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The Influence of Climate on Biological Conditions in the Barents Sea

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ABSTRACT

Already at the beginning of this century it was clear that variations in the physical conditions in the Barents Sea have great influence on the biological conditions. The cold period during the years 1977-82 initiated new investigations on the influence of oceanographic conditions on recruitment, distribution and growth of commercial fish species in the Barents Sea, both by Norwegian and Soviet scientists. The aim of the present paper is to review some of the most important results achieved so far.

Rich year classes of cod occur only in years with relatively high temperature on the spawning grounds and during the first half year of their lives. The distribution of the feeding area of cod, haddock and capelin depends on the climatic conditions in the Barents Sea. There is a more easterly and northerly distribution in warm years than in cold ones. The growth of fish also seems to depend on the environmental temperature, but there is probably not a simple temperature-growth relationship. The climatic fluctuations also influence the plankton production and thereby the food conditions for all plankton feeders. Temperature effects linked to the variability of food may be as important as the direct temperature effect.

INTRODUCTION

In a review of Norwegian cod and herring fisheries, HJORT (1914) reported fluctuations in fisheries back to the early 1700's. Some attempts had been made to explain these fluctuations, but most of the theories were valueless and only saved "as indications of the state of general knowledge concerning marine biology at the periods in which they arise" (HJORT 1914). A more scientific approach was made by HELLAND-HANSEN and NANSEN (1909). They believed that variations in the physical conditions had great influence on the biological conditions of various fish species, and that temperature variations in the sea "are the primary cause of the great and hitherto unaccountable fluctuations in the fisheries". HJORT (1914) was critical of this hypothesis, but later investigations have shown that the physical conditions, at least, are one important indicator for recruitment, distribution, and growth of the most important commercial fish species.

During the last half of the 1970's there was a marked temperature decrease in the whole Barents Sea, which resulted in great changes in the distribution areas of the Arcto-Norwegian cod (Gadus morhua L.), haddock (Melanogrammus aeglefinus) and capelin (Mallotus villosus). This led to new investigations on the influence of climate on biological conditions (recruitment, distribution, migration and growth), both by Norwegian and Soviet scientists. The intention of this paper is to summarize the results from investigations on this topic carried out mainly during the 1980´s.

PHYSICAL CONDITION

There are three main water masses in the Barents Sea. These are related to three different current systems: the Norwegian Coastal current, the Atlantic current, and the Arctic current system. Fig. 1 shows the main features of these current systems. Both the Coastal and Atlantic water masses flow into the Barents Sea from the southwest and occupy the southern part of the sea. In the northern Barents Sea, the Arctic waters flow in opposite directions, towards the south and west. Between the Arctic and Atlantic waters, there is an area called the Polar front, in which the two water masses mix. In the western part of the Barents Sea, the front is sharp, and it separates two distinct biological regimes (LOENG et al. 1987) In the eastern part of the sea, the front is diffuse and sometimes difficult to trace.

The different water masses may also be found in Fig.2, which shows the horizontal distribution of temperature and salinity at 100 m depth. According to HELLAND-HANSEN and NANSEN (1909), the Atlantic water is defined by salinities higher than 35.0. The salinity decreases gradually eastwards, and water with salinity higher than 34.9 and temperature above 2^{0}C may be considered as Atlantic water. The Coastal water has almost the same temperature as the Atlantic water, but is characterized by lower salinity ($S<34.7$). The Arctic water has a temperature below 0^{0}C, and in great areas below -1^{0}C, while the salinity varies between 34.4 - 34.8. In long cold periods the eastern part of the Barents Sea may be filled up with cold dense bottom water ($t<-1.7^{0}C$) which is formed on the bank areas of Novaya Zemlya and the Central Bank (MIDTTUN 1985).

The climatic variations in the Barents Sea depend mainly on the activity and properties of the inflowing Atlantic water (MIDTTUN and LOENG 1987). Climatic variations therefore can be recorded in sections crossing the Atlantic current. Fig. 3 shows temperature anomalies in the Kola-section after 1930 (along $33^{0}30´$E) based on data from BOCHKOV (1982) and MIDTTUN et al. (1981). After a warm period in the 1930´s, the years after 1945 are characterized by fluctations of duration 3-5 years. Since 1970, large variations have been observed in the Barents Sea. The period 1970-76 was warm, while the period 1977-82 was the longest continuous cold period observed after 1920 (LOENG 1988). During the year 1982 there was a strong temperature increase followed by a couple of warm years, while the last years have had temperatures below the long term mean.

The same variations in temperature as in the Barents Sea are found along the whole Norwegian coast (BLINDHEIM et al. 1981) indicating that these variations are large-scale. These climatic variations are of advective nature, as first suggested by HELLAND-HANSEN and NANSEN (1909). Thus a time lag is indicated of about 6 months between temperature variations in Lofoten, which is the spawning ground for cod, and that of the central/eastern Barents Sea (LOENG and SUNDBY 1986, ELLERTSEN et al. 1987).

Variations in the Atlantic inflow influence the ice conditions, especially during winter (LOENG 1988). Fig. 3 indicates a close relationship between temperature of the inflowing Atlanic water and the ice conditions.

RECRUITMENT OF COD

The year class strength of cod is mainly determined during the first year of life (HJORT 1914). BJØRKE and SUNDBY (1986) indicate that the first six months probably are the most important period. There are several factors that may be responsible for the variations of the year class strength. These include starvation at the start of exogenous feeding (HJORT 1914, WIBORG 1957, KISLYAKOV 1961, ELLERTSEN et al. 1976, 1980 and 1984), predation upon fish eggs and larvae (MURPHY 1961, MELLE and ELLERTSEN 1984) and physical factors acting directly on egg and larval population (GARROD and COLEBROOK 1978, KOSLOW 1984, SINCLAIR et al. 1985).

