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Impacts of climate change on commercial fish stocks in Norwegian waters

by

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Introduction

Declines in the abundances of the most important commercial fish species have often been considered as being the result of overfishing and, occasionally, a combination of environmental effect and fishing pressure (IPCC, 2001). The impacts of climate variations have, however, been shown to have substantial effects on decreases as well as increases in stock abundance, and according to McGowan et al. (1998) the success of future fish stock assessment depends to a large extent on the ability to predict the impacts of climate change on the dynamics of marine ecosystems. The sea temperature in the north-eastern North Atlantic has shown an increasing trend over the recent two to three decades. This might be an indication of climate change caused by emission of greenhouse gases. However, in addition to long-term climate change induced by anthropogenic activity, there is natural variability in the climate. Long-term variations caused by solar and tectonic factors and short- and mid-term variations related to atmospheric and oceanic conditions exist and have to be separated from the long-term climate change even though it is difficult to distinguish between them (IPCC, 2001). The longest time series on ocean climate is the Russian time series from north of Kola (Loeng, 2001). It goes back to 1900 and shows a slightly increasing trend over the entire time series (Figure 1). However, on top of this trend several longer and shorter term periods are displayed. An approximately 60-year cycle is evident with a maximum in the 1930-40s and a minimum in the 1960-70s (Loeng and Sundby, 2001). Another period displayed in the Kola time series is the 18.6 years cycle due to the earth nutation (Yndestad, 1999). In addition, there are decadal-scale periods associated with the North Atlantic Oscillation (NAO), and there is also a clear bi-annual signal. However, presently we do not have sufficient knowledge to predict these periodicities.

The IPCC (2001) states that "Although progress has occurred, it is still not possible to assess regional responses to shifts in climate trends, and it is unknown if a general warming will increase or decrease the frequency and intensity of decadal-scale changes in regions where national fisheries occur. Recent studies have not produced evidence to change the conclusion (Everett et al., 1996) that future saltwater fisheries production is likely to be about the same as present, though changes in distribution could affect who catches a particular stock". Such changes in distribution of fish stocks are one of the most likely effects of climate change. If the temperature regime in Norwegian waters is altered, there is a high probability that this alone will result in changes in distribution of some of the major commercial fish stocks. This again may influence the time spent in Norwegian EEZ and will be decisive of how much of the stock Norwegian fishermen can catch. The productivity of the fish stocks may also change due to increased temperature, and changes in distribution and production of important prey species. Therefore, climate effects on productivity and distribution of the stocks will be a main focus in this report. But first, some of the most important effects of climate change on the ocean are presented. These are mainly taken from the report of the Intergovernmental Panel on Climate Change (IPCC, 2001). Second, the effects of these changes on the biota are discussed in general terms. Previous episodes of warming or cooling of the ocean are important to assess when considering future effects of climate on fish stocks. In this report, some of these episodes and resultant changes in fish stocks, are presented. Then, two possible scenarios of future climate change in Norwegian waters are suggested and the likely effects on the most important commercial fish stocks are discussed. And finally, the effects of climate change on the occurrence of harmful algal blooms and aquaculture are discussed.

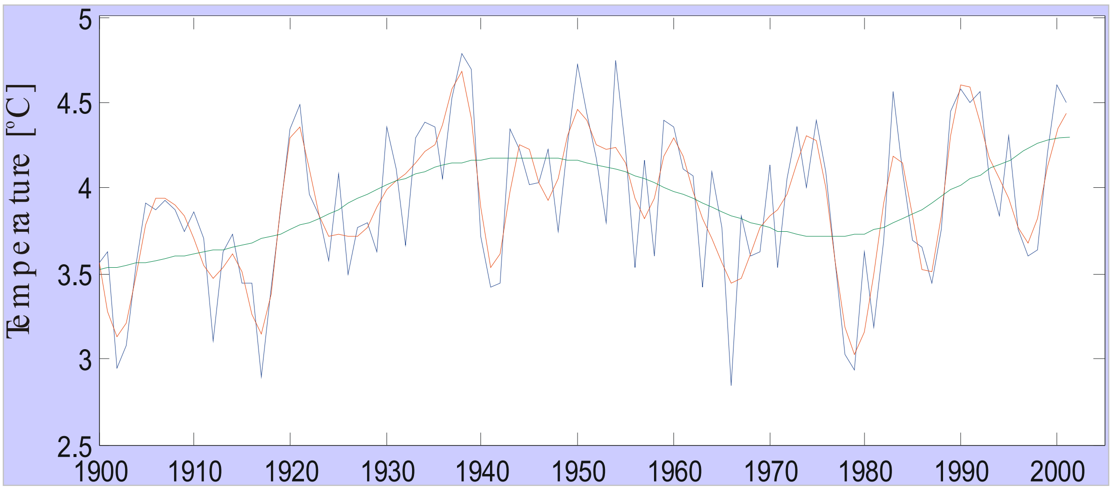

Figure 1. Sea-temperature (averaged over 0-200 m depth) at the Kola section in the Barents Sea. The blue line shows the annual mean, the red line shows three-years moving average and the green line shows the 60-years trend.

Climate scenarios produced by the Intergovernmental Panel on Climate Change

According to IPCC (2001), difficulty in obtaining many highly confident outcomes is why the term "climate scenarios" has been adopted in most impact assessments. Such scenarios should be regarded as internally consistent patterns of plausible future climates, not predictions carrying assessed probabilities. Since most climate models focus on the atmosphere, climate change scenarios for the ocean are particularly uncertain. It is, however, concluded that global warming will affect the ocean through changes in sea temperature, sea level, ice cover and ocean circulation.

