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REPORT OF THE WORKSHOP ON COD AND FUTURE CLIMATE CHANGE (WKCFCC)

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Executive summary

The Workshop on Cod and Future Climate Change (WKCFCC) was held on 17–20 June 2008 in Copenhagen, Denmark, at the ICES headquarters. It was sponsored by the ICES/GLOBEC Working Group on Cod and Climate Change (WGCCC) with objectives to develop scenarios for cod over the next 20–50 years given anthropogenic climate change. The idea was to take regional future climate scenarios over this same time period and using the knowledge gained by the WGCCC and other researchers on the impact of climate on cod to develop future scenarios for cod, taking into account not only the direct effects on cod but also consider the possible influence on cod of climate effects on their prey (including zooplankton), predators and competitors.

The workshop was informed of the problems with developing regional models downscaled from Global Circulation Models (GCMs). The few such models that do exist have usually not used the most recent IPCC model runs (2007) but rather are based on earlier IPCC GCMs. One regional model for the North Sea that was downscaled from a recent IPCC model found the GCM chosen was not doing an adequate job of reproducing the present climate for the region and thus the future scenarios are highly suspect. The conclusion of that study was that one should develop regional models by downscaling from several GCMs and that these should be chosen based on their ability to reproduce the current climate. However, many of the IPCC 2007 model results for the current climate also demonstrate large differences with observations especially on a regional basis. Also the GCMs are respectively not able to reproduce or not reproduced well the two major modes of variability over the last century respectively, the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO). Thus, the conclusion of the workshop is that the available global and regional climate models are not currently adequate for impact studies on the marine ecosystem. Without the development of regional climate model systems and the development of adequate downscaling strategies it was not possible to go on to implement coupled biological models of lower trophic level dynamics and its consequences for cod population for the next 20–50 years. A considerable scientific effort will be required to design, initialize, run and test regional models which produce output that is relevant to impact studies. Until this is done the impact assessments will have to be based on “what if” scenarios. On an encouraging note, however, models that assimilate recent climate data (and include the decadal modes) demonstrate useful forecasting skill, at least over periods of a few years.

Several “what if” scenarios were presented at the Workshop. Baltic Sea studies using statistical (multivariate autoregressive) models to assess the possible effects of cod under plausible climate scenarios have been carried out. These studies have also combined climate changes with different fishing mortality rates to explore the combined role of management and climate on cod. Results suggest that given even a relatively weak decrease in salinity (>3 psu), which would impair recruitment of Baltic cod through increased egg and larvae mortality, only a drastic decrease in fishing mortality could avoid future stock collapses and ensure the existence of Baltic cod for future generations to come. Such models combining the effects of fishing and climate to determine the impacts on cod and other species are encouraging. The results of a non-spatial model that includes temperature, zooplankton, prey and predators suggest raising the temperature in the Barents Sea by 1–4°C will lead to increased cod growth, increase cod production and decrease maturation rates. On the other hand, cod cannibalism is expected to increase as well. In another study exploring the gen-

eral effect of temperature on cod stocks, it was found that a 30% reduction in the carrying capacity of warm water stocks is expected with a 3°C rise in temperature. Other likely impacts on cod under future warming scenarios include a general northward shift in distribution, an increase in growth, and an increase in production in northern regions and a decline in southern regions. Fishing pressure will play an important role in determining the rates of change of the cod populations. On the other hand, fisheries management must evaluate the climate effects and models have and are continuing to be developed that allow such combined effects of climate and fishing to be addressed.

Future work should include: in the immediate future to extend the “what if” studies to develop future cod scenarios; in the longer term encourage improvements in GCMs, especially through conveying to the modellers what the needs of the impacts community are; develop regional models of future climate in those areas inhabited by cod using downscaling of results from several GCMs that are able to reasonably represent local present climate conditions; use the results of such models to force regional biophysical models to develop scenarios of phytoplankton and zooplankton under future climate; apply the results of both the ocean climate and lower trophic impacts to effects on cod; to develop models that include the higher trophic levels, especially cod; and to explore the combined effects of climate and fishing in order to determine better management strategies under climate change.

1 Overview

1.1 Introduction

Many of the regions currently occupied by Atlantic cod are predicted to undergo significant warming in response to climate change and in recent years much of the North Atlantic has experienced warming. Increasingly, managers, politicians and the general public have been asking what will be the impacts of future climate change. Such information for cod and the marine ecosystems have been limited. Indeed, the few published studies have usually considered the response of individual species to increased warming without considering other components of the marine ecosystem, such as their prey or predators. However, climate change is expected to impact both the structure and function of marine ecosystems and to develop more plausible impact scenarios we must consider the species as part of the ecosystem. In an attempt to determine the extent of the impact of future climate scenarios on the marine ecosystems of the North Atlantic with special reference to cod the ICES/GLOBEC Working Group on Cod and Climate Change held a Workshop on *Cod and Future Climate Change* in June 2008. It was based on the increased understanding gained through the ICES/GLOBEC Cod and Climate Change program, including past workshops, plus other research on the effects of climate variability on cod and its supporting ecosystem.

There were 16 participants from 6 countries (Denmark, Germany, Norway, Russia, UK and USA) plus the ICES/GLOBEC Coordinator. The list of participants appears in Annex 1.

In total, 13 presentations were given during the workshop (see Annex 2 for the meeting agenda). Extended abstracts are provided in Annex 3.

1.2 Terms of reference

A **Workshop on Cod and Future Climate Change [WKCFCC]** (Co-Chairs: K. Drinkwater, Norway, J. Dippner¹, Germany, and, C. Schrum, Norway, will meet at ICES Headquarters, Copenhagen, Denmark from 17 June (12 noon) –20 June (12 noon) 2008 to:

In response to future climate change scenarios

- a) adopt 20–50–year probabilistic projections of future temperature and salinity as a basis for projections of fish population dynamics and distribution (also nutrients)
- b) develop methodologies and make projections of likely changes phytoplankton and zooplankton production and distribution, especially those species eaten by cod and their predators or prey during their life histories;
- c) develop methodologies and make projections of likely changes in prey and predators of cod including the forage fishes, such as capelin, herring, sprat and mackerel;
- d) develop methodologies and make projections of likely changes in cod production (growth, reproduction, mortality, recruitment) and distribution.

¹ Could not attend.

This will be carried out using a combination of retrospective data analyses and a variety of modelling approaches.

WKCFCC will report by 20 July 2008 for the attention of the OCC, LRC, and ACOM.

1.3 Preparation for the workshop

In preparation for the workshop, the ICES established a SharePoint website within the ICES/GLOBEC website (<http://groupnet.ices.dk/EG/EG2008/WKCFCC/default.aspx>) to facilitate communication among the participants before and after the workshop. Terms of reference, list of participants, and agenda were posted before the meeting. Several participants also contributed a number of background papers for the workshop.

1.4 Workshop structure and working procedure

The agenda for the workshop as adopted during the opening session of the meeting is provided in Annex 2.

The workshop was initially divided into three activities: (i) presentations, (ii) break-out groups to discuss the terms of reference and the possibility of a potential paper coming from the workshop, and (iii) plenary discussion of the results from the break-out groups. Following general agreement of an outline for the report/paper, the participants were given, (iv) writing assignments and time for writing. Lastly a (v) plenary session was held to discuss on deadlines for writing assignments for the report, lead authors for the paper and recommendations coming out of the workshop.

Each participant who made a presentation was asked to write an extended abstract which would summarize the information that he or she presented. These abstracts are provided in Annex 3 in the sequence of presentation. At the start of Annex 3 is a table which lists the first author of each abstract and indicates which terms of reference were addressed.

2 Results and conclusions

2.1 General Discussion and Introduction

2.1.1 Prediction and confidence (K. Brander)

In order to predict the distribution and productivity of cod under climate change we need scenarios of future climate, information on the sensitivity of cod to the changing climatic factors and information on changes in other biotic factors which may affect cod indirectly. The credibility or confidence limits for such predictions depend on the reliability of each step in the causal chain and on including all the processes which may affect the outcome. Some general predictions can be made with reasonable confidence (e.g. distributions will follow shifts in thermal boundaries; growth, maturation and recruitment will follow known temperature response curves) and a number of studies are reported here. The level of confidence which can be ascribed to more specific, time-based, regional predictions is lower than the general predictions:

- They require regional climate forecasts, which include the necessary variables (temperature, salinity, oxygen, wind, vertical mixing, etc.)
- They require knowledge of local sensitivity to these variables (e.g. response of recruitment or growth to temperature depends on where the stock is located within the thermal range)

- They need to include all the relevant local processes and interactions (productivity, prey and predator abundance, effects on pathogens and other biotic interactions)

Thus although it is possible to assemble models which incorporate many of these factors and predict future dynamics of cod, we also need to make an estimate or judgment of the reliability of such models. This requires an assessment of the uncertainties which arise at each stage in the causal chain process, including the effects of process uncertainty, structural incompleteness, initialisation errors and model errors. The procedures for estimating error bounds and for quantifying levels of confidence are not dealt with formally in this report, but the major source of uncertainty are identified in order to (i) evaluate existing studies and provide some guidance on the associated degree of confidence (ii) identify steps in the modelling chain which require improvement in order to reduce the uncertainty of the predictions.

Other options for predicting changes in cod and in marine ecosystems are (i) to use spatial or temporal analogues (ii) to carry out experiments. A number of examples of temporal analogues are provided in this report (e.g. distribution during the Atlantic warm period 9000 – 5900 BP, distribution and abundance changes during the warm period from 1920–1960). To date very limited use has been made of experiments to study consequences of climate change for marine species, although this is changing very quickly, particularly for studying the effects of a decrease in pH. Extensive field experiments are the principal means of predicting future yields for terrestrial agriculture.

It is instructive to review our ability to identify the causes of observed changes in cod stocks, as has been done in Subsection 2.2.2.3, because confidence in predictions of future changes can only be justified if we are also confident that we have correctly identified the processes causing past changes.

2.1.2 Incorporating environmental information (K. Brander)

The Workshop on Integration of Environmental Information into Fisheries Management Strategies and Advice (WKEFA; ICES CM 2007/ACFM:25) provides a background for the present workshop. It supplied the principal term of reference for the present workshop (develop 20–50 year probabilistic projections of climate) and also set out a framework of time-scales, population processes and management issues. Although the present workshop is concerned with future climate and long time scales, many of the issues discussed are also relevant at shorter time scales.

The time-scales identified by WKEFA were:

- Extreme events – which cause migration, mortality or recruitment failure.
- Short term changes – which affect growth and maturation one or two years ahead and will affect TAC (Total Allowable Catch)
- Medium term changes – use stochastic projections and scenario testing e.g. temperature, salinity, oxygen dependence of survival, species interactions, and food availability.
- Long term – climate scenarios for sensitive areas such as the Baltic Sea

The population processes were: (i) entries and exits (recruitment, natural mortality (M), migration), (ii) internal population processes (growth, reproduction), (iii) location and habitat (e.g. vertical and horizontal movement) and (iv) multispecies interactions.

The management issues were: (i) to design management procedures which are either robust to or adapt to regime changes (ii) to allow for changes in habitat which influence stock carrying capacity and measurement (e.g. interpreting surveys) (iii) to improve our ability to estimate changes in recruitment, growth and maturation which influence short and medium term management advice (iv) to include information on expected environmental change and its impact as part of each stock assessment.

The WKEFA report provided numerous case studies of management adaptation to environmental variability, inclusion of multispecies aspects, and direct application of environmental information and simulation of the management consequences of productivity shifts.

The Working Group on Regional Ecosystem Description (ICES CM 2006/ ACE:03) reviewed the reasons why environmental information must be included in management advice and also the reasons why doing so is not easy. Their review, which was also presented by the ACE has been cited or paraphrased in several places in the current report and is well worth reading in the original. It includes commentaries on:

- long-term climate change and global warming,
- regime shifts and implications for fisheries management,
- recovery strategies and ecological niche theory,
- inclusion of environmental information (in 2005),
- why inclusion of environmental information is so limited and proposals for improving this.

2.1.3 What kinds of prediction are we aiming at? (K. Brander)

The title and terms of reference for the workshop (to develop 20–50 year probabilistic projections of climate) make it clear that the main time-scale of interest is the long-term. However there are interactions between the time-scales so that events of short duration may affect much longer time-scales. For example long-term trends in salinity in the Baltic depend on the frequency with which short term, extreme events (i.e. Baltic inflows) occur. Models of long-term changes in Baltic salinity therefore need to have sufficient spatial and temporal resolution to resolve such short-term events and their frequency. Short-term events, which have major effects on fish, may cause changes in populations which persist for long time periods (e.g. mass mortalities as a result of toxic blooms triggered by unusual conditions of temperature, salinity, nutrients and stratification).

The lead time over which climate forecasts are significant is difficult to estimate because it depends on the variable, region, initial state of the climate system and availability of observations for the initialization. The results of Smith *et al.* (2007) and Keenlyside *et al.* (2008) have shown that for some variables and regions predictability lies well beyond a decade. Because of scale interactions and because regional predictability for ocean climate degrades back to the global pattern after a relatively short time, we interpreted our time horizon to include all scales of climate forecasting. One to five year regional forecasts for which skill estimates are available will provide valuable additional information for fisheries management and will complement existing general global scenarios.

Predictions of future distribution and productivity of a particular cod stock can be separated into a climate prediction (or scenario) and the expected biological impact. The current state of appropriate regional climate models, including their improving skill and limitations, are dealt with in section 3. Depending on what kind of climate

information is or is not available, one can look at biological impacts under a range of “what if” scenarios and this is what has been done in several of the cases and studies which we review. A common approach is to predict the consequences of a succession of increasingly higher mean temperatures (e.g. 1–2–3–4 deg C) and for a given rate of warming these increases may be associated with particular time slices (e.g. 2020, 2050, 2080).

2.2 From climate to ocean dynamics and biology

2.2.1 Review of previous work on impacts on cod of climate change (K. Drinkwater)

There have been several previous studies on the response of cod to future climate change including two that have considered all of the major cod stocks in the North Atlantic. Drinkwater (2005) used “what if” scenarios of ocean climate change and considered changes to the cod stocks under increases of 1° to 4°C in ocean temperatures, which was in the range of changes suggested at the time (IPCC, 2001). His results were based on the relationship of recruitment to changes in temperature found by Planque and Frédou (1999) and earlier by Ottersen (1996) that showed increasing recruitment with increasing temperatures for cold water stocks and decreasing temperatures for warm water stocks. This relationship was converted into a change in recruitment as a function of surface temperature change vs. mean annual bottom temperature of the stock (Sundby, 2000; Drinkwater, 2005). At bottom temperatures <5°C, recruitment tends to increase with increasing temperature and at temperatures >8.5°C, the recruitment decreases. At temperatures between these 2 values, there is little change in recruitment with temperature. Drinkwater (2005) also used the present day observation that no cod stocks are observed in waters having annual mean bottom temperatures above 12°C. If bottom temperatures warm beyond 12°C he assumed that the cod will disappear. Based on these criteria, cod stocks in the Celtic and Irish Seas would be expected to disappear with only a 1° to 2°C increase while those in the southern North Sea and Georges Bank would begin to decline as a result of decreases in recruitment. If temperatures increased by 3° to 4°C these stocks would also likely disappear. Cod in the northern regions such as the Labrador, Iceland, West Greenland and the Barents Sea would see increased recruitment and abundance. Coupled with an expected increase in growth throughout the North Atlantic this would result in an increase to the overall Atlantic cod production despite the potential losses in the southern regions. Drinkwater (2005) also predicted that cod would likely spread northward along the coasts of Greenland and Labrador, occupy larger areas of the Barents Sea, and may even extend onto some of the continental shelves of the Arctic Ocean. For those cod stocks that migrate, spring migrations would occur earlier than at present and fall returns would be later. He speculated there is the distinct possibility that where seasonal sea ice disappears altogether, cod may cease to migrate altogether, such as in the Gulf of St. Lawrence.

Another study examining the response of cod throughout the North Atlantic was conducted by Cheung *et al.* (2008) using a bioclimate envelope model. Bioclimate envelopes are a set of physical and biological conditions that are suitable to a given species and are generally identified from present-day or past associations. Cheung *et al.* (2008) included sea temperatures, bathymetry, habitat and distance from sea ice as their set of variables and determined the responses to climate change from 1–30 years using a uniform hypothetical temperature increase. They predict a general northward shift in the distribution of cod, similar to Drinkwater (2005), with declines in the stocks to the south of their present distributional range, i.e. on Georges Bank, in the

Gulf of the Maine and on the Scotian Shelf in the Northwest Atlantic, and the in the North, Irish, Celtic and Norwegian seas in the Northeast Atlantic. On the other hand, the relative abundance of the Icelandic, Faroe Island and Barents Sea cod stocks would increase.

Several other more regional studies have carried out. Stenevik and Sundby (2007) in a paper on the effects of climate change in Norwegian waters commented on the effects on cod. They examined a global warming scenario in which there was a high North Atlantic Oscillation (NAO) and high Atlantic inflow to the Barents. Under this scenario, the cod in the North Sea was predicted to decline as a result of the reduction in *Calanus finmarchicus* and the warm temperatures. The northeast Arctic cod that spawns along the Norwegian coast off the Norwegian Sea, drifts into the Barents Sea as larvae and small juveniles and spends its adult life there, was predicted to increase in abundance as a result of higher recruitment and coupled with improved growth rates, higher biomass. The cod would also move farther north and eastward with a larger percentage of the total population moving into the Russian Economic Zone and out of Norwegian waters. Due to the overall increase in production, however, the total number of fish in the Norwegian Economic Zone would not decrease although their percentage of the population would decrease. Cod is also expected to spawn farther north than usual (Sundby and Nakken, 2008; Drinkwater 2005) and new spawning sites will likely be established.

Vikebø *et al.* (2007) examined the potential impact of a reduction in the thermohaline circulation (THC) in the North Atlantic under climate change on the larval drift of the North-east Arctic cod. This circulation pattern brings warm water north which cools, sinks and returns as a deep-water current. Using a Regional Ocean Modelling Systems (ROMS), they imposed a 3 times present river discharge to the Nordic Seas and the Arctic Ocean greatly reduces the strength of the THC by 35%. This is near the projected reduction of around 25% in the THC predicted by the end of the 21st century in the IPCC (2007) report. This reduction results in a south and westward drift of cod year classes from the Barents onto the Norwegian and Spitsbergen shelves, a reduction in the numbers of pelagic juveniles that survive, and an increase in the proportion of larvae and juveniles advected along West Spitsbergen and possibly into the Arctic Ocean through Fram Strait (Vikebø *et al.*, 2007). Cod that make it into the Arctic Basin are not expected to survive, however.

The projected increase in cod abundance, recruitment, and biomass, as well as the distributional shift farther east and north will depend to a large degree upon the future fishing intensity. Indeed, examining the effect of different management regimes on Norwegian cod fisheries in conjunction with climate change, Eide (2008) concluded that these management schemes will play a more significant role than climate change on the economic performance of the fishing industry in the Barents Sea.

Clarke *et al.* (2003) examined the role of temperature on cod in the North Sea. They found that temperature affects survival of cod through influences on recruitment. Given the expected rise in temperature under future climate change they suggested that the North Sea cod could disappear unless fishing mortality rates are drastically reduced.

MacKenzie *et al.* (2007) examined the possible responses of future climate change on the fish in the Baltic Sea, including Atlantic cod. Mean annual temperatures are expected to rise by 2°–3°C in the surface waters with higher increases during spring to summer period, especially in the central Baltic. Precipitation will increase leading to higher run-off and reduced surface salinities from 7–47% depending on location. A

stable or lower salinity would be detrimental for cod as a result of reduced reproductive success and possibly reduced larval survival as a result of changes in the zooplankton community. It is also predicted that there will be less frequent major Baltic inflows which will result in lower oxygenated waters in the deep basins. In the western Baltic, the reduced surface salinities and lower oxygen levels in the deep waters will reduce the cod spawning habitat. The effects of climate changes on the predators of cod eggs such as herring and sprat could have a big effect on cod depending upon their response to the climate changes. MacKenzie *et al.* (2007) speculated that cod stocks in the eastern Baltic could collapse completely under the warmer and fresher conditions there. Changes in the ecological basis for production of cod would have consequences for its management and exploitation, as well as for the overall management of the Baltic Sea foodweb. For example, fishery management thresholds that trigger reductions in fishing quotas or fishery closures to conserve local, genetically (Nielsen *et al.*, 2001; Nielsen *et al.*, 2003) and physiologically (Nissling *et al.*, 1994; Nissling and Westin, 1997) distinct populations of cod will have to be re-assessed as the basis on which existing thresholds have been established becomes more variable or changes to new levels.

On the other side of the Atlantic on the Scotian Shelf, Frank *et al.* (1990) speculated that under climate change there would be increased stratification through surface heating and anticipated increased precipitation, which would tend to favour pelagic over demersal fish, such as cod, and hence cod abundance would decline.

Fogarty *et al.* (2007) examined the potential impacts of future climate change on the distribution and production of Atlantic cod on the northeastern USA's continental shelf. Their analysis of future changes in water temperature based on output from three coupled atmosphere-ocean general circulation models under high and low CO₂ emissions showed a predicted increase of <1.5°C under the low emission scenario in spring and autumn by 2100. Under a high emission scenario, temperature increases range from ~2°C in the north to >3.5°C in the Mid-Atlantic Bight. Under these conditions, cod appear vulnerable to a loss of thermal habitat on Georges Bank, and possibly a substantial loss farther south. Cod survival during the early life stages declines with increasing water temperatures, offsetting any potential increases in growth under warmer temperatures. This results in a predicted loss in yield and increased vulnerability to high fishing mortality rates under climate change scenarios.

2.2.2 Lessons from natural climate variability of the past

2.2.2.1 Ice Age (G. Ottersen)

To predict how species' ranges may change under global warming scenarios, it is highly valuable to understand the factors that limit their distributions today and in the past. Terrestrial ecologists have developed accurate models of extant ranges by correlating information on species occurrence with annual rainfall and temperature. In addition, palaeoclimate records can be used to estimate how terrestrial species' ranges might have contracted or expanded during past climatic cycles (Hugall *et al.*, 2002). The study of climatically driven range changes for marine species is greatly complicated by the dynamic, three-dimensional nature of their environment. For marine fish conditions can vary greatly over a few metres in water depth, and different life cycle stages may occupy different habitats.

Bigg *et al.* (2008) address these major challenges when they examine the persistence of Atlantic cod populations during the last ice-age (last glacial maximum ca. 21 kyr ago) using two ecological-niche-models (ENM) and the first broad synthesis of multi-locus

gene sequence data for this species. One ENM uses a maximum entropy approach (MAXENT); the other is a new ENM for Atlantic cod, using ecophysiological parameters based on observed spawning locations rather than adult distribution. Envelopes defining suitable habitat are set for several factors including water depth where spawning occurs (0–400m), seasonality of spawning, and ambient temperatures for spawning (0–9 degrees; Figure 2.2.1).

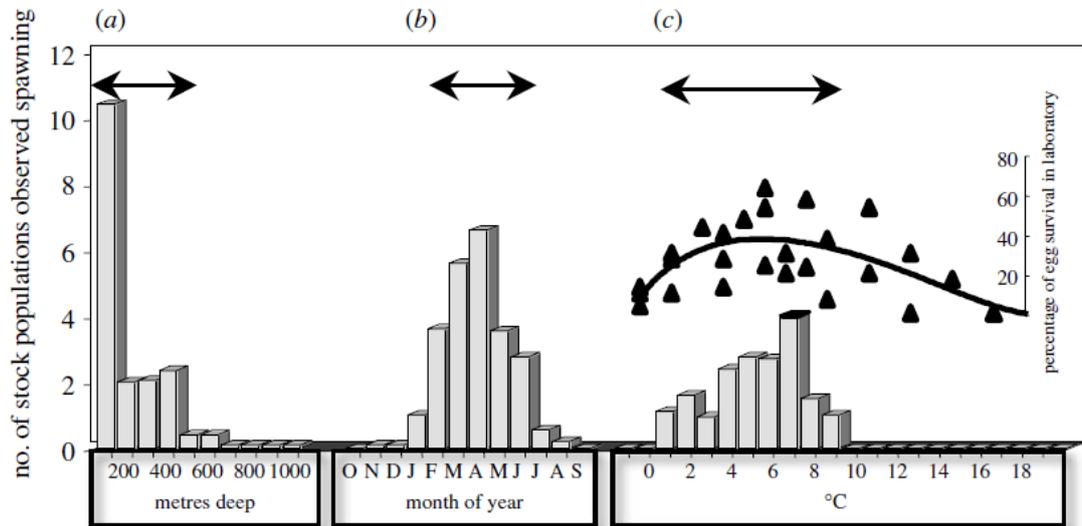


Figure 2.2.1. Environmental factors defining suitable habitat for cod, based on present-day distributions (Brander, 1994, 2005). (a) Water depth in which spawning occurs (data for 18 stocks). (b) Seasonality of spawning (n=23). (c) Ambient temperature for spawning and eggs (n=18). For each histogram, arrowed range shows boundaries used for modelling. Multi-stock laboratory egg survival data (Pepin *et al.*, 1997) also given in upper part of (c), as a function of temperature. The curve is fitted with a third-order polynomial. Figure from Bigg *et al.* (2008).

Both the ENMs were tested for present-day conditions, then used to hindcast ranges at the, employing climate model data (Figure 1). Although the LGM range of Atlantic cod was much smaller, and fragmented, both the ENMs agreed that populations should have been able to persist in suitable habitat on both sides of the Atlantic. The genetic results showed a degree of transatlantic divergence consistent with genealogically continuous populations on both sides of the North Atlantic because long before the LGM, confirming the ENM results. In contrast, both the ENMs and the genetic data suggest that the Greenland *G. morhua* population post-dates the LGM (Figure 2.2.2; Bigg *et al.*, 2008).

The ability of cod populations to maintain genealogical continuity over extreme natural climate variability, as shown by Bigg *et al.* (2008), suggests considerable inherent resilience. Yet the effects of future climatic conditions need to be considered in relation to demographic structures (Andrews *et al.*, 2006), as well as the major population changes as a result of human exploitation (Frank *et al.*, 2005).

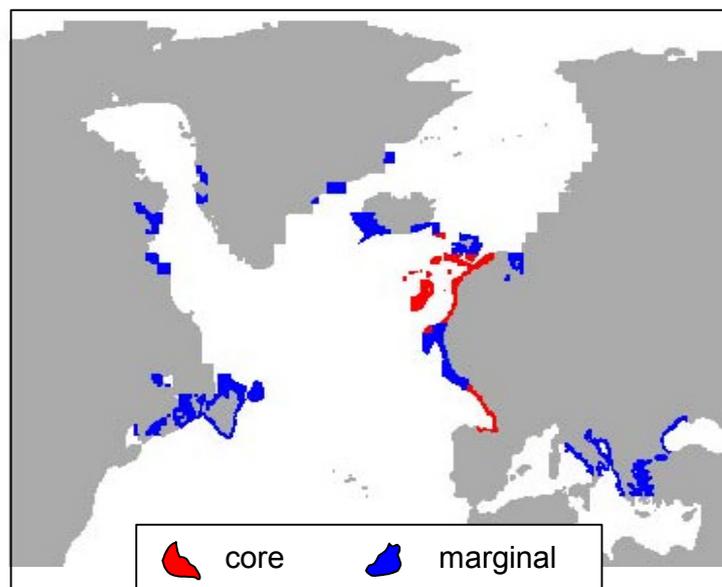


Figure 2.2.2. Result of model run for 21,000 years ago applying ecophysiological parameters, indicating habitat suitable for cod spawning at the last glacial maximum.