Recently, relationships between temperature conditions and the year class variations of Arcto-Norwegian cod have been examined. SÆTERSDAL and LOENG (1987) concluded that the major part of the year classes of high and medium abundance are either associated directly with positive temperature anomalies in the early part of a warm period in the Barents Sea, when the feeding areas are expanding, or they occur immediately prior to a shift to a warmer regime (Fig. 3). During the period 1900-1987, medium and strong year classes of cod have occurred 27 times. Only the year classes 1963 and 1985 do not fit into the picture of high recruitment with a regime of increasing temperature. Compared to the climatic variations, the years after 1970 (Fig. 3), there were strong year classes in 1970, 1983 and 1985, while the year classes of 1973, 1975 and 1984 were of medium abundance (SÆTERSDAL and LOENG 1987). During the cold period 1977-1982, all year classes were of low abundance.

The effect of the temperature at the spawning ground on the year class strength has been studied by ELLERTSEN et al. (1987). Fig. 4 shows the relation between year class strength and the mean temperature in Lofoten during the spawning period in March-April. Good year classes never occur in cold years, while they may be produced in warm years. The "triangle plot" indicates that high temperature is a necessary, but not a sufficient condition for the production of year classes of high abundance (ELLERTSEN et al. 1987). A similar "triangle plot" occurs when using temperatures from the Kola-section in August-September, which coincides with the time when the produced year class appears as 0-group fish in that area (ELLERTSEN et al. 1987). The existence of such a time lag could explain those cases where high recruitment occurs just before the shift from a colder to a warmer period, as pointed out by SÆTERSDAL and LOENG (1987).

Since the climatic variations are large-scale, one would expect that other stocks which reproduce in these ecosystem would be similary affected. DRAGESUND (1971) and SÆTERSDAL and LOENG (1987) found several years of common high recruitment in cod, haddock and herring, which gave a convincing demonstration of a close temporal relationship for larval survival. The favourable physical conditions seem to be directly or indirectly related to increased heat transport in the Atlantic current (SÆTERSDAL and LOENG 1987, MUKHINA et al. 1987).

DISTRIBUTION AND GROWTH OF YOUNG COD

Immature cod feed in the Barents Sea and in the Svalbard area, and make seasonal east-west and north-south migrations (MASLOV 1968, MIDTTUN et al. 1981). In addition, there are temperature-related displacement of concentration both on small and large time and space scales. EGGVIN (1938) reported more westerly fishing areas in the Barents Sea in cold years than in warm years. HYLEN et al. (1961) concluded that a connection exists between the environmental temperature and the distribution of young cod. When the temperature is high, the fish are easterly distributed, while the fish tend to move westward with low temperatures. KONSTANTINOV (1967, 1969) and MUKHIN (1979) come to the same conclusion on the basis of Russian trawl catches in the Barents Sea.

Since 1977 the Institute of Marine Research has carried out combined acoustic-trawl surveys in order to investigate the abundance and distribution of cod and haddock in the Barents Sea during early winter (DALEN et al. 1977, HYLEN et al. 1986). MIDTTUN et al. (1981) used data from these surveys to study the geographical distribution of each age group of immature cod during a period (1977-1981) with low temperatures in the whole Barents Sea (Fig. 3). Their results demonstrate a clear westward shift in the distribution of all year classes of young cod in the period with decreasing temperature, resulting in the restriction of cod to the western half of the Barents Sea. Later, SHEVELEV et al. (1987) and BOYTSOV et al. (1987) came to the conclusion that the distribution of both immature cod and haddock are determined primarily by the heat content of the water masses. In addition, SHEVELEV et al. (1987) concluded that cod responds to water temperature variations faster than haddock.

The intensity of Atlantic inflow to the Barents Sea also influences the distribution of 0-group cod and haddock. The distribution is determined by the strength of the current transporting them from the spawning field. An easterly distribution of 0-group of both species is probably caused by high activity of the Atlantic inflow (RANDA 1984, MUKHINA et al. 1987).

MIDTTUN et al. (1981) also found a westward displacement of cod with increasing age. SHEVELEV et al. (1987) suggested that the cod year class migrated westwards with an average of 80 nautical miles per year. Since the temperature decreases from west to east (Fig. 2), the younger age groups inhabit water of lower temperatures than older ones found farther west. This is clearly shown in Fig. 5, although large year-to-year variations appear for all age groups. On average, there appears to be a systematic increase in temperature by age of ~0.35°C year^{-1} for fish >3 years old (NAKKEN and RAKNES 1987). This indicates that these age groups maintain their distribution within the temperature field, relative to each other, more or less independently of the absolute values of temperature during the period of observation. For fish 1- and 2-years old the picture is more obscure, but this may be explained by the life history of the fish prior to first year (NAKKEN and RAKNES 1987).

NAKKEN and RAKNES (1987) also investigated the extent to which variations in the environmental temperature of the fish influenced the growth rates. Fig.6 shows the mean length of some year classes of cod at different ages plotted against the mean bottom temperature during winter for the last three years. Clearly, the mean length increased with increasing temperature. It may be hypothesized that the increasing growth was a consequence of decreasing stock in the considered period, but since the cod stock amounted to only a fraction of its normal level (~20 %), NAKKEN and RAKNES (1987) found that difficult to accept. They concluded that the increased growth was due to the increased environmental temperature.