Sea temperature

It has been shown that there has been a general warming of a large part of the world oceans during the past 50 years (Levitus et al., 2000). However, regional differences exist such that cooling has been observed in some regions. In the Arctic basin, indications have been found that sea-surface temperature increased by 1^{o}C over the past 20 years (Kotlyakov, 1997). It is, however, not clear whether these changes are a result of natural variability or of long-term climate change. In general, sea surface temperature is expected to increase by approximately the same amount as air temperature in areas that are free of ice, and remain unaffected in areas which are ice covered. The scenarios from the Bergen Climate Model (BCM) predict that the mean temperature will increase by 1.5 to 2.0 ^{o}C in the Barents Sea in 50 years time (Figure 2) (Furevik et al., 2002).

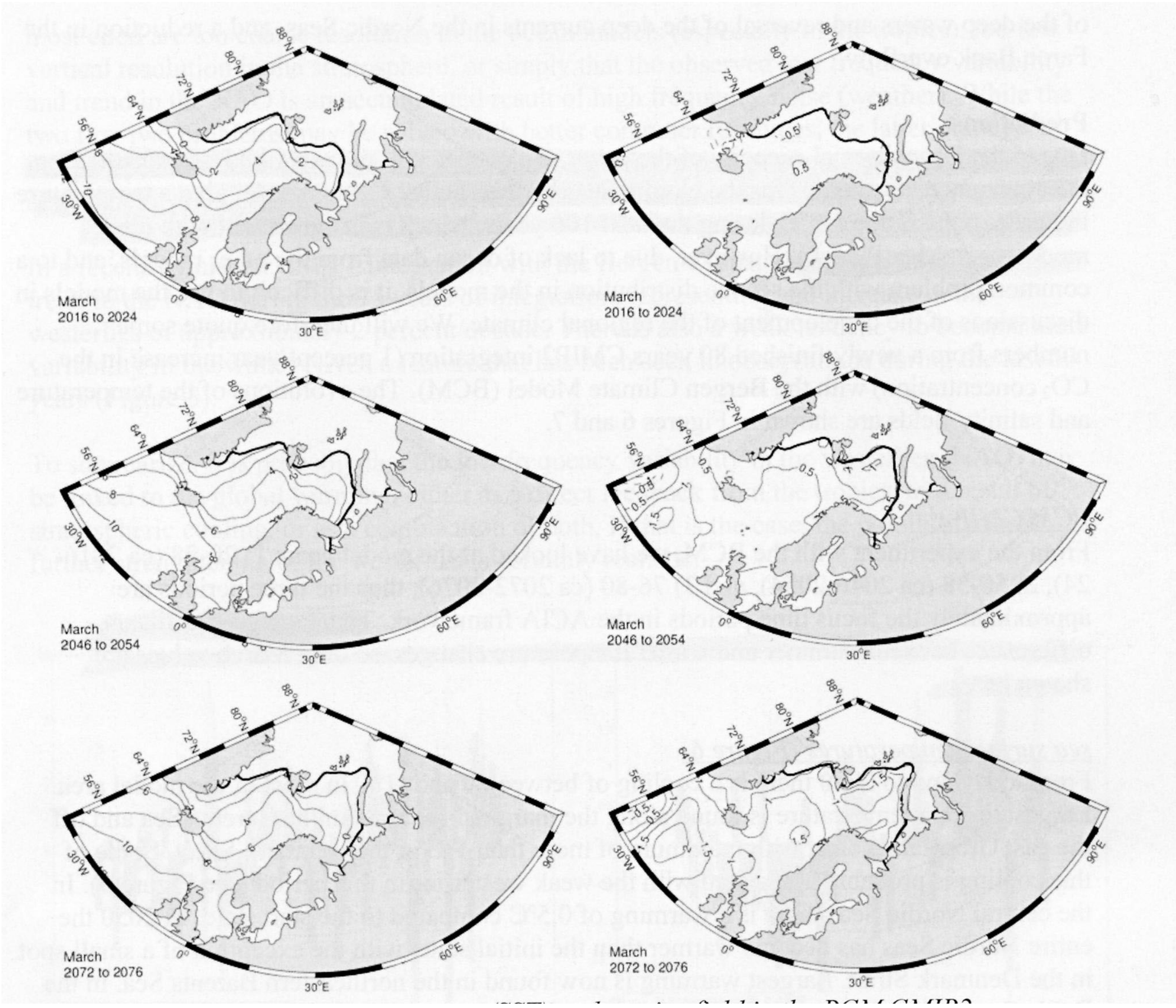

Figure 2. Predicted sea surface temperature and sea-ice border. Left column shows the March SST and sea-ice distribution around the years 2020, 2050, and 2075, and right column shows the changes from year 2000. From Furevik et al. (2002).

Sea level

The global sea level has risen by an average of 1-2 mm yr^{-1} over the past 100 years and is regarded as the most important aspect of climate change at the coast (Tsyban et al., 1990). Increased melting is expected on Arctic glaciers and the Greenland Ice sheet. There is high confidence (67-95 % probability) that these changes will make a significant contribution to sea-level rise. Projections have shown that sea level will rise by 0.09-0.88 m by year 2100.