2.2.2.2 Lessons from the Baltic (B. MacKenzie)

The Baltic Sea is a large brackish semi-enclosed sea whose species-poor fish community supports important commercial and recreational fisheries. The strong horizontal salinity gradient between the Baltic and North Seas has led to genetic differentiation in several marine fish species in the area, including cod (Nielsen *et al.*, 2001; Nielsen *et al.*, 2003). Reproduction in this species is also adapted physiologically to the lower salinity of especially the eastern Baltic Sea (Nissling *et al.*, 1994; Nissling and Westin, 1997). Trophic interactions in the Baltic foodweb are strongly affected both by climate processes (references below) and fishing (Casini *et al.*, 2008; Möllmann *et al.*, 2008).

The most important climatic-hydrographic influences on cod dynamics are related to variations in salinity and oxygen concentration. Cod eggs can be fertilized and hatch successfully at salinities > ca. 11 PSU (Vallin *et al.*, 1999). This physiological effect of salinity restricts successful cod reproduction to depths and areas in the Baltic Sea having relatively high salinity (i.e. deep basins). However oxygen conditions in waters having sufficient salinity can be too low for successful egg development (Plikshs *et al.*, 1993; Wieland *et al.*, 1994). As a consequence, cod reproduction, recruitment and population dynamics are significantly influenced by salinity-oxygen conditions in spawning areas (Plikshs *et al.*, 1993; Jarre-Teichmann *et al.*, 2000; Köster *et al.*, 2005). The salinity and oxygen concentrations themselves depend on climate-induced major inflows of salt water from the Kattegat and North Sea (Matthäus and Schinke, 1994). The frequency of these inflows between 1897–1979 was ca. 1 per year, but because then has decreased to ca. 1 per decade (Schinke and Matthäus, 1998). During this time, fishing pressure was high and stock productivity decreased; as a result biomass declined sharply to record low levels and has not recovered to long-term average level despite reductions in fishing mortality (ICES, 2008a).

With regards to temperature, long-term measurements in the Baltic at the surface (MacKenzie and Schiedek, 2007) and in deeper layers (MacKenzie and Köster, 2004; Alheit *et al.*, 2005) have increased in the last 10–15 years. However effects of temperature on cod biology and dynamics are relatively poorly documented, but effects via the foodweb are likely. For example, concentrations of copepod nauplii (potential

prey for larvae and 0-group juveniles) in spring is usually higher in warm years (MacKenzie *et al.*, 1996; Möllmann *et al.*, 2003; Alheit *et al.*, 2005), but higher temperatures also stimulate consumption rates of oxygen in cod spawning areas and reduce solubility of oxygen. These latter mechanisms reduce oxygen concentrations at depths where cod eggs are neutrally buoyant, thereby increasing the possibility of oxygen-related egg mortality. Warm temperatures also promote higher growth (Baumann *et al.*, 2005) and survival of predators (sprat, herring; (Köster and Möllmann, 2000)) of cod eggs and larvae (Axenrot and Hansson, 2003; MacKenzie and Köster 2004; Baumann *et al.*, 2006).

Considering historical information, there is archaeological evidence (cod bones recovered at human settlements) that cod was present near Bornholm, as well as other sites in Denmark (e. g., North Sea-Skagerrak-Kattegat coastal areas) during the Atlantic Warm Period, ca. 7000 – 3900 BC (Enghoff *et al.*, 2007). At that time, temperatures in northern Europe were ca. 2–3° C higher than during the late 20th century and therefore similar to sea temperatures which could be reached in the Baltic Sea by 2100 under future climate change (Döscher and Meier, 2004; BACC, 2007). These observations suggest that cod populations could persist in these waters even if temperatures rise by these amounts. However during the Atlantic Warm Period, Baltic salinities have been estimated to be ca. 4 PSU higher than at present (Sohlenius *et al.*, 2001). The higher salinity would have had a strong positive effect on cod reproduction in the Baltic Sea as a result of improved fertilization and hatch success of cod eggs at salinities > 11 PSU. In addition, cod populations in the Baltic and other areas near Denmark during the Atlantic Warm Period would have experienced much lower fishing mortality than during late 20th century, which may have partly offset potential detrimental effects of higher temperatures on overall cod productivity and population dynamics. These considerations suggest that cod populations could be maintained in these areas if exploitation were reduced.

2.2.2.3 North Sea cod distributions (G. Engelhard)

Within the North Sea, a northward shift in the mean latitudinal distribution of cod has occurred over the past 3 decades, as shown by several studies based on scientific trawl surveys (Hedger *et al.*, 2004; Perry *et al.*, 2005; Rindorf and Lewy, 2006). Perry *et al.* (2007) estimated that the centre of population shifted 117 km towards the Arctic between 1977 and 2001. Over the same period, the cod distribution has on average shifted to deeper waters (Hedger *et al.*, 2004; Dulvy *et al.*, 2008). Two main hypotheses have been put forward: one related to climate warming and one to higher fishing effort in the southern compared to northern North Sea. But although the public press has generally favoured the former of these two, published evidence supporting either of the two hypotheses (which are not mutually exclusive) remains equivocal.

Hedger *et al.* (2004) found that cod were caught in deeper water during the 1990s compared to 1980s but showed no change in their distribution with respect to temperature. Although this is suggestive that cod responded to changing sea temperatures by actively seeking out a temperature niche, such an explanation of “cod swimming north” is probably too simplified (see already discussion in Hedger *et al.*, 2004; and see Heath, 2007). Firstly, although the southern North Sea is typically warmer than the north in summer, the opposite is true in winter. Secondly, within North Sea cod distinct subpopulations appear to be reproductively isolated, implying little interbreeding and mixing (Hutchinson *et al.*, 2001; Wright *et al.*, 2006). Thirdly, data storage tags, recovered from 129 individual cod throughout the North Sea, revealed that these fish actually experienced a warmer fraction of the sea than was po-

tentially available to them (Neat and Righton, 2007). This was especially the case in the southern North Sea, where during summer most of the individuals experienced temperatures considered superoptimal for growth, well above 14°C. In the northern North Sea, temperatures experienced rarely exceeded 14°C but were nevertheless generally close to the upper seasonal trend in local bottom temperature; a few cod were exceptions actively seeking out colder temperatures, confirming that cooler waters were within reach of the fish (Neat and Righton, 2007). Most did not, however, leading the authors to conclude that the changing thermal regime of the North Sea is not yet causing adult cod to move to cooler waters.

As a possible climate-driven mechanism for distribution shifts, Rindorf and Lewy (2006) suggested that during a recent series of warm winters with southerly winds increased northward transport of eggs and larvae may have occurred, leading to a northward shift in the distribution of juveniles the following year. Once settled at more northerly locations, cod may 'home' to the same spawning sites year after year, resulting in genetically distinct spawning aggregations (see Ruzzante *et al.*, 2001 for northern cod). This may make it difficult for the southernmost spawning sites, after these have become depleted, to become visited again once a more northern distribution shift of adolescent cod has occurred (Rindorf and Lewy, 2006).

Meanwhile, in the southern and central North Sea trawling effort has generally been far higher than in the northern North Sea (e.g. Jennings *et al.*, 1999). Hence it is likely that unbalanced depletions of local cod concentrations (Hutchinson *et al.*, 2001) have taken place so that greater depletion in the south may well have caused the overall distribution shifts (Heath, 2007). There is also some evidence that the general decline in North Sea cod recruitment took effect earlier in the reproductively segregated sub-stock in the southern North Sea than in the north, contributing to the more serious decline in the south (Holmes and Wright, 2005; Heath, 2007).

Most recent studies on cod distribution shifts have used data from surveys limited to the last 3 decades, and this has motivated our recent study on cod distribution shifts over a much longer time span (9 decades) but based on commercial CPUE data (Engelhard *et al.*, see Annex 3). Preliminary results showed that marked North Sea cod distribution shifts have occurred throughout the 20th Century. However, shifts in 'centres of gravity' of distribution that temporarily were located at more northerly or southerly latitudes, were not clearly linked to long-term climatic fluctuations, such as the warmer period of the 1920–1930s or colder period of the 1960. The most recent, northward latitudinal shift documented by others (e.g. Perry *et al.*, 2005) was confirmed, but also shown to have a strong eastward longitudinal component. In fact, the distribution of the 1990s–2000s is particularly noteworthy as it is almost opposite (most cod in E, NE and far N of North Sea) to the situation of most of the 20th Century (most cod in NW and WC North Sea; see Figure 1 in Annex 3). Whilst this suggested that cod distribution shifts were not straightforwardly linked to climate change, a clear link with fishing pressure was neither found; for example, near-absence of fishing during WWII hardly affected cod distributions.

More thorough statistical analyses may shed light on the relative importance of climate change and fishing pressure. Further, the effect of the very strong decline *per se* on the very particular cod distribution of the 1990s–2000s needs to be investigated. Ideal Free Distribution theory predicts a declining population will contract into areas of highest habitat suitability; and Blanchard *et al.* (2005) showed that such "basins" of good habitat (based on bottom temperature) are fairly persistent and would be in the north-eastern North Sea for age-1 cod and in the northwest for age-2 cod. Finally,

effects of the marked age truncation in the current stock need to be investigated (B. Rothschild, pers. comm.) given that there are differences in average distribution patterns between younger, smaller cod when compared to older, larger cod. Indeed, the diminished North Sea stock may well have become increasingly confined to these sites.

The North Sea case suggests that cod populations are likely to show long-term distribution shifts. However these may not necessarily be linked to climate (temperature) fluctuations in a direct and readily predictable fashion; rather, they may result from interplay between climate, (local) fishing pressures, (truncations in) age distributions, and/or density-dependent effects on population area sizes.

2.2.2.4 Lessons from Greenland (K. Wieland)

The occurrence of Atlantic cod (*Gadus morhua*) at Greenland has been episodic in historical times. At West Greenland, two short periods of cod fishing are documented for the 17th and 19th centuries (Buch *et al.*, 1994, Dickson *et al.*, 1994) but in 1851 this fishery came to an abrupt end. Indications for a return of cod to West Greenland were first seen again in 1909 at southeast and southwest Greenland. In response to the large-scale North Atlantic wide warming in the 1920s and 1930s (Rogers, 1985; Johannessen *et al.*, 2004) cod spread gradually northward after 1917 and extended as far north as the Upernavik area at 73°N by the late 1930s (Jensen, 1939; Buch *et al.*, 1994). Catches culminated at about 460 000 t in the early 1960s. The offshore spawning stock collapsed completely at the beginning of the 1990s which was mainly as a result of overfishing as fishing mortality exceeded by far the appropriate level even for periods of favourable environmental conditions for growth and recruitment (Hovgård and Wieland, 2008). Warm conditions have prevailed again since the mid-1990s (Figure 2.2.3) but so far no substantial recovery of the stock has been observed (ICES 2008b). The Greenland case suggests that cod can rapidly take advantage of potentially favourable environmental conditions, but only if a minimum level of spawning-stock biomass is maintained.

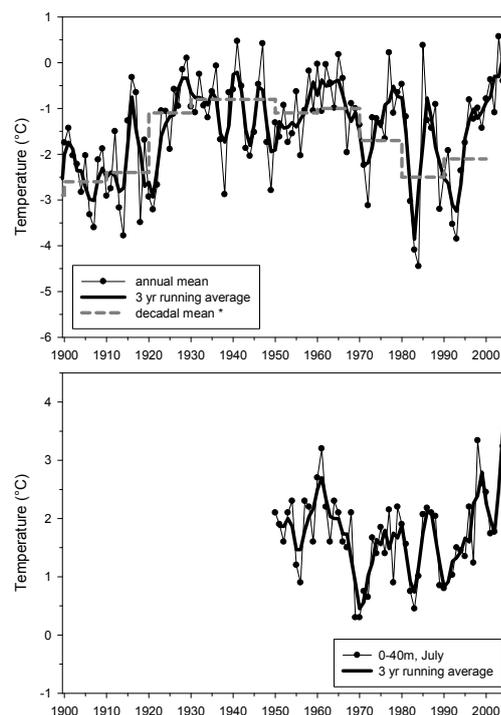


Figure 2.2.3. Air temperature measured in Nuuk (top panel) and ocean surface layer temperature recorded at Fylla Bank (bottom panel) taken from Ribergaard (2006). The decadal annual air temperatures in the top panel are derived from data collected at 12 locations along West Greenland (Vinther *et al.*, 2006).

2.3 Future Climate Projections (C. Schrum and H. Pohlmann)

The Intergovernmental Panel on Climate Change provides regular assessment of Global Climate Change and its impacts, comprising detailed information on the current state-of-the-art in paleoclimatic climate reconstructions, data analyses from historical instrumental records and understanding achieved by global climate modelling and regionalization. These assessments and model data provide typically the basis for regional and local climate change impact studies. In the following we discuss the science base, methods and knowledge achieved from the climate modelling based on the latest IPCC report and the meaning of provided climate scenarios before we conclude on the uncertainties and relevance of information available for the assessment of future climate induced impacts on cod stocks.

2.3.1 Projections vs. Predictions

In its fourth Climate Change assessment report (IPCC, 2007), the Intergovernmental Panel on Climate Change provided global climate change scenarios (Meehl *et al.*, 2007) and some first regional downscaling results (Hegerl *et al.*, 2007). These projections are sometimes misinterpreted as future predictions or forecasts. Herein the scenarios are consistently referred to as projections instead of predictions. A clarifying discussion on this issue was recently published in the 'nature' climate feedback blog (<http://blogs.nature.com/climatefeedback>). A clarification on this issue and a personal opinion on IPCC scenarios for assessment of regional climate change were provided by Kevin Trenberth, one of the IPCC (2007) authors (http://blogs.nature.com/climatefeedback/2007/06/predictions_of_climate.html). He pointed out that the IPCC did not provide predictions, but instead discussed what if scenarios based on consistent story lines and on a number of assumptions, and fur-

ther influenced by the specific set-up, properties and limitations of the models. He discussed specifically one main issue, i.e. the lack of initialization of climate models to the present state and, consequently their limited ability to deal with regional climate change. He postulated that regional climate change is impossible to deal with unless the climate models are properly initialized.

2.3.2 What skill do climate models have?

The quality and validity of impact assessment critically depend on the quality of the climate change scenarios and the ability of the climate models to correctly model the sensitivity of the climate system to changes in the CO₂ forcing. The projections themselves cannot be validated, only the ability of the model to simulate the present day climate state can be evaluated. This validation exercise then can be used to identify properties and limitations of climate models to accurately simulate the climate dynamics. Identification of bias and regional and temporal deviations of modelled time-space pattern from observed ones could provide some indicators regarding the capability of the climate models to accurately simulate the climate system. In chapter 8 of the IPCC report (Randell *et al.*, 2007), such a validation exercise was done in more detail for a number of properties in the atmosphere and in the ocean.

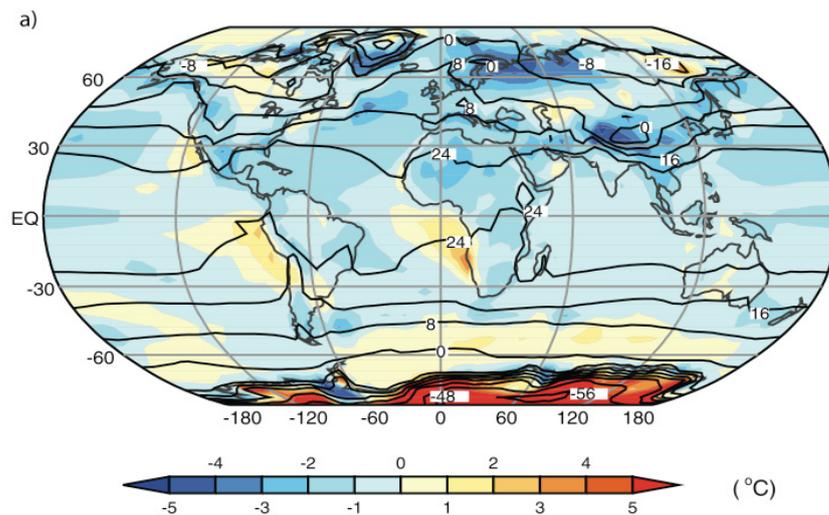


Figure 2.3.1. Climatic surface temperature (SST and over land surface air temperature; contour lines) and bias of the IPCC model ensemble mean (colours) (Randell *et al.*, 2007).

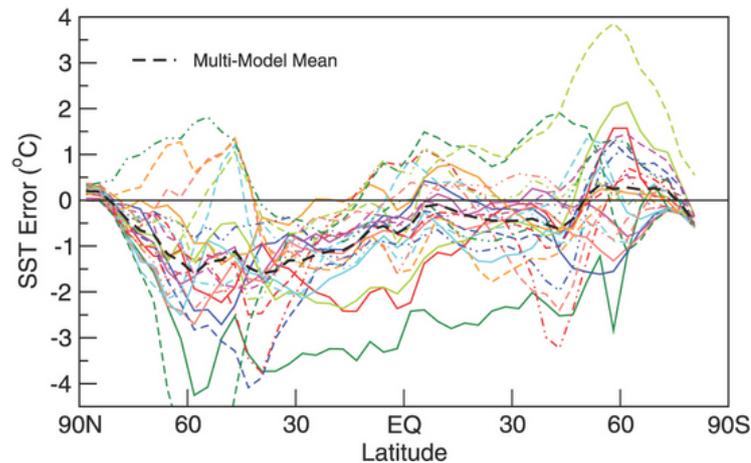


Figure 2.3.2. Zonally averaged SST error, i.e. simulated –observed. Results from the individual models (coloured lines) and the ensemble mean (dashed black line). Figure taken from Randell *et al.* (2007, IPCC report chapter 8 2007). For more details see the IPCC report.

Climate models are generally well tuned to reproduce the 20th Century global mean temperature trend; however, they do not reproduce the regional structure nor other properties of the climate system, such as precipitation, radiation or wind. The ensemble mean of the IPCC models (Figure 2.3.1.) show substantial errors compared to the present day climate, with pronounced regional patterns covering a range from -5° to +5°K. Validations of single models show larger error margins (IPCC, 2007, chapter 8, supplementary material). In Figure 2.3.2, the zonally averaged SST is presented. The errors of the model ensembles show the largest scatter in mid to higher latitudes, with the spread ranging from below -4° to +2°K, hence the error margin for SST in mid-to higher latitudes is larger than 6°K.

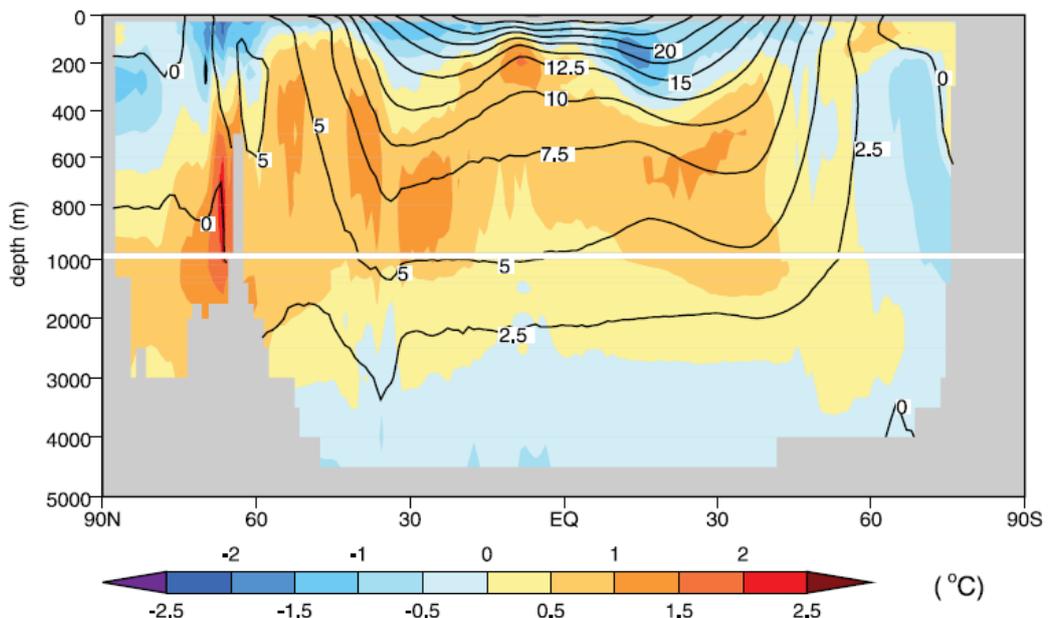


Figure 2.3.3. The simulated mean error, simulated –observed, in °K of the ocean’s zonally averaged potential temperature. The contour lines are the climatic mean potential temperature from Levitus *et al.* (2005). The figure taken from Randell *et al.* (2007).

Significant deviations are not only found for ocean surface characteristics, but as well for the deeper ocean. The bias of the ensemble mean ocean potential temperature var-

ies from -1.5° to $+2.5^{\circ}\text{K}$ (Figure 2.3.3), with systematic underestimation in temperature in the upper ocean (first 100–400 m) and systematic overestimation of temperature in the lower layers. Similarly to the ST and SST bias, the individual models show substantially higher errors.

Zonally mean wind stress over the oceans (Figure 2.3.4) shows good agreement in lower latitudes and substantial deviations in mid to higher latitudes, deviations of a factor 2 and even a change in direction are identified in latitudes relevant to cod.

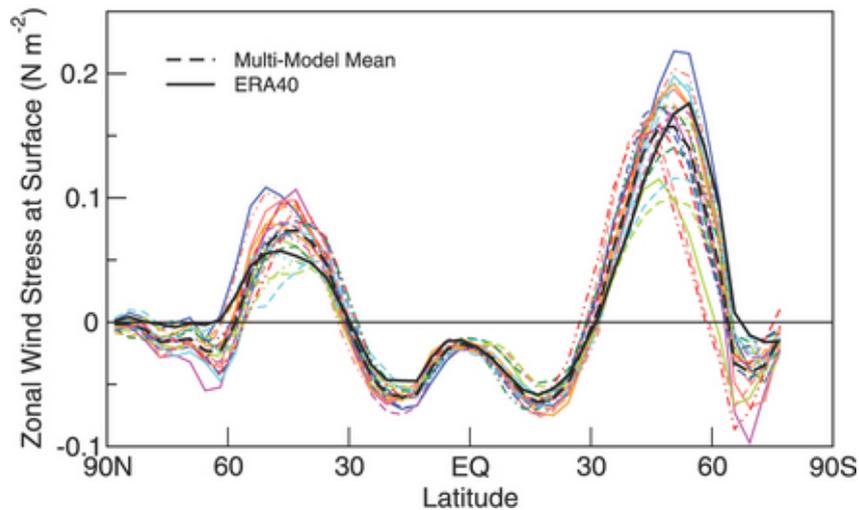


Figure 2.3.4. Zonally averaged wind stress over the oceans. Compared are results from the individual models (coloured lines), the ensemble mean (dashed black line) and observation-based data (ERA40, Uppala *et al.*, 2005). The figure is taken from Randell *et al.* (2007). For more details see the IPCC (2007) report.

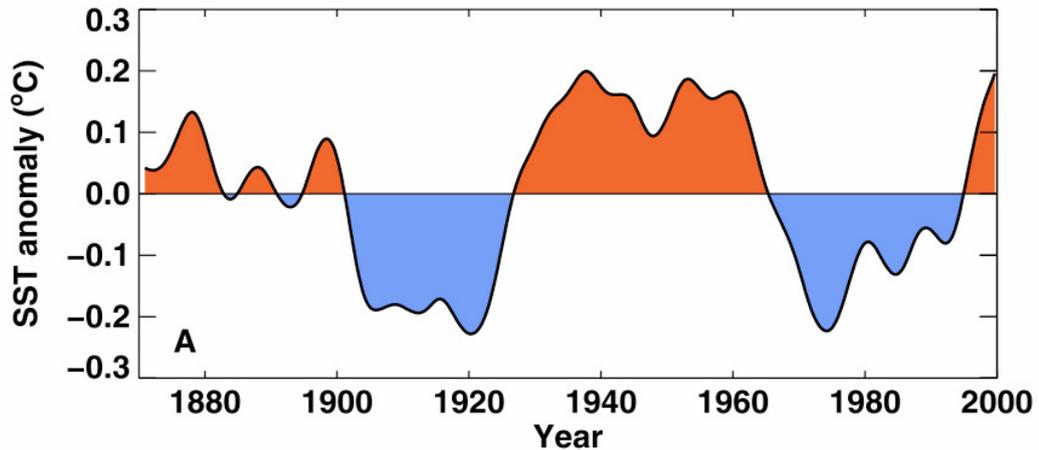


Figure 2.3.5. SST anomaly based AMO index in the North Atlantic de-trended. The figure is taken from Knight *et al.* (2005).

A validation of trends and variability of parameters other than the global mean temperature was not presented by the IPCC, hence an assessment of the models sensitivity to model change and variability in the climate system is not possible based on the material presented in the IPCC report, but the IPCC report does refer to the scientific literature. We will not discuss all of the conclusions based on the scientific literature, but concentrate on the 2 most relevant variability signals for those North Atlantic regions inhabited by Atlantic cod, the Atlantic Multidecadal Oscillation (AMO) and the

North Atlantic Oscillation (NAO). The AMO, with a period of about 60 years, is responsible for about 50% of the observed SST increase in the past decades in the North Atlantic region (Knight *et al.*, 2005, Figure 2.3.5). The NAO is the dominant signal most relevant to the SST variability in the shelf seas. The IPCC reports concludes, that both climate modes are not (AMO) or not well (NAO, too much variability in) reproduced by the IPCC climate models (Randell *et al.*, 2007).

2.3.3 Global projections and regional downscaling

The projected global changes depend strongly on the chosen scenario and model. In general, all the models show a significant future warming but with a magnitude range from 0.5° to 1.5°K for the average global surface air temperature in about 100 yrs. The uncertainty range in model spread is of the same order of magnitude as the projected change and uncertainties to simulate the present day climate pattern are significantly higher. The ensemble average projections show the highest temperature changes in the upper troposphere and the northern latitudes. Here air temperature changes reach 4.5°K in the highest latitudes. These high zonally averaged warming trends are of course not realized in the ocean, as a result of the higher density and heat capacity of water. Here the projected warming of the surface waters are below 1°K in high latitudes from global models (A1B scenario), however, locally stronger warming might be expected.

