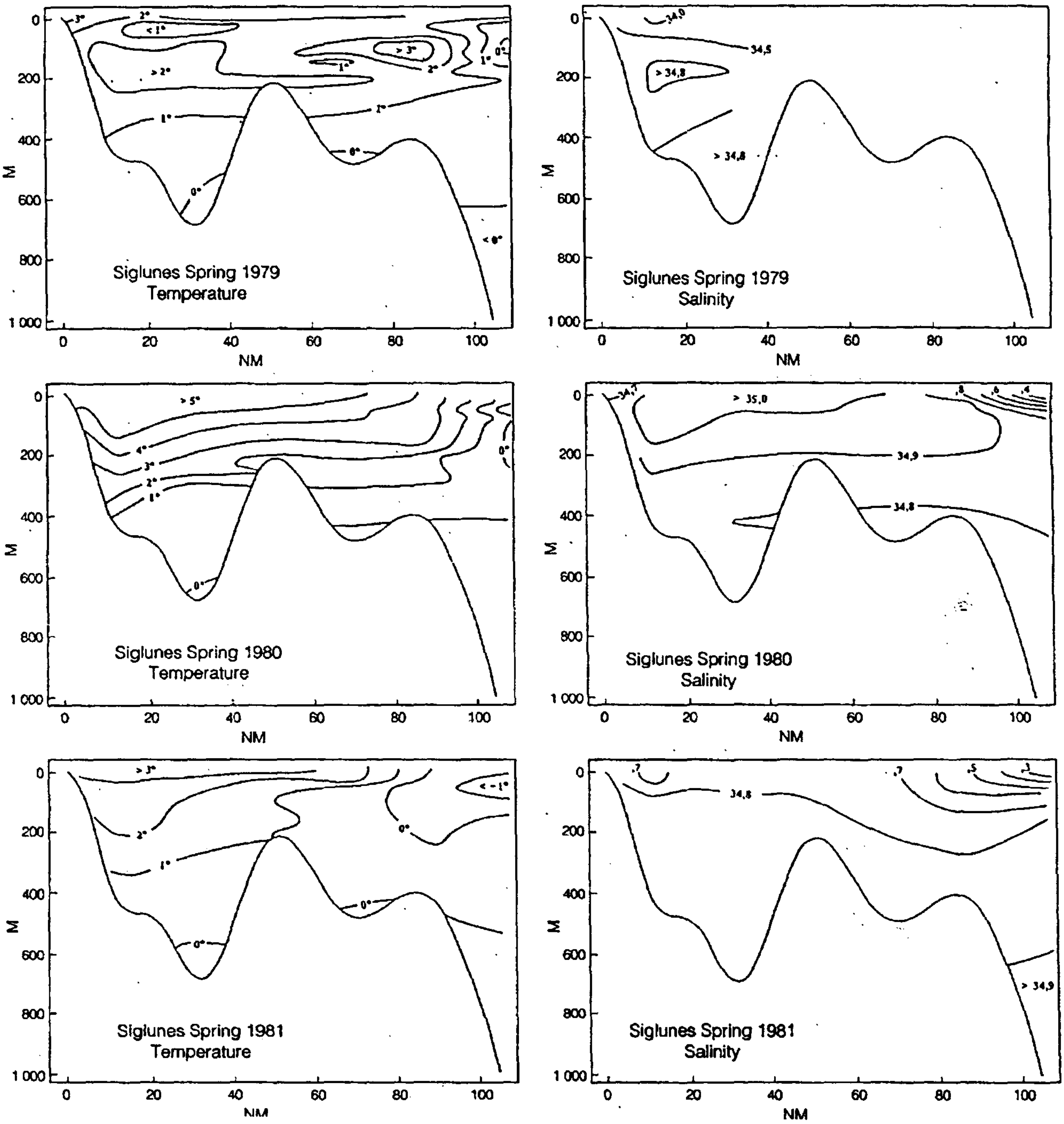

Figure 3 Vertical distribution of temperature and salinity on a section in North Icelandic waters (Siglunes) in May/June 1979, 1980 and 1981. (For location see Figure 1.; Malmberg and Blindheim 1994).

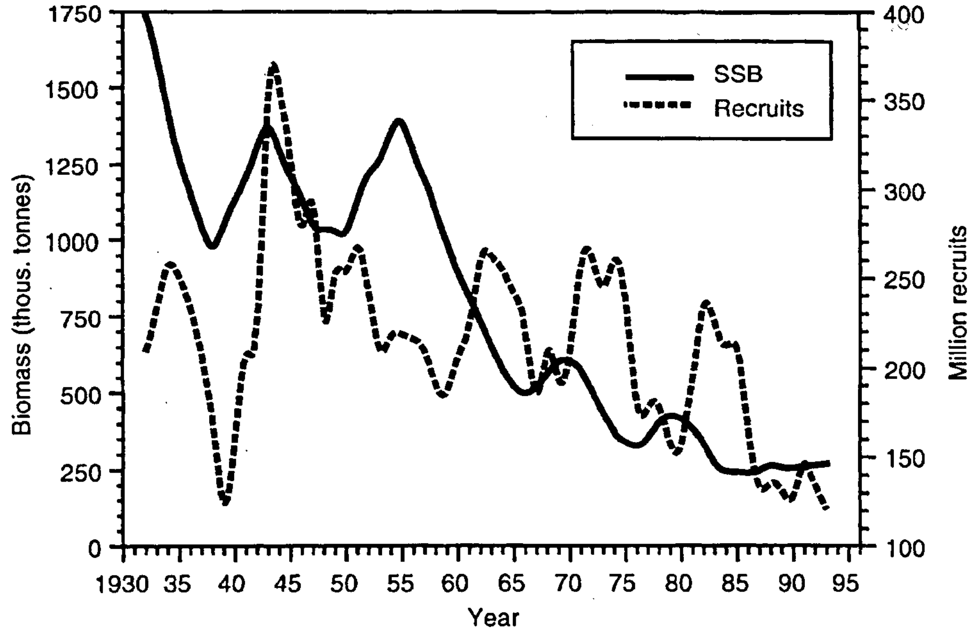

Figure 4 Five years running averages of spawning stock biomass and recruitment of cod at Iceland 1931–1993. (from Vilhjalmsson 1997 based on Schopka 1994).

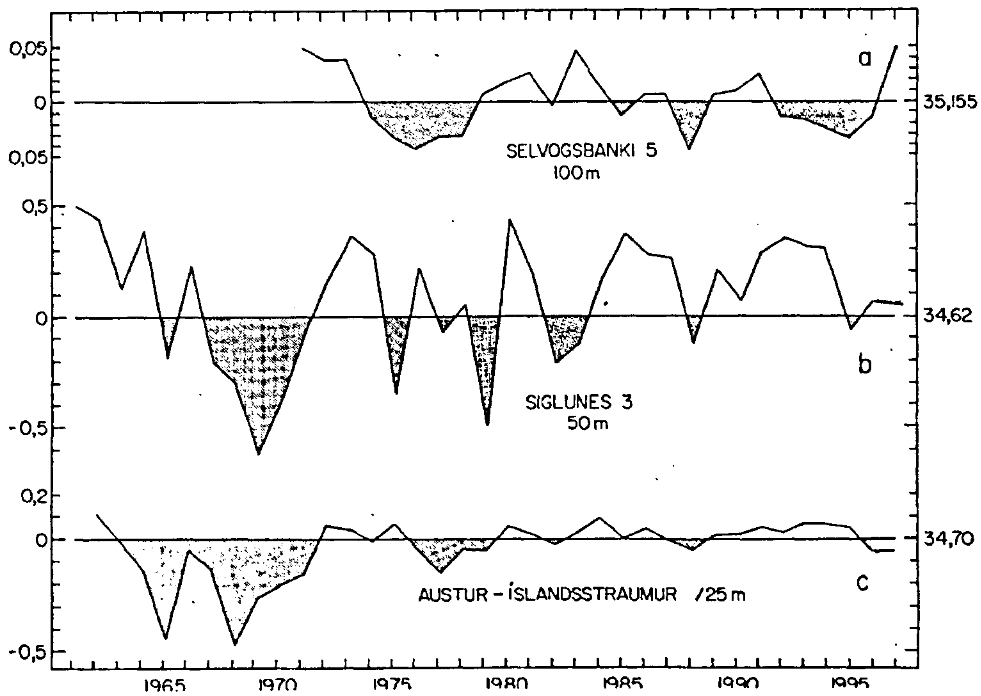

Figure 5 Salinity deviations in spring at

a) at 100 m depth in the Irminger Current south of Iceland

b) at 50 m depth in North Icelandic waters

c) at 25 m depth in the East Icelandic Current

(For locations see Figure 1).

INTERANNUAL VARIABILITY IN THE ATMOSPHERIC AND OCEANOGRAPHIC CONDITIONS IN THE LABRADOR SEA AND THEIR ASSOCIATION WITH THE NORTH ATLANTIC OSCILLATION

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The atmospheric conditions over the Labrador Sea and the ocean climate in its coastal regions are described, including their relationship to the North Atlantic Oscillation (NAO). Atmospheric temperatures in the region have varied from relatively cold in the late 1800s and early 1900s, warming in the 1920s and remaining above normal through to the 1960s, then decreasing into the 1990s. Since the 1960s, in addition the decreasing trend, there has also been an approximate decadal-scale variability with minima in the early 1970s, 1980s and 1990s. Air temperature minima are shown to correspond to periods of increased NW winds which push cold Arctic air masses further south. The increased NW winds are related to the intensification of the Icelandic Low and subsequent increase in the NAO index.

The cold air and strong NW winds result in earlier and more extensive ice cover, increased iceberg drift and cooling of the waters over the shelves, most noticeably along the Labrador and Newfoundland shelves. There is a strong relationship between ice cover and number of icebergs which originates from calving of glaciers on West Greenland and northern Baffin Island. Moreover, there is a significant correlation between the number of icebergs crossing the

48 ^{0}N and the NAO index. The influence of large-scale atmospheric circulation on the iceberg drift was pointed out already in 1931. Correlation between the NAO index and winter air temperatures at various sites in the Labrador region were run. The correlation for the winter air temperatures was slightly higher at the site in Baffin Island than at the sites in southern Labrador and West Greenland. The NAO index accounts for approximately 50% of the interannual climate variability in air and sea temperatures, winds and sea ice in the Labrador Sea region. The correlation with air temperature is highest in winter and show a rapid decrease with progressively later seasons. This indicates that the winter time NAO pattern does not have a significant influence upon air temperatures beyond the winter season. The total geostrophic transport of the Labrador Current across the shelf and the slope have no seasonal variation, but there is seasonal variations within the current: The offshore branch have a minimum in transport during March-April and a maximum in September-October, while over the shelf there is a opposite seasonal pattern in the transports. Correlations between the transports and the NAO index show increased southward flow in summer tended to occur in years of low NAO. Thus, the baroclinic flows increases during warm years with weaker NW winds and reduced ice. In 1996, the NAO index decreased dramatically with the largest annual decline in over 100 years of record. This indicated a weakening of the strength of the Icelandic Low, and resulted in weaker winds, warmer sea and air temperatures and less sea ice.

(This is an abstract of a 24 pages working paper presented at the Workshop by Ken Drinkwater)

FLUX VARIATIONS OF THE ATLANTIC INFLOW TO THE NORDIC SEAS

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The three gaps in the Greenland - Scotland region give rise to three separate branches of Atlantic inflow to the Nordic Seas which we (non-traditionally) may term: The Icelandic Atlantic Current, the Faroese Atlantic Current and the Scottish Atlantic Current (Figure 1). The water mass characteristics of these branches differ considerably, with temperature and salinity increasing by several degrees and tenths of salinity units respectively when crossing the flow from the Icelandic Atlantic Current to the core of the Scottish Atlantic Current.