Sea-ice cover

Sea-ice cover is an important factor in the Arctic, affecting albedo, salinity, and the thermal exchange between the ocean and the atmosphere. When the sea-ice melts during summer, it results in stratification of the upper ocean and increased solar radiation absorbed by the water column. The marginal ice zone is important for plankton production and fish which feeds on the plankton. The sea ice is an important breeding habitat for seals and is the main feeding area of polar bears. Although fluctuations in sea-ice extent have been identified both on decadal and inter-decadal scales (Mysak and Manak, 1989), large reductions in the extent, thickness and duration of sea ice is expected as a result of projected climate change. During the recent decades, Arctic sea-ice extent (Figure 3) has decreased by approximately 3% per decade (Kerr, 1999) and multi-year ice extent has decreased even more (7% per decade during the last 20 years according to Johannessen et al., 1999). There is a high probability that the sea-ice extent in the Arctic during summer will continue to decrease. In addition, results from submarine observations indicate that the ice cover in the Arctic is getting thinner and has decreased by 15% per decade over the past three decades (Rothrock et al., 1999). It is, however not clear if the observed thinning is representative for the whole Arctic or whether it is a result of changing distribution of ice thickness. It is possible that the measurements were conducted in areas where shifting ice occurred due to changing winds (e.g. Holloway and Sou, 2002). Even though it is not agreed whether the observed shrinkage of Arctic sea-ice is caused by global warming or natural fluctuations, some models predict that by 2050, sea ice extent will be reduced to about 80% of the area it covered at the mid 20th century (Vinnikov et al., 1999). At some point, with prolonged warming a transition to an Arctic Ocean that is ice-free in summer could take place. This will potentially have considerable impacts on the Arctic biology from algae, zooplankton and fish to higher predators such as seals and polar bears.

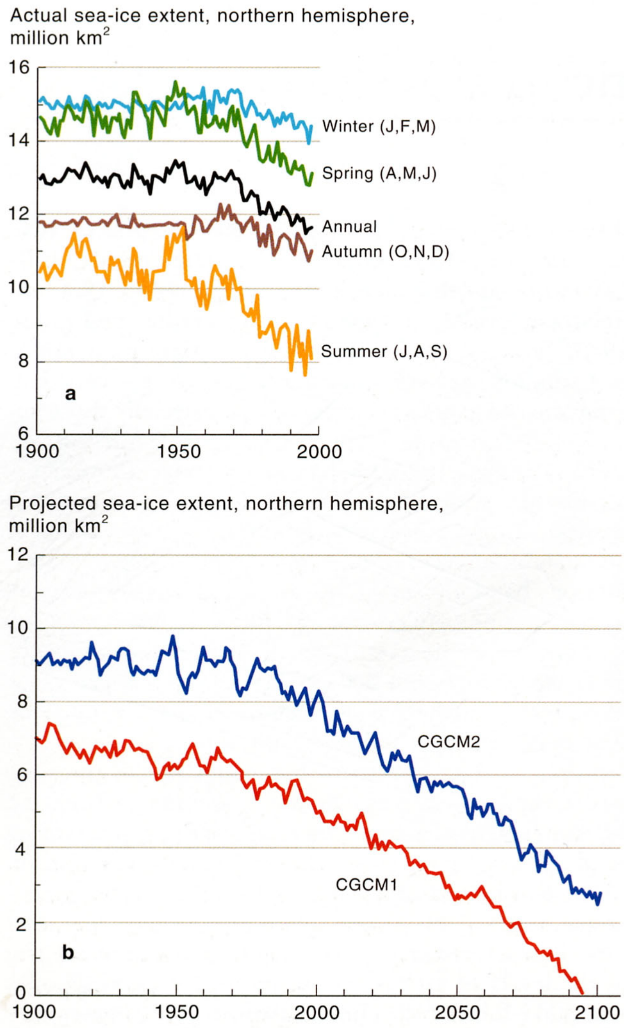

Figure 3. Sea ice extent in the Northern Hemisphere. The upper panel shows the time series of actual annual and seasonal sea-ice extent between 1900 and 2000 and the lower panel shows simulations of annual mean sea-ice extent from two climate models. From Macdonald et al. (2003).

Ocean circulation

The production of harvestable resources in Norwegian waters is to a large extent dependent on the inflow of warm nutrient-rich water from the Atlantic (Figure 4). The main forcings behind the circulation in the North Atlantic are the thermohaline circulation and wind. When larger areas of the Arctic become ice-free, the mixed layer depth will most likely increase due to exposure to wind mixing. This mixing may increase the availability of nutrients especially over the continental shelves. On the other hand, ocean-climate models predict increased stability of the surface mixed layer, reduction in salt flux, less ocean convection, and less deepwater formation due to increased influx of fresh water by the increased melting snow and ice in the Arctic. This could lead to a prolonged major reduction in thermohaline circulation and ocean ventilation (Budd and Wu, 1998). Oceanic thermohaline circulation, which results from differences in seawater density (temperature and salinity), is an important factor in the exchange of heat and greenhouse gases with the atmosphere. There is medium confidence (33-67%) that the global thermohaline circulation will weaken as a result of climate change. If the thermohaline circulation is reduced, this could have a great impact on the climate in Norwegian waters. The inflow of Atlantic water into the Nordic Seas is partly dependent on the thermohaline circulation, and this inflow could be reduced following a weakened thermohaline circulation. This will result in a cooling which could more than offset projected heating due to anthropogenic activity. However, the effect of an expected increase in wind activity may compensate for the effects of the reduction in thermohaline circulation. The future climate scenarios from the Bergen Climate Model (BCM) predict that the increased wind transport of warm Atlantic water will more than compensate for the reduction in the thermohaline circulation, and hence the net effect will be a warmer Nordic region.