Another example indicating temperature dependent growth is shown in Fig. 7. This shows the length distribution of cod 3 years of age in the Barents Sea during winter 1984. The length decreases from west to east in the same way as the temperature (Fig. 2). The same result is also valid for other age groups and in different years.

The increased growth indicated in Fig. 6, might have led to maturation of the cod at a younger age than in previous years. HYLEN and NAKKEN (1982, 1983, 1984) have shown that the percentage of younger fish in the spawning stock has increased significantly during the early 1980's. The year classes for which earlier maturation has occurred have inhabited gradually warmer waters and have shown a consistently increasing growth and decreasing abundance (NAKKEN and RAKNES 1987).

DISTRIBUTION AND GROWTH OF CAPELIN

The great temperature fluctuations which have occurred since the mid 1970's have had great effect both on the spawning and feeding migration of capelin and on the distribution of spawning, feeding and over-wintering areas. Changes in the environmental temperature have also influenced the growth rate of capelin.

During summer and autumn the adult stock of capelin feed in the northern part of the Barents Sea (Fig. 8). The fish are found in both Atlantic and Arctic waters, and the majority of adult capelin seems to stay in water masses with mean temperature between -1^0 and 2^0C (LOENG 1988). Large-scale changes of water temperature seem to generate a significant displacement of the distribution of capelin as indicated in Fig. 8 (LOENG 1981, LOENG et al. 1983, OZHIGIN and LUKA 1985). During warm periods, as in the first half of the 1970's (Fig. 3), the capelin may reach the extremity of their distribution area at almost 80^0N and along the northern coast of Novaya Zemlya. In cold years, such as the period 1977-81, capelin has a more southwesterly distribution (Fig. 8).

During the relatively slow temperature decrease from 1976 to 1979, the mean concentrations of 2-4 year-old capelin were found in a constant position relative to the temperature field (Table 1). From 1980 there was a change in the distribution of capelin relative to the environmental temperature and especially during the rapid temperature increase from 1982 to 1983 (Fig. 3). This indicates that capelin does not immediately respond to rapid thermal changes. According to USAKOV and OZHIGIN (1987) there is a 1-2 years delay in the respond of capelin to climatic influences.

The large scale temperature variations also cause changes in the location of the spawning grounds and the spawning migration routes. According to USHAKOV and OZHIGIN (1987) the temperature $2\text{-}3^0$C is optimal for spawning capelin. Therefore, in cold years, the main spawning grounds are found along the coast of northern Norway, while in warm years there is more easterly spawning (Fig. 8).

GJØSÆTER and LOENG (1987) have analysed the growth of capelin in relation to temperature. Within years, they found a close relationship between the two variates, and the growth increased by approximately 0.3 cm $^0C^{-1}$. However, in different years, a given temperature is associated with different levels of growth, as shown in Fig. 9. Growth differences from year to year cannot be directly assigned to temperature variations.

GJØSÆTER and LOENG (1987) also found a relationship between feeding area and growth. The growth in the southern and western parts is generally higher than in the northern areas. This relationship seems to be a function of temperature, and may be more useful as a management tool than the direct relationship between temperature and growth. In periods of constant ecological conditions, there seems to be a relationship between the climate and the distribution of capelin. Knowing the large-scale development of the sea climate, a valid forecast of the feeding area for the next year may be given (OZHIGIN and USHAKOV 1985), and thus also a rough estimate of the expected growth (GJØSÆTER and LOENG 1987).

DISCUSSION

When they studied the growth of cod, NAKKEN and RAKNES (1987) concluded that the coupling between environmental changes and population parameters such as areas of distribution, abundance, growth and maturity is probably far more complex than a simple length - temperature relationship. GJØSÆTER and LOENG (1987) came to the same conclusion when they studied the growth of capelin. Temperature effects linked to the availability of food may be as important as the direct effects. Various mechanisms are conceivable. A shift in climate could alter the general physical conditions, thus altering the availability of nutrients for the primary producers. It could affect the growth of organisms on different levels in the food web, and it could influence the abundance of food competitors, predators and so on.

The transport of zooplankton by current is known to vary with the rate of Atlantic inflow (OZHIGIN and USHAKOV (1985). Consequently, the currrent system will influence the growth of plankton feeders through variations in available food. This may partly explain the difference in growth for equal temperatures from one year to another, as observed for capelin by GJØSÆTER and LOENG (1987). In this case, the water temperature is not the primary cause of the change of food avalability, but is only an indicator of change in the water masses.

Variations in the Atlantic inflow will influence the temperature conditions in the southern Barents Sea, the position of the polar front and the maximum ice extent during winter and spring (LOENG 1988). This may, in turn, affect the local production of plankton. In the polar front area and in the Atlantic water just south of the frontal area, the spring phytoplankton bloom starts earlier in cold years and culiminates a month or more prior to the bloom in warm years (REY et al. 1987, SKJOLDAL er al. 1987). Both papers also concluded that in warm years the primary production from the spring bloom available for zooplankton would be larger than in cold years and most of it would be channelized to the pelagic ecosystem. The zooplankton spawning, however, starts later in cold years than in warm ones (DEGTEREVA 1979). Therefore the copepodites do not reach a size which allows them to fully utilize the early phytoplankton bloom (SKJOLDAL et al. 1987). This will of course result in less food for all plankton feeders.

The feeding conditions for fish larvae may also influence the year class strength. The temperature affects the timing of spawning of copepods and the development of copepod eggs and larvae is directly affected by the temperature (ELLERTSEN et al. 1987). Therefore, high water temperatures, may only be an indicator, and not a direct cause of a strong year class.