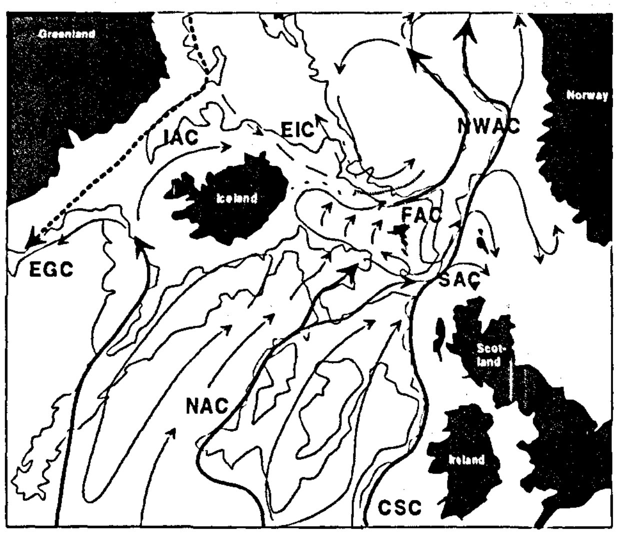

Figure 1. Main surface flows in the Greenland - Scotland - Norway region. NAC: North Atlantic Current. CSC: Continental Slope Current. IAC: Icelandic Atlantic Current. FAC: Faroese Atlantic Current. SAC: Scottish Atlantic Current. NWAC: Norwegian Atlantic Current. EGC: East Greenland Current. EIC: East Icelandic Current.

These differences reflect different origins, and the downstream fates of the branches differ as well. The Icelandic Atlantic Current mixes with water of other origins and looses its characteristics rapidly, usually within the Iceland Sea. The Faroese Atlantic Current looses some of its water to the Scottish Atlantic Current, but a considerable part of the water in the Faroese Atlantic Current recirculates into the southern Norwegian Sea and the Iceland Sea. Thus, the water that remains in the Norwegian Atlantic Current to enter the Barents Sea and the Arctic Ocean probably derives mainly from the Scottish Atlantic Current. This means that variations in the ratios of different branches may be as important as variations in the total influx of Atlantic water, affecting the ratio of intermediate to deep water production and affecting fish and other organisms. As an example, the Atlantic water influence on the Arcto-Norwegian cod stock is probably mostly through the Scottish Atlantic Current while the migration of Atlantoscandian herring will be more dependent upon the Faroese Atlantic Current.

Unfortunately, reliable estimates of the influxes are still not available in most regions. Two main strategies have been used to establish these: Budget estimates and measurements. The classical budget estimate by Worthington (1972) implied a total import of 9 Sv (10^6 m^3/s) of Atlantic water but budget estimates are based on uncertain assumptions and badly known parameters and other attempts have given widely different values. Also, budget estimates give only total influx, not the ratios between branches.

Measuring influxes has, likewise, been difficult. The highly barotropic character of the slope flows makes geostrophic transport estimates futile. Satellite altimetry has some potentials, but must be supplemented with information on the baroclinic component and must be calibrated by other means to account for uncertainties in the geoid. This leaves direct current measurements combined with water mass observations, but until recently these have not been very successful or comprehensive. For the Icelandic Atlantic Current, Kristmannsson (1991) has discussed current measurements in the period 1985–89 that indicated a transport on the order of 1 Sv with a marked decrease through the period. In the Faroese Atlantic Current, a Nordic group within the NANSEN programme estimated the flow of Atlantic water north of the Faroes to 3 Sv (Hansen *et al.*, 1986), but the measurements only lasted some 10 days and we can only guess at their long-term applicability. The volume transport of water over the south-eastern slope of the Faroe-Shetland Channel was estimated by Gould *et al.* (1985) using yearlong current measurements. They found an average transport value exceeding 7 Sv with a seasonal variation that had a maximum in winter. Their transport value, however, includes some Atlantic water from the Faroese Atlantic Current as well as some water from the East Icelandic Current and does not directly represent the Scottish Atlantic Current.

Together these measurements indicate that the total influx of Atlantic water may well reach or exceed Worthington's budget estimate, but as yet we cannot within a factor of 2–4 give a reliable value for the long-term influx. A major reason for that is the heavy fisheries activity in the region which induces great losses to traditional current meter moorings. To circumvent that difficulty, the Nordic WOCE project established 9 observational sites with ADCP's (Acoustic Doppler Current Profilers) moored in a way to provide maximal protection from fisheries. In the period from Oct. 1994 to may 1997, a total of about 10 ADCP-years of data has been collected as exemplified by Figure 2. To enable water mass identification, CTD observations have been carried out along three sections, along the ADCP moorings giving from 9 to 17 coverages of these sections.

When processed, this data set will provide the first realistic estimate of the total Atlantic water influx and may hopefully give some indication of its seasonal variation. The observational effort continues as part of the VEINS programme and, if the observations continue as successfully, a few more years will start to yield observational evidence for possible decadal variations in Atlantic water influx.

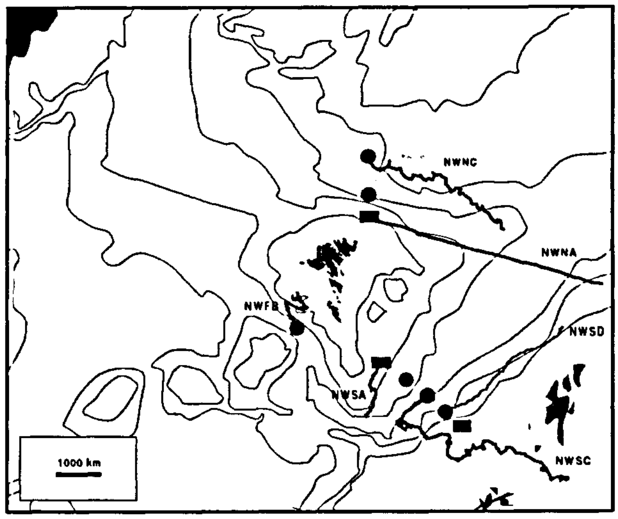

Figure 2. Progressive vector diagrams from six ADCP moorings for the period June 1996 - May 1997 (NWSD ends in Nov. 1996). All traces are at approx. 220 m depth.

Having to wait another ten years for this result is, of course, not very promising, but there is the possibility that the ADCP observations already acquired may help extract some answers from the historical hydrographic data set. North of the Faroes, a section across the Faroe Current has shown large variations in the width and cross-sectional area of the Atlantic water wedge, apparently with both seasonal and decadal components (Hansen and Kristiansen, 1994). In the Faroe-Shetland Channel the situation is more complicated, but also there water mass characteristics have varied on both seasonal and decadal time scales. By themselves, these variations do not give quantitative influx variations, but the Nordic WOCE ADCP measurements may give us the dynamical understanding of the system necessary to interpret water mass variations in terms of influx. Also, they should facilitate altimeter calibration.

Thus, before the end of this century, we should finally be able to quantify the Atlantic influx to the Nordic seas, its total value, the ratios between different branches, seasonal and perhaps also decadal variations.

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WATER MASS CHARACTERISTICS IN THE NORWEGIAN SEA IN RELATION TO VARIATIONS IN MSLP

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Large quantities of Arctic water are accumulating in the upper layers of the Nordic Seas, mainly west of the Arctic Front (Figure 1), but to some extent it also affects the branches of the Norwegian Atlantic Current. Hence, the present situation in the Nordic Seas is that the deep water is warming while the upper layers are cooling. This trend has actually been going on since the 1960s. As a result, both at Ocean Weather Station "M" as well as in Russian time series further south, the "Great salinity anomaly" in the 1970s which has attracted much attention, is no longer the period with lowest salinity. It is not readily understood whether the cooling and freshening depends on increased outflow from the Arctic Ocean to the East Greenland Current or to what extent changes in the winter convection in the Greenland and Iceland Seas plays a part.

The East Greenland Current with its branches, the Jan Mayen and East Icelandic Currents, forms the main carrier of this Arctic water. In its upper layers it carries surface water of low salinity, including ice, from the Arctic Ocean. A warmer intermediate layer carries water of Atlantic origin which recirculates from the West Spitsbergen Current, but intermediate water which is modified in the Greenland Basin, is also an important component in this system.

Much of the water in the East Greenland Current leaves the Nordic Seas through the western Denmark Strait to enter the subarctic (subpolar) circulation in the North Atlantic. Fluctuations in volume and properties of this water which is supplied from the East Greenland Current and in its mixing with waters of the North Atlantic Current, may create fluctuations in the properties of the Atlantic inflow to the Nordic Seas. Due to this, waters coming from the East Greenland Current may affect the water mass structure in the Norwegian Sea in two ways. It may occur either by transport of Arctic water, mainly in the East Icelandic Current, directly into the Norwegian Basin, or more indirectly through the Subarctic Gyre in the North Atlantic by varying admixture to the Atlantic water which later flows into the Nordic Seas. In this process the Arctic water may remain in the Subarctic Gyre for many years before it returns to the Nordic Seas, strongly modified after mixing with Atlantic water. The present trend probably involves both these effects with direct influence via the East Icelandic Current resulting in gradually decreasing salinities in the upper and intermediate layers of the Norwegian Basin, and also through the Atlantic inflow in which it is indicated by a weaker decreasing salinity trend in the Atlantic water carried by the Norwegian Atlantic Current.

A time series of temperature and salinity off Siglunes on the North Icelandic coast, shows that there was a change in both temperature and salinity during the later half of the 1960s. The shelf water which earlier was of Atlantic character with salinities on average about 35 and temperatures mostly near 5°C was replaced by colder, more Arctic waters. During the following years, temperature and salinity have on average remained low, but the conditions have been much more variable than before 1965.

The observations at Ocean Weather Station M (OWS M) at 66°N, 02°E in the Norwegian (Figure. 2), show cooling and freshening in the upper layers. There are variations with time scales of a few years, but also a more long-term trend toward lower values in both temperature and salinity. For example at 400 m both temperature and salinity are now at he lowest level since the station was established in 1948.

Time series from Russian surveys in the southern Norwegian Sea since 1954 show similar trends. In the upper 500 m of the water column there is a clear long-term decrease in temperature and salinity. Averages over 0 - 200 m and 200 - 500 m depth in a section along 63°N show a decrease similar to that at OWS "M". As a consequence, the 200 - 500 m salinity was at a lower level both in 1983 and 1995 than at the minimum of the anomaly in the 1970s (Fig 3).

This trend is similar to the development at OWS "M" during the same period, but it is different from the conditions north of Iceland where there was an abrupt decrease in temperature and salinity during 1964 -1969. A possible explanation to this may be that some of the Arctic water carried by the East Icelandic Current, has a rather long residence time in the Norwegian Sea where it mixes into upper and intermediate layers in the Norwegian Basin. The temperature and salinity in the Norwegian Basin may then decrease gradually as the volume of "new" water from the Iceland Sea increases. Increased transport in the East Icelandic Current is another possibility which may have the same effect.