Although the global projections provide a certain frame of ranges for anticipated climate changes, they are not sufficient for climate change impact studies regarding cod. Detailed assessment of the impact of climate change on cod can only be performed based on regional projections, global projections are assumed to be too coarsely resolved to identify the regional structures. Regional climate change projections are presented in Chapter 11 of the IPCC report (Christensen *et al.*, 2007). Two major drawbacks of the regional downscaling scenarios can be identified. Firstly, most of them are carried out with atmosphere only models; hence do not provide regional ocean estimates nor estimates on lower trophic level productivity. Secondly, as a result of similarly complex and computational demanding regional models, there is a significant time-lag for providing the regional scenarios. The regional scenarios presented in the 2007 IPCC report are based on global model runs and scenarios from previous IPCC report or previous model runs. Hence, they are not necessarily consistent with the results from IPCC 2007 results and the present state-of-the-art in climate modelling. Furthermore, only very few of these scenarios were performed with coupled ocean-atmosphere models or ocean models on the regional scale. The only scenarios available for the regional oceans in the North Atlantic region are currently these produced by Meier *et al.* (2004, 2006) for the Baltic Sea and a scenario run produced by Bjørn Ådlandsvik for the North Sea and the adjacent Northeast Atlantic (Ådlandsvik, 2008, Ådlandsvik and Bentsen, 2007). The latter is the only one based on the latest IPCC assessments (2007).

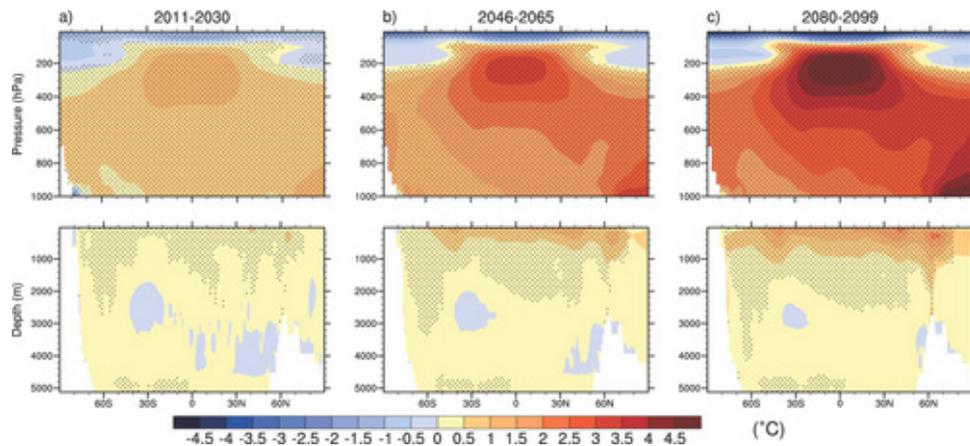


Figure 2.3.6. Projected change in zonal mean air temperature (upper) and ocean temperature (lower) for the IPCC scenario A1B, results from multi-model ensemble.

Only Markus Meier utilized different regional and global models for his scenarios. A consistent positive SST trend was modelled in all of the different scenarios, with an ensemble averaged SST increase of 2.9°K , a significantly stronger temperature increase than the projected changes in the open ocean which are in the order of magnitude of only 1°K (Meehl *et al.*, 2007), this could either be explained by basing the scenario on the less mature global models from the previous scenario assessment, by additional biases of the regional atmospheric models or by a higher sensitivity of the regional sea.

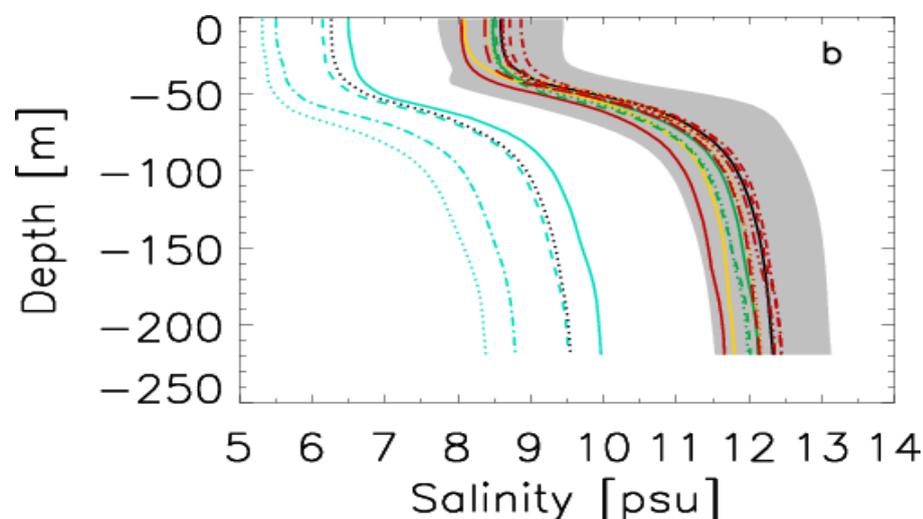


Figure 2.3.7. Projected changes in salinity at Gotland deep for (2071–2100), the colours indicate different regional and global models. For details see Meier *et al.* (2006).

Interestingly, the projected changes in salinity show significant differences, depending upon the global model used to force the regional scenarios (Figure 2.3.7). For example, a significant decrease in salinity (outside the present day climatic variability) is found only for the runs forced by ECHAM4. This clearly points to deviations in regional dynamics in the global models as being one of the most significant factors for regional projections. Interesting as well are the results of Ådlandsvik (2008). He identified a major drawback in the characteristics of the global climate model he selected as the westerly winds were displaced too far south in both the present day 20th century simulation and was in a similar location in the future projection (Figure 2.3.8). Hence, the climate of the present day reference simulation has no connection to

the observed climate over the North Sea. This implies that the impact study is a purely academic study, and might not at all provide a base for assessment of the future climate change on the regional system of the North Sea.

To our knowledge, no regional scenarios using a coupled physical-biological model have yet been established for the Northeast Atlantic. Only for the Baltic Sea are a few scenarios available using one single ecosystem model (Meier pers. comm.) and these are based on the previous IPCC assessment (i.e. 2001). Results of these scenarios are currently unpublished, as well as for the results of the skill and validation exercise documenting the performance of the regional ecosystem model. From complementary investigations comparing different ecosystem modules and their potential to simulate variability in primary production significant increase of uncertainties could be expected to be added by the regional ecosystem modules (Skogen and Moll, 2005, c.f. 2.4).

In conclusion, the results here indicate that there is high potential to decadal predictability in the North Atlantic on the decadal scale, which in future have to be used to establish regional predictions.

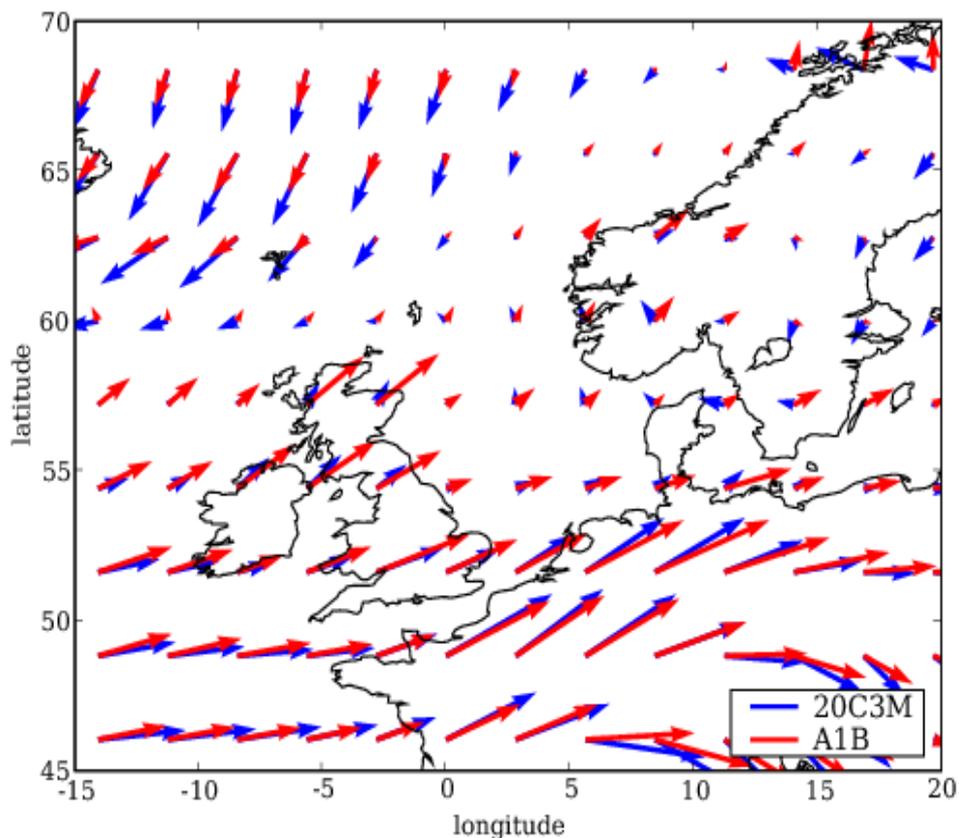


Figure 2.3.8. Wind stress from BCM averaged over the period 1972–1997 (20C3M) and future scenario A1B. Figure taken from Ådlandsvik (2008).

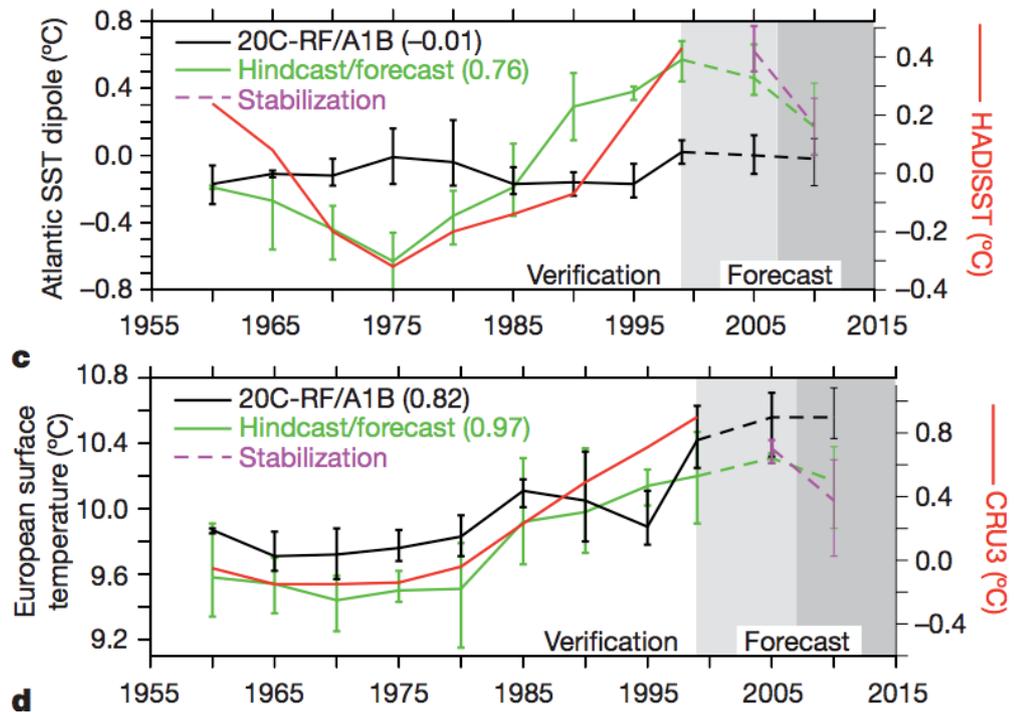


Figure 2.3.9. Modelled Atlantic SST dipole and European surface temperature with the decadal prediction systems of Keenlyside *et al.* (2008) and the IPCC 20th Century reference and an A1B projection run.

2.3.4 Advances for the short time scales

The initialization problem in climate models, which was mentioned previously as one important limitation of global climate models, has been addressed in 2 recent climate modelling publications, i.e. the publications of Smith *et al.* (2007) and the one by Keenlyside *et al.* (2008). These 2 publications describe a significant step forward in climate science with respect to predictability.

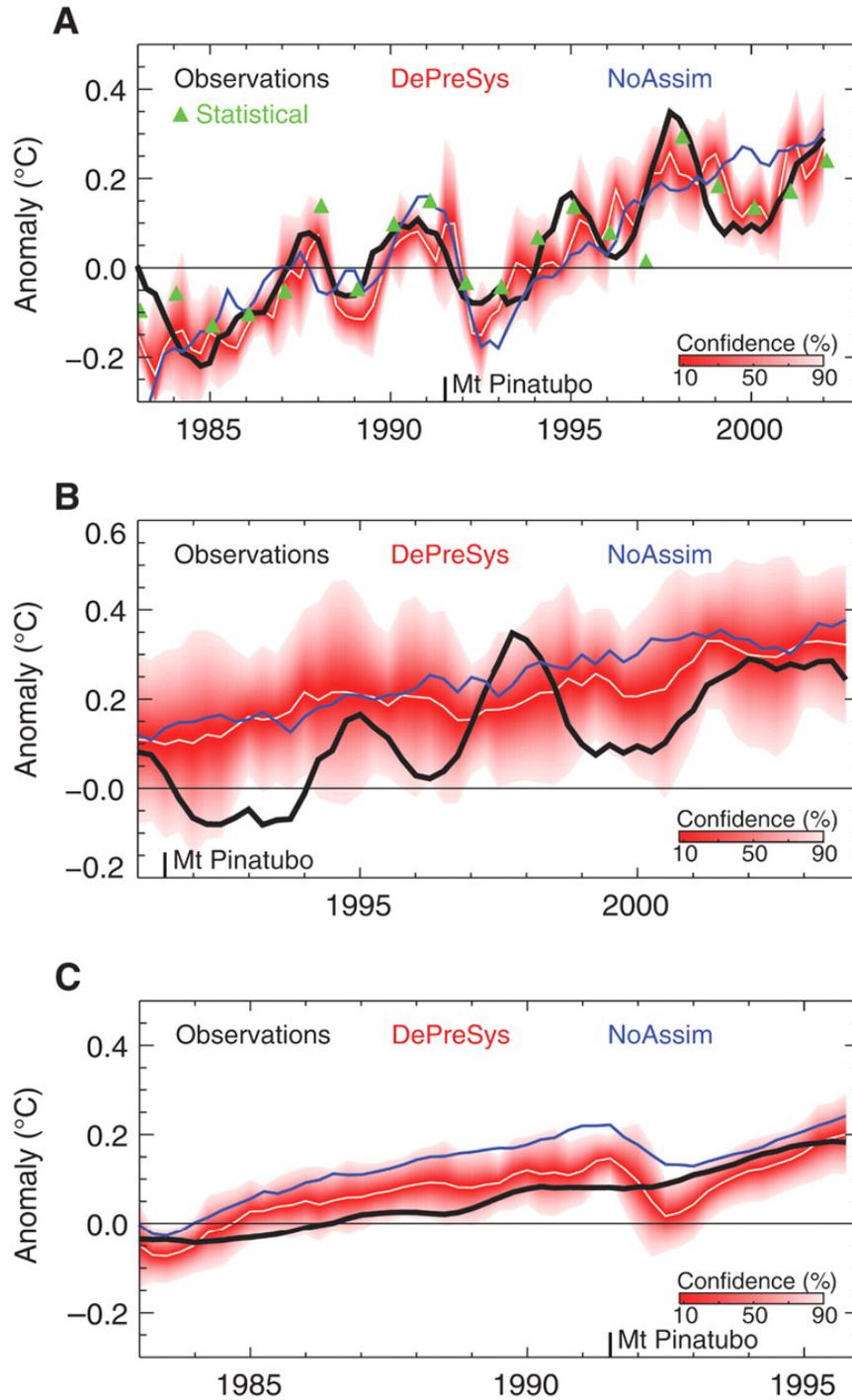


Figure 2.3.10. Results from DePreSys prediction system compared to no-assimilation runs. Upper: the 1- year forecast, middle year 9 of the forecast and lower: 9-year average of the forecast.

The model runs presented were in both cases initialized by the observed and present state, using different modelling techniques. The performed runs and predictions showed in both cases a significantly better performance in the North Atlantic region and a better performance to model the internal oscillations of the North Atlantic Climate Systems (Smith *et al.*, 2007; Keenlyside *et al.*, 2008). Both results showed that the internal oscillations have the potential to locally offset the global warming trend for a couple of years (Figure 2.3.9). In common, both model exercises show that the warming trend is recovered after several years to decades. The interpretation of the latter

conclusions is complicated by the fact that the decadal prediction systems loose performance after a couple of years, i.e. after a decade. The model runs from Smith *et al.* (2007) were presented during the workshop (see extended abstract by Holger Pohlmann in Annex 3) and time-series for North Sea and Baltic Sea SST were shown. From these results, the SST is predicted to increase in about 30 yrs, but shows a modulation and even drop in the first years. Temperature and salinity results from the decadal prediction (Smith *et al.*, 2007) were provided to the workshop participants to establish decadal predictions. However, detailed 3-d model runs are not possible using these results, since full model output necessary to run 3-d regional models has not been stored. To allow future predictions, cooperation between regional and global modellers has been established.

2.3.5 Present limitations

Uncertainties in the climate models arise from a combination of a number of sources and processes which have been reported and discussed by IPCC and in the scientific literature. The most important ones are the initialization problem of climate models, empirical parameterisations of key processes, lacking closure and simplification of climate models (i.e. no earth system models, carbon feedback mechanisms not included), parameterisation of ocean mixing and excluded tidal forcing in addition to numerical errors and forcing data uncertainties.

Although present day climate models are quite complex and (computational) resource demanding, they are still simple in many respects and currently far away from being fully based on first principles. These limitations have been mentioned and briefly discussed in the IPCC report. However, a detailed assessment of the empirical process and subsystem approximations with respect to their impact on climate change projections was not performed. Hence, one of the most burning questions with respect to assessment of limitations and potentials of climate models is currently not answered. However, from the previous discussions it remains clear that uncertainty estimations based on validation provide ranges of uncertainties, that are in the order of magnitude of the projected changes or even larger. This strongly limits the potentials for quantitative future assessment and assessment could only be qualitatively, concentrating on understanding of potentials of change.

The establishment of holistic scenarios comprising hydrodynamics, lower trophic level dynamics and cod recruitment dynamics for the next 20–50 years as intended by the workshop was not possible for the North Atlantic key regions, as a result of a lack of these computational very expensive regional scenarios.

Alternatively so called 'what-if' scenarios can be performed involving a range of different model approaches to address the direct and indirect thermodynamic impacts as well as wind induced impacts on the prey field variability. For these scenarios and model exercises impacts of wind changes, radiation changes and temperature changes can be separated and linear combinations and non-linear interactions can be identified. A similar approach was presented at the workshop for the North Sea by Daewel *et al.* (see Annex 3), estimating cod-potential survival and its sensitivity to changing climatic parameter, to disentangle the direct effects from observed indicator relationships. These "what if" scenarios could provide some insight into the sensitivity of cod recruitment on climate change and improve understanding and identification of relevant climate controls.

2.4 Review of Biological Approaches to Climate Change Impacts

2.4.1 Mechanistic coupled physical-biological models (U. Daewel, C. Schrum)

Before briefly reviewing mechanistic coupled physical-biological models, a short clarification on the terms mechanistic and deterministic modelling is provided (for more details see <http://lorien.ncl.ac.uk/mining/dynamics/modelling.pdf> or http://www.epa.gov/ord/crem/library/CREM%20Modelling%Glossary%2912_03.pdf)

A mechanistic model is a term used to identify a model based on fundamental knowledge of (interacting) processes. Parameters indexing the processes are usually derived from experiments (observations, lab experiments and model experiments) or the literature. A mechanistic model needs little input data, just initial and boundary conditions. Observed data of the output variables are used only to validate the model. Based on this validation, re-examination of process parameterizations may be required. The mechanistic model does not require many data for development and hence is not subject to any idiosyncrasies in data. Instead it requires fundamental understanding of the physics, chemistry and biology of the governing processes. Usually mechanistic models are very time consuming to develop.

A deterministic model is one that provides a single solution for the one or more state variables. It is not able to explicitly simulate data uncertainty or variability. Changes in model solutions can therefore be directly attributed to changes in boundary and initial conditions (model input). The complex 3-d coupled physical-biological models used in ecosystem research, including the 3-d IBM models, are commonly both, mechanistic and deterministic.

To address the question of how climatic, hydrodynamic and biological processes interrelate to each other in a complex 3d-system the use of a mechanistic-deterministic model approach appears to be expedient for the following reasons. First, using this approach, in contrast to observations, it is possible to cover a sufficient temporal and spatial resolution for all the modelled variables and combine them in a dynamically consistent approach. Second, by having detailed knowledge of the process parameterization it is possible to disentangle different impacts in a 3-d context.

The parameterization and complexity of biophysical models vary with respect to the trophic levels and processes that are included as well as the scientific question being asked. In the following a very brief overview of the most important approaches is provided.

NPZD models

The currently running 3-d ecosystem modules used to study marine ecosystems and related environments are still quite simple. Typically they include up to 3-nutrient cycles and one or two functional groups of phyto- and zooplankton (e.g. NORWECOM: Skogen *et al.*, 1995). Additionally oxygen and a detritus class(es) are considered. The intermediate complexity models (e.g. Schrum *et al.*, 2006a (ECOSMO); Wassmann *et al.*, 2006; Slagstad and McClimans, 2005 (SINMOD); Neuman, 2000 (ERGOM)) are closed by prescribing zooplankton mortality, simpler models by prescribing phytoplankton mortality as a consequence of predation by zooplankton. The only more complex model currently used for the Northeast Atlantic in the coupling mode with 3-d hydrodynamic models is the ERSEM (European Regional Seas Ecosystem Model, Baretta *et al.*, 1995). The highest trophic level dynamically considered in this model is planktivorous fish. The model has been applied to the North Sea and

British coastal waters (POLCOMS-ERSEM; Allen *et al.*, 2001; Holt *et al.*, 2005; Blackford *et al.*, 2004; Allen *et al.*, 2007a,b).

Spatially explicit IBMs

As a step forward towards understanding interannual variations of stock recruitment, individual based models (IBM) for larval fish are utilized in order to examine processes affecting vital rates of the early life stages of fish. Depending on the question being asked IBMs vary in their structure and complexity. Depending on the question being addressed, two main approaches have been developed with different levels of complexity. The first approach includes information about one or two environmental factors (e.g. temperature, prey availability) and is based on empirically derived equations for these processes (e.g. Heath and Gallego, 1997). Although this approach provides estimates of spatial and temporal variability in growth that are particularly useful for some purposes (i.e. in drift modelling studies), growth variability as a result of changes in the prey field is usually ignored. Therefore a more complex, mechanistic approach has been applied in a number of different studies (e.g. Letcher *et al.*, 1996; Lough *et al.*, 2005), including subroutines with functions describing factors affecting the underlying processes of energy gain (foraging) and energy loss (via metabolism).

By using a Lagrangian approach IBMs have been coupled to 3-d hydrodynamic models, allowing the explorations of the spatial-temporal variability in the interaction between marine organisms and their environment. Advances made in this area during the 1990s were reviewed by Werner *et al.* (2001). Some modelling studies focused on the role of currents and circulation patterns, yielding insight regarding fish spawning areas, nursery grounds and pathways of larval drift and the general influence of tides, residual currents and turbulence on the migration and spatial distribution of fish early life stages (e.g. Werner *et al.*, 1993). These studies clearly linked the physical properties of the environment to changes in the vital rates of individuals. To address more complex questions, spatially explicit IBMs have been employed that incorporate 3-d fields of hydrographical properties (e.g. temperature, salinity, current velocity and diffusion) experienced by individuals during early life (e.g. Hinckley *et al.*, 1996, Bartsch and Coombs, 2004). Utilizing a 3-d IBM is especially important within ocean shelf systems like the North Sea where a complex topography and the presence of different frontal regimes lead to horizontal as well as vertical spatial variability in physical properties.

Recent efforts were also made in linking spatially explicit IBMs to 3-D zooplankton fields, by using observed prey fields on the one hand (Kühn *et al.*, in press) but also by developing links to NPZD model results (Daewel *et al.*, in press). The advantage in using such a coupled model system including dynamics throughout different trophic levels is clearly the possibility to incorporate spatial and temporal dynamics into the investigation. Nonetheless it also increases the uncertainties we need to account for.

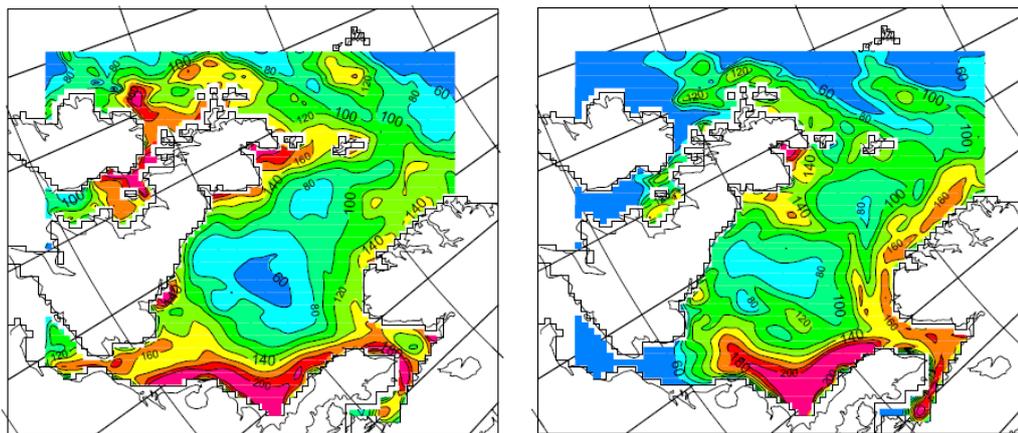


Figure 2.4.1. Mean annual production ($\text{gC/m}^2/\text{year}$) from the NORWECOM model and the ECOHAM1 model. Figure taken from Skogen and Möll (2005).

Limitations

These models still lack closure of the life cycle and hence are of limited applicability to resolve population dynamics. Scenarios based on these models cover only bottom-up control of the early life stages.

The simplicity of model approximations, the lack of closure and the diversity of concepts are quite problematic when it comes to assessment of climatic variability impacts, marine resource management or predictions of potential future scenarios. Results from impact studies carried out by Denman and Pena (2002) showed that different ecosystem model concepts significantly impact on model predictions. Moreover, the employed hydrodynamic model and the coupling mode were identified to account for significant differences in ecosystem assessment by Skogen and Möll (2005). These authors had to perform massive tuning before a simple ecosystem model could be used within another hydrodynamic framework. After new tuning the best fit simulations using 2 different ecosystem cores still showed significant deviations in local annual mean primary production, differences of a factor of 2 or more (Figure 2.4.1). Further results from their study showed a clear impact on modelled interannual variability using the same hydrodynamic core (Figure 2.4.2). The two ecosystem modules they used estimated different and even reversed trends in total productivity, a fact that would significantly impact on scenario predictions based on these concepts. The relevant conclusion to draw from this study is that research is needed to identify valid model systems (i.e. identify the necessary key processes to be included for estimation of total productivity) for respective regions to ensure the scientific quality and value of scenario predictions.