If an adult fish experiences a temperature near the boundaries of its tolerable range, it could in most cases move actively away from such areas. Therefore it is plausible that the temperature conditions affect the northern and eastern boundaries of fish distribution in the Barents Sea. Temperature observations may therefore be used to forecast the outermost limits of distribution for the different fish species.

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Table 1. Mean temperature (°C) in the distribution area of 2, 3 and 4 year old capelin in the period 1974-1985 (GJØSÆTER and LOENG 1987).

Year		Age	
	2	3	4
1974	-1.15	-0.18	0.32
1975	-0.03	-0.29	-0.26
1976	0.16	0.46	0.76
1977	-0.32	-0.38	-0.37
1978	0.03	-0.11	0.13
1979	-0.05	-0.19	-0.05
1980	0.78	0.68	0.85
1981	0.63	0.53	0.53
1982	1.12	0.99	1.13
1983	1.82	1.95	2.11
1984	0.56	0.99	1.04
1985	0.29	0.55	0.61

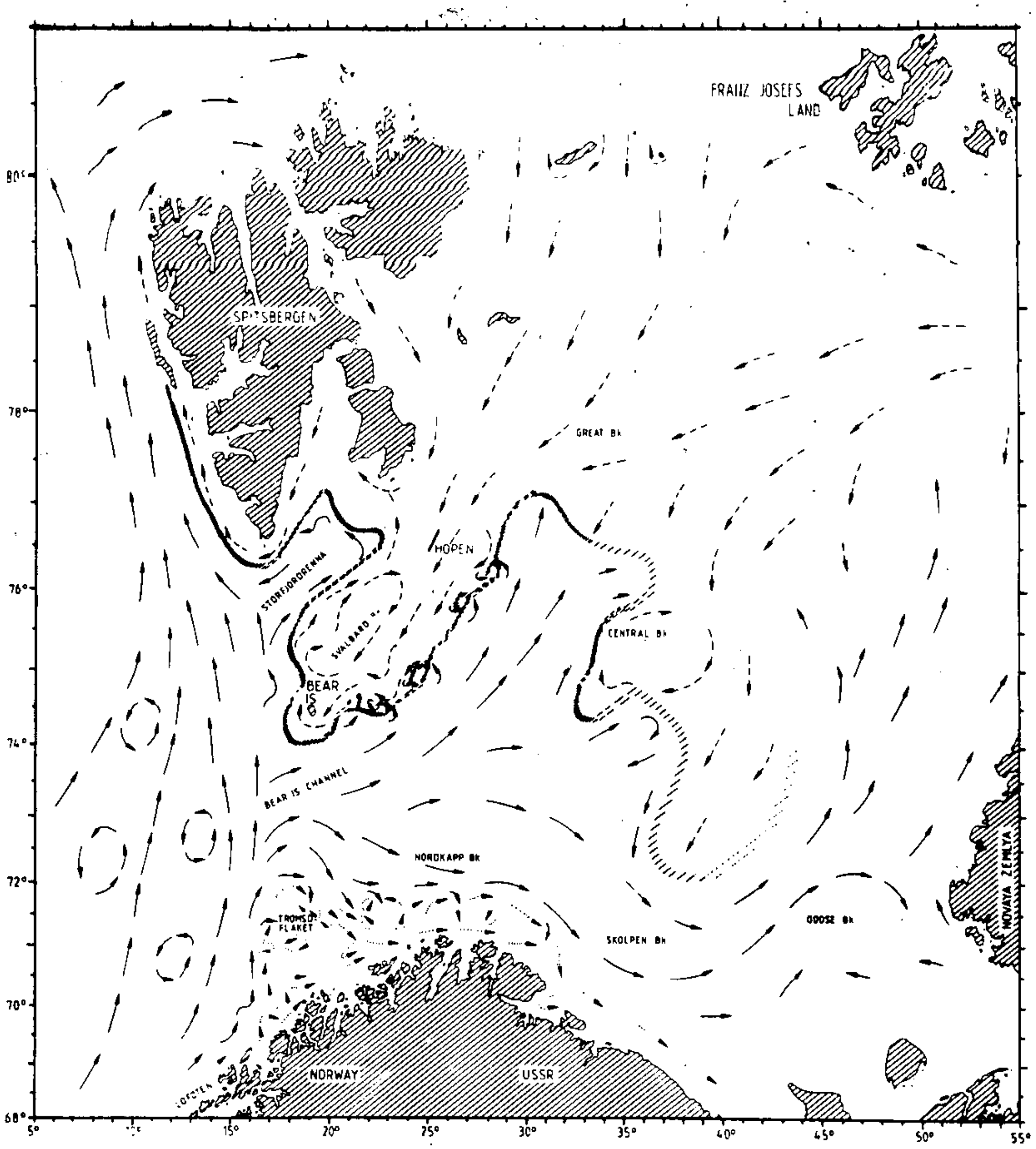

Fig. 1. Surface currents in the Barents Sea. Atlantic currents (——>), Coastal currents (····>) and Arctic currents (---->). The hatched line indicates the position of the Polar front (LOENG 1988).