Similar fluctuations are common features in several time series in the region, and the variation in time scale is rather rich as it ranges from inter annual to inter decadal and possibly secular. Hence, one of the longest time series in the area, the Russian Kola Section in the Barents Sea, shows a wide spectrum of frequencies, ranging from 2.6 to 17.5 year. This section has been observed since the turn of the century and its trends also indicate a fluctuation of similar wave length as the whole observational period. From about 1900 there was a general temperature increase which went on to about 1940 while the later part of the time series indicates a long-term decreasing trend which still may be going on. This is in agreement with the decreasing trends in the upper layers at OWS "M" and with the Russian observations further south, but the long-term decrease is larger in the Norwegian Basin than in the Barents Sea. It seems likely that the reason for this is that the fluctuations in the Barents Sea are associated with the conditions in the main branch of the Atlantic inflow which flows along the shelf break. This part of the inflow is less influenced by the arctic waters coming from Greenland and Iceland Seas than the waters in the western part of the Atlantic regime in the Nordic Seas. Changes of its properties obtained in the North Atlantic are of importance.

Observations further south in the Norwegian Atlantic Current support this, for example in the Svinøy section (Running NW from 62°22' N on the Norwegian Coast.). Although this section has been observed only since 1978, its fluctuations agree fairly well with the Kola Section. In the same region, at Ona light house (62°52' N, 06° 33' E), the Norwegian Meteorological Institute has observed sea surface temperatures on a daily basis since 1868. Also these observations show a similar trend as the Kola Section.

The evidence from all these series of observations, spread over a wide area, show that this is a major ocean climate fluctuation with a large impact on the oceanographic structure of the Nordic Seas and the ocean-atmosphere interactions in the area.

It is likely that the forcing of these fluctuations is found in the ocean atmosphere interrelation, particularly in the atmospheric pressure distribution and the related wind field. Although there is no high correlation between the pressure field and the temperature/salinity trends in the time series, there are indications of some interrelations. The Greenland high and the Iceland low show parallel fluctuations, both with decreasing values of mean sea level pressure since about the mid 1960s. As a result, the pressure gradient between Iceland and Scandinavia has been increasing (Figure 4). This is suggestive of increased northward flow on the eastern side of the Nordic Seas which for continuity reasons also will result in increased southward flow on the western side.

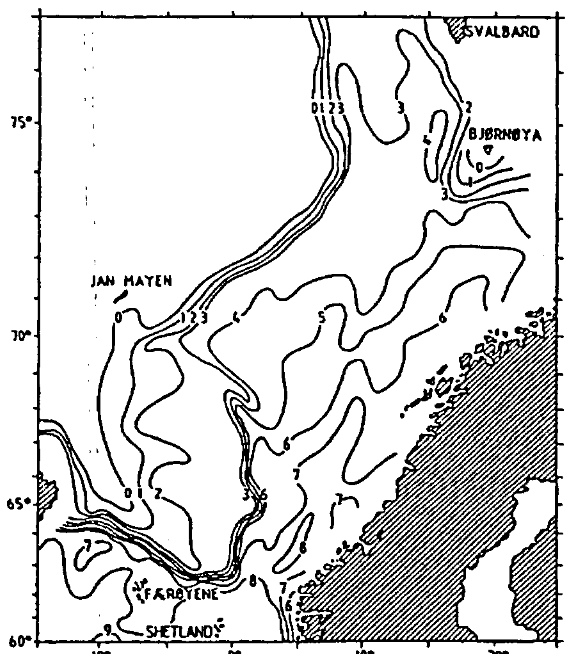

Figure 1. Temperature distribution in the Norwegian Sea in July/August 1984, indicating the position of the Arctic front at 400 m depth.

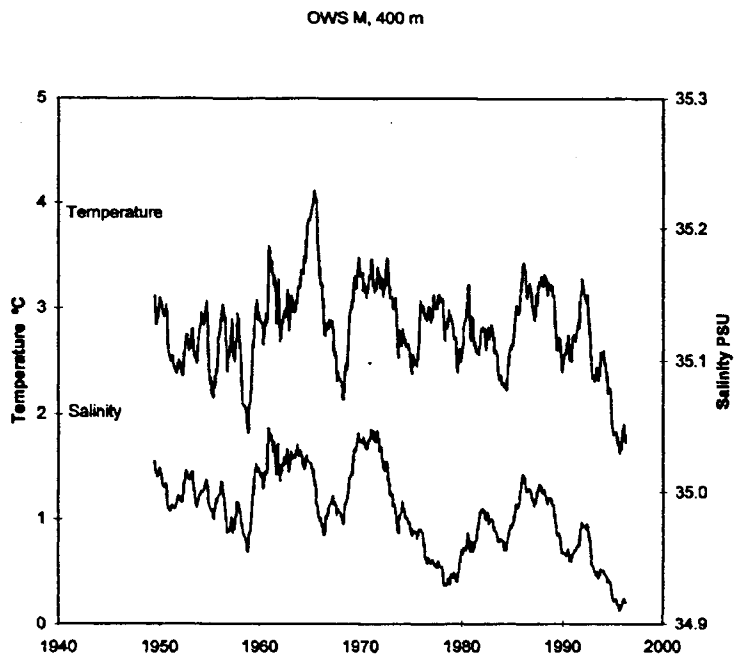

Figure 2. Temperature and salinity at 400 m depth at Ocean Weather Station M. The curves are base on monthly means, smoothed by calculation of 13 month running means. Data from the Geophysical Institute, University of Bergen.

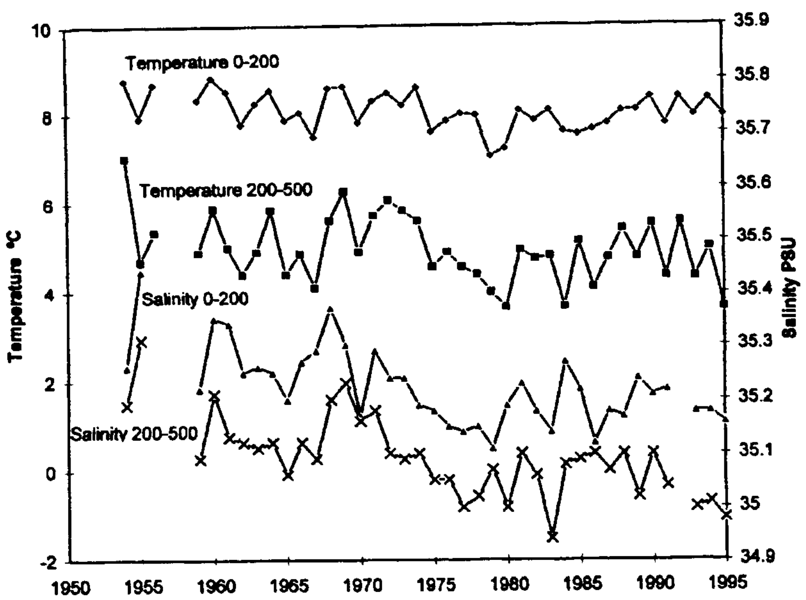

Figure 3. Time series of temperature and salinity averages in the Russian section 5S along 63°N, averaged over the depth intervals 0–200 m and 200–500 m and over 5 stations between 0.1°E and 3.5°E. Data from PINRO, Murmansk.

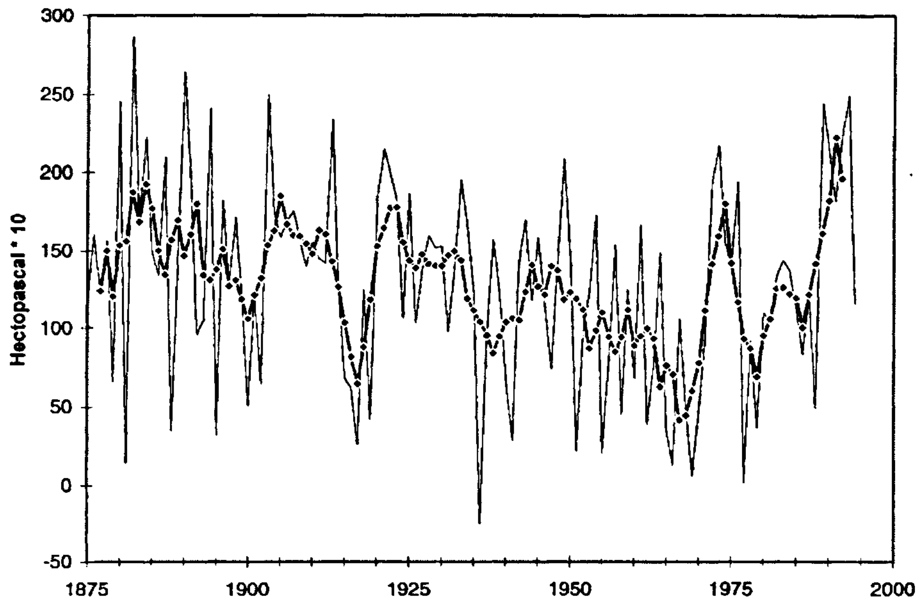

Figure 4. Gradient of mean sea level pressure between Stykkisholmur, Iceland, and Nordby, Denmark.

ON NORTH ATLANTIC INTERDECADAL VARIABILITY: A STOCHASTIC VIEW

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We investigate in this paper the dynamics and predictability of North Atlantic interdecadal variability. Observations of the last hundred years reveal the existence of substantial interdecadal variability in both the ocean and the atmosphere in the North Atlantic region, and it is obvious that the interdecadal changes in both climate sub-components are linked to each other. One has therefore to consider the North Atlantic interdecadal variability within a coupled ocean-atmosphere framework.

The simplest paradigm for the generation of interdecadal variability is the stochastic climate model scenario. The ocean integrates the high-frequency weather noise (e.g., the variations arising from passage of low and high pressure systems) giving rise to slow variations in the ocean's surface temperature. The stochastic climate model concept explains one of the main characteristics of typical climate spectra, namely their redness. While the simplest version of the stochastic climate model yields relatively featureless spectra, spectral peaks also can be understood within the concept of the stochastic climate model, with the atmospheric noise exciting (damped) eigenoscillations of the ocean or the coupled ocean-atmosphere system.

The results of a multi-century integration with a coupled ocean-atmosphere general circulation model are largely consistent with the stochastic climate model. Two distinct modes exist in the North Atlantic region: A 15-year mode and a 35-year mode. Both modes depend critically on ocean-atmosphere interactions and must be regarded as inherently coupled air-sea modes. The memory of both modes, however, resides in the ocean. While the 15-year mode appears to be related to variations in the subtropical gyre circulation, the 35-year mode is related to variations in the termohaline circulation. Predictability experiments with the coupled model indicate that subsurface quantities in the North Atlantic may be predictable one or two decades in advance, while surface quantities seem to be predictable only for a few years. These results imply that the coupling between the ocean and the atmosphere (although critical for the existence of interdecadal modes) is too weak to influence significantly the predictability characteristics of the atmosphere at decadal time scales.

(This abstract was prepared for the proceedings of the Ocean Forecasting Workshop, Torregrande, Oristano, Italy, 29 June - 13 July 1997)

CLIMATIC EXPERT SYSTEM FOR THE NORTH ATLANTIC (CESNA): LEARNING TO PREDICT INTERANNUAL TO DECADAL CLIMATIC VARIATIONS.

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Although climate forecasting on the interannual to decadal time scale is still an emerging research area, there is a growing belief that some temporally and spatially averaged climatic characteristics can be predicted with sufficient skill to be beneficial for economic applications. So far, most of the efforts have been directed toward the prediction of El Nino/Southern Oscillation (ENSO) events in the tropical Pacific -- the largest source of interannual climate variability. The Prediction Branch of the Climate Prediction Center (CPC/NOAA) routinely produces ENSO forecasts (with the lead time up to 15 month) using such methods as canonical correlation analysis, linear inverse modelling, and Cane-Zebiak model. The results of these forecasts are published by the CPC as Forecast Forum in the *Climate Diagnostics Bulletin*. Skilful seasonal predictions are also available for other tropical regions around the world (see the *Experimental Long-Lead Forecast Bulletin* published by the CPC). Some methods used for such predictions are based on empirical associations between elements of the general circulation of atmosphere and ocean derived from historical data. Others represent variations of coupled ocean-atmosphere modelling.