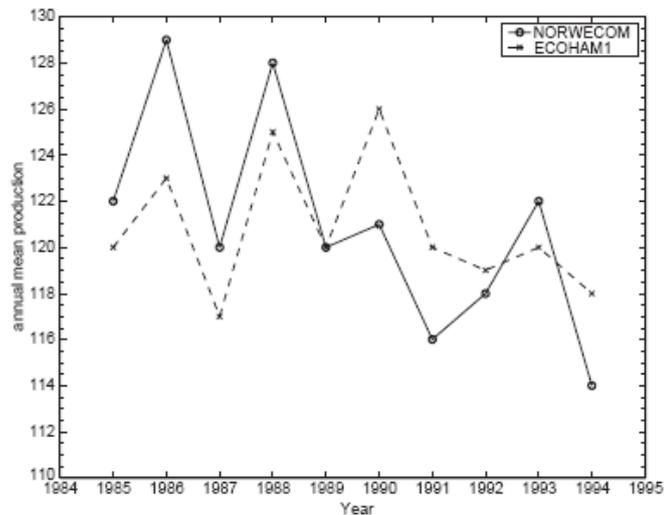


Figure 2.4.2. Mean annual production ($\text{gC/m}^2/\text{year}$) from the NORWECOM model and the ECOHAM1 model. Figure taken from Skogen and Möll (2005).

2.4.1.1. What can they do?

The use of such complex model systems means large uncertainties in the outputs, as a result of inadequate parameterizations, the number of simplifications that have to be made and a number of important processes that are probably not included. Nonetheless these models provide useful tools to understand and identify patterns in ecosystem dynamics. For lower trophic level dynamics, Schrum *et al.* (2006b) applied EOF analyses on 3-D model results of phyto- and zooplankton production and biomass, in order to identify both their relationship with hydrodynamic features, especially tidal mixing fronts, and the corresponding time scales and seasonal dynamics. Another example focused on bottom-up processes affecting larval cod (*Gadus morhua*) on Georges Bank. A coupled biophysical model was applied by Lough *et al.* (2005) in combination with highly resolved *in situ* observations of zooplankton abundances. The focus of this study was on the vertical structure and temporal evolution of feeding and growth.

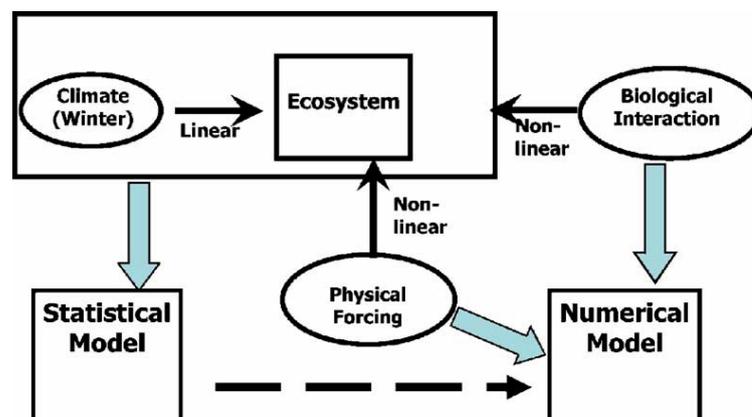


Figure 2.4.3. Schematic sketch (taken from Dippner, 2006) of the model application (large arrows), which depends on the property of the mediator (small arrows). The sketch indicates that in case in linear mediators, the statistical model is appropriate. If the mediator is non linear, the use of numerical models is necessary.

Besides helping to identify patterns of ecosystem dynamics, mechanistic coupled physical-biological models can provide information on processes and process interac-

tions. In contrast to statistical models, that find correlations or linear relationships between variables, mechanisms that directly or indirectly influence the abundance or biomass of marine organisms (“mediators”; see Dippner, 2006) can be determined from the mechanistic model approach (Figure 2.4.3). It is clear, that the knowledge of these mediators, not only provides a deeper understanding of the processes observed in the field, but also is important for future predictions of ecosystem responses to climate variability.

The utility of biophysical models, in terms of identifying underlying mechanisms, can be illustrated by a number of examples. The variability in the flowfield, usually linked to changes in the large-scale atmospheric pressure system (e.g. NAO), has a strong impact on larval fish survival, since it defines the environmental conditions a fish experienced during its early life stages. An investigation concerning the impact of drift of mackerel (*Scomber scombrus*) was conducted by Bartsch and Coombs (2004), who studied environmental impacts on growth and survival of fish early life stages, by combining an IBM with a hydrodynamic model. Another factor effecting growth and mortality of larval fish is turbulence, as a result of its strong impact on fish ingestion rates (MacKenzie *et al.*, 1994). The sensitivity of walleye pollock (*Theragra chalcogramma*) growth and mortality to turbulence was studied by Megrey and Hinkley (2001), as well by utilizing an IBM approach. A third example pointed out the importance of individual larval behaviour for fish growth, mortality and dispersion (Fiksen *et al.*, 2007). These examples indicate the ability of mechanistic biophysical modelling to obtain a basic understanding of ecosystem dynamics.

This process understanding can further be incorporated into biophysical models in order to test future climate scenarios. In contrast to observation-based studies, the models are able to reflect interactions between atmospheric forcing, physical environment and ecosystem dynamics with a continuous spatial and temporal resolution (e.g. Daewel *et al.*, in press). Thus the model provides an expedient tool to perform scenario tests, e.g. by increasing the air temperature or changing the wind field. Further the model can be used to develop “what-if” scenarios to test the response of the marine ecosystem to predicted climate change.

2.4.1.1 What do ecosystem models require from climate models (resolution, error margins)

To develop a regional climate scenario using a downscaling approach involving 3-D hydrodynamic and physical-biological models requires that: (i) the climate models be skilful in the region of interest with the validity and skill of the models having been tested with a present day reference simulation; and (ii) the validation exercise needs to be performed regionally for the following variables:

- the winds and air pressure (i.e. the correct location of the mean large-scale pressure systems is the single most important requirement),
- short wave radiation (clouds) and air temperature,
- humidity,
- precipitation and run-off, and
- temperature and salinity in the ocean.

The regional models need to be skilful not only for the average climate signal but also for the seasonal signal, the interannual variability and the diurnal variability, since variability on all of these different time-scales can be an important drivers of biological processes. To allow for reasonable predictions, the regional bias and model errors in dynamically active (non-linear processes) variables (temperature gradients, wind

fields) need to be clearly smaller than the climate change signal, while error margins need to be given with reference to the present day climate simulations. Larger error margins have to be corrected and specific corrections have to be developed.

Variables needed to force the regional ocean physical-biological models are wind fields (10 m), sea level pressure, sea surface air temperature and dew point temperature (humidity), short wave radiation, cloud cover, atmospheric long-wave radiation, run-off, and sea ice. It might also be necessary to correct for resolution bias in the global models. Oceanic data requirements are initial and boundary conditions in the temperature, salinity and sea level. Temporal resolution needed is 3h-6h for the atmosphere and daily to weekly for the oceanic parameters.

2.4.2 Statistical models (M. Lindgren and J.E. Stiansen)

In contrast to mechanistic models, models establishing a statistical relationship between two or more variables infer a link between the variables, though the specific mechanisms behind the interactions may be unknown. Two of the most common statistical models are correlations and regressions. Defined as the covariance of two standardized descriptors, a correlation measures the degree of linear dependence between variables. Given multiple variables, it is possible to construct the correlation matrix, whose elements are the coefficients of linear correlation between each pair of variables respectively (Legendre and Legendre, 1998). The square of these coefficients is the coefficient of determination, i.e. a measure of how much of the variance of each variable is explained by the other.

As with correlations, regression models in general assume linearity between response and predictor(s). In a simple linear regression, the model equation corresponds to a straight line defining the nature of relationship between predicted (y) and explanatory (x) variables. In case of several explanatory variables (x_1, x_2, \dots, x_n), a multiple linear regression is often used to infer a linear relationship between the predicted and all of the explanatory variables. Using such general linear models (GLMs), one must be aware of the fact that a linear model is imposed. In other words one assumes that the relationship between variables may be adequately described by a straight line (Legendre and Legendre 1998). In many cases, such generalizations may not be valid.

To overcome the assumptions of linearity, non-linear models have been developed. Such approaches include for instance polynomial regressions, partial linear regressions and in case the actual function is known (e.g. Logistic growth) even non-linear regression can be applied. Generalized additive models (GAMs) provide a combination of both linear and non-linear techniques, as linear predictor depends, in part, on a sum of smooth functions of predictors. The key idea here is that the dependence of the response on the predictors can be represented as a parametric submodel plus the sum of some (functionals of) smooth functions of one or more of the predictor variables software (www.r-project.org).

Since statistical models often fail to address the actual mechanisms of interactions between variables, a way to introduce a more theoretical-mechanistic approach to statistical models has been developed in the field of population dynamics. Log-linear first-order autoregressive models AR(1) (Royama, 1992; Bjørnstad *et al.*, 1995; Stenseth *et al.*, 1996) provide a theoretically well supported framework for modelling population dynamics under environmental stochasticity (Ives 1995). Hjermmann *et al.* (2004, 2007) effectively demonstrate how such an approach can be used in modelling the Barents Sea cod stock dynamics in response to climate variability and fishing.

Elaborating from essentially a single species point of view, multivariate autoregressive models (MAR(1)) provide a multispecies extension for modelling foodweb interactions at several trophic levels (Ives, 1995; Ives *et al.*, 1999; 2003). MAR(1) models can essentially be viewed as a linear approximation to a non-linear first-order stochastic process (Ives *et al.*, 2003) and in general functions as a set of lagged multiple linear regression equations (one for each species of the foodweb) solved simultaneously to arrive at the most parsimonious model overall (Hampton *et al.*, 2006). Combined with internal species interactions, the MAR(1) framework allows any external forcing e.g. climate variability or commercial fishing to be included as covariates (Ives, 1995; Ripa and Ives, 2003). Since, the MAR modelling may integrate internal foodweb dynamics and external forcing it has the potential to serve as an important tool in modelling and even forecasting population responses to climate change. Surprisingly it has hardly been extended beyond theory by applying it to real foodwebs (Ives *et al.*, 1999; Hampton *et al.*, 2006).

2.4.2.1 What can they do?

The use of correlations and regressions in climate-fish relations can be very useful. However, these approaches must be used with great care, and may in some cases be misleading. Here we discuss some of the possibilities and caveats.

Correlations and regressions can be useful in revealing possible relations between a climate variable and a fish stock variable. Since they are simple to use they are well suited as a first test or approach. Multiple regressions, that combine stock and climate variables, can be useful for assessment purposes, especially if they have predictive power (i.e. the predictor variables precedes the response variables in time). An example of this is given in Figure 2.4.4. In order for correlations and regression/multiple regressions to be believable they need to have a plausible cause-effect reasoning linked to them. In all cases they should always be treated with great care, since they are a very simple approach to describe parts of a generally complex structure of nature.

There are a number of limitations or caveats connected to the use of these methods. Here we briefly mention a few primarily related to correlation and regression analysis.

- Statistical relationships may be as a result of pure coincidence. Significant correlation is a necessary, but not sufficient, criteria for a relationship.
- Multiple regressions often break the statistical assumptions that the explanatory variables should be independent (or for practical reasons at least have low correlations).
- Autocorrelations in the explanatory and predicted variables need to be evaluated for determination of statistical significance.
- The relationships may be time dependant, i.e. a link may only hold as long as the explanatory variable is the dominant influence. Often the relationships are only valid over a certain time span or time window, and break down outside this interval.
- If the true relationship is non-linear, this may not show properly in linear regressions or correlations (in some cases the correlation may be zero, even if there is a clear non-linear relationship).
- For multiple regressions, too many explanatory variables compared to the number of data points leads to pure curve-fitting, which reduces the

analysis to a mathematical exercise, which is unlikely to be linked to a plausible cause and effect.

- The relationships may not be as a result of a cause-effect response, but is as a result of an “undetected” cause, which both variables respond to.

Though there are many traps for those that use statistical correlations and regressions these approaches still are valid within their limitations. The largest problem for practical use is the risk of breakdown of the relationship. Therefore identified relations should be followed in time, and methods for continuous evaluation of the relations should be provided. In the time window where the relations are valid correlations and regressions can be valuable tools.

Example 1. Use of multiple regression to predict the number of North East Arctic (NEA) cod recruits

In today’s fish stock assessments, climate is rarely taken into account. One of the most accessible places to add climate information is in the short-term projection of recruitment. Regression models may in many assessment models substitute the existing recruitment prognoses module.

Stiansen *et al.* (2005) suggested a model with 2 year prediction possibility:

$$R3 \sim \text{Temp}(-3) + \text{Age1}(-2) + \text{MatBio}(-2)$$

Where R3 is the number of 3-yr old NEA cod, Temp is the Kola annual mean temperature (averaged over 0–200m), Age1 is the winter survey bottom-trawl index for cod age 1 (Table A3), and MatBio the maturing biomass of capelin. The number in parenthesis is the time-lag in years. The observed and modelled recruits of NEA cod using this model and applied to the years 1984–2005 are shown in Figure 1. The outlook for years 2006 to 2009 are also shown.

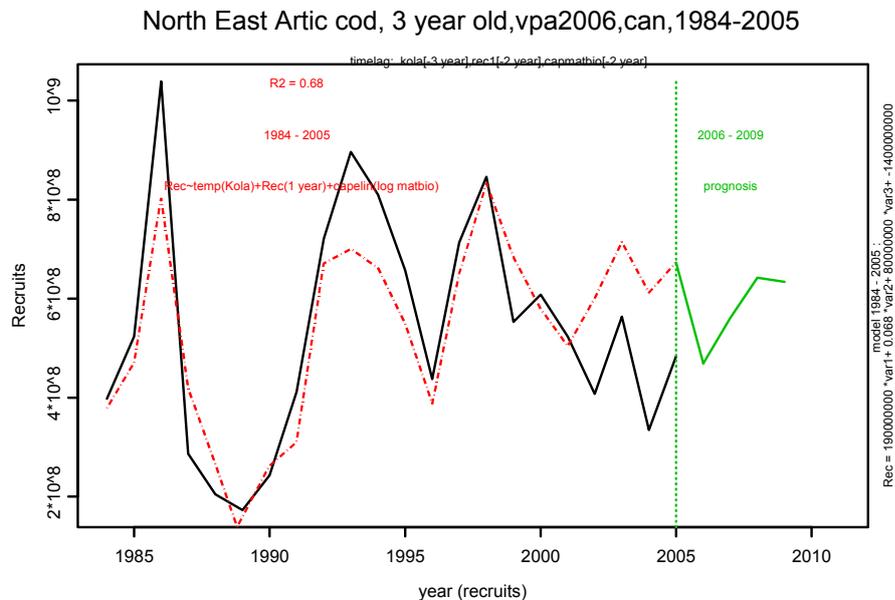


Figure 2.4.4. NEA cod recruitment projection, using multiple regression.

Example 2. Use of MAR(1) models in predicting Baltic cod stock dynamics in response to climate change.

As a first step implementing MAR(1) modelling within fisheries management and forecasting, a fishing and climate driven multispecies MAR(1) model for the Baltic Sea was developed that was able to accurately recreate the past dynamics of Baltic cod, sprat and herring (Lindegren *et al. in preparation*). Based on the findings of the *Assessment of climate change for the Baltic Sea Basin* (BACC), we used a simple climate model (Ripa and Lundberg, 1996) to simulate plausible climate scenarios for the 21st century. Taking into account that marine climate is “red shifted” (i.e. positively auto-correlated) (Steele and Henderson, 1984), we generated “red-shifted” time-series of spring sea surface temperature and summer salinity based on actual data from 1974–2004. To mimic the predicted increase in SST by 3.5°C and salinity decrease by 0.8 or 5.5 psu respectively, a gradual trend in the mean over 100 consecutive years was applied. Coupling the foodweb and climate model we explored the impact of climate change on the future dynamics of Baltic cod. Further, by including different fishing scenarios for Baltic cod, we elaborated on the role of management in relation to climate change. Running a vast number of stochastic simulations for combinations of climate and fishing mortalities, the probability of the stock falling below the limiting stock size (Blim) of 160 000 tonnes was computed (Figure 2.4.5). Model runs show that given even a relatively weak decrease in salinity (> 3 psu), thus impairing recruitment of Baltic cod through increased egg and larvae mortality (Nissling 2004; Köster *et al.*, 2005), only a drastic decrease in fishing mortality could avoid future stock collapses and ensure the existence of Baltic cod for future generations to come.

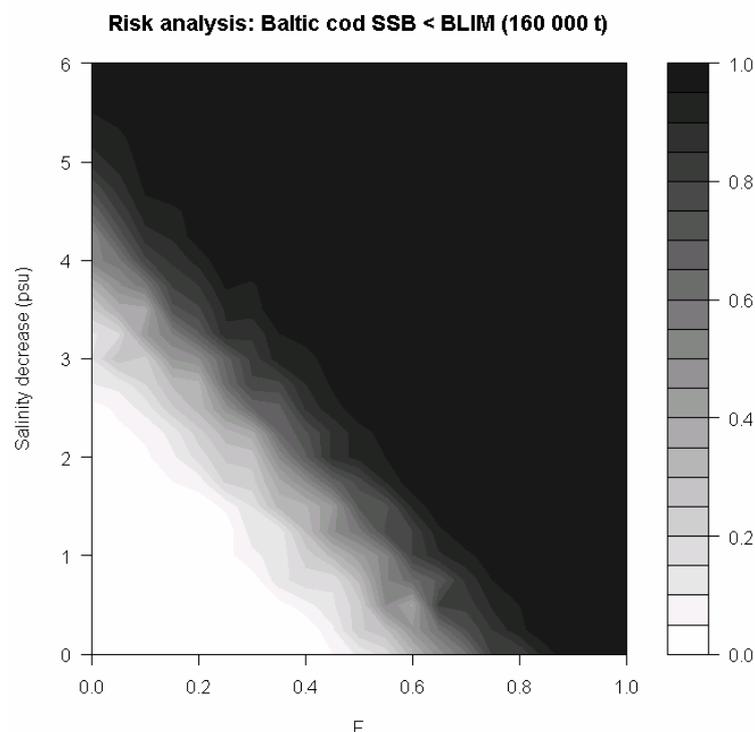


Figure 2.4.5. The probability of Baltic cod SSB falling below the limiting stock size (Blim) is computed as the % of model runs where the predicted SSB falls below 160 000 tonnes. Simulations are run for all combinations of fishing mortalities from 0–1 and decreases in salinity from 0–6 psu (relative to the mean salinity from 1974–2004). The risk of falling below Blim increases rapidly and non-linearly as salinities decrease with increasing fishing mortalities.

2.4.3 Mechanistic-stochastic models (Irene Mantzouni)

The need for and the needs of

The workshop emphasizes the need to broaden our insights into the processes that link climatic factors, and their variability, to cod life-history parameters and hence to population dynamics. This calls for the development of mathematical or empirical models to describe and combine mechanisms through which environmental impacts operate on the stock level, to incorporate the various sources of uncertainty and, consequently, to discern and illustrate patterns despite ecosystem complexity. A further advantage of such models is that their parameters have a meaningful interpretation and, thus, population characteristics of interest, and their dynamics and/or variability, can be directly obtained. Such examples include the stock-recruit (SR) models, which are broadly used in fisheries management in order to derive reference points. However, process modelling usually involves non-linear relationships, that may (e.g. Ricker SR model) or may not (e.g. Beverton-Holt or Deriso-Schnute SR models) be possible to express in a linear form. Empirical estimation can be hampered in such cases, especially when the data series are short and noisy and the interannual variability in the forcing environmental factor low, a situation not uncommon to natural fish populations.

Accommodating the needs by Meta-analysis

In this context, the advantages and the potentials of joint /comparative studies in fisheries science have long been advocated (e.g. Pauly, 1980; Brander, 1995) and have provided fundamental insights on spawner-recruit dynamics (Ricker, 1954; Beverton and Holt, 1957; Cushing, 1971), especially in cases when single-stock inference does not have enough power to produce clear results (Brander, 2000; Myers, 1998; Myers, 2001). Theoretical and technological advances in the recent years, have allowed the more widespread use of synthetic approaches, such as meta-analysis, mixed (variance-components) and Bayesian models, especially in stock assessments (e.g. Punt and Hilborn, 1997) and SR dynamics (see Myers and Mertz, 1998; Myers, 2001; Myers, 2002 for reviews). In particular, such analyses have revealed relationships between cod and environmental variables (e.g. Planque and Frédou, 1999; Brander, 2000; Dutil and Brander, 2003; Brander and Mohn, 2004; Stige *et al.*, 2006), based on the fact that stocks within species, or related species with similar life-histories, share common population dynamics patterns and respond to environmental effects in comparable ways (Brander, 2000, Myers *et al.*, 2002; MacKenzie *et al.*, 2003). Consequently, it is possible to “borrow strength” (Myers *et al.*, 2001) or “stand on the shoulders of giants” (Hilborn and Liermann, 1998) by combining data across stocks. Such approaches can yield superior parameter estimates, thereby reducing uncertainty for management reference points, allow inference at a higher level and improve estimation for stocks with limited data (Myers *et al.*, 2001).

Accommodating the needs by Hierarchical modelling

To couple the needs both for mechanistic, possibly non-linear, models and robust parameter estimation for the empirical research of natural phenomena, hierarchical or multi-level models can provide a useful and flexible toolbox, describing stochastic processes of various forms and allowing for inference across stocks (Gelman and Hill, 2007). Hierarchical modelling is a rigorous probabilistic framework offering two mutually implicative advantages: (a) the explicit incorporation and thus, isolation of uncertainty sources and (b) the combination of data across various independent sources (Gelman and Hill, 2007, Hilborn and Liermann, 1998). Uncertainty arises mainly as a

result of two sources of variation or error: (i) observation and (ii) systematic model error (e.g. Hilborn and Walters, 1992). Observational process uncertainty arises from non-systematic effects, such as measurement error in recruitment and/or spawner biomass, resulting in random model or sampling error (Hilborn and Walters, 1992). Systematic model error can be decomposed into process variation and parameter uncertainty. The former is as a result of insufficient or improper specification of the model functional form. Defining the process generating the data are, in general, the most fundamental step in model development. Errors of this type arise from misspecification or oversight of stochastic, usually environmental, factors impacting on the basic model mechanism, thus affecting recruitment success probabilities (e.g. Bakun, 1996; Jarre-Teichmann *et al.*, 2000). Finally, parameter variability across stocks, apart from observation error, stems also from the fact that parameters do differ across stocks (Hilborn and Liermann, 1998), possibly as a result of differences in the size and magnitude of dynamics response to underlying processes.

Case study: Hierarchical development of the Beverton –Holt SR model

Hierarchical implementation is based on the model decomposition into three stages, or levels, according to the probability theory (Clark, 2007) and here it will be illustrated for SR models. On the first level, the data model is specifying the data distribution given the model (i.e. the functional form of the SR model and the associated parameters). For example, the hierarchical Beverton-Holt SR model can be written as:

$$y_{it} = \alpha_{it}^{BH} + \beta_{it}^{BH} - \log(\exp(\beta_{it}^{BH}) + x_{it}) + \varepsilon_{it} \quad (1)$$

where $y_{it} = \log(R_{it} / S_{it})$, $x_{it} = S_{it}$. Parameters α_{it}^{BH} (maximum reproductive rate) and β_{it}^{BH} (log of S giving half of asymptotic recruitment) can be assumed to depend on stock i specific temperature (T) time-series thus, being time-varying:

$$\alpha_{it}^{BH} = c_{oi}^{BH} + c_{T1}^{BH} T_{it} + c_{T2}^{BH} T_{it}^2 \quad (2.1)$$

$$\beta_{it}^{BH} = d_{oi}^{BH} + d_{T1}^{BH} T_{it} + d_{T2}^{BH} T_{it}^2 \quad (2.2)$$

Equation (1) incorporating the above relationships, is the data- level model, represented by the likelihood in the Bayesian framework and expressing the probability of observing the data given the functional model and its parameters:

$$y_{it} \sim N(\alpha_{it}^{BH} + \beta_{it}^{BH} - \log(\exp(\beta_{it}^{BH}) + x_{it}), \sigma_{yi}^2) \quad (3)$$

Secondly, the process models describe the mechanism based on the associated parameters. In the present context, they specify the distribution of the SR model parameters across the cod stocks and can also be extended to account for the factors generating the among stocks differences. Thus, they are referred to as the stock-level models, acting as priors for the coefficients in relationships (2.1) and (2.2). Models for the temperature-related terms allow for the possibility that *alpha* and *beta* have different degrees of sensitivity to temperature effects in the individual stocks. These across stocks distributions are of the form:

$$c_{Tii}^{BH} \stackrel{iid}{\sim} N(\mu_{cT1}^{BH}, (\sigma_{cT1}^{BH})^2) = p[c_{Tii}^{BH} | \mu_{cT1}^{BH}, \sigma_{cT1}^{BH}] \quad (4)$$

The stock-level models for the intercepts account for among stocks differences in Beverton-Holt *alpha* and *beta* parameters, arising from additional effects not included in the data-level model. For parameter *beta*, representing carrying capacity (CC), variation is partly as a result of differences in the habitat size occupied by the individual stocks. Therefore, the intercepts in (2.2) can be modelled as a function of *H* and the corresponding priors become stock-specific:

$$d_{oi}^{BH} \stackrel{iid}{\sim} N(k_o^{BH} + f_{H1}^{BH} H_i + f_{H2}^{BH} H_i^2, (\sigma_{d_o}^{BH})^2) = p[d_{oi}^{BH} | k_o^{BH}, f_{H1}^{BH}, f_{H2}^{BH}, \sigma_{d_o}^{BH}] \quad (5)$$

The third level is known as the parameter model and it concerns the hyper-parameters, which are used to specify the probability distribution of the parameters in the previous stages. These last two levels, based on the assumption that certain SR model parameters are connected across stocks, lie in the core of the hierarchical meta-analytic inference. The common probability distribution and the process generating these parameters, or describing the differences among them, both described by the hyper-parameters of the third stage, form the interface for the combination of the individual datasets and thus, for exchange of estimation strength across stocks (Gelman *et al.*, 1995).

Perspectives

Hierarchical approaches offer multiple advantages for the modelling of climate change effects on cod stocks, by bringing together the within and among stocks sources of variability and also a broader range of environmental conditions across the species distribution. Certainly, the environmental factors acting on local scales differ across regions. The flexibility of the Bayesian framework, apart from multi-level structures, allows the simulative implementation of mechanistic models, incorporating complex processes for single stocks. Thus, patterns inferred on the species level, coupled with models describing the stock specific dynamics, either directly or as priors, can provide further insights for the future of cod under the climate change perspective.

2.5 Management

2.5.1 How can management strategy be improved by applying climate impact models/prognosis

2.5.1.1 Management advice on sustainable yield (A. Filin)

Management of fisheries is always based on decision making under uncertainty. Incorporating data on ocean climate in management procedures should reduce uncertainty of scientific recommendations for harvest levels. The fisheries strategy at first has to ensure a sustainable harvesting. For the achievement of this aim the principles of the precautionary and ecosystem approaches should be used.

Environmental information related with future climate change ought to play an important role in the design of management strategies. We can use environmental information to exploit a stock either more efficiently or more carefully, according to the prevailing environmental conditions. We also should take environmental impact induced by climate change into account in the evaluation of a management strategy.