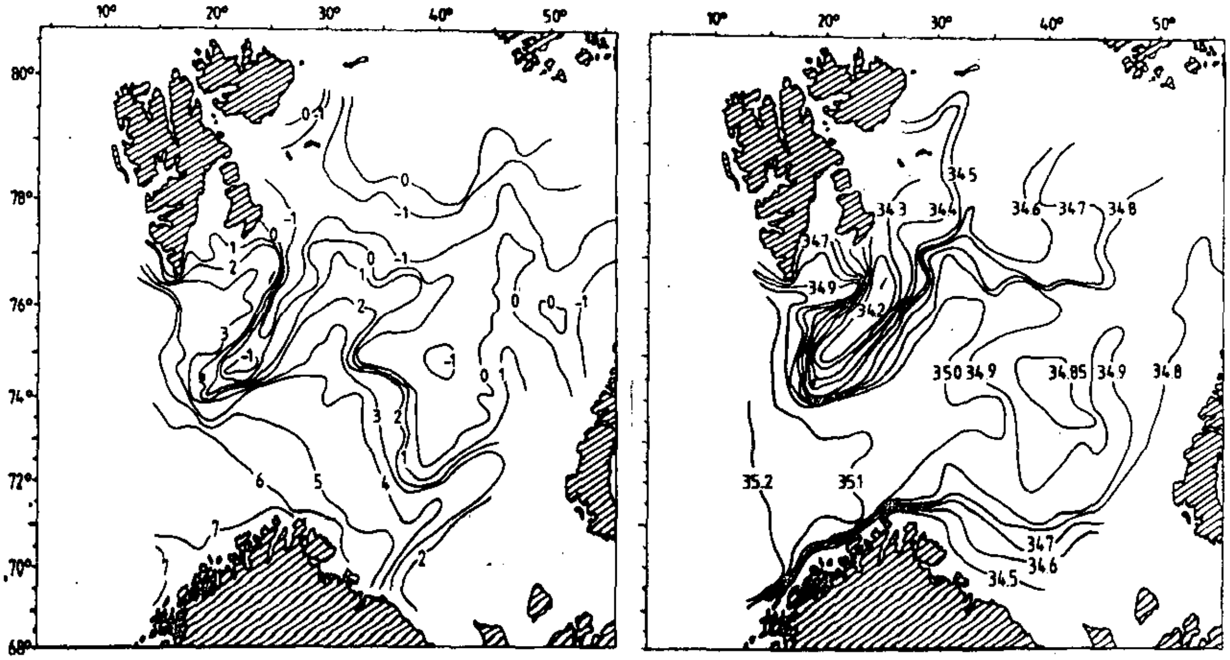

Fig. 2. Distribution of temperature (left) and salinity (right) at 100 m depth, during autumn (LOENG 1988).