Unfortunately, the skill score of these forecasts is currently at a minimal level, their lead time, in most cases, is less than one year, and they do not cover neither the North Atlantic nor the North Pacific to be of direct interest for northern fisheries. This situation stimulates scientists to search for new techniques and approaches to climatic predictions on interannual to decadal time scale. One of these approaches, that is different from currently existing both dynamical and statistical methods, is being under development at the Computer Science Dept. of the University of Colorado at Boulder (Rodionov and Martin, 1996). This approach is based on concepts and techniques from Artificial Intelligence (AI) and Expert Systems (ES) and has been materialised in the Climatic Expert System for the North Atlantic (CESNA). The system is designed to predict mean seasonal climatic characteristics one to several years in advance. The current version of CESNA is focused on the winter climate and forecasts with a lead time of one year. The system's description along with real-time forecasts for the winters of 1995–96, 1996–97 and 1997–98 are available on the Internet at *http://www.cs.colorado.edu/~sergei/cesna.html*

In CESNA, the climate system is represented as a set of macroclimatic objects or conceptual features, such as centers of action, upper ridges and troughs, jet streams, temperature anomalies in key regions, extension of polar ice cover, precipitation patterns, etc. An evolution of the system is described as a sequence of events that involve large-scale interactions between these macroclimatic objects. While mechanisms of these interactions are still poorly understood, they may reveal themselves through statistical relationships or empirical rules-of-thumb. Thus, there is a possibility that if we can account for all of these processes, as well as external factors such as solar activity, we might be able to make progress even in predicting climatic fluctuations up to several years in advance.

In preparing a forecast CESNA exploits several features of the climate system and external factors that make it possible to project the current state of climatic parameters into the future such as:

- *Cycles*, for example, the 11-year cycle of solar activity, or quasibiennial oscillation (QBO) of stratospheric winds over the Equator. There are also numerous other cycles found in variations of climatic characteristics, but they are less stable;

- *Persistence*, that can be caused by enormous thermal capacity of the ocean, or by positive feedback loops in the large-scale air-sea interaction and may exhibit itself in so-called climatic regimes;

- *Teleconnections* with a significant time lag. One of the possible reasons for the time lag is gradual transportation of temperature and salinity anomalies along the ocean currents.

Currently, CESNA's knowledge base contains more than 400 empirical relationships, presented in the form of IF-THEN rules. For example, a relationship between central pressure and geographical position of the Icelandic low (Glowienka, 1985) may be written as:

IF central_pressure = low

THEN position = shifted_north, CF = 50.

Certainty factor (CF), that accompanies each rule, represents a numerical measure of confidence in the validity of the rule. In our system it varies from 0 to 100. A certainty factor with a zero value shows that we do not believe in the rule at all, while CF = 100 indicates knowing the premise of the rule gives us 100% confidence that the conclusion will occur. In some cases, CFs are based on observed correlations between climatic variables. However, it is important to note that such certainty factors represent a subjective, rather than statistical, value; they may reflect a personal belief in correctness of the statistical analysis, whether or not it has been confirmed by other independent studies, model experiments and so forth. Furthermore, CFs are not constant and may change over time. Thus, during the 1980s, which were characterised by strong westerlies and deep Icelandic low, the latter, contrary to the above rule, was shifted somewhat to the south of its normal position (Rodionov, 1996, pp. 180–195), that reduced our confidence in this rule.

From practical reasons, all the rules in CESNA are conditionally divided into seven separate sets: 1) Solar activity, 2) Global characteristics, 3) ENSO, 4) Time series, 5) Lag relationships, 6) The North Pacific, and 7) North Atlantic. Predictions are based on a coordinated use of these rules that involves a certain combination of CFs. Currently, a lead time of the forecasts is about 9 months. They are usually made in spring when the information about the past winter becomes available and can be used to predict next winter. CESNA then systematically processes the rules in the rule sets and combines confidence factors to create a scenario for the forthcoming winter.

To illustrate a forecasting process, consider a fragment of the ENSO rule set presented in Figure 1. In this figure, year 0 is the year when the forecast is to be made. Since in early spring of this year we don't know whether it will be a year of El Niño or La Niña we need to determine this first. ENSO event is the goal variable in this rule set and, using a procedure known as "backward chaining", CESNA tries to find its value along with the confidence factor. To do this, CESNA, asks the user to compare global SAT distribution in the winter of year 0 and preceding seasons with the typical SAT distributions before El Niño event. It uses also other precursors as well as ENSO forecasts prepared by the Climate Prediction Center. As soon as the ENSO event and its CF are determined, CESNA uses another procedure, called "forward chaining", to calculate possible consequences of that event both for the North Pacific and North Atlantic.

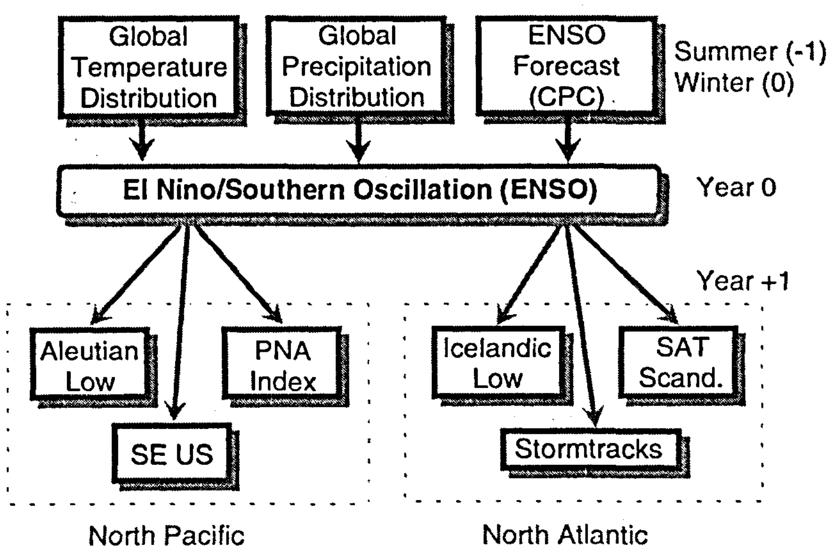

Figure 1. ENSO knowledge base (fragment).

When the consultation session comes to the last, "North Atlantic", set of rules, CESNA asks the user to specify the climatic variables and region that he or she is interested in, and comes up with the final assessment of this variable.

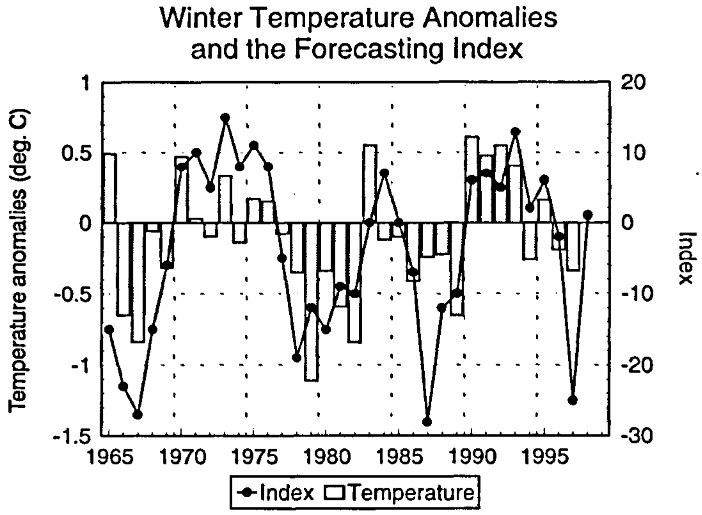

Figure 2. Mean winter (DJF) temperature in the upper 200-m layer of the Kola Section in the Barents Sea (1965–1997) and its forecast one year in advance. The forecasting index represent the difference between the confidence factors for warm and cold gradations.

Our experiments with CESNA have shown that even though some rules may be poor predictors in a given year, the combined evidence from the remaining rules can result in accurate predictions. Figure 2 shows the forecasts for the Kola Section (Barents Sea), which is considered as an excellent indicator of thermal conditions in the Northeast Atlantic and adjacent Arctic Seas. The skill score (SS) of these forecasts for the period 1965–1997 with an approximately 1-yr lead time is 0.60, which is significantly higher than for the forecasts based on persistence (SS = 0.23).

Of course, there is no guarantee that a relationship that worked well in the past will work in the future. But by piecing together bits of historical evidence from many different sources and areas of the world we can create a necessary "critical mass" of rules, so that even some of them fail, the remaining rules collectively lead to the correct result. It is interesting to note that informal empirical rules, as shown by Luger and Stubblefield (1993), are often more important than the standard theory presented in textbooks and classes. Sometimes these rules augment theoretical knowledge; occasionally they are simply shortcuts that seem unrelated to the theory but have been shown to work.

There is no doubt that we need to know more about the origin of interannual to decadal climatic variations and those mechanisms that control them, if we want to be able to predict them with a reasonable accuracy. But the advantage of the described approach, compared to the conventional forecasting methods, is that CESNA can easily update and modify its knowledge base in the light of new findings and ideas. Moreover, CESNA highlights those areas where further research is most needed. Thus, one of the major directions in out future work will be to find a way how to better predict not only one of the two major types of atmospheric circulation, associated with the high and low North Atlantic Oscillation (NAO) index, but also the positioning of upper atmospheric ridges and troughs during the meridional (low NAO index) type of atmospheric circulation.

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EXPERIENCES WITH ENSO MONITORING AND PREDICTION OF RELEVANCE TO PREDICTION IN THE NORTH ATLANTIC

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The ENSO phenomena in the tropical Pacific is the largest climatic signal on an interannual time scale and also the phenomena where most resources have been allocated to oceanographic and atmospheric prediction up to 1 year ahead. The idea behind this talk is that theories and methods from ENSO monitoring and prediction may be useful also in the North Atlantic. A brief characterisation of ENSO will be given, some aspects of monitoring / data gathering will be looked at and some models briefly described at and compared. The talk is NOT about the effect of ENSO teleconnections on the North Atlantic.

ENSO consists of an oceanographic (El Nino) and an atmospheric (Southern Oscillation) component which interact. The term El Nino (warm event) is associated with the unusually warm surface waters and deeper thermocline which appear at irregular intervals of a few years off the coast of Peru and in the eastern and central equatorial Pacific. El Nino occurs when the trade winds are weak and the atmospheric pressure is low over the eastern and high over the western equatorial Pacific, while anomalously cold ocean temperatures (La Nina, El Viejo) occur during the opposite phase of the Southern Oscillation. Dry air normally sinks over the cold eastern equatorial Pacific surface waters, flows westward as trade winds and, after being warmed and moistened, rises in the deep convective zone of heavy rainfall over the western Pacific, returning eastwards aloft. This Walker circulation is driven by the atmospheric pressure gradient associated with the equatorial SST gradient. As the latter decreases during El Nino, the Walker circulation is weakened, resulting in a eastward displacement of the convective zone into the central and eastern Pacific.