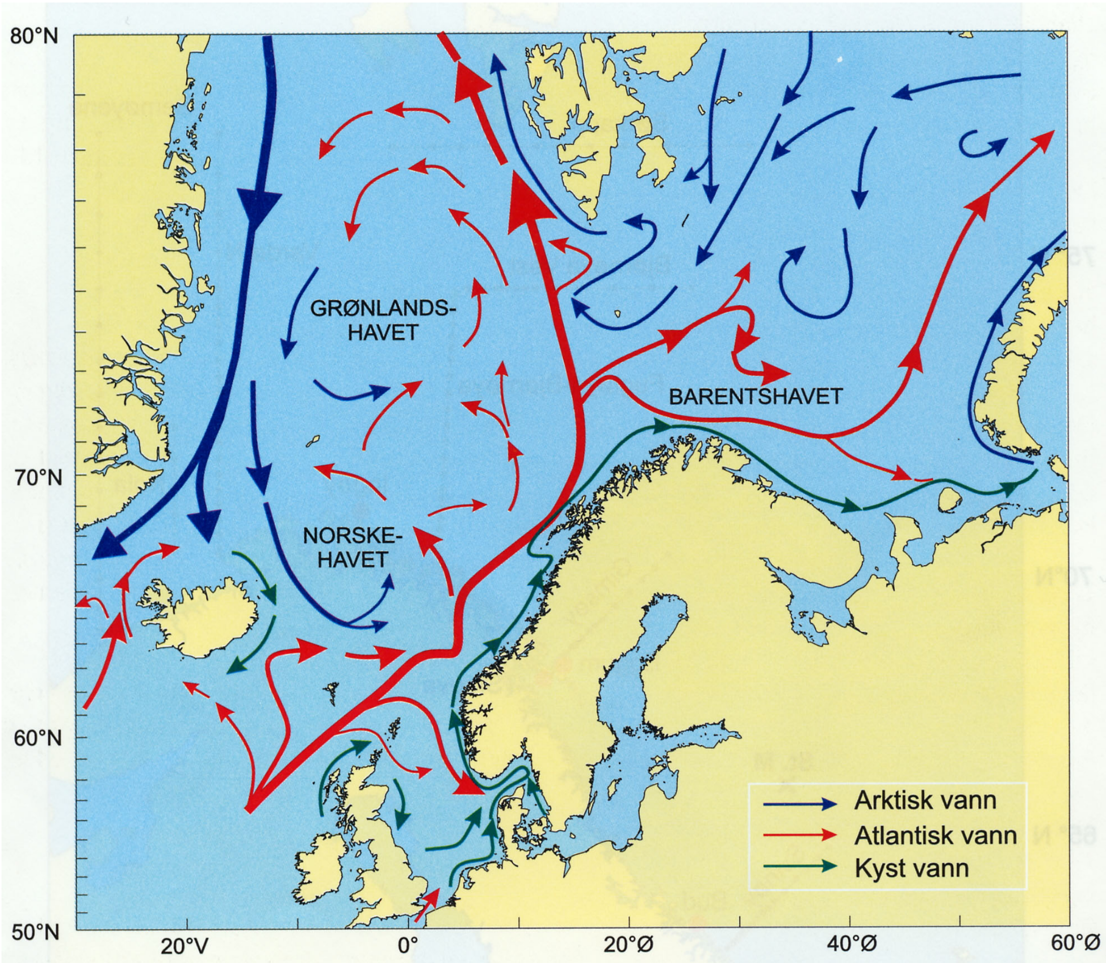

Figure 4. Mean circulation in the North Sea, the Nordic Seas and the Barents Sea. Red arrows indicate Atlantic water and blue arrows indicate Arctic water. From Aure (2000).

North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is a very important factor when considering climate-induced effects on marine biota in the North Atlantic. The NAO index (Figure 5) is an expression of the normalised difference in wintertime sea-level atmospheric pressure between the high-pressure zone over the Azores and the low-pressure zone south of Iceland. A high (positive) NAO index indicates a large difference in the pressure with an intense Icelandic low and a strong Azores high. This will affect the wind pattern in the region and result in more and stronger winter storms following a more northerly track in the Atlantic Ocean. A low (negative) NAO index will on the other hand produce weaker winter storms following a more west-east pathway. During a phase of high NAO index, the transport of warm Atlantic water into the Barents Sea and the Arctic Sea will increase and there is a high correlation between the NAO index and the temperature in Norwegian waters. Since the 1960s, there has been a general increase in the NAO index (Parsons and Lear, 2001), although with decadal-scale oscillations superimposed. This increase has been the strongest observed since measurements of air pressure started 150 years ago, and it is assumed to be partly related to anthropogenic activity (Blindheim et al., 2001). According to Paeth et al. (1999) the variance of the NAO on decadal scales will decrease and the mean is expected to increase stabilizing the NAO in the positive phase. This will lead to more westerly winds and milder climate in Europe. Gillett et al. (2003) state that even though the recently observed upward trend in NAO index is possibly not unique over the past 600 years, tests have shown that the trend is outside the range of internal variability. They conclude that most authors agree that increase in greenhouse gases are likely to be at least partly responsible for the observed upward trend in NAO index.

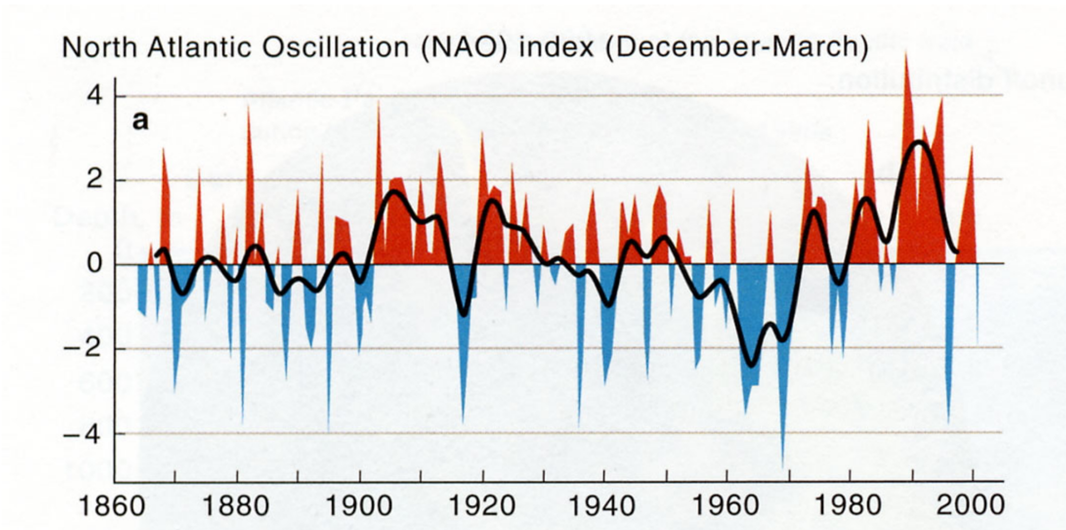

Figure 5. The North Atlantic Oscillation index from 1860 to 2000 (source: Hurrell, 2002). From Macdonald et al (2003)