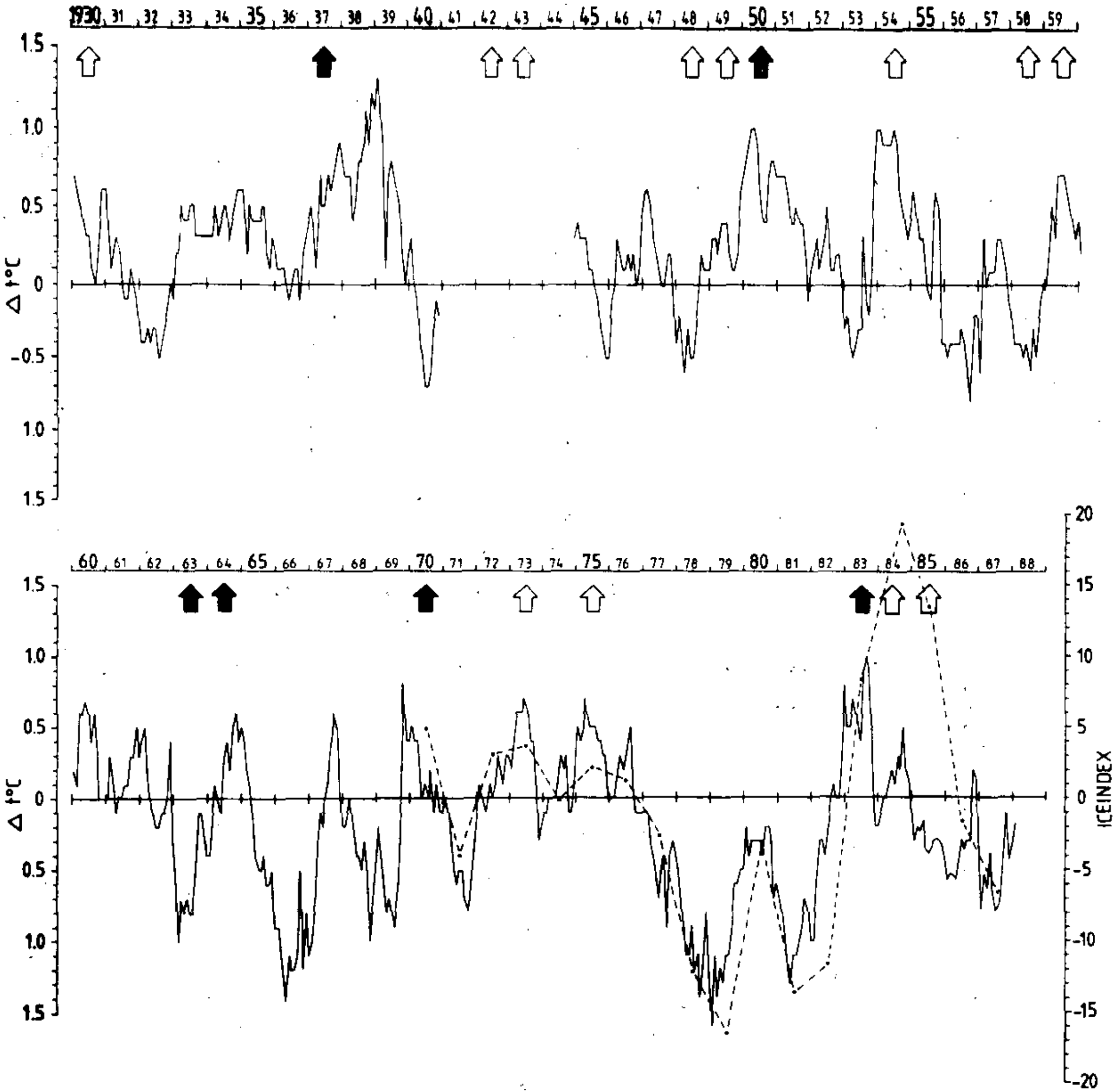

Fig. 3. Temperature anomalies in the Kola section (along 33^0 30´ E) in the period 1930-1988 (continous line) together with the ice index in the period 1970-1988 (broken line). Black arrows show year class of cod with high abundance and open arrows show year class with medium abundance (BOCHKOV 1982, MIDTTUN <u>et</u> <u>al.</u> 1981, SÆTERSDAL and LOENG 1987).

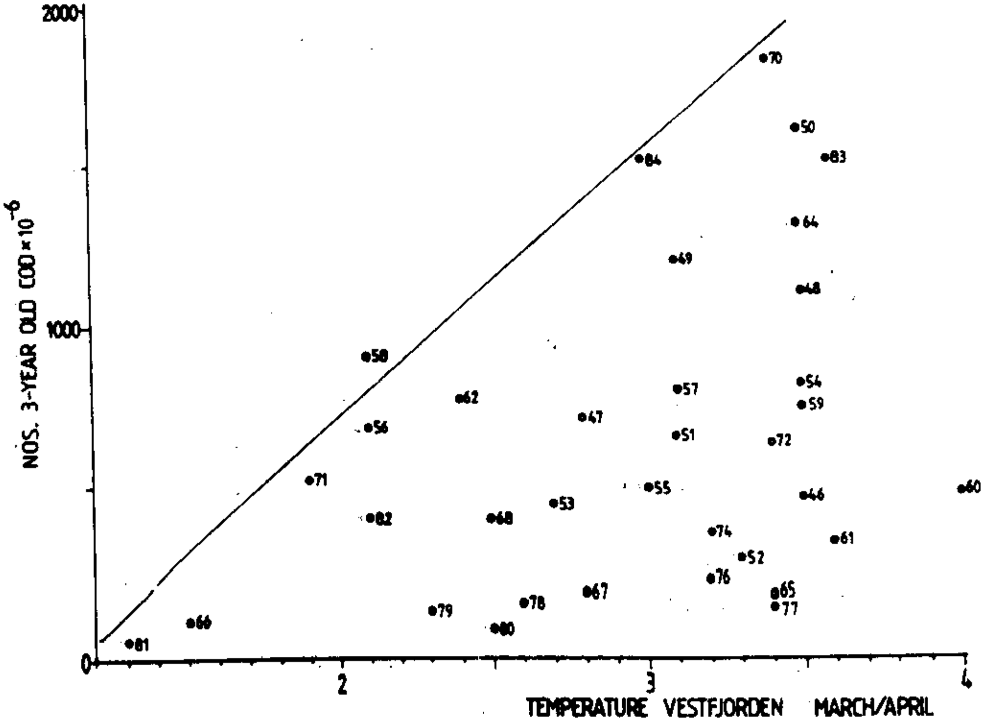

Fig.4. The relation between the year class strength of cod and the mean temperature in March-April at the spawning ground (ELLERTSEN *et al.* 1987).

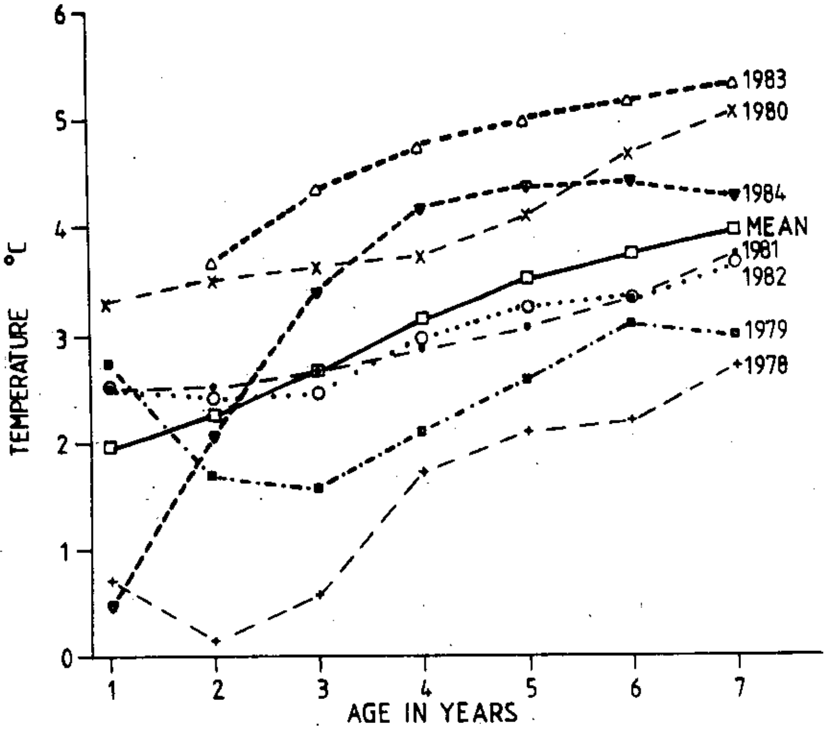

Fig.5. Mean environmental temperatures for various age groups of cod in February for the years 1978-1984 (NAKKEN and RAKNES 1987).