A lot of data of different types are gathered to observe climate variability in the tropic Pacific and as necessary input to El Nino prediction systems. The Tropical Atmosphere Ocean (TAO) array of moored buoys in the Pacific Ocean measures oceanographic and surface meteorological variables critical for improved detection, understanding and prediction of seasonal-to-interannual climate variations originating in the tropics, most notably those related to ENSO. The array spans one third the circumference of the globe, from 95W near the Galapagos Islands to 137E off the coast of New Guinea. Moorings are deployed every 2–3 degrees of latitude between 8N and 8S along lines that are separated by 10–15 degrees of longitude. The TAO Array was developed under auspices of the recently completed 10-year (1985–1994) international Tropical Ocean Global Atmosphere (TOGA) program. A major objective of TOGA was to develop an ocean observing system to support studies of large scale ocean-atmosphere interactions on seasonal-to-interannual time scales. TAO is now one of the cornerstones of this observing system, which also includes drifting buoy arrays, a volunteer observing ship, expendable bathythermograph network, island and coastal tide gauges, an island wind profiler network, and remotely sensed measurements from both operational and research satellites. Moreover, the TAO Array provides a broad geographical perspective and long time history to aid in the interpretation of measurements from shorter duration, regional scale observational studies.

From its orbit 1336 kilometres above the Earth's surface NASA / CNES satellite TOPEX/Poseidon measures sea level along the same path every 10 days using the dual frequency altimeter developed by NASA and the CNES single frequency solid-state altimeter. This information is used to relate changes in ocean currents with atmospheric and climate patterns. Measurements from NASAs Microwave Radiometer provide estimates of the total water-vapour content in the atmosphere, which is used to correct errors in the altimeter measurements. These combined measurements allows for charting the height of the sea across ocean basins with an accuracy of less than 13 centimetres. El Nino episodes are connected with positive surface level anomalies in the eastern tropical Pacific. By means of TOPEX/Poseidon propagation of rapid eastwards moving Kelvin waves and westwards moving Rossby waves can be monitored as they move through the open ocean and El Nino episodes detected several months before they occur. Data from TOPEX/Poseidon provide valuable input to El Nino prediction models.

The aims of El Nino modelling can roughly be described by order of difficulty as:

1) 1) Reproduce the characteristics of a typical El Nino episode, 2) Reproduce historical situations and 3) Recognise the changes in ocean and atmosphere which signal an oncoming El Nino episode, forecast such episodes. The last few years better systems for data acquisition and assimilation, greatly increased computer power and better understanding of the physics involved have made predictions with acceptable levels of certainty for lead times of up to one year feasible.

There still a long way to go before these predictions are as reliable as weather forecasts so a lot of work is at present being put in on developing and testing a variety of different models. Models can roughly be classified as dynamic or statistical, but some are hybrids, combining a dynamic and a statistical approach. Statistical techniques include constructed analog, canonical correlations and neural nets. The terminology for dynamic models may vary, but one way to classify them is as intermediate, limited area GCM (General Circulation Models) or global GCM. Intermediate models employ simplified physics and tight dynamical constraints and a construction designed to resolve the basic dynamics of the ENSO phenomenon alone. Limited area simulations of ENSO are typically higher resolution models, with explicit physics that embed a fine meshed grid of the Pacific Ocean region with a coarser global representation of the remaining tropical and subtropical regions. Many attempts have been made to capture the known physical characteristics of ENSO by means of fully coupled ocean-atmosphere global GCMs. This may well be the future of ENSO modelling, at present most of these models show significant differences from observations. Finally a brief look will be taken at the results of the comparison done by Barnston *et al.* (1994) of prediction skill of long lead ENSO forecasts by different statistical and dynamical models.

LONG-TERM CLIMATE FORCING UPON EUROPEAN HERRING AND SARDINE POPULATIONS

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Records of the herring fishery off the Swedish coast of Bohuslän, in the Skagerrak, date back to the 10th century. Nine periods each one lasting several decades are known during which large quantities of herring were caught very close to the shore boosting up local economy. So, in the 1895–96 season, more than 200 000 tons have been landed. During the 'interim' periods, which stretched over 50 or more years, the herring fishery played no role in this region.

Neither is it known what caused the herring, very likely originating from the North Sea, to amass such large concentrations in inshore waters nor is there any certainty whether local/regional or global environmental forcing influenced appearance and disappearance of the fish. However, some clues are pointing to a more global scenario. The peaks of the French herring fishery in the channel overlap with the two last Bohuslän periods whereas both, the Bohuslän and the French fisheries, are out of phase with the Norwegian herring fishery. These correlations instigated our attempt to suggest a climatological-hydrographic scenario which is based on historical data and which might have been associated with the Bohuslän periods reported.

All Bohuslän periods coincide with times when there was a relative minimum in the frequency of south-westerly winds on a decadal scale. Prevailing wind directions strictly depend on the average position of the atmospheric polar front zone (PFZ) and the frequency of embedded cyclones travelling eastwards. Changes in its meridional position reflect climatic variations on the global scale and control the main wind direction over the North Atlantic Ocean, the North Sea, and the Skagerrak.

A relative minimum of south-westerly winds should be associated with a minimum in the frequency of coastal upwelling events along the Norwegian shore in the Skagerrak which is orientated in a south-west-north-east direction. Other westerly winds favour hydrographic blocking situations for the near-surface water exchange between the North Sea and the Skagerrak. Along the entrance of the Skagerrak, the frequency of occurrence of a more or less meridionally positioned frontal zone increases which separates the Skagerrak water from that of the North Sea. Upwelling events distort and destroy this frontal system and favour the outbreak of water of low salinity concentrations from the Baltic Sea into the Norwegian Coastal Current. These mechanisms change the water properties along the Bohuslän coast significantly. They depend on decadal scale changes in the mean position of the PFZ which can be described by the index of the North Atlantic Oscillation.

Whether the Bohuslän herring periods are caused by global mechanisms such as presented here or whether they are simply a consequence of local phenomena is discussed in this contribution.

NORTH ATLANTIC OSCILLATION (NAO) AND PRIMARY PRODUCTION IN THE GULLMAR FJORD, SWEDEN (1985–1996).

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Abstract

An evaluation of a 12-year-long time series consisting of measurements of primary production in the Gullmar Fjord, SW Sweden, made as a part of the Swedish Monitoring Program revealed the importance of considering climatic forcing among the factors responsible for fluctuations in the primary productivity. The pattern of fluctuations suggested the presence of a possible cyclic behaviour rather than a trend regulated by different environmental factors. However, the results pointed to the need for continuous quality monitoring programs and new statistical methods for detecting trends and cycles in ecological time series in order to be able to improve our understanding of the different factors determining natural fluctuations in primary productivity on a global scale.

Study area

The study area (Figure 1) is located along the Swedish west coast. The Gullmar fjord is both influenced by the surface Baltic current running parallel to the coast and by input from off shore coming from the central Skagerrak resulting in an inflow along the Swedish coast of North Atlantic deep water, and North Sea water regulated by different physical processes and climatic forcing such as the North Atlantic Oscillation. The large bloom of *Chrysochromulina polyepsis* in 1988, clearly pointed out the importance of coastal currents for bloom formation, related to advection and hydrodynamical processes in the Skagerrak (Lindahl, 1993).

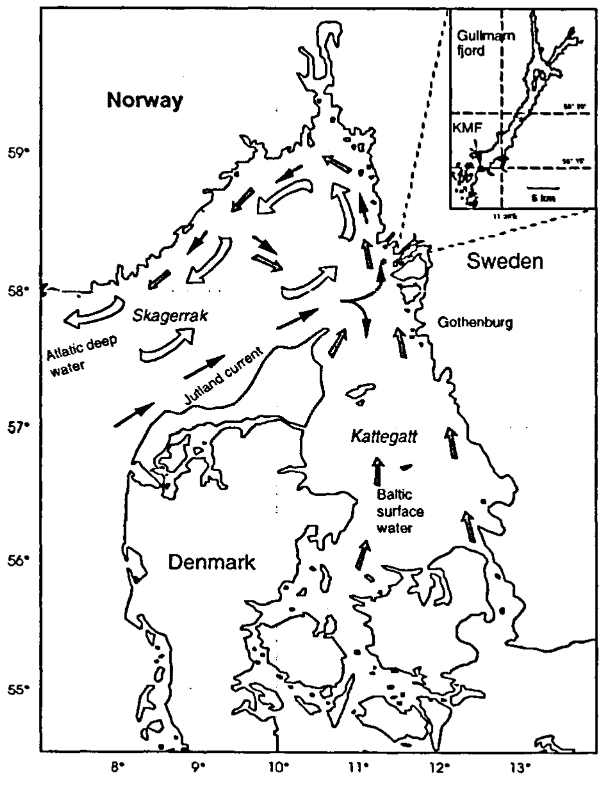

Figure 1. The Skagerrak and Kattegat area and the Gullmar fjord. The sampling site correspond to the arrow indicating KMF in the top right hand corner.

Statistical analysis

Time series of monthly means of NAO winter index (December-March), sea surface temperature, and primary production were analysed using Pearson correlations on both original and detrended series. The detrended series (original series minus polynomial trends) were used to detect correlations not due to long-term trends or to year-to-year fluctuations (Fromentin and Planque, 1996). The primary production time series decomposition was carried out according to Chatfield (1996). The significant correlation coefficients that remained after recomputing the correlation coefficients on the detrended series are reported.

Primary production

The primary production time series is presented in Figure 2. as the adjusted series after removing the seasonal component and the remaining smoothed trend cycle. This preliminary results showed the oscillations patterns present in the data, and in particular two periods of high primary productivity values were observed from 1987–1988 and in 1990 and 1994. A period of lower primary productivity values was observed in 1989 and from 1991–1993.

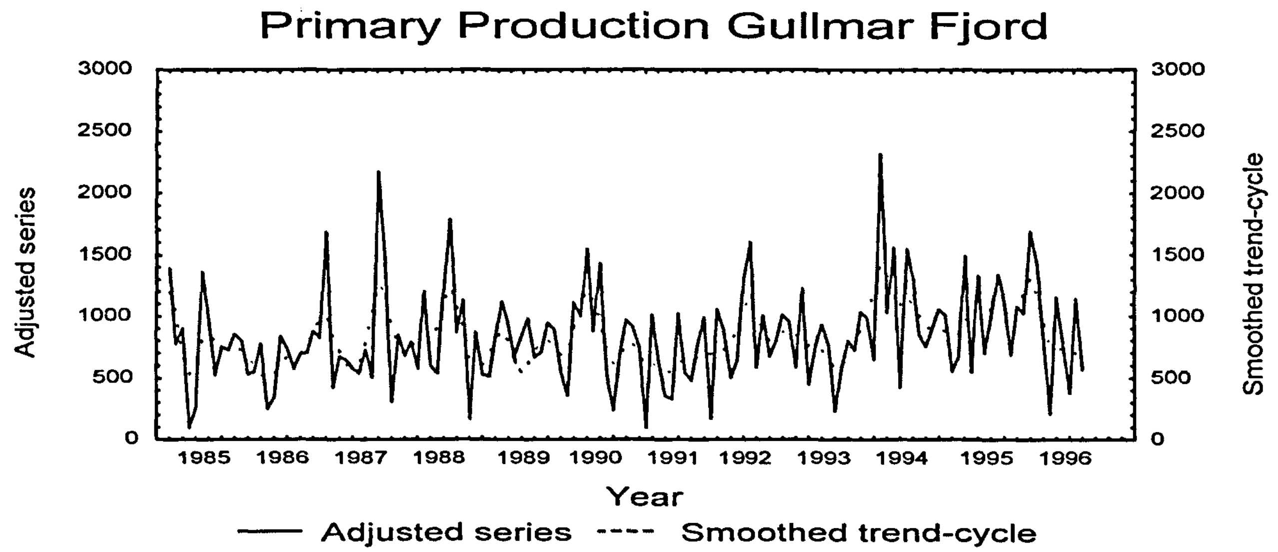

Figure 2. Daily mean primary production ($mgC{\cdot}m^{-2}{\cdot}d^{-1}$) for each month presented as an adjusted series after removing the seasonal effect on the left axis and the remaining smoothed trend on the right axis.