Effects on biota

According to IPCC (2001) there is uncertainty regarding what effect the predicted climate change will have on the structure of marine communities and on the overall marine productivity. This uncertainty arises because existing biological models are not yet sufficiently developed to provide authoritative and quantitative estimates. In addition, the complexity of marine ecosystems could result in changes which are difficult or impossible to predict. To illustrate such possible surprises, the following example was provided by Macdonald et al. (2003). The projected loss of ice in the Arctic Ocean, particularly over the shelves, could result in increased secondary production including fish. This would be expected as a consequence of increased primary production due to more mixing, light penetration and upwelling. However, in the Bering Sea, massive blooms of jellyfish were observed during the 1990s (Brodeur et al., 1999) and this was explained by an increase in sea temperature and loss of ice cover.

However, observations of changes to fish stocks due to climate variability in the past allow us to predict some general responses concerning production and distribution of the stocks. There is no doubt that climate variations will have consequences for our most important commercial fish species. Both abiotic and biotic factors affected by climate change will impact the productivity and distribution of fish stocks. Important abiotic factors include water temperature, nutrients, ocean circulation and amount of sea ice. Biotic factors include food availability and the presence of competitors and predators. Generally, in Arctic and Arcto-boreal ecosystems, increased temperature results in increased growth and reproduction of most, but not all, fish stocks. Also, the habitat will change with variations in circulation and temperature resulting in modified distribution patterns. Below, some of the most important effects of climate variations on fish stocks are discussed.

Water temperature can have a direct effect on spawning time of fish, but also the survival of the larvae can be affected. Temperature also has a profound influence on growth in fish. Thoresen and Østvedt (2000), using a smoothed temperature index with a 19-years moving average, found a significant relationship between temperature in the Kola section and stock biomass of Norwegian spring spawning herring (Figure 6). Generally, increased temperature leads to increased growth. But even though the thermal limits for somatic growth are wide, the temperature range over which growth is possible is narrower than that permitting short-term survival (Jobling, 1997). The effect of higher temperatures on growth will fluctuate with food availability and therefore both these two parameters should always be considered when discussing growth effects (Jobling, 1997). The effects of temperature on recruitment may vary depending on the environment in the area inhabited by the stock. For instance Ottersen (1996) found that there is a positive relationship between temperature and recruitment for cod stocks in the lower part of the temperature range (e.g. Barents Sea) and a negative relationship for stocks inhabiting areas in the upper range of the temperature range of this species (e.g. North Sea). Several recent papers have found correlations between temperature and productivity of cod stocks in the Northeast Atlantic (e.g. O'Brien et al., 2000; Parsons and Lear, 2001). According to Sundby (2000), the higher recruitment during warm periods in the Barents Sea and lower recruitment in the North Sea during warm periods there, however, is not solely a result of direct effect from the temperature increase itself. It is often caused by a combination of several factor such as turbulence, light and indirect effects of temperature through higher production in lower trophic levels, in addition to the direct effects of temperature. Temperature may therefore act as a proxy for a number of environmental factors affecting the production in fish stocks. In a comprehensive review, Sundby (2000) focuses particularly on temperature as a proxy for the advection of zooplankton from the Norwegian Sea and into the Barents Sea and the North Sea. One of the dominant zooplankton species which is important as food for pelagic fish and for larvae and juveniles of cod in Norwegian waters, is the copepod *Calanus finmarchicus*. Sundby (2000), based on an extensive literature review, suggests that the concentration of overwintering *C. finmarchicus* in both the Barents

Sea and the North Sea is not sufficiently high to support the abundance observed in spring, and that the populations are to a large extent sustained by advection from the overwintering stock in the Norwegian Sea. The conclusion from Sundby's review is that if the increased advection of copepods is directed along a negative temperature gradient (i.e. from the Norwegian Sea to the Barents Sea), the import of copepods will be accompanied by an increased temperature. On the other hand, if the increased advection is directed along a positive temperature gradient (i.e. from the Norwegian Sea to the North Sea), the import of copepods will be accompanied by a decrease in temperature.

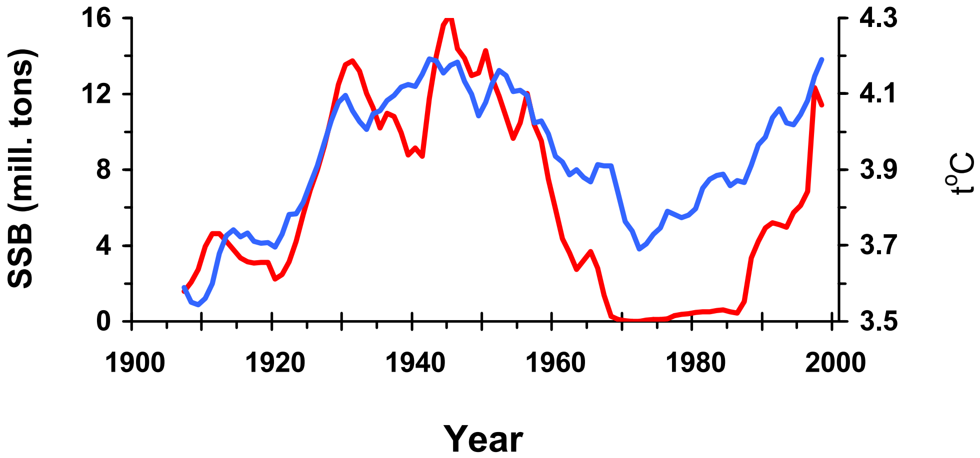

Figure 6. Spawning stock biomass of Norwegian spring-spawning herring (red line) and mean annual (moving average over 19 years) temperature at the Kola section (blue line). From Toresen and Østvedt (2000).