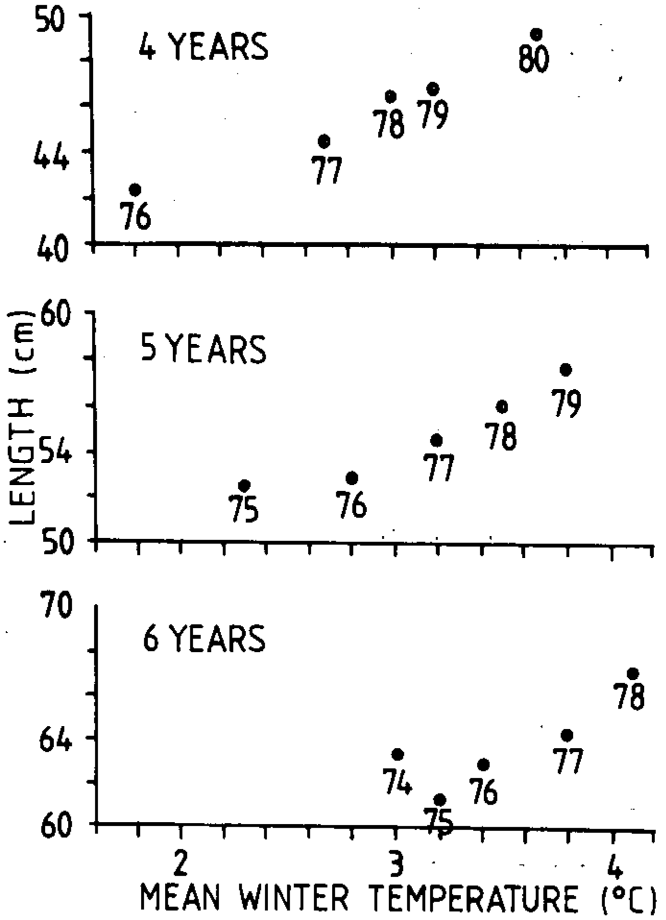

Fig.6. Mean length of some year classes of cod at different ages (4, 5 and 6 years), plotted against mean environmental temperatures in February averaged over the last three years (NAKKEN and RAKNES 1987).

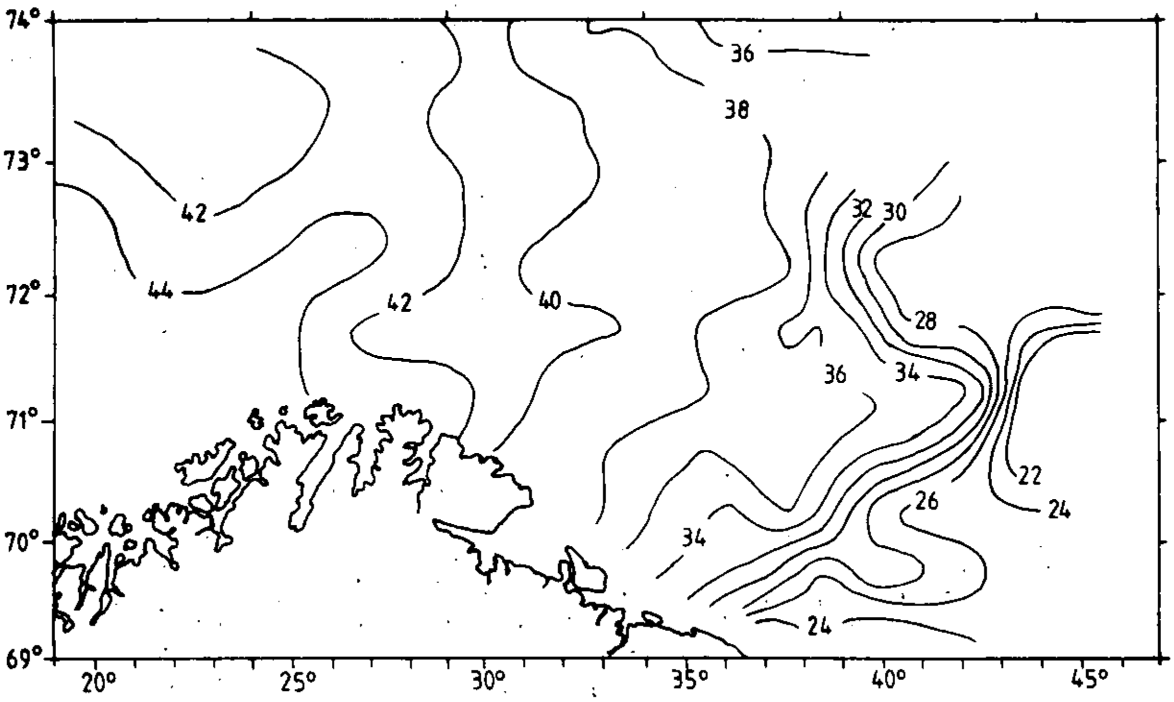

Fig.7. Length (in cm) of three-year-old cod in February 1984.