In order to check the possible link between the primary production signal at the Gullmar Fjord and the North Atlantic Oscillation, the correlation analysis between sea surface temperature (SST) the NAO Winter Index (NAOWI) and May primary production are presented in Figure 3. and reported as follows:

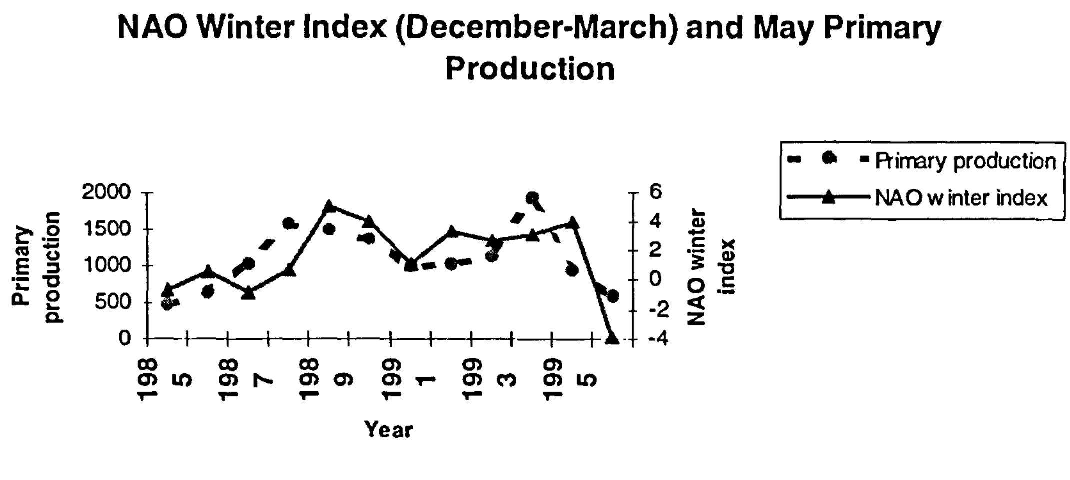

Figure 3. May daily mean primary production ($mgC{\cdot}m^{-2}{\cdot}d^{-1}$) and NAO winter index distribution 1985–1996.

Correlations

Correlations on NAO Winter Index (NAOWI) and SST (Sea Surface Temperature 0–10 m) and on NAOWI and Primary production (PP) for the Gullmar Fjord time series (1985–1996) were tested by a Monte-Carlo approach (5000 simulations). Significant correlations were found at the: *** 0.1% level, ** 1% level, * 5% level.

NAOWI and SST February $r = 0.8462$***

NAOWI and SST March $r = 0.7692$**

NAOWI and May PP $r = 0.5664$*

The only significant correlations between NAOWI and SST were found during February and March as an indication that changes in the NAO can be reflected in the changes of the SST structure. The NAOWI was also correlated with the primary production in May as an indication that the occurrence of the phytoplankton bloom can be connected with climatic events occurring during the winter months in the North Atlantic. A new approach to the analysis of the time series data set using Neural Network Modelling is currently being tested. It is important to study in more details the pattern of climatic events such as the NAO and carry out reanalysis of historical data. These results were a preliminary indication of the possible link between changes in the patterns of the North Atlantic Oscillation and the response of biological processes to climatic forcing in the pelagic ecosystem of the Gullmar Fjord and adjacent areas.

Acknowledgements

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COMMON SIGNALS BETWEEN PHYSICAL, ATMOSPHERIC VARIABLES, NORTH IBERIAN SARDINE RECRUITMENT AND NORTH ATLANTIC ALBACORE RECRUITMENT

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Time series (1960–1996) of air temperature, atmospheric pressure, precipitation, wind, mean sea-level as well as biological time series of catches and recruitment of albacore (1975–1995) and sardine recruitment (1976–1995) were studied. The aim of this work is to compare some general North Atlantic index like the North Atlantic Oscillation index (Hurrell, 1995) and the latitude of the Gulf Stream (Taylor, 1997) with some meteorological time series measured on the North Iberian Coast, local oceanographic data (sea level, temperature and salinity) and distributions of recruitment and catches of a pair of fish species, one located on the North Atlantic (albacore) and a second one locally distributed (sardine). The albacore a highly migratory species spends most of its life in the North Atlantic oceanic waters, while in contrast, the sardine is distributed around the shelf and rías where coastal upwelling and shelf processes have large influences on it. For this purpose statistical analyses based on time series analysis, spectral analysis, correlation and Principal Component Analyses (PCA) were performed.

Spectral analysis was performed for the monthly values of the meteorological and oceanographic time-series. An annual peak of twelve months related to seasonal warming and cooling due to solar heating was found, a second peak of 6 months is also found mainly in temperature, precipitation and sea level. In addition there are two peaks with periods larger than 12 months related to seasonal and decadal-scale variability. The first has a period of between 2.4 and 2.7 years and corresponds to the Quasi Biannual Oscillation (QBO). The second peak has a periodicity of around 7.5 years. Both are found mainly in air temperature and the NAO. These values are similar to the cycles reported by Fromentin and Ibañez (1994) in the Bay of Biscay.

As the data on biological variables data (recruitment and catches) are evaluated yearly, a PCA of the yearly values of the different variables was done. The three main components explain 67% of the variability of the system. The first component is related to westerly winds, precipitation and an inverse relationship with temperature and latitude of the Gulf Stream, the second one to sea level and easterly winds and the third component is related to the NAO and the albacore recruitment.

Correlation for the time-series (1976–1995) among the different factors was calculated with a significance < 0.05 (See Table 1, significant values in bold). Among the meteorological and oceanographic conditions, we found significant correlation between precipitation and westerly winds and inverse correlation between both of these and temperature and the latitude of the Gulf Stream. Also the NAO is inversely correlated to sea level. We must point out that when the NAO index is high there is a northward displacement of the intensified Westerlies (Alheit and Hagen, 1997), Northern European weather is mild, but the Iberian Peninsula is blocked from the Westerlies and a strong high pressure cell is located in the western part. Seasonal correlation must to be higher than the annual mean as has been shown in the Moroccan precipitation (Lamb *et al.*,, 1997)

Climatic variability is one of the main causes of the natural changes occurring in marine ecosystems. The importance of environmental parameters in the space-temporal variability of the species has increased greatly. In this case we have chosen two species of different behaviour. The albacore is a highly surface migratory species, recruitment occurs in the Western North Atlantic and the immature catches in the Eastern North Atlantic and Bay of Biscay.

Correlation between the albacore recruitment (Anon, 1996) and the NAO index is negative and significant. During periods of high NAO index, the westerly winds intensify and the recruitment of albacore is low. Increase in turbulence due to the strong winds could be a negative factor for the recruitment. During periods of low NAO index convective activity in the Sargasso Sea is high (Dickson *et al*, 1996), this fact may provide good conditions for recruitment. We have calculated the anomalies on both values NAO and albacore recruitment values, normalised by dividing by the standard deviation, and adding up to get the cumulative sum of the anomalies. In Figure 1 A we have shown them to see the effect over time and the opposite changes produced in both parameters on the same time scales.

With respect to aggregated immature catches (ages 2 and 3) of the northern stock, correlation is significant and negative with the index of Gulf Stream latitude and mean sea level. These two factors may provide an idea of the influence of the

North Atlantic current on the young albacore. The northward displacement of the current could bring these fish out of the area of fisheries (mainly the Bay of Biscay). None of the local atmospheric variables have significant correlation with catches of immature albacore.

Related to a locally distributed species such as the sardine, we found a significant and negative correlation of the sardine recruitment (Anon, 1997) with air temperature and the latitude of the Gulf Stream index. In Figure 1 B we have plotted the cumulative sum of anomalies in sardine recruitment and annual air temperature, and the behaviour is found to be similar but opposite. An attempt can be made to work out the mechanisms for this behaviour. Variability in regional air temperature on time scales of several decades is controlled not only by anomalies in atmospheric circulation, but also by low-frequency variations of Atlantic sea surface temperature (SST; Werner and von Storch, 1993). Sea surface temperature in coastal waters of the Southern Bay of Biscay has increased in recent years (Lavín *et al.*,, submitted). This increase in water temperature has produced an increase in the thermal stratification of the water column. A linear decreasing relationship between water column stratification and the number of copepod species has been observed in the shelf waters of the Southern Bay of Biscay during the sampled period 1991–1996, (Valdes *et al*, 1997). Also Roemmich and McGowan (1995) have suggested that observed warming in the Pacific is related to zooplankton decay due to reduction in nutrient supply to the photic layers. Thus the relationship between air temperature and sardine recruitment may be explained by a cascade of relationships between water column stratification and low food availability in the warmed area. In the same way that Alheit and Hagen (1997) found an alternating period with sardine favourable warm periods in the North Sea, the Iberian sardine seems to be negatively conditioned by the warm periods. The Gulf index provides a connection between northward displacement of the current and sardine recruitment. Long-term SST could help to understand the connection found between sardine recruitment and the Gulf Stream latitude

More effort will be made to find seasonal correlation. Winter NAO indexes will be used, as winter is the most influential part of the year. This index will be correlated to seasonal variables as has been done by Drinkwater (this volume) and Lamb *et al.*, (1997).

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We wish to thank the Centro Meteorológico Zonal de Asturias y Cantabria del Instituto Nacional de Meteorología for the data-series on meteorological variables, J. Hurrell, for the NAO index, A. Taylor for the latitude of the Gulf Stream index and María Jesús Garcia from the Instituto Español de Oceanografía for the sea-level time-series.

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Table 1: Correlation

Marked correlation are significant at $p< 0.05$

	Temp	Precip	NAO	WC4V7	WC4V4	WC1V7	WC1V4	R.Alb	C Alb	S Lev	Atm. P.	GULF
Temperature												
Precipitation	**-0.73**											
NAO	0.24	0.09										
WC4V7	**-0.52**	**0.73**	0.34									
WC4V4	**-0.65**	**0.80**	0.07	**0.82**								
WC1V7	0.25	-0.08	-0.13	0.19	0.03							
WC1V4	0.00	-0.04	-0.27	0.13	-0.04	**0.82**						
R. Albacore	-0.18	0.02	**-0.45**	-0.29	-0.18	-0.17	0.00					
C. Albacore	-0.05	0.27	-0.19	-0.10	0.07	-0.09	-0.01	0.17				
Sea Level	0.24	-0.28	**-0.47**	-0.25	-0.17	0.40	0.41	0.02	**0.51**			
Atm. Press.	-0.09	0.37	0.37	0.39	0.28	-0.13	-0.12	0.18	0.09	-0.36		
GULF	0.44	**-0.45**	0.10	**-0.44**	**-0.54**	-0.18	-0.30	0.05	**-0.47**	-0.40	-0.23	
Sardine	**-0.46**	0.31	-0.23	0.36	0.43	0.03	0.29	-0.10	0.20	0.11	0.26	**-0.56**

Table 1: Correlation between yearly time-series from 1976 to 1995, Wind components are labelled as: WC4V4 (number of days of westerly winds with velocities > 4 m/s), WC4V7 same but velocities > 7 m/s), WC1V4 (number of days of easterly winds with velocities > 4 m/s), WC1V7 same but velocities > 7 m/s).