In addition to enhanced advection of *C. finmarchicus*, it is to be expected that an increase in temperature, especially in the lower temperature range, will increase the production of this species both through a direct effect of temperature on growth and generation time, but also as an indirect effect through increased production of phytoplankton, which is the food for *C. finmarchicus*.

According to Wood and McDonald (1997) most, if not all, fish species have an optimal temperature they prefer if given a choice. The response will, however, differ depending on whether the temperature increases towards or away from the optimum, Since most fish are not able to control their body temperature by physiological means, they are to a large extent dependent on behavioural control of their body temperature (Jobling, 1997). This behavioural thermoregulation is common among fish species and may result in large fluctuations in distribution following temperature changes. A change in ambient temperature of 1°C will produce behavioural adjustments in many fish species and a change of 4°C will lead to major changes in fish distribution (Crawshaw and O'Connor, 1997). Changes in prey availability will especially influence the distribution of highly migratory fish such as herring and mackerel. Changes in circulation pattern may also influence distribution. Eggs and larvae of most marine fishes are planktonic for longer periods. They are therefore dependent on the local currents to transport them to their nursery areas. Hence, change in circulation pattern may not only influence recruitment but also distribution, especially of the young stages. Ådlandsvik and Sundby (1994) showed that the pelagic juveniles of cod in the Barents Sea had westerly distributions in some years and easterly distributions in other years. This can be explained by variations in circulation pattern, mainly induced by the wind forcing.

Examples from historical climate change events

Warming along the coast of West Greenland 1920s and 1930s

One of the best documented effects of climate change on fish stocks is the warming from the mid 1920s through to the mid 1960s, which had a profound effect on the major commercial fish stocks of Iceland and Greenland. There occurred both a noticeable northward extension in range and increased abundance of several "warm water" species including Atlantic cod, Atlantic salmon and haddock (Drinkwater et al., 2003), in addition to increased abundance of a number of previously absent and rare species in the region (Jensen, 1939). The distribution of cod in the area extended poleward by about 1000 km between 1920 and 1930.

Warm periods in the North Sea

During 1920-23 and 1931-35, warm periods occurred in the North Sea (Reid et al., 2003). During the latter period there was evidence of major intrusion of horse mackerel into the North Sea in addition to extensive blooms of phytoplankton. Horse mackerel is a good example when linking climate to fish resources in the North Sea. According to Iversen et al. (2002), the relationship between transport of Atlantic water into the North Sea and catches of horse mackerel in the northern North Sea is one of the clearest relationships between a single marine climate variable and fisheries yield. They found that 70% of the variability in the catch of this species could be explained by the modelled winter volume flux into the North Sea for the period 1976 to 2000. One possible explanation for this could be that the increased inflow may have resulted in a higher temperature and higher plankton production in the North Sea and that the horse mackerel follows this increased production into the catch areas (Iversen et al., 2002).

Aurich (1953) and Postuma (1978) have documented increased abundance of anchovy and sardine in the North Sea during periods of warming in 1948 to 1952. It has also been reported that tropical species such as the blue-mouth have extended their distribution northwards into the North Sea during the later warming period in 1990/91 (Heessen et al., 1996). Even though there seems to be some conservatism in the migration pattern of herring (Corten, 2001), the North Sea herring and mackerel changed its distribution during the warming period in the late 1980s (Corten and van de Kamp, 1996).

O'Brien et al. (2000) showed that there is a negative correlation between recruitment of North Sea cod and temperature. They state that this is because the cod in this area is near the southern boundary of its range and strong year-classes have historically been associated with relatively low temperatures. Therefore, if warming continues, this may prevent high recruitment of this stock. There are strong indications that this temperature signal is linked to a reduced advection of the *C. finmarchicus* into the North Sea along the Norwegian Trench (Heath et al., 1999; Rothschild, 1998).

Climate change and effects of the main fish resources in Norwegian waters. Possible scenarios

Because of the documented importance of the NAO on climate in Norwegian waters, this report will focus on possible effects of two scenarios of the future development of the NAO. First, a scenario with a continuing high and increasing NAO index is assessed and then a scenario with a reduction in the NAO is discussed.

Scenario 1. High NAO and high inflow of Atlantic water

Following an increase in inflow of Atlantic water and an accompanying increase in temperature, the character of the ecosystems in Norwegian waters will most likely change. The borders between the temperate ecosystem in the Atlantic, the boreal ecosystems of the Norwegian Sea/Barents Sea and the Arctic areas may move northwards, resulting in substantial changes to the fish communities in the different areas.

North Sea

The production in the North Sea is highly dependent on inputs of nutrients from the North Atlantic through the Atlantic inflow. It has been suggested that close to 90% of the major nutrients in the North Sea are supplied from the North Atlantic (NSTF, 1993). Variations in this inflow could, therefore, have profound effects on the circulation and ecology of the North Sea (Edwards et al., 2002). According to Reid et al. (2003), a regime shift occurred in the North Sea around 1988 from a cold to a warm period. The length of the present warm period, which appears to be linked to increased inflow of oceanic water from the North Atlantic, seems to be unique in at least the last century (Reid et al., 2003), and the effects on the North Sea ecosystem is pronounced in both the abundance and composition of the plankton, benthos and other trophic levels. The increase in inflow of oceanic water is caused by a change in the wind pattern to stronger and more westerly winds, which in turn are highly correlated with the NAO.