The existing ICES advice system was designed to provide advice only on a very short-term basis: one year ahead based on recent past. As we now move to provision of longer-term advice in a more rapidly changing environment there is a need to alter

the way we consider the future and to provide advice that is both more robust and more adaptive to change. In the face of global warming we need to evaluate not only stochastic variability but also trends and shifts in the environment as we develop scientific advice. Exploitation rates estimated from observations taken over several climate regime changes will not be optimal for any specific set of environmental conditions.

The existing management strategies for cod stocks are based on the precautionary approach and use the biological reference points, which are expressed in terms of fishing mortality and spawning-stock biomass. Today, the reference points on which the cod harvesting rules are based are constant, and independent of the state of the ecosystem. For this reason they are inconsistent with the ecosystem approach. If we see a long lasting change in the productivity of the cod stocks induced by a climate regime change or are able to identify good qualitative relationships between environmental factors and growth or recruitment, we may imagine that the reference points will be set as a function of the state of the environment. This would allow stocks to be harvested more heavily in more productive periods than in poor periods.

The stock management strategy is based on expected estimate of long-term yield. Such estimates are used to set optimal harvest intensity according to the accepted management targets. The only method for estimation of expected long-term yield is mathematic modelling. So to move from the constant biological references points for harvesting control of cod stocks, which are used today, to biological references points, which will be dependent on the ecosystem regime, there is a need to develop relevant cod ecosystem coupled models. Such models should be regional specific according to ecosystem specific. On the other hand they can be based on the same approaches to simulate the cod growth, maturation, cannibalism and other population variability.

The cod ecosystem coupled models will need a relevant prognosis of the state of the environment that corresponds to expected climate changes. Where there is no basis for predicting environmental drivers into the future, management strategies should be based on scenario testing. This implies development of scenarios of temperature changes as well as dynamics of cod prey and predators abundance.

Simulations should be based on a stochastic approach. Taking into account uncertainties, the probability can be expressed in terms of a risk estimate of undesirable consequences for the stock and harvest implementing a testing strategy. Especially it concerns the probability of declines in stock level below the established threshold level. Alternative future scenarios should be used to evaluate future risks and uncertainties for management.

Presently the complete procedure for estimating environmental dependent biological reference points for harvesting control of cod stocks is lacking. However existing models demonstrate their power not only to evaluate cod responses to climate change but also to test management and recovery strategies for cod stock at the different climate scenarios. One example is provided in Example 2 of Section 2.4.2. Another example of such models is STOCOBAR that describes STOCK dynamics of COD in the BARents Sea taking into account trophic interactions and temperature influences (A. Filin presentation).

The projections of the consequences of expected warming in the Barents Sea for cod stock and its harvesting are shown in Figure 2.5.1. The stochastic Riker recruitment equation was used to couple the cod spawning stock and recruitment at-age 1. Avail-

able observations on the Kola section were the basis for development of the temperature scenarios for the long-term simulations. The alternation of cold, moderate and warm periods was introduced in the temperature scenario. In addition to temperature, changes in biomass of capelin in the Barents Sea were considered in these evaluations as an element of the ecosystem scenario. The harvest control rule for cod in the simulations was used as to the management strategy, which is based on the precautionary approach. The total allowable catch was calculated using existing values of the biological reference points for the Barents Sea cod stock. Long term-simulations were performed for 5 temperature regimes: current temperatures and at temperature increases of 1, 2, 3 and 4°C.

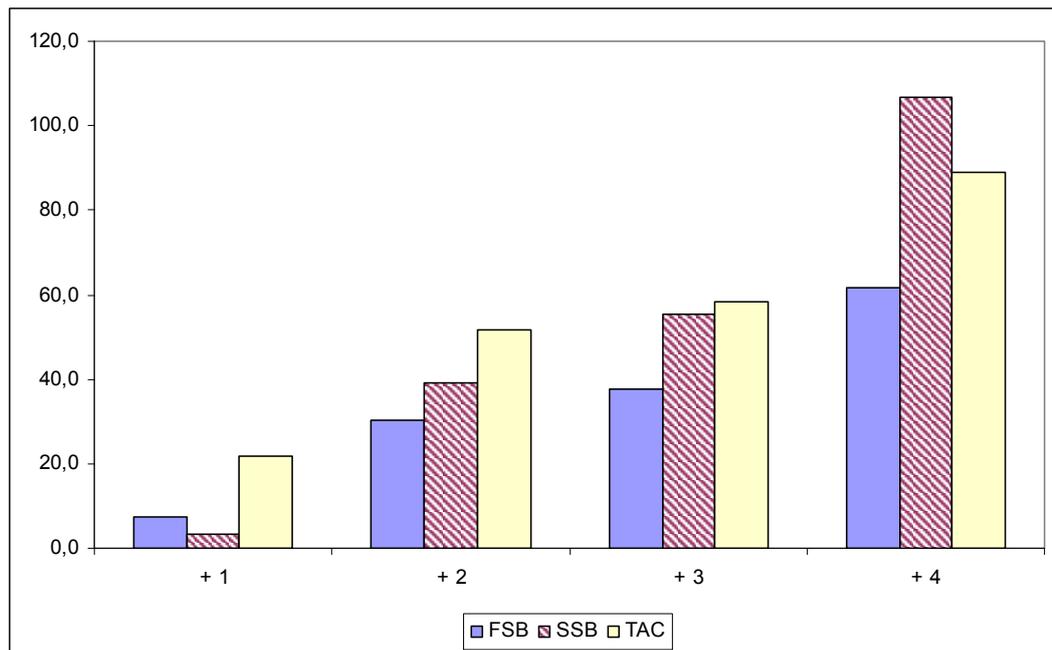


Figure 2.5.1. Relative changes (% to simulated values under the current temperature regime) of cod stock biomass and catches at temperature increase in the Barents Sea of 1–4°C according to the STOCOBAR simulations.

The results of simulations show temperature increases in the Barents Sea of 1–4°C will lead to acceleration of cod growth and maturation rates. This will affect the general production of the cod stock positively. On the other hand cannibalism in cod will also likely increase in response to expected warming in the Barents Sea. The last will have a negative effect for cod recruitment and total abundance. The results of simulations show also that with warming the cod stock can be harvested more heavily (Figure 2.5.1).

Another example of environmental impact on harvesting potential for cod in STOCOBAR simulations is presented in the Figure 2.5.2. It shows dependence of cod recovery rate on the temperature regime and capelin abundance in the Barents Sea. Thus models can be viewed as a potential tool for scenario testing of cod rebuilding strategies.

Further development of existing cod ecosystem coupled models should ensure a transition from theoretical studies of improvement in cod management to their practical implementation through updating and revaluation of referent points for harvesting control of cod stocks.

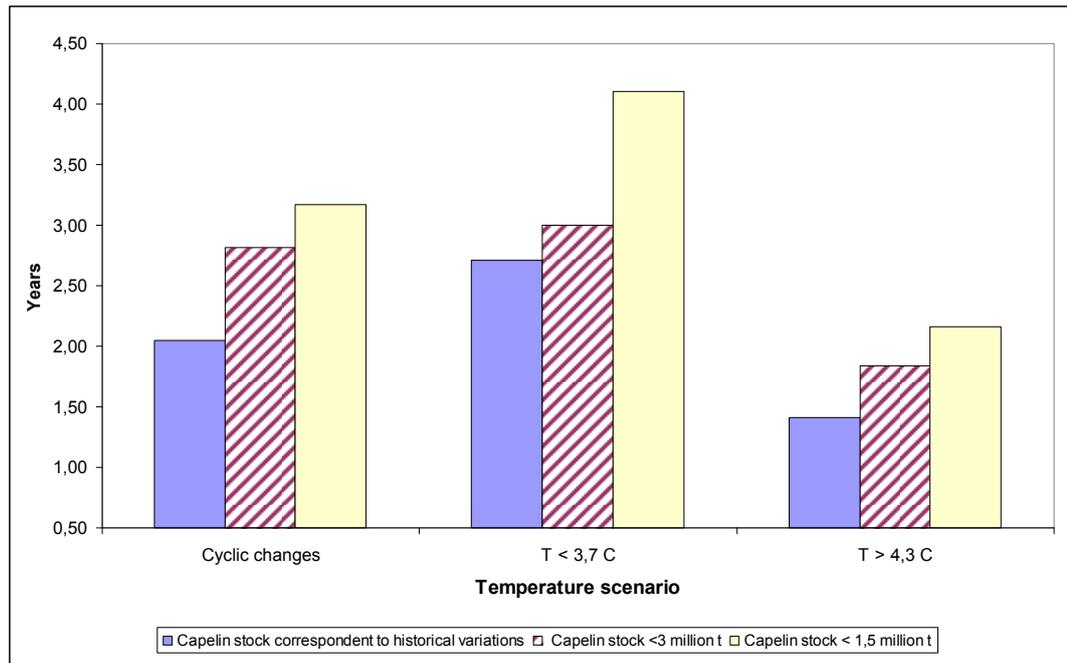


Figure 2.5.2. Mean recovery period for the Barents Sea cod stock in the SOCOBAR simulations.

2.5.1.2 Time scales: centennial, decadal, interannual (S. Sundby and B. Rothschild)

Climate periodicities and theirs ecosystem effects

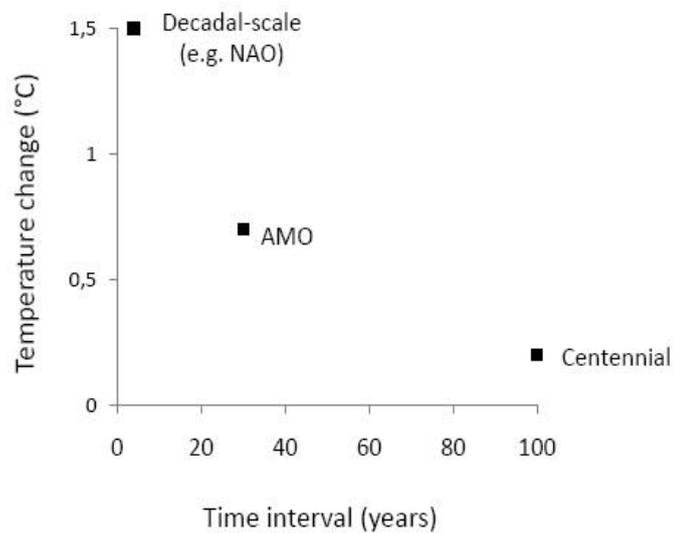


Figure 2.5.3. Change in sea temperature for three periods, from interannual to centennial, in the Northeast Atlantic during the 20th century.

The signals of sea temperature variability in the North Atlantic Ocean have occurred over a range of periods from interannual to multidecadal time scales. Within the 20th century the amplitudes of these periods have exceeded that of the human-induced climate change signal. During the 20th century the long-term average increase of sea surface temperature in the North Atlantic region has been about 0.2°C. In comparison, the multidecadal climate oscillation, known as the Atlantic Multidecadal Oscillation (AMO), in the North Atlantic shows rates of changes of 0.4°C over a 30-year time

interval averaged over the entire North Atlantic (Sutton and Hodson, 2005). The AMO signal increases with latitude (Johannessen *et al.*, 2004). For the European waters of the Northeast Atlantic (e.g. the Kola section of the Barents Sea) the rate of temperature change is typically about 0.7°C over a 30-year time interval. Interannual to decadal-scale climate variations have larger amplitudes than the multidecadal signal. Typically the rate of change of the decadal-scale signal is up to 1.5°C over a time interval of 4 years for the Kola section of the Barents Sea. The amplitude of the observed ocean temperature changes during the 20th century as a function of periodicity is shown in Figure 2.5.3. The figure may give an impression of a logarithmic relation. However, it should be strongly emphasized that this is only valid for the observations of the limited time span of the 20th century, and that extrapolation to longer time scales cannot be justified. On a millennial time scale we know that the temperature change increases again. Moreover, what is expected of anthropogenic sea temperature changes of the northern North Atlantic during the present century, i.e. in the order of 2°C, will exceed any earlier observed changes on a centennial time scale.

The marine ecosystems of the northern North Atlantic have responded to the natural climate periodicities experienced during the past century in a multitude of ways. These responses provide some insight into how marine ecosystems might respond to the predicted climate change of the 21st century. It is to be expected that the interannual to decadal-scale temperature changes will be of similar amplitudes as during the 20th century. However, as mentioned above, on a centennial time scale the amplitude of the anthropogenic climate change will far exceed that of the 20th century experience, more specifically with one order of magnitude. Therefore, the lesson from the 20th century on the effects of climate change on marine ecosystems needs to be treated with care when applied on the climate projections of 21st century.

Interannual to decadal-scale temperature changes has been shown to have strong effects on individual growth, survival and recruitment in fishes. Particularly, there are numerous documentations on the effects on Atlantic cod (Elizarov, 1963; Koslow *et al.*, 1985; Sætersdal and Loeng, 1987; Ellertsen *et al.*, 1989; deYoung and Rose, 1993; Brander, 1995; Ottersen and Sundby, 1995; Rodionov, 1995; Svendsen *et al.*, 1995; Campana, 1996; Planque and Fox, 1998; Planque and Frédou, 1999; Ottersen and Loeng, 2000; Rindorf *et al.*, 2008; Sandeman *et al.*, 2008). Moreover, it has been shown that the geographical distribution and of adult cod in the Barents Sea vary on an interannual time scale with the climate variations (Nakken and Raknes, 1987; Ottersen *et al.*, 1998). These shorter-time responses to climate change seem to be associated with processes linked to population ecology in the way that we can see that individual populations respond with respect to growth, reproduction, recruitment and distribution (Sundby and Nakken, 2008). The mechanisms behind these can partly be linked to a direct effect of temperature changes, particularly with respect to growth rates (e.g. Brander, 1995). However, it is often an indirect link where the apparent temperature response is a proxy for other processes such as variability in ocean currents which in turn influence advection of zooplankton-rich water masses (e.g. Sundby, 2000). Flux variability of ocean currents typically acts on interannual to decadal-scales, and in the northern North Atlantic such variability is influenced by the North Atlantic Oscillation (NAO) (Sundby and Drinkwater, 2007).

The shorter term ecosystem responses described above, i.e. interannual to decadal-scale responses, indicate a relatively direct mechanistic link between the climate variability and the response of the biological processes in the ecosystem. Temperature-dependent growth rates of individuals from larvae and juveniles to adult fish are such direct short-term responses. Early focus on recruitment of fish stocks showed

large interannual variations (Hjort, 1914). Recruitment processes like the match-mismatch hypothesis of the abundance of prey for larval fish (Cushing, 1974) and the bigger-is-better hypothesis (Leggett and deBlois, 1994) are other examples of short-time responses where direct effects from temperature and the direct link to the trophic level below (the abundance of the copepod prey) are involved.

Another type of ecosystem responses are those associated with longer-term climate variability, i.e. the multidecadal climate variability as exemplified by the AMO. Drinkwater (2006) showed how the general warming of the North Atlantic from the 1920s towards the end of the 1930s resulted in substantial northward shift in distributions of Atlantic fishes species. For example, most of the cod stocks of the North Atlantic showed a more northerly distribution by the end of the 1940s compared to the situation of the beginning of the 20th century when climate was cooler (Tåning, 1953). During the recent warming from the cool 1960s and 1970s a distinct northward shift has occurred for Northeast Atlantic zooplankton from temperate to arctic species (Beaugrand *et al.*, 2002). The spawning areas of Arcto-Norwegian cod along the Norwegian coast have oscillated northward and southward with the AMO during the 20th century (Sundby and Nakken, 2008). These examples show that the longer-term climate variations have different influence on the North Atlantic marine ecosystems than the shorter term variations. Despite the moderate temperature amplitude compared to the amplitudes of interannual periodicity (Figure 1) the change of species habitats are considerable. Sundby and Nakken (2008) suggested that these kinds of ecosystem responses are more indirect and act through the foodweb. This implies that such changes are associated with system ecology rather than population ecology.

Some considerations about effects of future climate change of the 21st century

It is to be expected that the projected climate change of the 21st century will generate ecosystem responses of the similar type as those generated by the multidecadal climate oscillation during the 20th century. This means that zooplankton species as well as pelagic and demersal fish species will continue to move northwards. However, the uncertainty of such assessments is that the amplitude of the projected change is substantially larger than those experience of changes from the AMO, and we will probably pass average temperatures of any earlier experiences before the mid of the 21st century. It is highly uncertain whether this might cause abrupt responses of the ecosystem and thus are impossible to predict. Understanding such abrupt changes depend on that we need to explore the mechanisms behind the changes. Simple correlations between sea temperature (or NAO) and ecosystem variables will not be successful approach towards this understanding. We need to understand the linkage with a range of the climate variables, i.e. temperature, salinity, wind mixing, stability, advection, ice cover and light. Then we need to understand how these climate variables influence fish stock directly and indirectly through the foodweb. Such an approach is only possible by combining experimental studies in laboratory and field, time-series, and basin-scale to local-scale physical-biological modelling. This approach was described by the initiation of the ICES Cod and Climate Change Programme (Anon, 1990). ICES CCC, indeed, has developed in this direction, but there are still considerable lack of process understanding, particularly, because there are still a long way go in combining experimental studies with physical-biological modelling.

2.6 Further development and improvement of climate impact models (C. Schrum and K. Drinkwater)

2.6.1 Model chains from climate models to regional models: coupled physical models-prediction models

Regional scale modelling is time consuming and cannot be performed using the ensemble approach currently chosen for the global climate modelling. It is technically impossible to use the different number of ensemble runs provided by the climate models and perform for all of them ensemble runs on the regional scale with the different model concepts involved. Identification of regional bias and errors of global models is time consuming and correction techniques need to be developed regionally for different time and spatial scale. Hence, research is required to develop regional downscaling techniques for the regional hierarchy of models involved. The employment of coupled regional ocean-atmosphere climate models might be desirable. However, currently only a few of these research tools are available and validated with respect to climate variability, an essential precondition for quantitative climate change assessment. Atmospheric regionalisation only, seems not to be a very important step forward to simulate the regional marine climate impacts and delays the process of regionalisation for the marine environment as a result of the technical work and man power involved to proceed with climate impact studies.

Major steps forward can be expected from coordinated regional climate impact studies with coupled physical-biological ecosystem models, such as those initiated by the EU-FP7 project MEECE and other parallel national and international impact projects. For the time being, the uncertainties in regional environmental changes induced by global climate change strongly limit regional assessment of climate change impact on regional ecosystems and key fish species. Alternative approaches to the marine ecosystem management are so-called 'what-if-scenarios' and sensitivity to change investigations.

2.7 References

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3 Suggestions for future work and recommendations

It is clear that in order to provide realistic impact scenarios for cod we must have good regional models to develop climate scenarios. This will require downscaling from the GCMs. However, for the latter to be useful for regional downscaling they should be able to at least recreate the current climate reasonably well. This will require research to improve the GCMs, including the necessity requirement for initialization. To help ensure that the models will deliver the necessary information required for impact studies, the impacts community should convey their requirements to the GCM modellers. Downscaling studies from the GCMs should continue to be undertaken, however, only those models that can best reproduce the present regional climate well should be used. Also, downscaling should be performed using the results from several GCMs not just one. Research should continue into the shorter term forecasting using assimilation of recent data. Until these are done the impact assessments will have to be based on “what if” scenarios. These should be carried out to help understand possible influences of climate change on cod and their ecosystems.

The combined effects of climate and of fishing need to be further explored, including methodologies using various models to determine such.

The effect of size-selective mortality on size-at-age should be further investigated covering more stocks. In addition examination of how the age structure and geographical substructure of the spawning stock affects resilience to climate change should be extended to cover as many other stocks as possible, e.g. by comparing the correlation between recruitment and temperature with the mean age of the female spawning stock. The effects of small-scale features such as fronts and eddies on cod productivity appear to be important in several areas. These are often not incorporated into even regional models although this is improving. Continual work to further improve the models in this regard is suggested.

The WKCFCC plans to write a paper for publication in the primary scientific literature to inform the impacts community in particular about the problems and difficul-

ties of generating reasonable climate scenarios. This will be undertaken from workshop participants under the lead of K. Brander and B. MacKenzie.

Recommendations within ICES

The WKCFCC recommends that WGCCC consider publishing the workshop results as an ICES Cooperative Research Report in order to make the results of the workshop more accessible to the wider scientific community.

Annex 1: List of participants for WKCFCC Meeting

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Annex 2: Agenda

Tuesday June 17

- 13:30 Welcome and Introduction (Corinna, Ken)
- 14:00 Presentations
- C. Shrum: Challenges in modelling regional climate change: Uncertainties and predictability
- H. Pohlmann: Future climate scenarios: Results from the Hadley Center
- U. Daewel: Response of larval cod to environmental changes: Scenario modelling in the North Sea

15:30 Break

- 16:00 Presentations
- G. Ottersen: Ice-age survival of Atlantic cod: agreement between paleoecology models and genetics
- M. Lindegren: The future of Baltic cod - modelling interactions between climate, foodweb dynamics and fisheries
- B. Mackenzie: Cod in the Baltic in response to climate change
- 17:30 End of the Day

Wednesday June 18

- 9:00 Continuation of Presentations
- K. Drinkwater: Response of cod to future climate change
- I. Mantzouni: Could warmer years mean good years for cod? A pan-Atlantic meta-analytic perspective
- A. Filin: Modeling analysis of the consequences of expected warming in the Barents Sea cod stock

10:30 Break

- 11:00 Continuation of Presentations
- G. Engelhard: Climate and North Sea cod distribution: a long-term approach
- P. Munk: Oceanographic changes during the last three decades at the North Sea nursery ground of 0-group cod – ideas for physical-biological linkages

12:00 Lunch

- 13:30 Discussion Group/Groups
- In addition to developing future scenarios for cod, we will address the following questions during the discussion:
- What kinds of predictions are we trying to make?
- What kinds of models will help us to make them?
- What are the critical structural inadequacies and gaps in knowledge?
- Can we quantify and communicate the uncertainties?
- How can we produce a product which is relevant and credible?
- 17:30 End of the Day

Thursday, June 19

- 09:00 Continuation of Discussion Group/Groups
- 12:00 Lunch
- 13:30 Break into Writing Groups
- Writing assignments begin to write paper on cod under future climate change, which can also be used for Workshop Report.

15:00 Break

15:00 Discussion on items arising from writing

16:00 Back to writing assignments

17:30 End of the Day

Friday, June 20

09:00 Report on Writing Assignments and Discussion on Items arising from writing. Are there issues that have not been addressed that are needed?

10:30 Break

11:00 Final discussion: Recommendations, where to go from here, deadlines for writing assignments.

11:30 Final Wrap-up (Corinna, Ken)

We are also considering writing a paper that addresses what will happen to cod under future climate change. This will be discussed during the meeting to gauge the interest and enthusiasm for such an undertaking.

Annex 3: Extended abstracts of presentations

Decadal Simulations at the Met Office Hadley Centre

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This extended abstract summarizes results from the Decadal Climate Prediction System (DePreSys), which is described in more detail in Smith *et al.* (2007). The skill of decadal predictions is examined by using the DePreSys, which is based on the Hadley Centre Coupled Model, version 3 (HadCM3, Gordon *et al.*, 2000), a dynamical global climate model (GCM). Initial conditions are generated by using HadCM3, relaxing oceanic temperature and salinity, and atmospheric horizontal winds, temperature and surface pressure, to analyses of observations. The ocean analyses (Smith and Murphy 2007) are created by four-dimensional, multivariate optimal interpolation technique. DePreSys is designed to avoid trends during forecasts caused by systematic model errors. This is achieved by assimilating observed anomalies added to the model climatology and removing the model climatology to produce forecast anomalies. The accuracy of DePreSys is assessed in a set of 10-year hindcasts (forecasts made retrospectively using only data that would have been available at the time), starting from the first of March, June, September, and December from 1982 to 2001. The impact of initial condition information is assessed by comparing DePreSys against an additional hindcast set (hereafter referred to as NoAssim), which is identical with DePreSys but does not assimilate the observed state of the atmosphere or ocean. The global annual mean surface temperature and heat content of the upper (113m) ocean were predicted with significantly more skill by DePreSys than by NoAssim throughout the range of the hindcasts. The increased skill of DePreSys over NoAssim results from an improved ability to predict El Niño for the first 15 to 18 months and thereafter mainly from initializing the low-frequency variability of the oceanic heat content. Regional improvements in surface temperature are found in many regions. Much of the regional improvement in DePreSys relative to NoAssim is coincident with improvements in upper ocean heat content.

Having established the predictive skill of DePreSys, climate forecasts started in 2005 for the coming decade are analysed. The DePreSys forecast is closer to the verifying changes observed since the forecast start date. Both NoAssim and DePreSys, however, predict further warming during the coming decade, with the year 2014 predicted to be $0.30^{\circ} \pm 0.21^{\circ}\text{C}$ [5 to 95%confidence interval] warmer than the observed value for 2004. Furthermore, at least half of the years after 2009 are predicted to be warmer than 1998, the warmest year currently on record. In the DePreSys forecast, internal variability offsets the effects of anthropogenic forcing in the first few years, leading to no net warming before 2008. In contrast, the NoAssim forecast warms during this period. An updated forecast, which is started in 2007 over a period of 30 years, confirms these findings with DePreSys global annual mean temperature being cooler than NoAssim over the coming decade. However, the Atlantic meridional overturning circulation is stronger in DePreSys than NoAssim for the whole 30 year period, with associated increased warming in the North Atlantic. Regional improvements are demonstrated in terms of the North and Baltic Seas surface temperature. Especially in the Baltic Sea initial errors which are present in the NoAssim experiment are removed in the DePreSys, letting the forecasts start from the observed state

(Figure 1). However, analysing climate changes in terms of the annual means can hide the effect that the temperature increase will be stronger in summer than in winter (Figure 2).

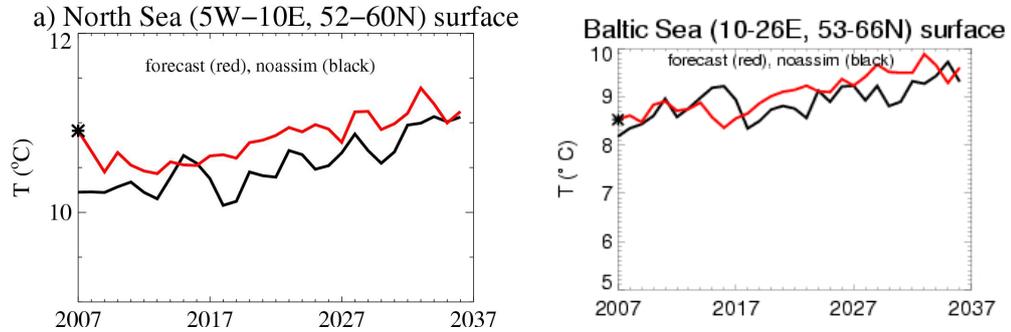


Figure 1. Surface temperature of the (a) North Sea and (b) Baltic Sea for the forecast (red) and NoAssim (black) experiments. The forecast starts (per definition) from the observed values.