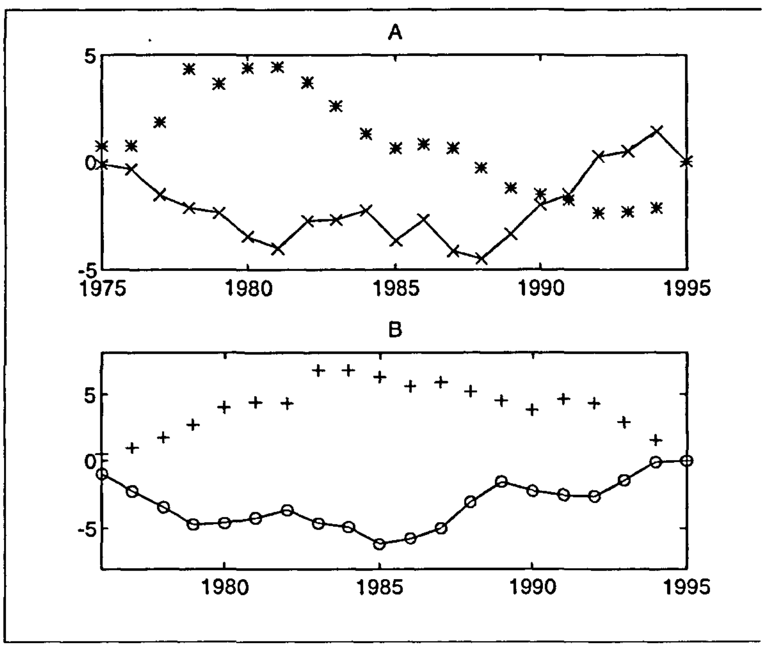

Figure 1: A: cumulative sum of anomalies of NAO (x) and albacore recruitment (*) between 1975 and 1995, and B: cumulative sum of anomalies of air temperature (o) and sardine recruitment (+) between 1976 and 1995

CLIMATE INFLUENCE ON THE FAROESE COD STOCKS

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Cod in Faroese waters is generally described as consisting of two separate stocks: The Faroe Plateau cod (FP-cod) and the Faroe Bank cod. The talk will focus on the FP-cod which is by far the most important for the Faroese economy, and which has exhibited dramatic fluctuations during the last decade. The reasons for these fluctuations are only partly understood, but there are strong indications that meteorological and/or oceanographical processes on climatic time scales have contributed.

The fluctuations were apparent in stock estimates and catch, but most dramatically in the 0-group index which should represent the number of FP-cod juveniles at some 3 months of age. This number decreased by one to two orders of magnitude in the late 80s and early 90s. Overfishing cannot explain this recruitment collapse and no purely biological processes have been identified either. On the other hand, two physical processes have been proposed as causal mechanisms for this: Winds and changes in the oceanic currents around the Faroes.

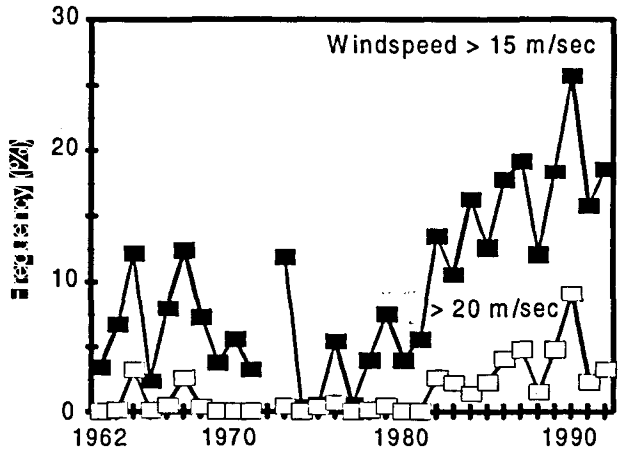

Figure 1. The frequencies of wind speeds above 15 m/sec and 20 m/sec in the March-May period as observed at Akrabyrgi, Faroes 1962–92.

As in other North Atlantic areas, wind speed in the Faroes has increased since the late 70s (Figure 1). This increase may have various effects on the ecosystem as a whole. For FP-cod, south-westerly winds may be especially disruptive to the spawning success (Figure 2). The main spawning ground of FP-cod is north of the Faroes at the border of the well-mixed Shelf-water and the seasonally stratified offshore water (close to the 100 m isobath). From there, eggs and larvae drift with the anticyclonic residual circulation. The well-mixed Shelf-water is supposed to be the main habitat of the juveniles and one condition for reproductive success is minimal loss along the advection path from the spawning ground to the Shelf-water. In the period of recruitment failure, south-westerly winds were exceptionally strong and they will tend to push the upper water layers with their contents of eggs and larvae offshore so that they have less chance of entering the shelf region.

The implied wind-recruitment relationship was not, however, sufficiently clear-cut to warrant any definite conclusions as to winds being the only or main reason for the recruitment collapse and variations in the oceanic currents around the Faroes have been suggested as another causative mechanism.

The rationale for this is through the advection of the copepod *Calanus finmarchicus*. This is a dominant zooplankton species in Faroese waters and its nauplii are assumed to be important as food of first-feeding cod larvae. This copepod enters the Faroe Plateau in spring, apparently from the Faroe Bank Channel mainly (Figure 2) where the deep overflow current with speeds exceeding 1 m/sec acts as a giant conveyor belt from the overwintering areas in the deep Norwegian Sea.

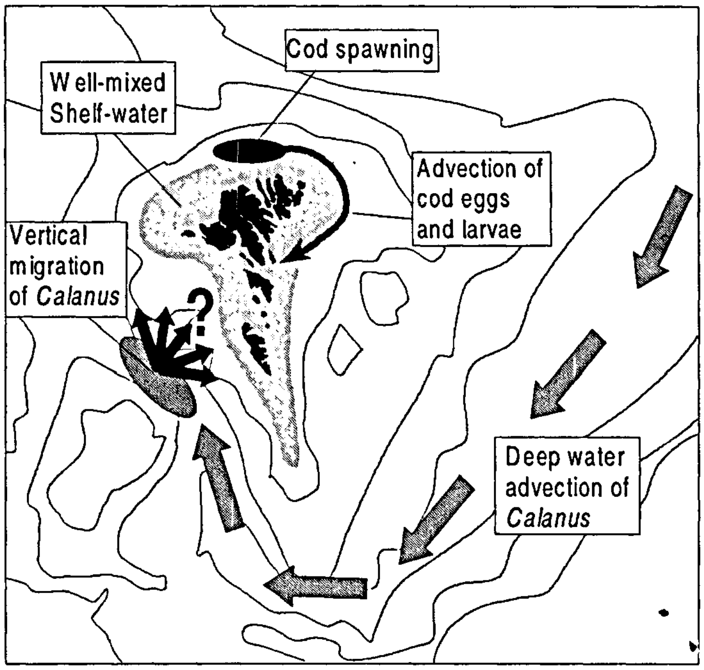

Figure 2. Key elements affecting recruitment success of Faroe Plateau cod.

After ascending from the deep overflow water into the upper Atlantic water, the copepods then have to be advected onto the shallower parts of the Faroe Plateau and ultimately into the well-mixed Shelf-water. The amount of overwintered *Calanus* in the Shelf-water in spring has been shown to vary by almost an order of magnitude. Strangely enough, years with low cod recruitment have had high numbers of overwintered *Calanus* but recently it has been argued that in these years the *Calanus* is able to suppress and delay the primary production by grazing (Gaard *et al.*, in press). As a consequence, the food available for each *Calanus* female in spring may be much less in these years and *Calanus* egg production is known to be strongly dependent upon food intake. Thus, paradoxically, a high influx of overwintered *Calanus* might lead to small numbers of *Calanus* nauplii at the critical time of cod larvae first feeding. Although the observational material of nauplii is not very complete, the available evidence does support this hypothesis (Gaard, pers. comm.).

The large variations of overwintered *Calanus* in the Shelf-water may have several explanations, but clearly the flow pattern in the upper parts of the Faroe Bank Channel will be critical and recent observations show that the flow pattern indeed has variations which may lead to large variations in copepod influx (Figure 3). It has also been argued that the Atlantic water flow past the Faroes was abnormal in the early 90-ties (Hansen and Kristiansen, 1991). As yet, there are too many missing links to draw firm conclusions, but large efforts are being made in acquiring observations of *Calanus* (TASC), of currents (Nordic WOCE, VEINS) and in modelling and testing this hypothesis is almost within range.

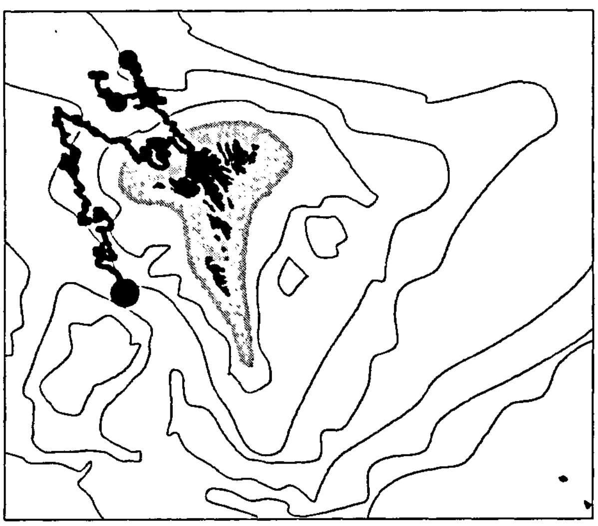

Figure 3. Progressive vector diagram from a Nordic WOCE ADCP moored in the Faroe Bank Channel from June 1996 to May 1997 showing flow at 220 m depth.

Gaard, E., B. Hansen, B. and S. P. Heinesen. Phytoplankton variability on the Faroe Shelf. Submitted to ICES J. Mar. Sc.

Hansen, B. and R. Kristiansen 1994. Long-Term changes in the Atlantic water flowing past the Faroe Islands. ICES CM1994/S:4, 16 pp.

THE NORTH ATLANTIC OSCILLATION, THE TEMPERATURE SEESAW AND THE EFFECTS ON COD RECRUITMENT IN THE NORTH ATLANTIC.

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The first observations of the inverse relationship between winter air temperatures in the Scandinavian and the Labrador regions was made by Hans Egede Saabye. He lived at the West Greenland coast and wrote in 1776: «All winters in Greenland are strong, although with difference. The Danes have noticed that when winters (in Denmark) are strong, the winters in Greenland are relatively mild and conversely.» Almost 200 years went before Elizarov and Ishevskii revisited the topic. In the beginning of the 1960s they found, based on measurements in 1940s and 1950s, that sea temperatures in the Barents and Labrador Seas tended to fluctuate inversely and, moreover, they found that these fluctuations influenced growth of cod in the two regions. More recently, van Loon and Rogers (1978) tested Saabye's statement by analysing winter air temperatures for a longer time series in Oslo, Norway and Jakobshavn, Greenland. Walsh and Johnson (1979) analysed the variations in the extent of ice cape in the Polar basin and adjacent seas, and they found the ice extent in the Barents Seas on the one side and the East Greenland/Baffin Bay/Davis Strait on the other side varied inversely. The links of such temperature features to the North Atlantic Oscillation has been pointed out (Lamb and Peppler 1987).