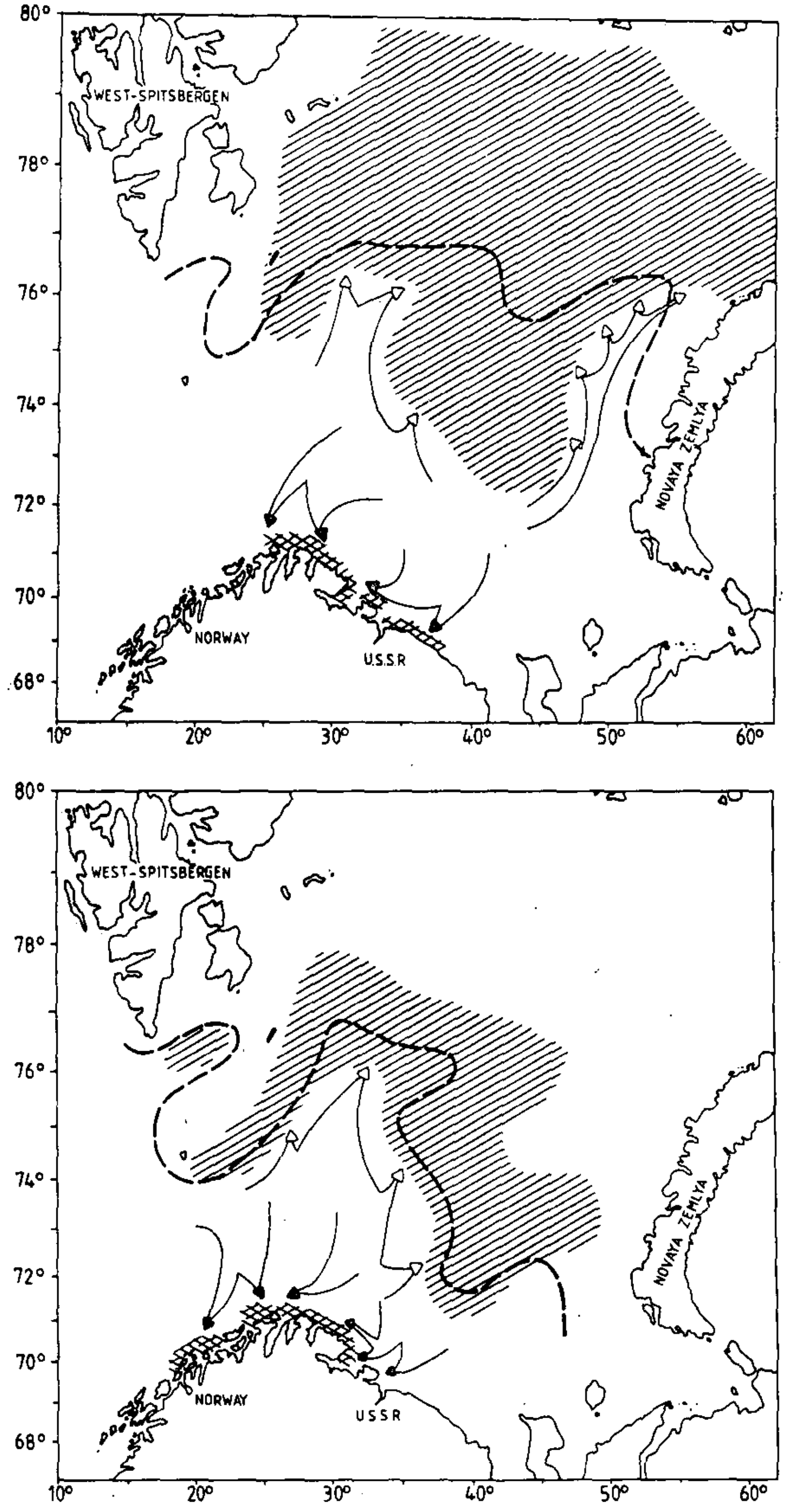

Fig.8. Distribution of feeding area (hatched) and spawning ground (dobble hatched) in warm years (upper) and in cold years (lower). Arrows with open heads indicate feeding migration and arrows with black heads indicate spawning migration route. The broken line show the approximate position of the 0^{0}C-isotherm at 100 m in warm and cold years (LOENG 1981, LOENG *et al.* 1983, OZHIGIN and LUKA 1985).

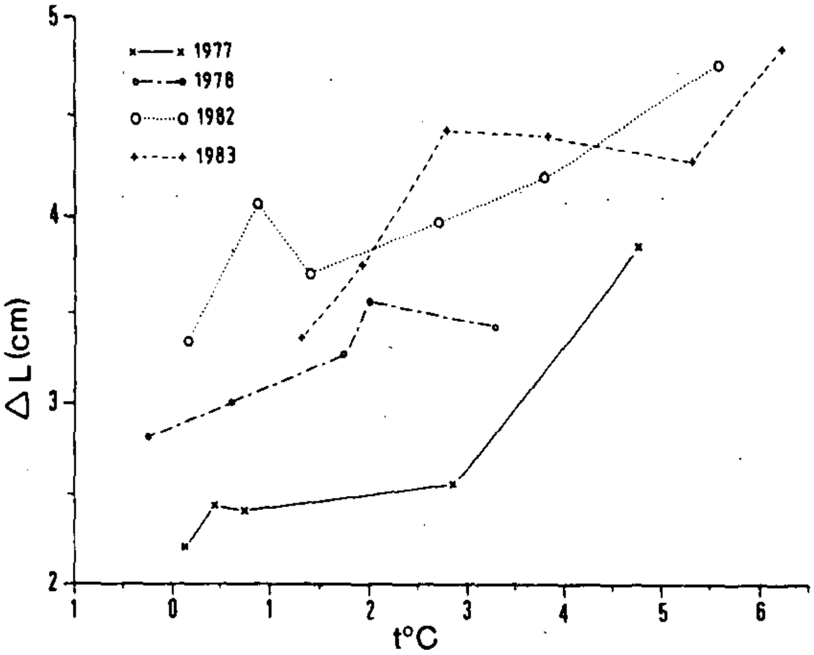

Fig.9. Length increment plotted versus temperature for two years old capelin in different areas in the Barents Sea in the years 1977, 1978, 1982 and 1983 (GJØSÆTER and LOENG 1987).