According to IPCC (2001), a temperature increase of 1-2°C is expected in the North Sea over the next century. With this scenario, the advection of the most important prey organism, *C. finmarchicus*, will be directed from the Norwegian Sea and into the Barents Sea. The inflow of this copepod species into the North Sea will probably decrease. It should, however, be noted that one of the important routes of advection of *C. finmarchicus* into the North Sea occurs at great depths in the Faeroe-Shetland Channel (Sundby 2000), and it is not certain how an increase in NAO will influence this inflow. The higher inflow of Atlantic water will increase the advection of southern copepod species such as *Calanus helgolandicus* into the southern part of the North Sea and this may further contribute to the change in fish community. Together, the increase in the temperature and change in copepod composition in the North Sea will most likely result in increased abundance of more southern species such as anchovy and sardine. The herring and mackerel stock will probably have a more northerly distribution.

As mentioned earlier, the cod in the North Sea is near the southern boundary of its range. It is therefore expected that the increased temperature and reduction in the abundance of *C. finmarchicus* will be negative for recruitment of this stock, which will result in a decline of the stock. According to Drinkwater et al. (2003), there is a negative relationship between cod recruitment and the NAO index in the North Sea and this is explained by a limitation in energy resources which are needed to achieve higher metabolic rates during warm years (Planque and Fox, 1998). A reduced inflow of *C. finmarchicus* from the Norwegian Sea could partly explain this. It has been suggested that the cod in the North Sea, due to overexploitation, is at present particularly vulnerable to climate variability since the stock mainly consists of a few year-classes (Cook et al., 1997). Based on the small stock size and poor recruitment, the ICES recommendation for 2004 is that no cod should be caught in the North Sea. Even though the total abundance of fish in the North Sea is not reduced, the catch value could be reduced due to changes in species composition following an increase in temperature (Blindheim et al., 2001).

Norwegian Sea and Norwegian coast

A high NAO results in a strong but relatively narrow inflow of Atlantic water in the Norwegian Sea. The temperature in the eastern part of the Norwegian Sea and along the Norwegian coast will increase. During later years, the mackerel have been observed farther north along the Norwegian coast than what was normal distribution historically, and this tendency is expected to continue with increased warming. Bluefin tuna which were frequently caught in Norwegian waters during earlier periods may again enter the Norwegian Sea and become available for the Norwegian fishing fleet. The recruitment of Norwegian spring spawning herring and the Northeast Arctic cod which spawns along the Norwegian coast is positively correlated with temperature and an increase in temperature could therefore result in higher abundance of these stocks. During the warming of the Norwegian Sea in 1920 to 1930, the biomass of the Norwegian spring spawning herring increased almost ten-fold (Toresen and Østvedt, 2000).

Barents Sea

The Barents Sea is characterised by relatively warm coastal and Atlantic water flowing eastward in the southern part and cold Arctic water flowing south-westward in the north (Blindheim, 1989; Loeng, 1991). The Polar front separates these two bodies of water. The position of the Polar front is to a large extent influenced by the bottom topography in the western part of the Barents Sea, but more by the Atlantic inflow in the eastern part. An increased transport of Atlantic water will increase the temperature in the southern and eastern parts of the Barents Sea. This will most likely result in a more north-eastward distribution of both capelin (Sakshaug et al. 1992) and cod (Ottersen et al., 1998) and could reduce their time spent in Norwegian EEZ. If the strong inflow occurs during spring, when the major zooplankton species *Calanus finmarchicus* ascends from its deep winter habitat, the transport of this important prey species will also increase and could enhance the conditions for species such as herring and capelin (Sundby, 2000). The combined effect of higher temperature and increased prey availability could enhance growth and reproduction of cod, capelin and herring which all use the Barents Sea as nursery areas. Ottersen and Stenseth (2001) have shown that that there is a positive relationship between recruitment of cod and the NAO. The NAO index alone explained 53% of the variability of recruitment. The scenarios from the Bergen Climate Model (BCM) predict ice-free winters in the Barents Sea in 50 years time, and the mean temperature will increase by 1.5 to 2.0 ^{o}C (Furevik 2002). Skjoldal et al. (1987) showed the relation between the Barents Sea winter ice index and the mean temperature in the Barents Sea. Extrapolation of these results to ice-free winter conditions in the Barents Sea indicate an increase of mean temperature in the Barents Sea of about 3 ^{o}C.

Scenario 2. Reduction in NAO and lower inflow of Atlantic water

North Sea

Since the recruitment of cod in the North Sea is negatively related to the NAO index, a reduction of NAO will increase the probability of good recruitment and population growth of this stock. The abundance of southern species such as anchovy and sardine will not increase and the herring and mackerel will not extend their distribution northward along the coast.

Norwegian Sea and Norwegian coast

With a reduced NAO index, the inflow of Atlantic water will become weaker but broader. This could lead to increased temperature in the western part of the Norwegian Sea and could result in changes of the migration pattern of Norwegian spring spawning herring. During its feeding migration, the herring could enter the western part of the Norwegian Sea near Iceland. Instead of wintering in the Vestfjord area, the stock could resume its traditional migration pattern with feeding near Iceland and wintering in the Norwegian Sea. This will reduce the time spent of this stock in Norwegian EEZ.

Barents Sea

During a phase of negative NAO index, the inflow of Atlantic water to the Barents Sea will be reduced. This will lead to a colder climate particularly in the southern part of the Barents Sea. Also, the abundance of *C. finmarchicus* will decrease due to less inflow. Since Ottersen and Stenseth (2001) showed that 53% of the recruitment of cod could be explained by the NAO index, it is expected that such a scenario will lead to lower recruitment for cod and herring. However, both the cod stock and the capelin stock will probably spend more time in Norwegian EEZ during this scenario compared with Scenario 1.