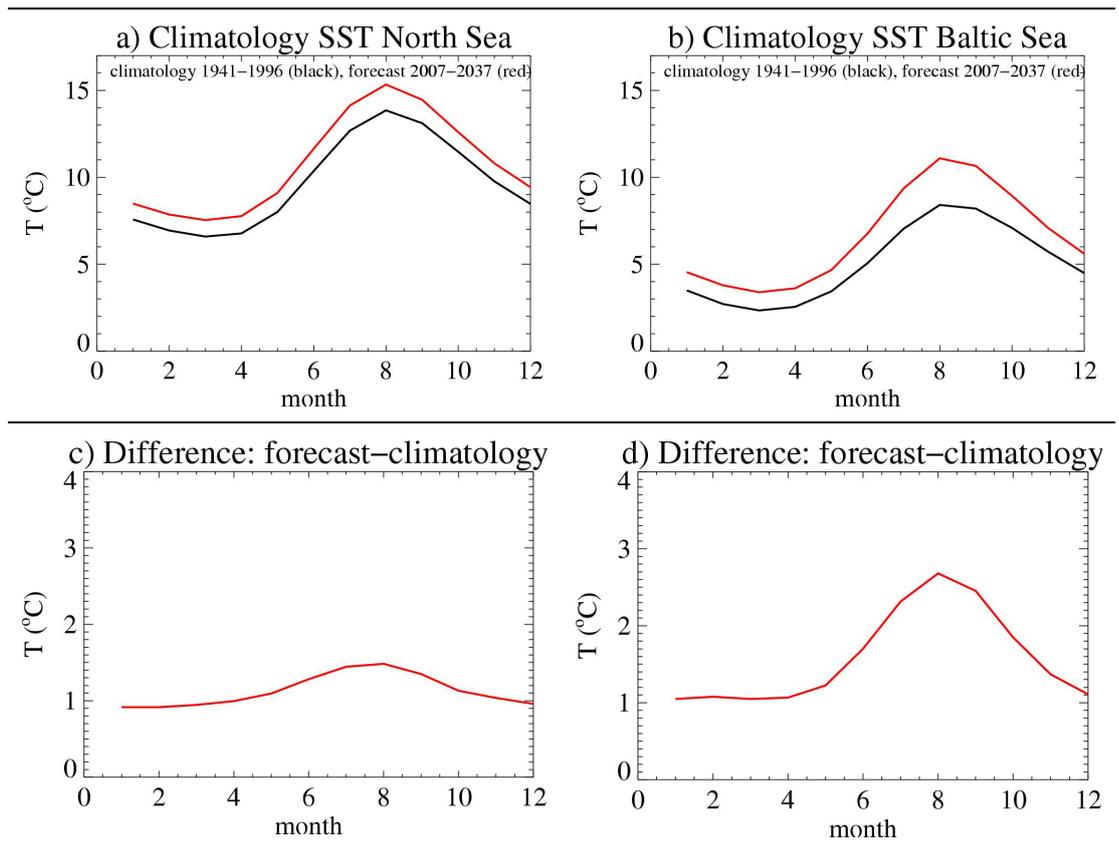


Figure 2. Surface temperature climatology of the (a) North Sea and (b) Baltic Sea average over the period 1941–1996 from a 20th century experiment (black) and 2007–2037 from the forecast experiment (red), together with the differences (forecasted temperature anomalies) of the time-series for the (c) North Sea and (d) Baltic Sea.

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Challenges in Modelling Regional Climate Change: Uncertainties and Predictability

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The presentation focused on 3 related aspects: (i) interpretation of IPCC climate scenarios, predictions vs. projections; (ii) evaluation of uncertainties of climate model projections based on their skill in modelling present-day climate and based on model spread of future projections; and (iii) discussion of some aspects of regional climate projections including the lack of regional scenarios.

The following conclusions relevant to the workshop ToRs were presented:

- Uncertainty as a result of global, regional and biological models is larger than the expected signal as a result of climate change.
- Available regional scenarios are largely based on the previous IPCC report (IPCC 2001) and are likely to be outdated.
- Only a few Regional Climate Models (RCMs) employ more than one General Circulation Model (GCM) and perform ensembles.
- IPCC scenario model projections (and consequently the RCMs based on these) are only of limited use for regional climate change assessment.
- We might be able to learn more while performing controlled sensitivity tests with validated regional models.
- Decadal-scale predictions from GCMs might provide improved forcing data, but performance declines significantly after approximately 1 decade.
- Decadal scale predictions show improvements in modelling the Atlantic Multidecadal Oscillation (AMO), but NAO variability is still not modelled sufficiently well in these models.

Remaining problems to establish regional predictions based on global decadal prediction systems face several practical problems. Regional model predictions with coupled physical and biological models for the North Atlantic waters are similarly resource demanding as the global climate models; hence we have to accept a time-lag for the regional predictions. In addition, regional climate projections are still a matter of research and many aspects and problems relevant to regional downscaling are currently not yet solved and a significant international research effort is necessary to improve the situation.

Response of larval cod to environmental changes: Scenario modelling in the North Sea

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The dynamics of the ecosystem depends on a complex interplay between a number of different factors. Not only biotic (e.g. prey, predators), but also abiotic (hydrodynamic, meteorological), and anthropogenic factors need to be considered. In terms to disentangle the impact of different processes affecting cod (*Gadus morhua*) eggs and larvae in the North Sea we developed and utilized a 3d interlinked model system (Daewel *et al.*, 2008a; Schrum *et al.*, 2006). Based on a 3d hydrodynamic model, two model systems were applied to assess on the one hand processes important for larval cod survival and on the other hand variability and interactions between environmental factors (Figure 1).

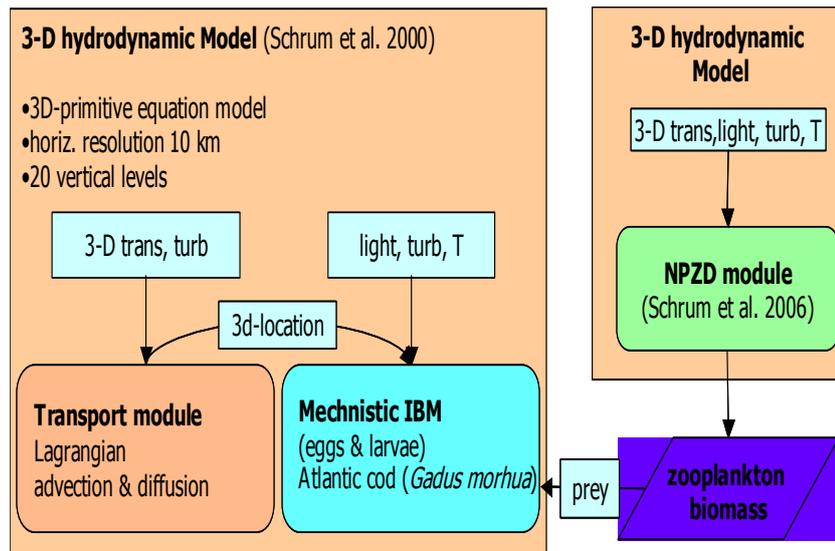


Figure 1: Schematic diagram of the coupled model system to simulate cod eggs and larvae. Right panel: online coupling of hydrodynamic Lagrangian transport model and mechanistic IBM; left panel: coupled hydrodynamic-NPZD model (comp. Schrum *et al.*, 2006) providing prey for the IBM (Daewel *et al.*, 2007).

Three types of experiments were performed to investigate a number of processes impacting larval survival:

- 1) Assessment of inter annual differences using the fully coupled model system.
- 2) Assessment of changes in environmental variables and prey biomass separately applying changes only to the IBM part of the coupled model system.
- 3) Assessment of changes in environmental variables on lower trophic level production applying the changes only the coupled NPZD part of the model system.

For the first sets of experiments, 4 climatically different years (cold: 1986, 1996; median: 1992; warm: 1990) were chosen and potential larval survival were calculated based upon prey fields obtained from the NPZD module for the relevant year. The second set of experiment was designed to investigate single environmental factors on cod larval survival, by changing three parameters of the environmental forcing separately (1: Tair ±1°C and ±2°C; 2: westwind+30%; 3: prey biomass ±20%) based on calculations for the intermediate year 1992. The third experiment deals with interrelationships between environmental factors and was applied only on the ecosystem model (ECOSMO). Again the air-temperature and the west wind forcing have been increased (1: Tair ±2°C; 2: westwind+30%).

The results from the first experiment show a strong relationship between larval survival and winter water temperature of the recent year, indicating water temperature to be a major factor. Two basic internal processes of the IBM are impacted by temperature, on the one hand the duration of the non-feeding phase on the other hand the metabolism. Associated with it is the response of larval survival and growth to changes in temperature and the prey biomass. A scenario with an increased air-temperature indicated the importance of these processes on inter annual variability.

The results from the temperature scenario (experiment 2; Figure 2) showed that even if survival is related to temperature, the temperature dependence of fish vital rates is not the dominant process, explaining the high correlation of natural variability in modelled potential survival.

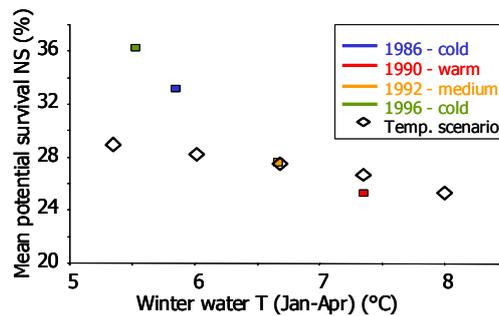


Figure2: North Sea averaged potential survival calculated by the coupled model system vs. mean winter (Jan-Apr) water temperature. Coloured: model calculations for four years, Diamonds: temperature scenario tests for 1992.

The two other scenarios tested with the IBM resulted in similarly important changes of larval fish survival in relation to changes in west wind as well as zooplankton biomass.

Our results indicate that strong interrelations among the environmental factors contribute to the strong temperature relations modelled for the simulated years. While for the North Sea a relationship of temperature and west wind has already been reported in combination with changes in the NAO index, the scenarios also calculated an earlier start of the zooplankton bloom for increasing west wind. In contrast an increase in air-temperature didn't affect the calculated zooplankton production significantly.

In conclusion, the results point to complex ecosystem dynamic affecting larval fish survival in the North Sea and we can clearly state, that a correlation with temperature is not necessarily as a result of a temperature dependent process, but rather temperature serve here as a proxy for connected process combinations.

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The future of Baltic Cod - modelling interactions between climate, food-web dynamics and fisheries

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Atlantic cod (*Gadus morhua*) is among the commercially most important fish species in the North Atlantic and has been subjected to excessive fishing pressure for many years (Brander 2007). Partly as a result of overfishing, many of the stocks have declined dramatically and are now at historically low levels (Myers *et al.*, 1996; ICES 2005b). Additionally climate variability has influenced cod stocks, principally through effects on recruitment (Brander and Mohn 2004; Stige *et al.*, 2006) but also on growth (Brander 1995; Brander 2007). The climate effect generally works through a suite of different physical and biological processes, mainly related to effects of temperature, salinity, oxygen, turbulence and advection (Ottersen *et al.*, 2001).

In several areas, the collapses of Atlantic cod stocks were part of major drivers of large-scale reorganizations of ecosystems (Frank *et al.*, 2005). These so called regime shifts are frequently caused by climatic changes (Hare and Mantua 2000; Beaugrand 2001; Reid *et al.*, 2001; Alheit *et al.*, 2005) or by overexploitation resulting in cascading trophic interactions (Frank *et al.*, 2005; Lees *et al.*, 2006). Such changes in ecosystem structure will necessarily affect species interactions, eventually influencing foodweb dynamics (Paine 1980) by producing positive and negative feedback loops that determine the ultimate response of populations to environmental changes (Ives 1995; Bakun and Weeks 2006). The recognition of this ecosystem context of the collapse of fish stocks has led to the development of more holistic ecosystem-based fisheries management (EBFM) approaches. EBFM considers both the effects of fishing on foodwebs, and the effects of physical oceanic conditions on ecosystem and hence fish stock dynamics (Pikitch *et al.*, 2004; Marasco *et al.*, 2007).

Multivariate autoregressive models (MAR(1)) provide a framework for modelling foodweb interactions at multiple trophic levels (Ives *et al.*, 1995; 1999; 2003). Within the MAR(1) framework external forcing by climate variability and commercial fishing may be included as covariates (Ives 1995; Ripa and Ives, 2003). Since, the MAR modelling may integrate internal foodweb dynamics and external forcing it has the potential to serve as an important tool in modern EBFM. Surprisingly it has hardly been extended beyond theory by applying it to real foodwebs (Ives *et al.*, 1999; Hampton *et al.*, 2006).

By statistically fitting a MAR(1) model to time-series data from the Baltic Sea, we developed a fishing and climate driven multispecies model for the Baltic Sea being able to accurately recreate the past dynamics of Baltic cod, sprat and herring (Figure 1). Based on the findings of the *Assessment of climate change for the Baltic Sea Basin* (BACC), we used a simple climate model (Ripa and Lundberg, 1996) to simulate plausible climate scenarios for the 21st century. Taking into account that marine climate is "red shifted" (i.e. positively autocorrelated) (Steele and Henderson, 1984), we generated "red-shifted" time-series of spring sea surface temperature and summer salinity based on actual data from 1974-2004. To mimic the predicted increase in SST by 3.5° C and salinity decrease by 0.8 or 5.5 psu respectively, a gradual trend in the mean over 100 consecutive years was applied. Using these scenarios as inputs, we forced our foodweb model bottom-up, exploring the impact of climate change on the

future dynamics of Baltic cod. Further, by including different fishing scenarios for Baltic cod, we elaborated on the role of management in relation to climate change. Running a vast number of stochastic simulations for combinations of climate and fishing mortalities, the probability of the stock falling below the limiting stock size (Blim) of 160 000 tonnes was computed (Figure 2). Model runs show that given even a relatively weak decrease in salinity (> 3 psu), thus impairing recruitment of Baltic cod through increased egg and larvae mortality (Nissling 2004; Köster *et al.*, 2005), only a drastic decrease in fishing mortality could avoid future stock collapses and ensure the existence of Baltic cod for future generations to come.

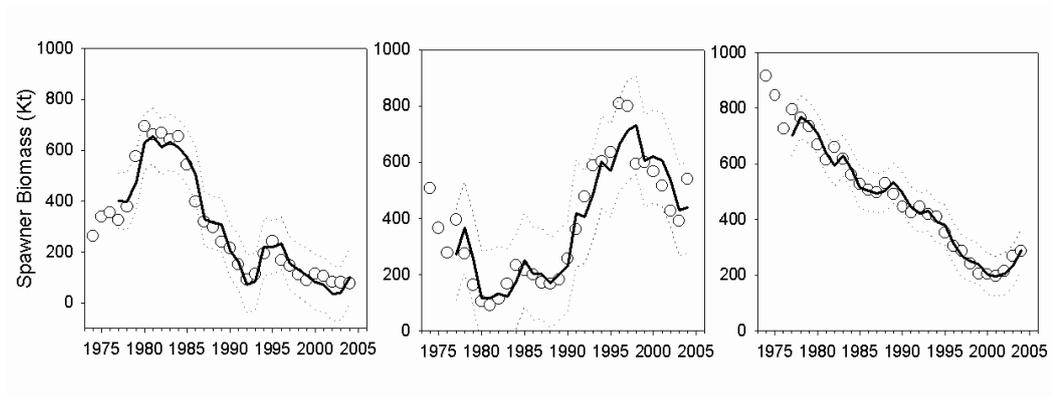


Figure 1. Development of CBS fish populations. Observed (circles) and fitted SSB values (black line) for cod (left), sprat (middle) and herring (right) from 1974–2004. Upper and lower 95% prediction intervals are displayed by dotted lines.

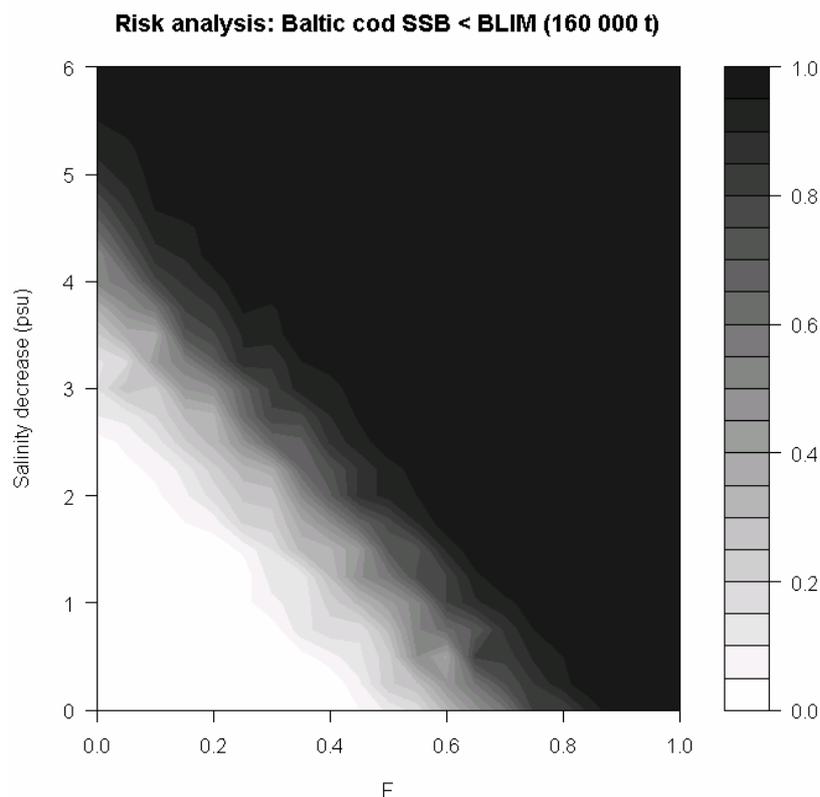


Figure 2. The probability of Baltic cod SSB falling below the limiting stock size (Blim) is computed as the % of model runs where the predicted SSB falls below 160 000 tonnes. Simulations are run for all combinations of fishing mortalities from 0-1 and decreases in salinity from 0-6 psu (relative to the mean salinity from 1974–2004). The risk of falling below Blim increases rapidly and non-linearly as salinities decrease with increasing fishing mortalities.

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The response of Atlantic cod (*Gadus morhua*) to future climate change

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Global Circulation Models (GCMs) predict significant warming throughout the globe under higher levels of greenhouse gases (IPCC, 2007). Although the amplitude of the warming varies upon the particular GCM used, they all show proportionately greater warming in the Subarctic and arctic regions. In this presentation (based upon Drinkwater, 2005) I coupled knowledge of the impact of climate variability on Atlantic cod (*Gadus morhua*) with predictions of future climate change. The focus is restricted to the impact of temperature changes on cod and I took a pan-Atlantic perspective considering the effects of warming on all of the major cod stocks from Georges Bank and the Gulf of Maine in the southwest, around the continental shelves of the North Atlantic covering Canada, Greenland, Iceland, Barents Sea and south to the Celtic Sea, southern North Sea and the Baltic. These areas cover temperatures ranging from below -1°C to over 20°C although adult cod are usually found in bottom temperatures with annual means of between 0° – 12°C s are expected to experience some of the largest anthropogenic-induced climate changes in the world.

Climate Scenarios

For quantitative analysis of the response of each of the cod stocks to anthropogenic-induced warming, we need coupled atmosphere-ocean regional models to determine the extent of the warming. These are not yet available, so I chose to use the IPCC (2001) multi-model scenarios for an indication of the rise in temperature expected in the waters occupied by cod. If we assume similar changes in the upper layer ocean temperatures as suggested might be the case by Loeng *et al.* (2005) and that the amplitude of the temperature anomalies are relatively similar with depth over the ranges occupied by cod (mostly 50–400 m), which is based on examination of depth dependent temperature anomalies throughout the cod regions (K. Drinkwater, unpublished analysis), we can use these temperature changes as at least an indication of what could be experienced by cod stocks. Therefore, the mean temperature change by 2100 ranges from a minimum of 2° – 3°C to upwards of 6°C in the northern and eastern Barents Sea. In most of the areas inhabited by cod, the modelled temperature changes range from 2° – 4°C with the uncertainties comparable to the means (IPCC, 2001).

Cod Stock Responses to Warming Temperatures

To predict the abundance response of the present day cod stocks to future warming, I relied upon the following. Since today's cod stocks are not observed much above annual mean bottom temperatures of 12°C (Dutil and Brander, 2003), I assume that this relationship will continue to hold into the future. Thus, if bottom temperatures warm beyond 12°C , I assume that the cod will disappear. Second, the temperature-recruitment relationships found by Planque and Frédou (1999) and shown in Figure 1 was converted into a change in recruitment as a function of surface temperature change and plotted against the mean annual bottom temperature of the stock (Figure 2). At bottom temperatures $<5^{\circ}\text{C}$ the recruitment increases with increasing temperature and at temperatures $>8.5^{\circ}\text{C}$, the recruitment decreases. At temperatures between these 2 values, there is little change with temperature. This provides a clue as to what will happen to recruitment under the predicted temperature changes. For example, Georges Bank cod live in bottom waters with an annual average of approximately 8°C and there is currently no rela-

tion between SSTs and recruitment (Figure 2). However, if mean bottom temperatures increased by just one degree, then it is expected that recruitment would become temperature dependent such that the warmer temperatures would result in decreasing recruitment. If the higher temperatures were to continue, this would tend to reduce the stock.

With a sustained 1°C change, several of the southern cod stocks become stressed. It is predicted that the cod stocks in the Celtic Sea and the English Channel would eventually disappear as the waters warmed to 12°C and higher (Figure 3). Stocks in the Irish Sea, the southern North Sea and Georges Bank would decline owing to decreasing recruitment with increasing temperatures. On the other hand the cold-water stocks, such as most of those off eastern Canada, as well as off Greenland, in the Barents Sea and the Kara Sea would benefit from increased recruitment as a result of the warmer waters. The recruitment levels of the remaining stocks would not change appreciably. As the temperature increased from 1° to 2°C above present day values, it is expected that the Irish Sea stock would disappear. The Georges Bank and North Sea stocks would continue to decline and the stocks in the Kattegat, off West Scotland and the Faroes would begin to decline owing to decreasing recruitment. Those stocks that increased under a 1°C change would continue to increase with the exception perhaps of the Flemish Cap stock whose recruitment would level off. The remaining stocks would not see any change in recruitment. At a temperature increase from 2° to 3°C, we expect to see the disappearance of the Kattegat and North Sea stocks. The southern most stocks on the western Atlantic (Georges Bank, the Gulf of Maine and the Browns Bank/Bay of Fundy) would all be in decline. Icelandic stocks would begin to show signs of declining recruitment, joining the Faroes and the West Scotland stocks on the eastern side of the Atlantic. The recruitment of the Barents Sea stocks would level off, as would the southern Grand Banks stocks but most of the Canadian stocks, as well as those off West Greenland and in the Kara Sea, would continue to improve. For a change from 3° to 4°C temperature change above present day values, the Georges Bank stock is likely to disappear. The Norwegian coastal cod stocks would begin to see declining recruitment along with the Flemish Cap stock. The recruitment of the eastern Scotian Shelf, northern Gulf of St. Lawrence, southern Newfoundland, Greenland, and the Kara Sea stocks would no longer increase. Only in the southern Gulf of St. Lawrence and southern Labrador/northern Newfoundland stocks would the recruitment continue to increase.

Possible Additional Changes

The above analysis suggests the possible disappearance and decline in abundance of the southern stocks and increased recruitment and abundance of the northern stocks. Warming temperatures should also result in improved growth rates in general (Brander, 2000) and cod production (Dutil and Brander, 2003) resulting in higher biomass especially in the northern regions. There should also be a northward range extension as observed in past warm periods (Jensen, 1939; Blacker, 1957), perhaps including beyond the Barents Sea further into the Arctic. Spawning locations will also move northwards as observed in the past (Vilhjálmsón, 1997; Sundby and Nakken, 2008) and changes in migration times for those stocks undertaking annual movements from their overwintering grounds to their summer feeding and spawning areas.

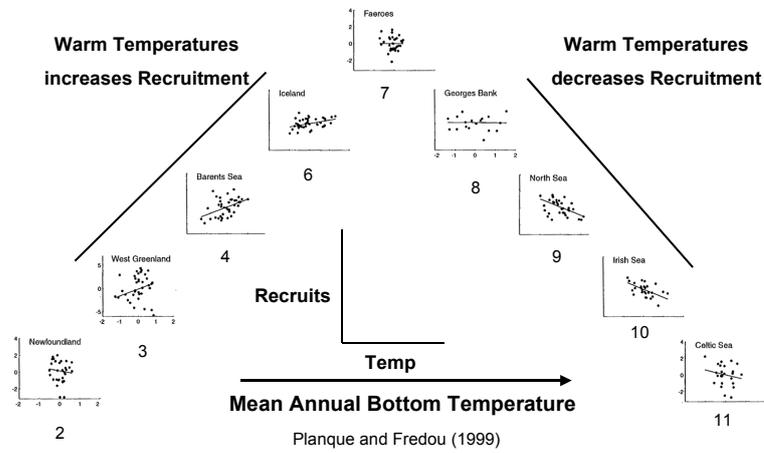


Figure 1. The relationship between recruitment and temperature for various cod stocks. The numerical values at the bottom of the plots represent the mean annual bottom temperatures. Note that for the cold stocks the relationship is generally positive while for the warm water stocks it is negative. There is no relationship in the mid-temperature range. This is based on Planque and Frédou (1999).

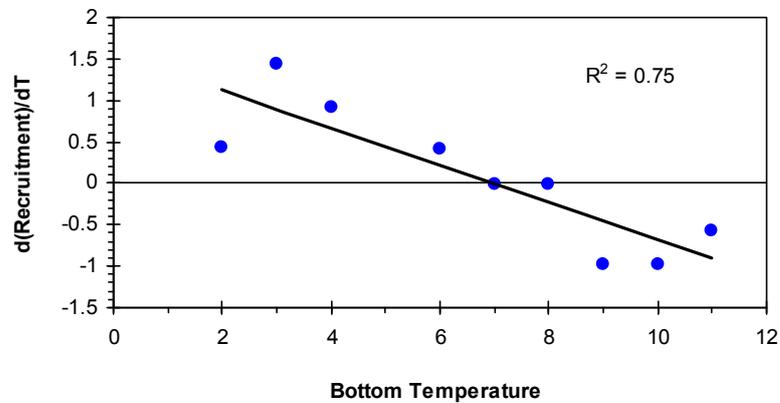


Figure 2. The change in recruitment with surface temperature for various stocks as a function of their mean bottom temperature.