The pattern seesaw in temperature in the northern North Atlantic and links to the North Atlantic Oscillation, as reviewed above, are here further inspected by: 1) sea temperature time series for the period 1900 -1995 from the Russian Kola Hydrographic Section which represents the Atlantic water masses of the Barents Sea, 2) time series on the North Atlantic Oscillation Index for the same period, 3) time series on sea temperatures of Labrador Sea, for the period 1948–1994, taken from Drinkwater, Colbourne and Gilbert (1996). The inverse relationship between the temperature in the Barents Sea represented by data from the Kola section and the temperature in Newfoundland waters represented by data from station 27 is shown in Figure 1. The time series is 3-years mean and the data from Newfoundland waters are presented with a two years lag. The relationship between temperature, NAO winter mean index and recruitment of cod is demonstrated by using data on year-class strength of the Arcto-Norwegian cod from 1943 (Figure 2).

In the Barents Sea and in other parts of the northern North Atlantic the amplitude of the interannual to decadal-scale water temperature fluctuations are greater than the amplitude of the 100-year trend. Moreover, such fluctuations are accompanied by fluctuations in other important ocean climate parameters like wind, turbulence and light conditions. These are all important parameters influencing basic biological processes linked to plankton production and trophic transfer. The strong interannual to decadal-scale variation in climate is also reflected in data on zooplankton and cod stocks. The climate effects on the fish production is hypothesised to act both directly and indirectly through trophic transfer. There is a basic difference between the influence of ocean climate parameters on growth and the influence of ocean climate parameters on recruitment in fish stocks. Recruitment processes are considerable more sensitive to spatial and temporal variations in the ocean climate parameters than growth and maturation of the adult stock. It is also shown that the ocean climate parameters specifically influencing recruitment processes, e.g., turbulence, light and plankton concentrations, shows a considerably larger spatial and temporal variability than the variability of sea temperature. This makes a basic difference in our potential ability to predict recruitment compared to predictions of growth and maturation.

The climate time series confirm earlier works on the relation between high (low) annual 3-years running mean sea temperature in the Barents sea and a high (low) 3-year running mean NAO Index. However, in two periods in the present century the relation breaks down. This is in the period from the mid 1920s to the end of the 1930s when annual sea temperature in the Barents Sea steadily increased while the NAO Index steadily decreased. The other period was from late 1940s to early 1950s when temperature fluctuations in the Barents Sea were small. In both periods the year-to-year fluctuations in the NOA Index were large, but the decadal-scale amplitude was small. Over the last thirty years, however, the decadal-scale variation of the NAO Index has been strong and a similar strong decadal-scale amplitude in the sea temperature has appeared. The inverse relationship between the sea temperatures in the Barents Sea and the Labrador Sea has also been prominent over the same recent period, while in the previous period of weak decadal-scale fluctuation of the NAO index, the inverse relationship was poor. These features demonstrate role of North Atlantic

Ocean in climate variations: The ocean has large momentum compared to the atmosphere. It dampens short-time (year-to-year) atmospheric variations, and responds to variations longer-term (decadal-scale) variations.

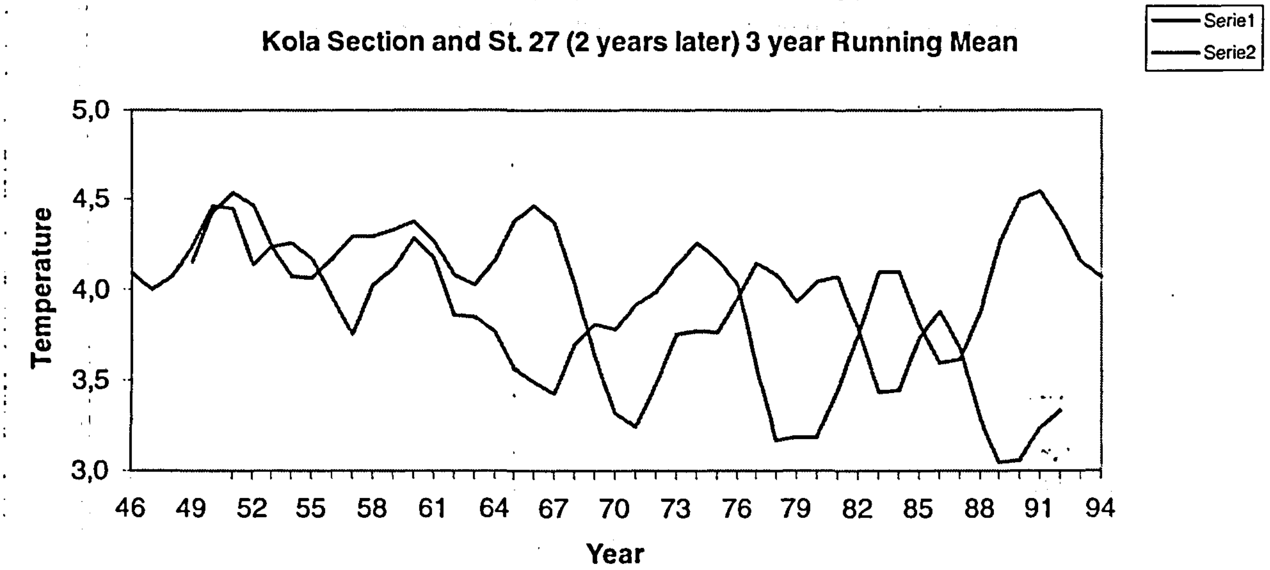
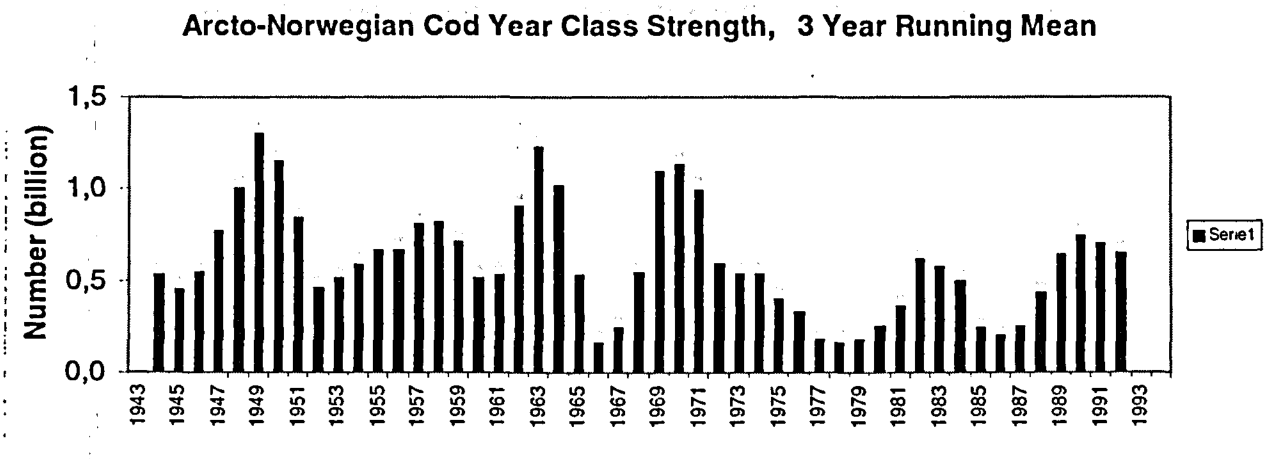
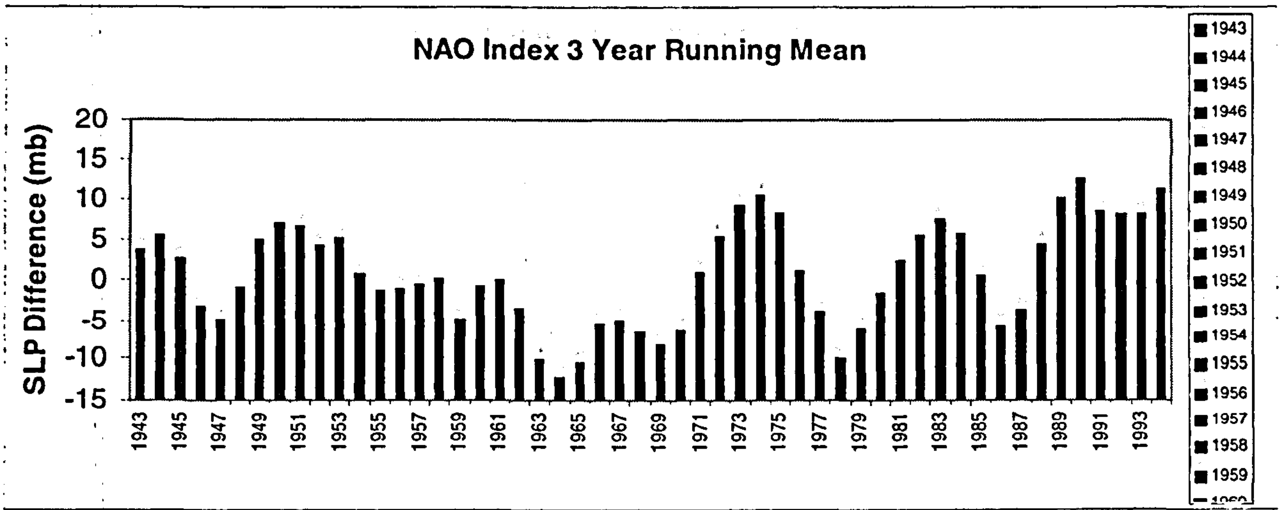


Figure 1. Temperatures, 3-years running mean, at Kola section in the Barents Sea and station 27 off Newfoundland. The station 27 data is presented with a 2 years lag.





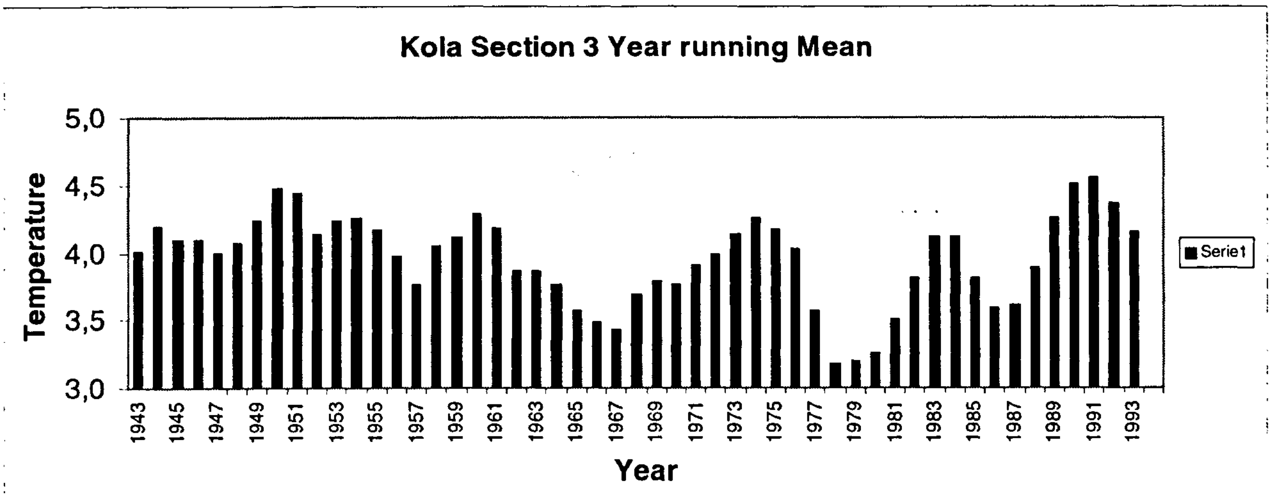


Figure 1. Three-years running means of a) year-class strength of the Arcto-Norwegian cod; b) NAO index; c) Kola section temperature 0–200m; for the period 1943–1994.

APPENDIX 3

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