Most likely scenario

If the trend with warming and high NAO index continues, the mean temperature in the entire northeastern Atlantic, including the North Sea, the Nordic Seas and the

Barents Sea is expected to increase by 1 – 3 °C over the next 50 years. The highest temperature changes are expected to occur in the northernmost part of the region. Moreover, the model scenarios predict ice-free summers in the Arctic basin in 50 years. Associated with such a temperature change is also an increased wind-induced flux of warm Atlantic water to the region and changes in stratification of the euphotic zone. Such changes in ocean climate will substantially impact the marine ecosystems of the region. The changes will impact abundance and distributions of fish species as well as abundance and distributions of key plankton species. Generally, we expect a northward shift in the distribution of all species and an increased biomass production of the Arctic and Arcto-boreal regions. In the North Sea, however, we expect present fish species to decline, but new species will invade from south.

In the North Sea it is to be expected that the area will be dominated by pelagic species such as herring, mackerel in the northern part and possibly anchovy and sardine in the southern part. The cod stock in the North Sea will probably remain small and this could reduce the value of the catch in this area. Total production will probably not change much, but species composition will change.

In the Barents Sea and the Norwegian Sea, both the herring stock and the cod stock will most likely benefit from the warming. The abundances will increase and the distributions will expand, resulting in greater availability for the Russian fishing fleet. The presently relatively unimportant Atlantic cod spawning areas along the Finnmark coast will become more important. New species are likely to appear. For example Atlantic mackerel might be available in the Barents Sea. Capelin will probably move eastwards and Novaja Semlya might become new spawning areas.

In the Arctic Basin ice-free summers might give the *C. finmarchicus* the possibility to inhabit the region. If *C. finmarchicus* expands to the Arctic Basin, it will have the potential to become a very productive region. Good conditions for capelin summer feeding might expand the population substantially. The Barents Sea will then also get supply of *C. finmarchicus* from north in addition to the supply from the Norwegian Sea. This will further increase the fish production in the Barents Sea

The production at the Siberian continental shelf will also benefit from a possibly establishment of *C. finmarchicus* in the Arctic Basin. Also here it is to be expected that *C. finmarchicus* will be advected onto the shelf regions and result in high fish production. Capelin and Atlantic cod are the most probable species to inhabit this region in addition to walleye pollock from the Pacific.

Harmful algal Blooms

Harmful algal blooms have caused considerable mortality of fish in Norwegian waters. Farmed fish are especially vulnerable since they cannot escape, but also wild fish mortality has been observed (Dahl et al., 1999). In Norwegian waters the most important harmful algae belong to the genera *Gyrodinium*, *Chatonella*, *Chrysochromulina* and *Prymnesium*. The effects of harmful algal blooms have been most pronounced in the Skagerrak area with decreasing effects northward along the Norwegian coast.

During recent years, blooms of algae from the genus *Chatonella* have been a major concern along the southern coast of Norway. These algae belong to the algal group Raphidophyceae, which includes most of the potential harmful algal species (Naustvoll et al., 2002). No toxic substances have been found in *Chatonella* from Norwegian waters, but the algae do produce mucus which in combination with high concentrations of the algae may block the gills of fish and cause mortality (Aure et al., 2000). The first *Chatonella* bloom was observed in Norwegian waters in 1998. It was then the dominating algae along the coast north to the Boknafjord area. Blooms of *Chatonella* have since been observed in 2000 and 2001. In 2001, the bloom caused a loss of 1100 tons of farmed salmon in farms east of Lista (Naustvoll et al., 2002).

It is difficult to quantify the effect of climate change on the probability of an increase in harmful algal blooms (Peperzak, 2003). In addition to temperature, factors such as stratification and nutrient supply are important for the occurrence of blooms. Therefore, the blooms will to a great extent depend on discharge from the major rivers surrounding Norwegian and adjacent waters and this will depend on how the land in the catchment area is used (Peperzak, 2003). In addition, new algal species may appear in Norwegian waters, for instance introduced in ballast water. It is impossible to predict the effect of this. However, it is possible to assess the effect of an increased temperature on the growth of the algae which are presently causing fish mortality in Norwegian waters and several such studies have been conducted. Peperzak (2003) studied growth of several algal species, both harmful and non-harmful, in the southern part of the North Sea, and found that growth rates of four of the harmful algae increased when a temperature scenario for 2100 (4^{o}C increase) was used. Peperzak (2003) concluded that “without making a quantitative assessment, the main conclusion is that due to climate change the risk of harmful dinoflagellate and Radiophyte blooms in the Dutch coastal zone will increase rather than decrease”.

The algae which until now have caused harmful algal blooms in Norwegian waters have temperatures of optimum growth ranging between 15 and 20^{o}C (Nilsen and Tønseth, 1991; Rhodes et al., 1994; Yamaguchi et al., 1997; Larsen and Bryant, 1998), although differences between strains of the same species from different areas are known to occur (Larsen and Bryant, 1998). This means that an increased sea-temperature during the spring bloom may increase the growth of these potentially harmful species and thereby increase the probability of harmful algal blooms.

Effects of climate change on aquaculture

The Norwegian coast has optimal natural conditions for mariculture of Atlantic salmon. This is due to the sheltered coastal regions and because of optimal temperature conditions for salmon growth. Critical factors here are the minimum winter temperature and the maximum temperature during summer. The northern part of the western Norway coast between Hordaland and Møre has optimal conditions in this sense. Here, the minimum winter temperature seldom goes below 4-5 ^{o}C, and the summer maximum temperature is normally below 18^{o}C. With a 1- 3 ^{o}C increase of mean temperature the optimal salmon farming region will move northward and attain a center of gravity around northern Helgeland coast and good farming conditions will extend to Finnmark that today has suboptimal rearing conditions.

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