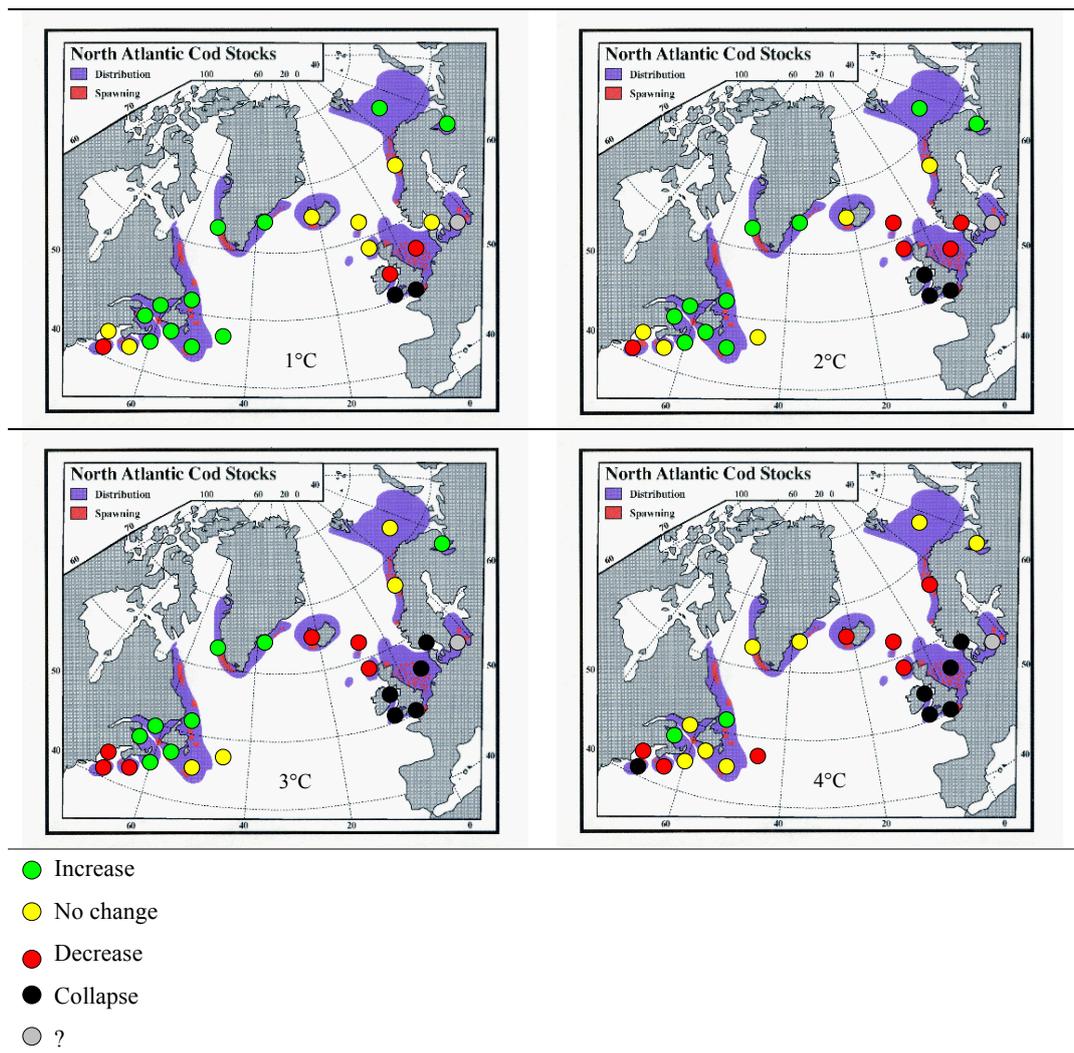


Figure 5. The expected changes in the abundance of the cod stocks with 1°C (Upper Left) temperature increase above present day values, increase from 1° to 2°C (LL), 2 to 3°C (UR) and 3 to 4°C (LR).

Concluding Remarks

These projections have been made ignoring industrial fishing that we know will play a strong and in some cases dominant role on fish abundance, distribution and growth. Future changes to the cod will also depend on the changes to other parts of the ecosystem including the overall primary and secondary production in the North Atlantic and more specifically in the specific food for larval, juvenile and adult cod such as *Calanus finmarchicus* for the more northern stocks and *Paracalanus* and *Psuedocalanus* for several of the more southern stocks (Heath and Lough, 2007). I have only considered changes in ocean temperatures associated with local atmospheric heating. Temperature may also change substantially as a result of variations in the circulation patterns, as well as in the strength of the mixing and stratification. Thus, while the predictions presented of what might happen to the Atlantic cod under future warming are consistent with our present understanding, the actual response still remains highly uncertain.

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Could warmer years mean good years for cod? A pan-Atlantic meta-analytic perspective

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This study aims to identify the effect of temperature on cod (*Gadus morhua*) population dynamics by meta-analyzing data across the species distributional range in the North Atlantic. Our dataset consists of spawner (S), recruitment (R) and temperature (T) time-series for 21 eastern and western cod stocks. Regarding T, we use annual spring (spawning season) estimates in the upper water layer (0-100m). We are employing a twofold approach, aiming at different but complementary issues; (i) the identification of the general pan-Atlantic pattern of T impacts, with special focus on the extreme temperature and/or recruitment events and (ii) the incorporation of these climatic effects in the spawner-recruit (SR) models in order to improve the predictive capacity and investigate the possibility that SR parameters depend on ecosystem characteristics.

The first method focuses on the identification of the influence exerted on R or R survival ($\log(R/S)$) during years of extreme low or high T. It is therefore based, in large part, on the classification of exceptional population observations according to the exceptional T events. Similar non-parametric, classification approaches have provided insights both in stock specific and in broad scale, comparative analyses of SR data (e.g. Rothschild and Mullen, 1985, Myers and Barrowman, 1996). Within stocks, we define these extremes as corresponding to observations below the 25th or above the 75th percentiles, respectively. In a similar way we have defined the years of weak or strong R year-classes. Also, we expect that the T effects will be stronger at the extremes of the cod thermal distribution (Myers, 1998). Therefore, we have defined two sets of stocks: "Hot" and "Cool", including stock data within either the upper or the lower temperature intervals, respectively. The interval limits were approximated by the 25th ($T_{25\%ile}$) and the 75th ($T_{75\%ile}$) percentiles of temperature across the species range. For every Hot or Cool stock, we estimate effect sizes quantifying (a) the probability of strong R year-class during years of low T vs. the probability during low T years and (b) whether R strength differs significantly between years of high and low T and (c) the correlation between the entire time-series of R or $\log(R/S)$ and T. The effect sizes (ES) on an across stocks basis are analyzed using random effects meta-analysis (Cooper and Hedges, 1994), a conservative approach which allows ES to differ not because of various amounts of data available for each stock but also as a result of variability in their responses to environmental forcing.

The results provide strong evidence that extremely warm years result in extreme strong (weak) R year classes for the Cool (Hot) stocks and vice versa. Suggestively, in Figure 1a it is shown that for the Cool stocks, the probability of strong R is higher at high T. In Figure 1b, for the Hot stocks, we plot the stock specific estimates of the log ratio between mean $\log(R/S)$ during extreme high and low T. Using the non-parametric Wilcoxon test it is seen that in the upper thermal limit this log ratio is negative.

The next approach involves the study and integration of T effects on the parameters of the SR models. To this end, we develop the models using hierarchical (mixed

models and Bayesian inference) approaches which allow the parameters to be modelled across the cod stocks (Gelman and Hill, 2007). The method offers various advantages and can be especially useful with fisheries data which are usually limited and characterized by high variability (Myers, 2001). SR parameters, maximum reproductive rate at low stock size (alpha) and habitat carrying capacity (CC), are biologically and ecologically meaningful and thus depend on both species traits, which are common across stocks, and also on the ecosystem conditions experienced by individual populations. These across stocks relationships in the parameters can be integrated in the hierarchical model structure and thus “strength is borrowed” across stocks (Hilborn and Liermann, 1998). It is shown that CC depends on the stock specific habitat size (40-300m) and this can explain almost half of the variability observed across the species range. More importantly, by combining data across the cod distributional range, and thus from the whole thermal range, it is proved that T has significant effects on R survival (parameter alpha). The relationship is shown to be non-linear; on average, survival increases with T up to almost 5°C and after this point negative effects prevail (Figure 2a). The critical T varies among stocks between 3-5°C. Differences in T across the cod range can explain 60% of the variability across stocks in alpha. It is also revealed that the variability left unexplained is stronger in the lower thermal range compared to stocks in colder waters. Thus, temperature seems to be the limiting factor for stocks experiencing higher T on average, while in the lower limit other factors can have a substantial influence.

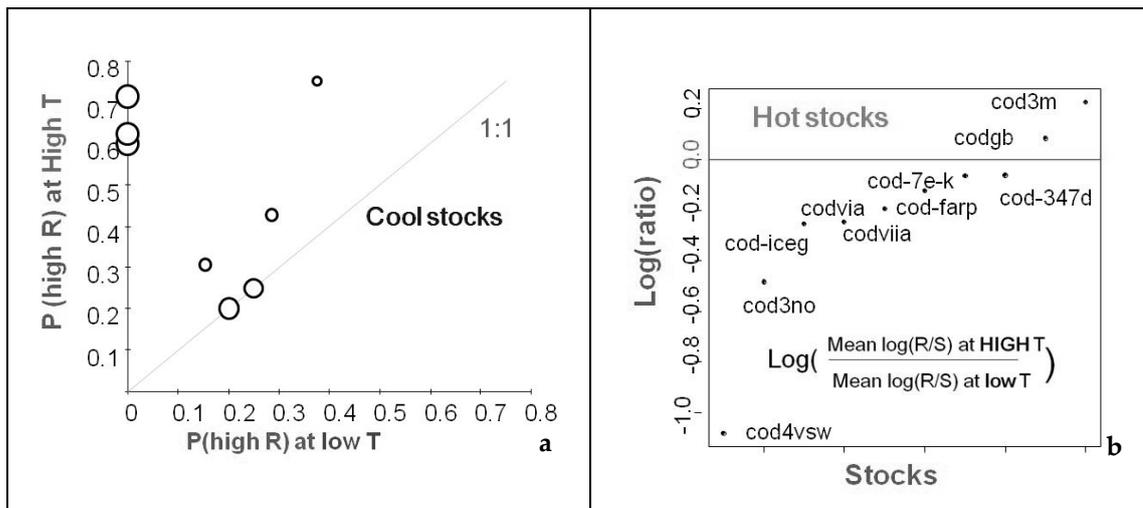


Figure 1. a. Probability of strong R year classes during years of extreme high T plotted against the corresponding probability during low T years for the Cool stocks. b. The log ratio of mean R survival between years of high and low T (formula on the plot) for the Hot stocks.

In Figure 2a, the expected change in alpha following an increase of 3°C in mean T is shown. Climatic effects on alpha have implications also for the CC, defined either as the maximum R or R at equilibrium, and for stocks in warmer waters the expected reduction can be up to 30%. The hierarchical SR models can be extended to include additional factors that influence R strength and CC on a pan-Atlantic or regional basis. The technique could be also applied to growth models incorporating T effects. Coupled SR and growth models can provide further insights to a climate change sensitive management approach (Kell *et al.*, 2005).

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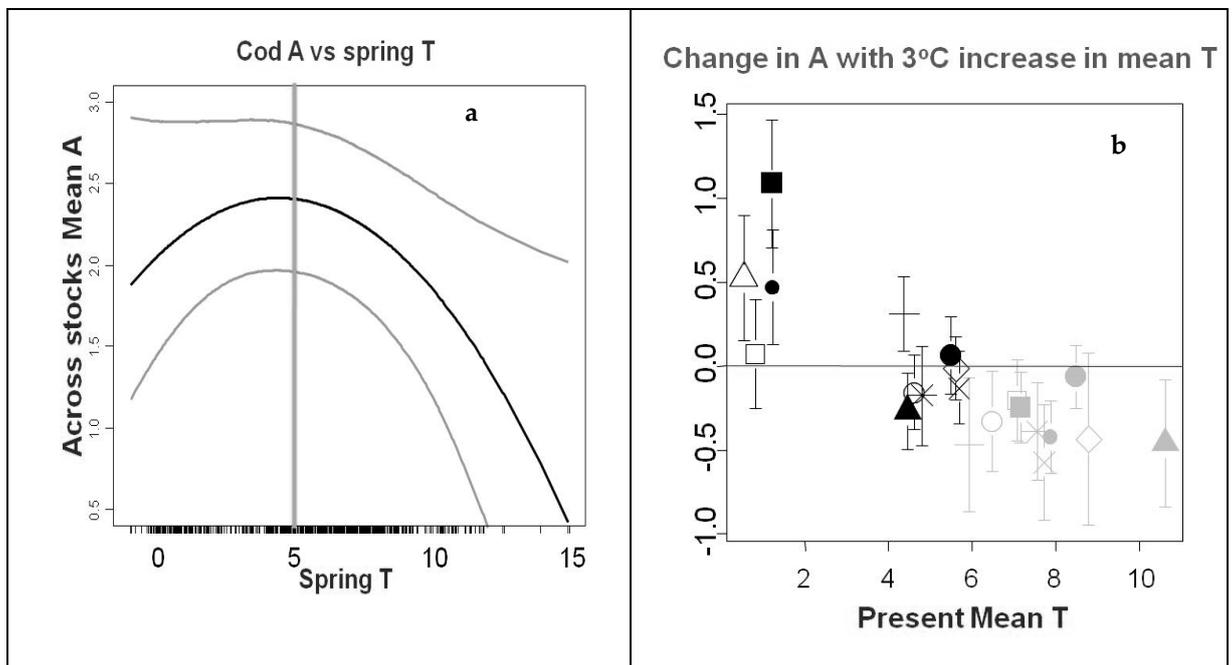


Figure 2. a. The mean quadratic relationship of parameter alpha (slope at the origin in the Ricker model) with T. **b.** The expected change in stock specific alpha's following an increase of 3°C in mean T. Grey (black) symbols correspond to stocks in warmer (colder) waters.

Modeling the consequences of expected warming in the Barents Sea on the Atlantic cod stock

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The aim of this study was to conduct quantitative analysis of the response of the cod stock in the Barents Sea to future climate changes using the STOCOBAR (STOCK of COd in the BARENTS Sea) model which has been developed at PINRO. This is a fish-ecosystem coupled model that describes stock dynamics of cod in the Barents Sea and takes into account trophic interactions and environmental influences. It can be used for predictions and historical analysis of cod stock development, as well as for estimation of effectiveness of different harvest and rebuilding strategies.

The STOCOBAR model has no geographical resolution, i.e. the processes are simulated without area differentiation. The time-step of the model is one year. The model includes cod as a predator and seven of their prey species: capelin, shrimp, polar cod, herring, krill (euphausiids), haddock and young cod (cannibalism). In our study we included capelin and juvenile cod only as a prey species. The standard Ricker recruitment equation was used to couple the cod spawning stock and recruitment at-age 1. The stochastic nature of the recruitment processes was realized by including residues in the simulated data.

Long-term estimations of the influence of ecosystem factors on the cod stock development are realized in the model by using stochastic ecosystem scenarios generated within the model. Kola section observations were the basis for development of the temperature scenarios for our simulations. We introduced the alternation of cold, moderate and warm periods in the modelled temperature scenarios. This may be regarded as a deterministic component in long-term year-to-year dynamics of water temperature. In our study the cold periods include temperature less than 3.7°C, the warm periods have temperatures higher than 4.3°C and for the moderate periods temperature ranged from 3.7°C to 4.3°C. The duration of these periods were set equal to 5 year. The actual values of temperature for cold, moderate and warm periods were selected randomly from historical data within the various periods.

In addition to temperature scenarios, the long-term simulations of cod dynamics in the Barents Sea need a scenario of year-to-year variations in the capelin stock. This we developed taking into account the observed relationship between changes in cod and capelin stocks. Historical data indicate that the probability of appearance of a large capelin stock is much higher if the cod spawning stock in the previous year was lower than 400 thousand tones. Therefore we set the scenarios for capelin stock dynamics on the basis of random selection of values from historical data of the cod spawning-stock biomass calculations in the model. In our analysis we used such an approach for the development of capelin stock dynamics scenario with current temperature regime and a temperature increase of 1°C or 2°C. For ecosystem scenarios at temperature increases of 3°C or 4°C we applied another approach. Taking into account that capelin is a cold species we assumed that at high temperature increases in the capelin stock size in the Barents Sea will decrease independent of the cod stock. We assumed that at temperature increase of 3–4°C the capelin stock will be at a low historical level only. Therefore in this case we set the capelin scenario by random selection of values from available historical data that were less than 2 000 thousands tones.

For the analysis of impact of expected warming on cod in the Barents Sea we conducted the long-term-simulations at 5 temperature regimes: current temperature regime and temperature increases of 1°C, 2°C, 3°C and 4°C. To obtain temperature scenarios for temperature increases of 1-4°C we simply add an expected temperature increment to the current temperature regime. The harvest control rule for cod in our simulations corresponds to the management strategy, which is based at the precautionary approach. The cod yield at the all temperature scenarios was calculated using existing values of the biological references points for the Barents Sea cod stock.

For every temperature regime we carried out 10 runs with a modelled period of 250 years for every run. The mean long-term values for the following parameters in the cod stock were estimated: growth rate (increments in body weight and in body length); maturation rate (proportion of mature fish by age, mean age of fish in spawning stock); annual consumption of young cod by cod (cannibalism); recruitment at-age 3; abundance and biomass of fishable and spawning cod stocks; and total allowed catch (TAC). The results of the simulations show that raising the temperature in the Barents Sea of 1-4°C will lead to acceleration of cod growth and maturation rates. This will positively affect the general production of the cod stock. On the other hand, cannibalism will also increase in response to expected warming in the Barents Sea. The last will have a negative effect on cod recruitment and total abundance. The summarized consequences of temperature increase in the Barents Sea for the cod stock and catches are presented in Figures 1-2.

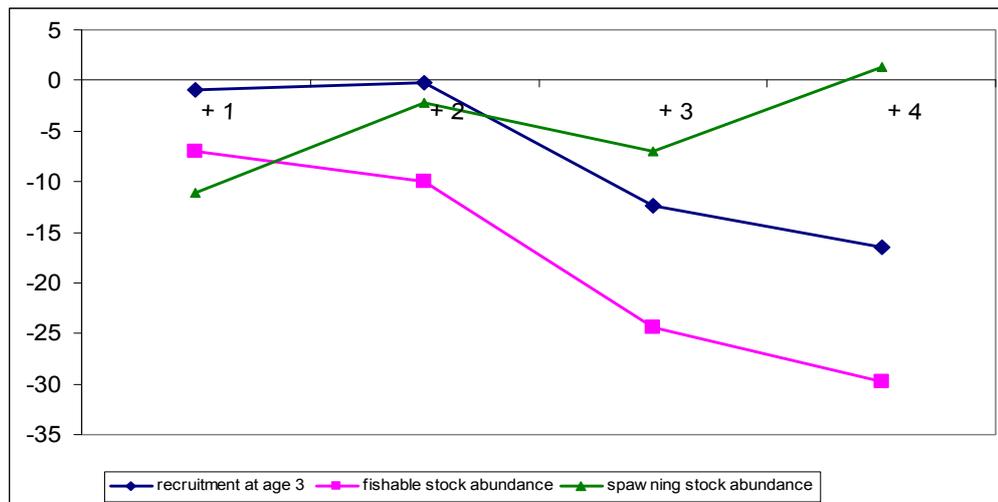


Figure 1. Relative changes (in % relative to the current temperature regime) of recruitment, fishable abundance and spawning stock abundance of cod at temperature increases in the Barents Sea from 1 to 4°C according to the STOCOBAR simulations.

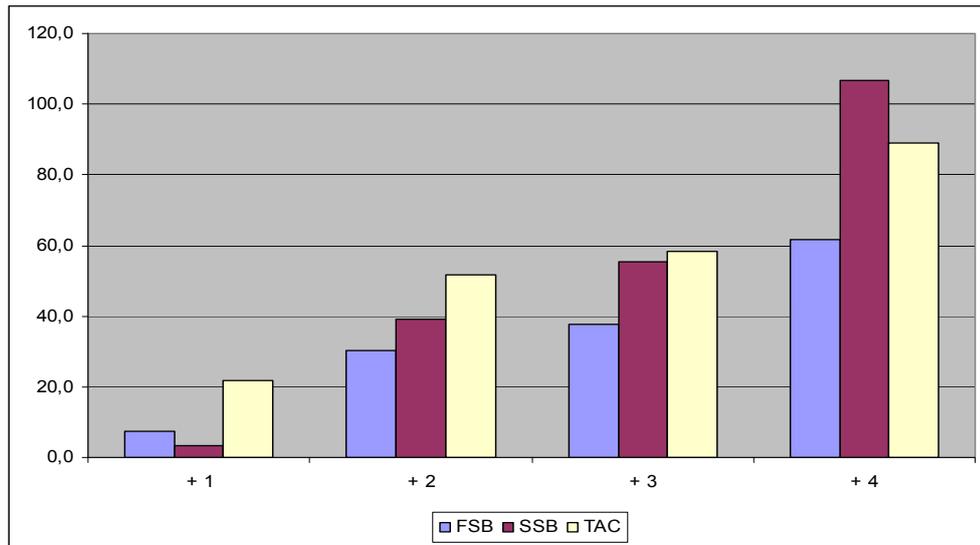


Figure 2. Relative changes (% to simulated values under the current temperature regime) of cod stock biomass and catches at temperature increase in the Barents Sea of 1–4°C according to the STOCOBAR simulations.

Climate and North Sea cod distribution: a long-term approach

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Recent studies based mainly on IBTS survey data have highlighted that cod *Gadus morhua* within the North Sea, over the past 3 decades, have shown a northward shift in mean distribution (Hedger *et al.*, 2004; Perry *et al.*, 2005; Rindorf and Lewy 2006). Two main hypotheses have been put forward, one related to climate warming and one to higher fishing effort in the southern compared to northern North Sea; but the rather short time span of the survey data has complicated disentangling these hypotheses. This has motivated the current study based on British commercial catch per unit effort (CPUE) data over a far longer time span (past 9 decades) covering both warming and cooling periods, and including periods of contrasting levels of fishing effort.

For the period 1913–1980 (except war years), data were from historical fisheries ‘statistical charts’ (catalogued in Engelhard 2005), which were produced by the UK Ministry of Agriculture, Fisheries and Food (MAFF; now the Department for Environment, Food and Rural Affairs [DEFRA]). These show fishing effort (hours fished) and fish landings by British otter trawlers (either steam or motor driven) for each ICES rectangle in the North Sea, into England and Wales (1913, 1967–1980) or into England, Scotland and Wales (1920–1967). For 1968–2007, data on otter trawler landings into Scotland were from the Scottish Sea Fisheries System (SSFSS) held by the Fisheries Research Services (FRS, Aberdeen) database (e.g. Greenstreet *et al.*, 1999). For 1982–2007, data on otter trawler landings into England and Wales were from the Fisheries Activity Database (FAD) of DEFRA. Combined, these data represent almost all British trawling effort in the North Sea during 1920–1938 and 1947–2007 (and about 10% of the effort in 1913), spatially detailed by rectangle (specialised trawling fleets such as *Nephrops* trawlers were not included in the analysis).

Indeed, long-term CPUE data indicate that marked shifts in North Sea cod distribution have occurred throughout the 20th century. We are assuming that relative CPUE by the commercial fleet gives a reasonably good indication of the spatial distribution of the species. We acknowledge that potential bias might arise from uneven distribution of effort by more or less powerful vessels within the North Sea.

Figure 1 shows, by decade, the distribution of cod CPUE over the North Sea, from the 1920s up to the 2000s. We have normalized the data for each period, to overcome the confusing effect of the increase in fishing power of trawlers particularly after the 1960s. In the 1920s and 1980s, cod CPUE tended to be highest around the Orkneys and Shetlands, from the 1930s to 1950s to the north-east of England, and in the 1990s and 2000s more in the eastern half of the North Sea. Interestingly, the spatial distribution of cod in the 2000s appears almost opposite to that during most decades of the Twentieth Century.

A marked southward (and less marked eastward) shift occurred from the 1920s–1950s, followed by a generally more northward shift from the 1950s onwards, but with fairly irregular changes in latitudinal centre of gravity of distribution during the 1980s and 1990s (e.g. relatively south in the late 1990s). A noticeable eastward shift occurred in the 1980s–1990s. Finally, in the 2000s there was again a north- and westward shift (related to cod becoming somewhat more numerous off Shetland and very

rare in the southern North Sea). The trend in depth distributions of cod (cf. Dulvy *et al.*, 2008) closely mimics that of the latitudinal distributions, which is unsurprising given the general north-south depth gradient in the North Sea. Meanwhile, temperatures were generally low in the 1920s, increased up to the 1940s, then dropped until the 1960s, since when the current period of substantial warming has begun.

Initial analysis suggests that long-term cod distribution shifts are not straightforwardly linked to either climate change or fishing pressure. A more thorough statistical analysis will be needed for a firmer conclusion about the factors behind the long-term cod distribution shifts, including interpretation in the light of recent process-oriented studies. This may include additional environmental variables as suggested during the 2008 ICES Workshop on Cod and Future Climate Change (WKCFCC; e.g. marine monitoring data described by Mackenzie and Schiedek [2007]).

Acknowledging this, the preliminary results strongly suggest that it would be too simplistic to solely attribute the recent northward distribution shift of North Sea cod to global warming.

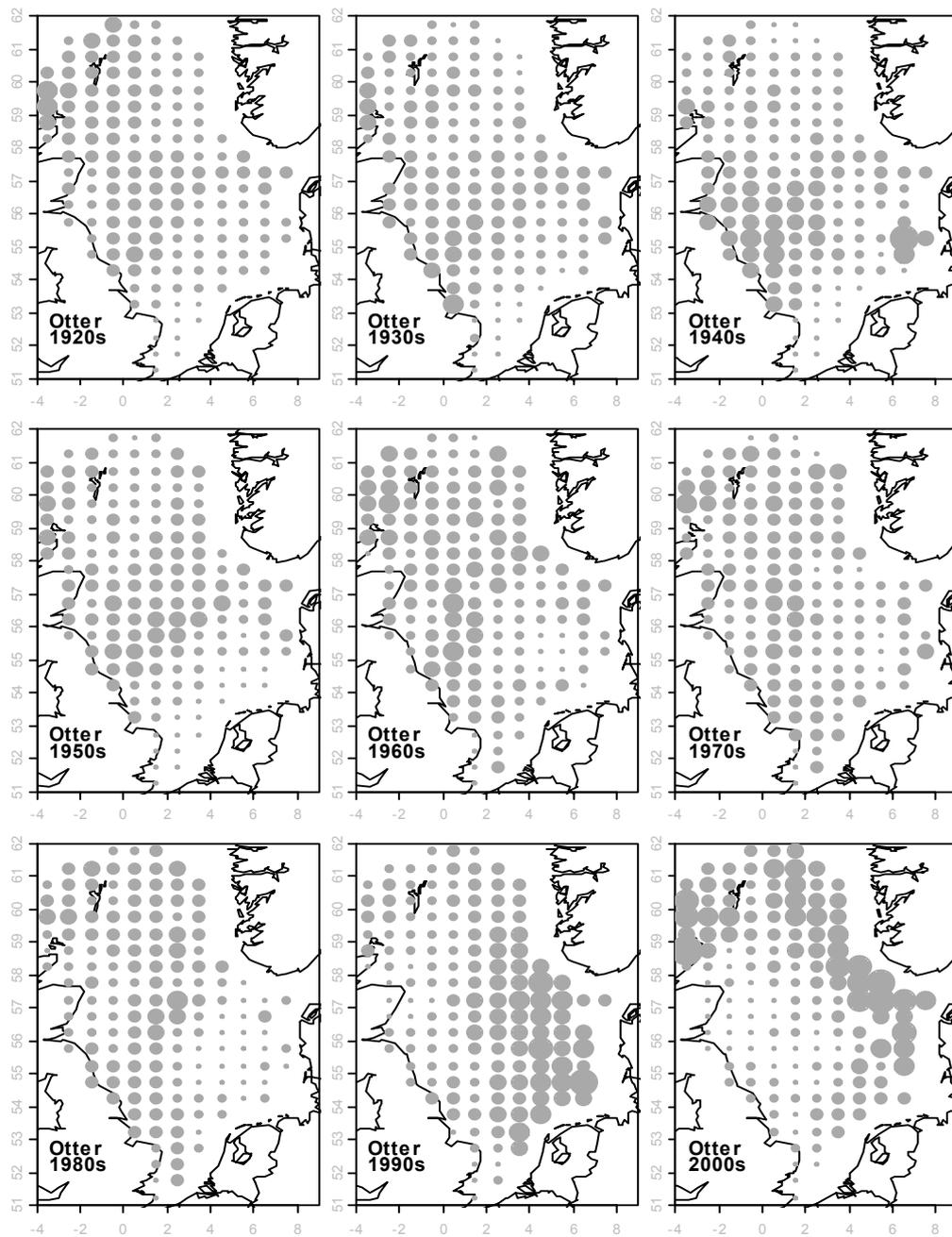


Figure 1. Long-term changes in relative cod catch per unit effort within the North Sea. For each decade, maps show spatial distribution of cod CPUE by British trawlers landing in England, Scotland & Wales.

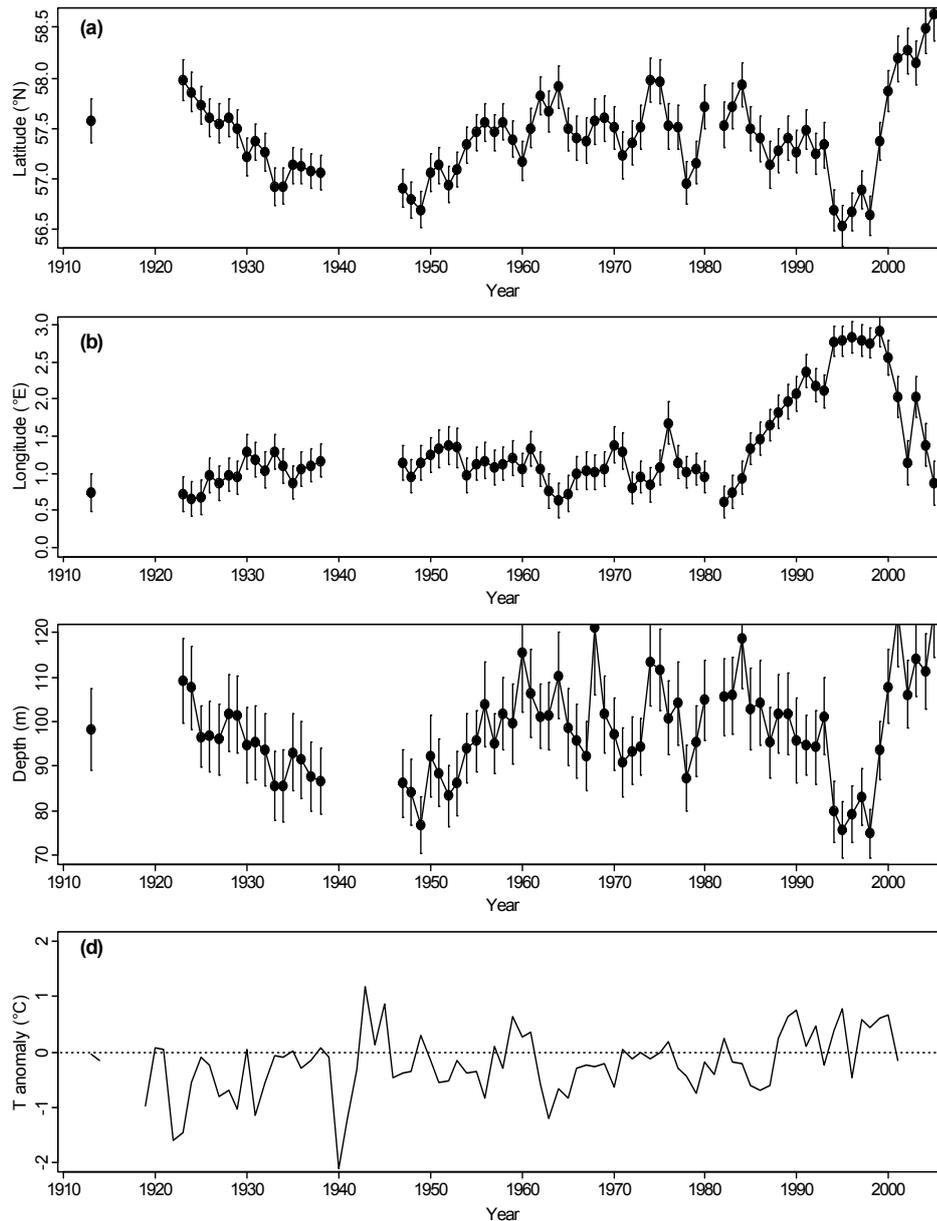


Figure 2. Long-term changes in (a) latitudinal and (b) longitudinal centre-of-gravity of estimated North Sea cod distribution based on commercial landings (calculated as the mean latitude and longitude weighted with cod CPUE; bars indicate SE of weighted means); (c) long-term changes in mean depth distribution of North Sea cod (with SE); and (d) variability in mean gridded SST in the North Sea (data from Ken Drinkwater, IMR), expressed as annual anomalies against a 1971–2000 baseline.

The study was supported by CEFAS Seedcorn project DP233 (Spatial Analysis of Historical Fisheries Data) and the European Union Framework 6 project Reclaim (resolving Climatic Impacts on Fish Stocks). Joyce Petrie, Bill Turrell and Phil Kunzlik (Fisheries Research Services) provided Scottish fisheries data from 1967 onwards. Suzy Baldry contributed to the digitizing of CEFAS historical fisheries data and Peter Robinson extracted the data from the England & Wales Fisheries Activity Database.

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Influence of oceanographic changes at the nursery grounds of 0-group North Sea cod

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Consideration of realistic spatial heterogeneity is important when interpreting vital rates and population structure of marine organisms. In the marine environment, fronts, boundary layers, pycnoclines, gyres and other smaller spatial features play a significant role in determining conditions for marine life. Specifically processes related to hydrographic fronts appear to play an important role in the advection and/or retention of fish eggs/larvae and other planktonic organisms. This has been evidenced by a number of field studies (Kiørboe *et al.*, 1988, Munk and Nielsen, 1994, Lochmann *et al.*, 1997), and by biophysical modelling studies exploring drift and dispersive processes in well-known nursery areas of fish larvae (e.g. Werner *et al.*, 1996, 2001). These studies demonstrate the importance of the mesoscale variability in water density, and of the flowfield in the vicinity of frontal features. Flow convergence and divergence are particularly intense near fronts, and fish larvae and other plankters can potentially be concentrated in the frontal zone as a result of factors which direct the horizontal/vertical movement of the organism. Among these are physical factors such as light, water turbulence and flow, as well as the biological factors such as larval buoyancy, swimming performance and availability of prey (Sclafani *et al.*, 1993).

Studies on the early life of North Sea cod carried out during the last two decades illustrate a marked correspondence between frontal features and peak abundances of cod eggs, larvae and pelagic juveniles. Apparently the hydrographic fronts enhance conditions for cod early life, as evidenced by elevated prey abundances and elevated cod growth rates in the central section of the fronts (Munk, 1997, 2007). Hence it is hypothesized that the oceanographic changes in the North Sea influenced the strength and spatial extension of hydrographic fronts in the area, and thereby influenced the conditions, growth and survival of recruiting cod.

This hypothesis is investigated by inspecting hydrographic variability at major nursery grounds for cod in the North Sea. The nursery grounds are identified and demarcated from catch data of pelagic juveniles from the North Sea International 0-group Gadoid Surveys (Holden, 1981). Three major grounds are identified, named after the adjacent bank: Viking Bank, Ling Bank and Great Fisher Bank, and for each of these, an area of three ICES statistical rectangles are chosen as central nursery area. From the ICES hydrographic database bottom salinity and temperature measurements are retrieved from these areas for the months June, July and August from the years 1965 to 2005. Subsequently, the average for each year and area is calculated and illustrated.

These observations of hydrography at the nursery grounds during the four decades illustrate the significant variability, a marked decline in salinity during the second half of the eighties, and a general increase in temperature since the late eighties. Changes in salinity and temperature resulted in a general decline in bottom-water density during the period. Comparison between observed bottom-water density and hydrographic fronts at the grounds indicate that water density could be used as proxy for frontal performance; hence, it is likely that conditions for 0-group cod varied markedly during the investigated period. In addition findings illustrate the likelihood of different hydrographical changes for the different sub-populations of North Sea cod.

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Spatial distribution of 0-group fish in the Barents Sea

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Capelin (*Mallotus villosus* Müller), juvenile herring (*Clupea harengus* L.), cod (*Gadus morhua* L.), and haddock (*Melanogrammus aeglefinus* L.) are commercially and ecologically important fish species in the Barents Sea, representing different biogeographic groups. All these stocks have nursing areas in the Barents Sea. However, the response of the spatial distribution of the fish larvae from climate variability is not well known. For more than 20 years spatial data on fish larvae have been collected in August-September in the Barents Sea, together with hydrographic data. These spatial data span a period with a strong increasing temperature trend, from the cold 1960s-1970s to the very warm 1990s-2000s. The presented data are from the period 1980-1996. Climatic variation is represented by time-series of spatial temperature fields based on observations, observed mean temperatures in Atlantic water masses, and modelled inflow of Atlantic water masses into the area. Fish larvae are presented as 0-group fish (age 0, about a half year old). Geographic distributions of the 0-group are based on field observations from designated 0-group surveys. Results from the spatial analysis of variation in fish larvae distribution as affected by climatic variation are presented. Further, a study of temperature limits for the distribution areas is shown. Finally, the results are discussed with respect to expected future climate changes in the Barents Sea.

The results show that for cod the 0-group has increased their distribution area and had a more easterly mean displacement during the warming period from the 1980s to today.

Also interesting for the WKCFC is the work that is done in the AFWG with multiple regression models.

All these approaches have the possibility to give quantitative projections into the future, and may therefore be useful when evaluating the effect of human induced climate change scenarios for the next decades. However, the results of the spatial development is still novice, and need to evaluate density-dependence and trophic interactions to be a trustworthy before it should be used in projections. This work will be carried out for the Barents Sea by the FishExChange project (2007-2010). FishExChange aims at giving possible future distribution of the main fish species in the Barents Sea, and further the effect on fisheries and socio-economics. A central part of the project is to develop an equal area (25x25 km) grid, which datasets from the entire ecosystem is interpolated into.

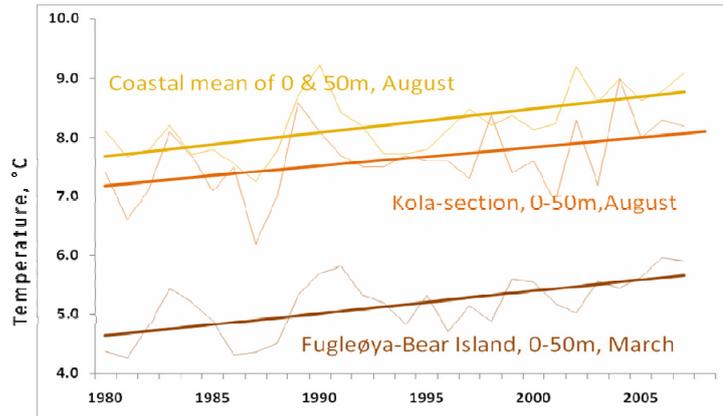


Figure 1. Temperature development in different areas of the Barents Sea.

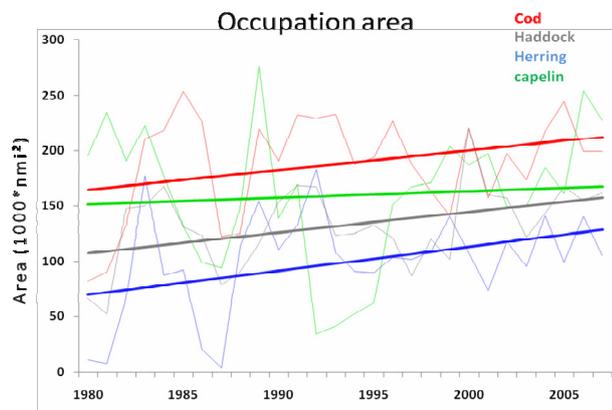


Figure 2. Occupation area of 0-group fish in the Barents Sea.

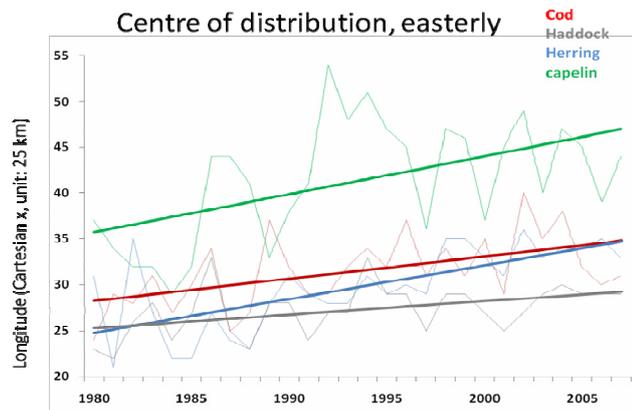
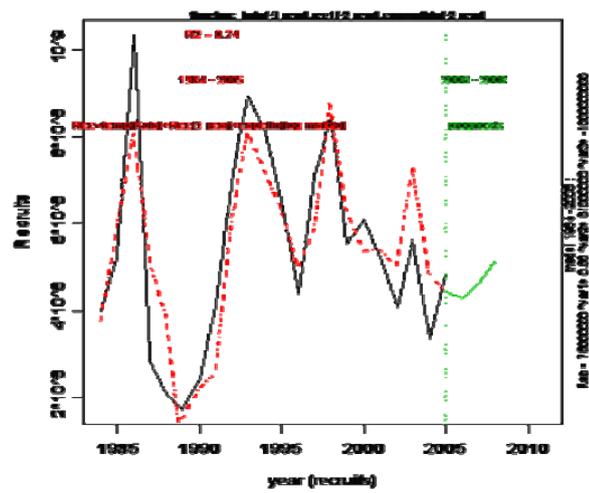


Figure 3. Development of centre of gravity of 0-group fish in the Barents Sea.

North East Arctic cod, 3 year old, vpa2006, can, 1984-2005



JES2: $R \sim k_0 \text{latemp} + \text{age2} + \text{capmatbio}$

Figure 4. Example of multiple regression model for the number of recruits of NEA cod.

Comments on coherence of cod stock dynamics in the Northwest Atlantic Ocean

Brian J. Rothschild

This extended abstract is based on the paper “Coherence of Atlantic Cod Stock Dynamics in the Northwest Atlantic Ocean” (Rothschild, 2007). The figures and some material are taken directly from the paper.

There are nominally eleven stocks of cod in the northwest Atlantic Ocean (3NO, 3M, 3Ps, 2J3KL, 4RS3Pn, 4TVn, 5Z, 5Y, 4VsW1, 4X, and 4VNMO). The location of these stocks is shown in Figure 1. Most studies of these stocks refer to individual stocks or stock groups. Sinclair (1996), however, reviewed the few studies that considered the stocks as an ensemble. This paper extends Sinclair’s work.

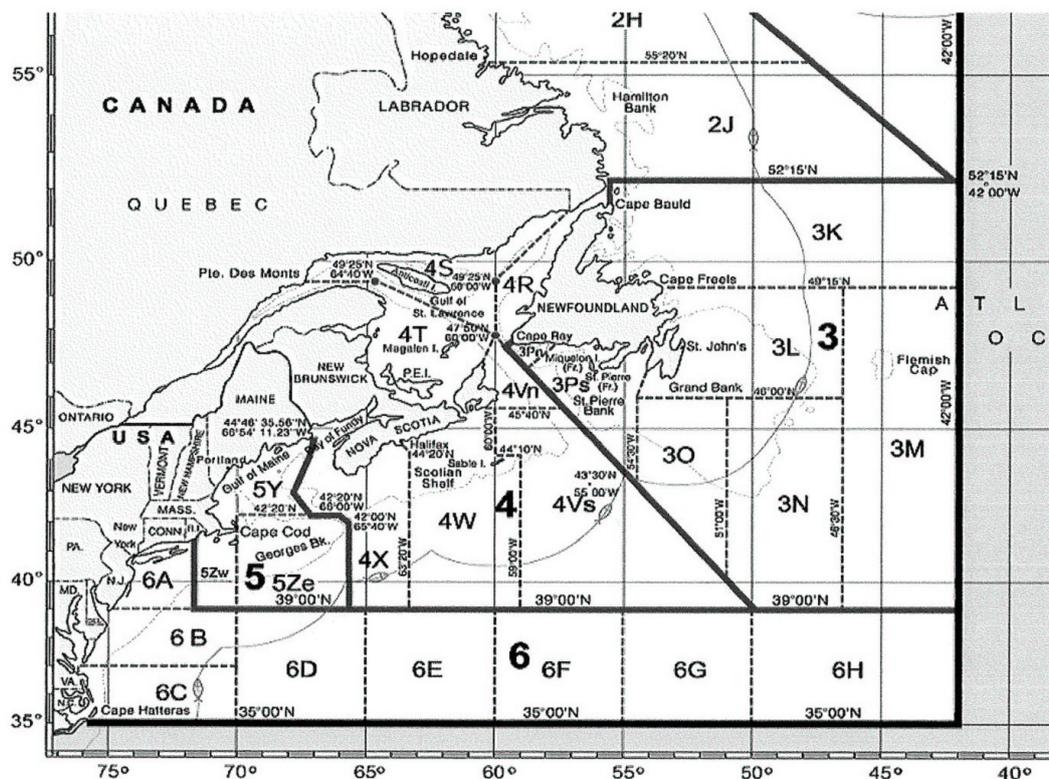


Figure 1. Areas associated with nominal Atlantic cod stocks in the Northwest Atlantic Ocean as defined by the North Atlantic Fisheries Organization.

Shelton *et al.* (2006) provided estimates for the spawning-stock biomass (SSB) for the eleven stocks. Here the reported SSB statistics were normalized in standard deviation units and plotted in Figure 2. There is a remarkable temporal coherence in the SSB values for the eleven stocks (Figure 2). Essentially the stocks were relatively abundant in the 1960s, declined to very low levels in the mid 1970s, increased to peak abundance in the mid 1980s, then reached unprecedented low values in the early 1990s. The declines in the separate stocks have been widely attributed to overfishing. However, the temporal coherence in stock abundance suggests that all stocks would have to be exposed to the same intensity of fishing; that the stocks are truly not separate stocks; or that if the stocks are separate, then all stocks experienced the same coherent sub-basin scale environmental forcing.

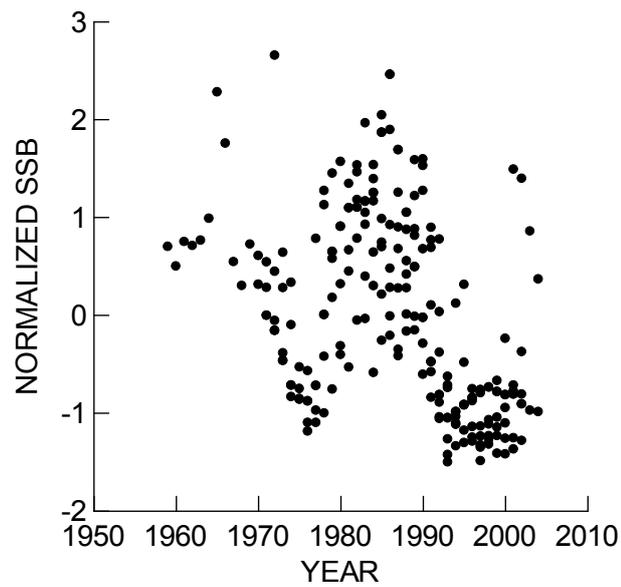


Figure 2. Normalized spawning-stock biomass (SSB). The ordinate is in standard deviation units. Note the depression in 1975, the peak in 1985, and the general decline after 1985.

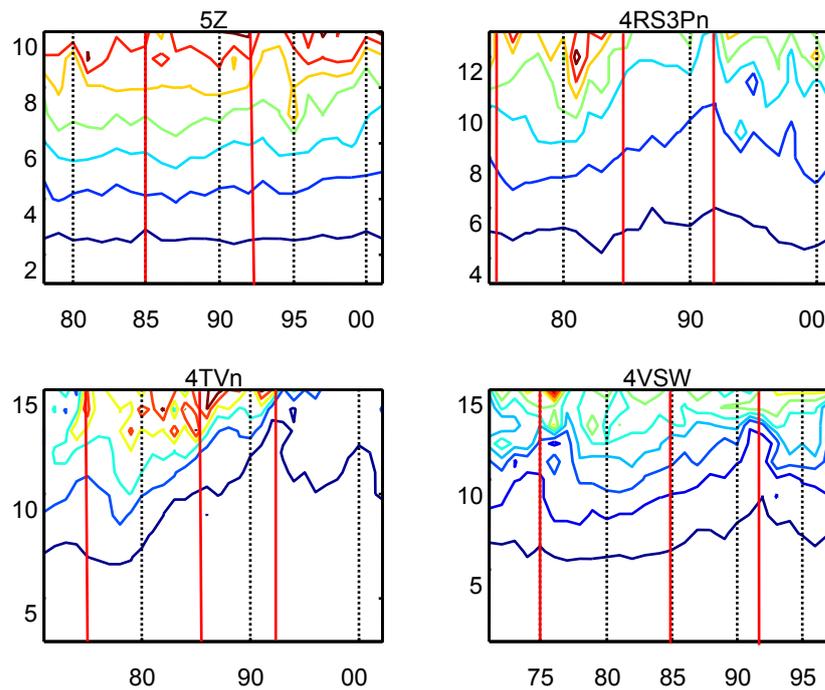


Figure 3. Weight-at-age contours for 4 stocks of Atlantic cod (see Figure 1 for stock codes). The y -axis is age, the x -axis is year, and the contoured z -axis is weight. An upward movement in a contour indicates a reduction in weight-at-age. The vertical red bars mark the 1975 and 1992 minima and the 1985 maximum in spawning-stock biomass. Because early data are lacking for the 5Z stock, the year scale is different. Contour intervals are in 2-kg units except for the 4RS3Pn stock, which is in 1-kg units.

There is a variety of evidence that can be brought to bear on the causal basis for the dynamical changes in cod stocks. The evidence primarily involves 1) the weight at-

age, and 2) the interrelated dynamics of spawning-stock biomass (SSB), fishing mortality (F), and recruitment (R). With regard to weight-at-age, there is evidence of dramatic changes for stocks where data were readily available. A striking example of a decline in the weight-at-age is shown in Figure 3 for the 4TVn cod stock in the Gulf of Saint Lawrence. At the beginning of the time-series, in the early 1970s, a 7-year old cod weighed 2 kg; by the early 1990s, a 12-year old cod weighed 2 kg. There was an almost constant decline in weight-at-age for a twenty year period. The decline in weight at-age might have been expected as a density-dependent response to the increasing population up to 1985. But the continuing decline along with the decline in abundance after 1985 surely signalled a major change in the productivity of the ecosystem, or at least changes in the energy flow through the ecosystem.

With regard to the dynamics of SSB and F, normalized SSB and F is plotted in Figure 4. The abundance of the ensemble of cod stocks began to decline (1985-1990) before fishing mortality reached high levels; in other words, Figure 4 could be interpreted as a decrease in cod causing the increase in fishing mortality. The general interpretation then is that environmental factors were the primary cause of the post 1960s coherent fluctuations in cod abundance. The decline in average weight began in the early 1980s and could be related to the increase in cod abundance at that time. However, the continuing decline in average weight as the stock declined precipitously after 1985 signalled major changes in the ecosystem structure supporting cod and other stocks. These changes were undoubtedly related to a major change in the forage structure of the Northwest Atlantic. This is speculation, but there are a number of more or less local studies that support the contention. Unfortunately, there is no overview of a sub-basin scale change in forage structure.

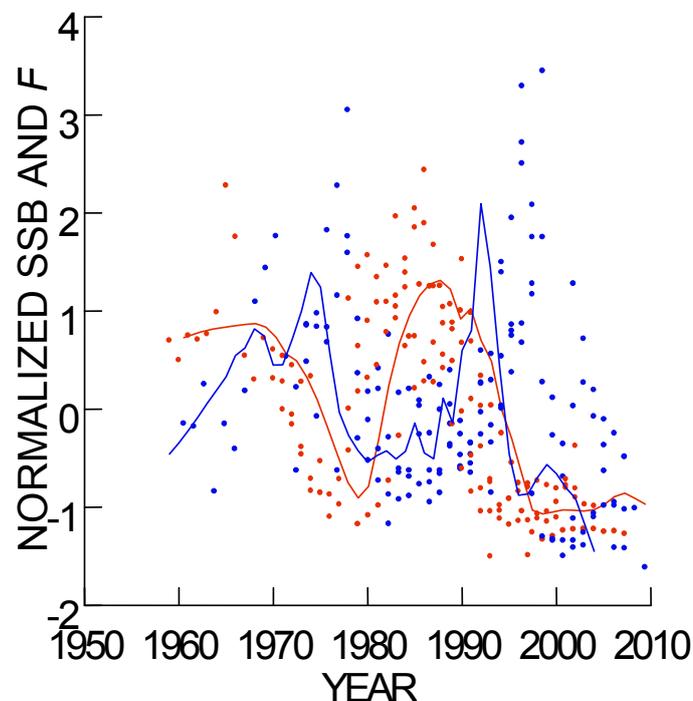


Figure 4. Ensemble of normalized spawning-stock biomass (SSB; red circles) and fishing mortality (F; blue circles) data from nominal stocks 3NO, 4TVn, 4VsW, 4X, and 5Z (see Figure 1). LOW-ESS smoothers (tension = 0.1) are fit through the data (red and blue lines).

Contributing to the puzzle is a possible climate effect, which is the occurrence of the great salinity anomaly in the Northwest Atlantic in 1972, the early 1980s, and the early 1990s. It could be reasoned that the anomalies reduced production and resulted in changes to the forage that affected the abundance of cod. These anomalies are significant from a climate point of view because increased run-off from the Canadian archipelago would enhance the fresh-water storage during the extensive ice years coupled with the anomalies.

While fishing did not seem to cause the coherent variations in cod, it is apparent that it played an important role in the sense that as the stock declined, nominal fishing effort remained relatively constant, while fishing mortality increased substantially, accentuating the decline.

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