Effects of climate and stocks interactions on the yield of north-east arctic cod. Results from multispecies model run

by

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Abstract

A conceptual climate dependent multispecies model for stock interactions and harvesting of herring, capelin and cod in the Norwegian Sea-Barents Sea region has been developed. The concept presupposes that good recruitment of herring and cod is linked to warm ocean climate, which may occur with frequencies of 8 to 10 years. Strong herring year classes overlap the distribution of capelin larvae in 3-4 years causing mass mortality of the capelin fry, and depletion of the capelin stock. At that time the herring is about to leave the Barents Sea, and lack of food in subsequent years reduces the potential yield of cod. Immature cod is the main predator on mature capelin and cannibalism is an important factor in reducing the abundance of juvenile cod when the capelin stock is rebuilding. The model is used in a study of the effects of different fishery management strategies on stocks and yield. Results show that optimum yield of cod is obtained by high fishing mortality on immature cod from the end of a warm period until the spawning stock of capelin is rebuilt In subsequent years the fishing mortality should be reduced until a new warm period occur. This harvesting strategy of cod gives an optimum biomass production of capelin and an optimum potential yield of cod for a spawning stock limit of 200 thousand tonnes. The results are in accordance with the catch history of cod. Prior to the 1970's, the effort of the fishery in the Barents Sea followed to a large extent the abundance of immature cod, resulting in large catches when the stock was abundant. The yearly catches varied from 0.4 to 1.3 mill. tonnes, and the average catches obtained in the two periods 1950-1958 and 1959-1969 are the highest on record. Moreover, the trawlers fished with small meshes in the cod end, discarding considerable quantities of small fish.

Introduction

In 1983-86 the strong herring year class 1983 occurred in the southern part of the Barents Sea, and coincided with a dramatic fall in the recruitment to the capelin stock, which collapsed in 1986. The lack of prey fishes in subsequent years caused mass mortality in the fish-eating stocks of fish, sea birds and marine mammals, and the collapse of stocks was associated with the occurrence of the herring, which had been absent from the Barents Sea since the 1960's (Hamre 1985, Anon., 1987, Moksnes and Øyestad, 1987, Gjøsæter and Bogstad, 1998). A conceptual model 'Systmod', which linked the observed interrelations between herring, capelin and cod to changes in the ocean climate has been developed in cooperation between

The Institute of Marine Research and the Norwegian Government Computing Center (Hamre and Hatlebakk 1998).

The conceptual hypothesis of the model presupposes that the herring has a decisive impact on the recruitment of capelin and is governed by periodic changes in the ocean climate. A warm climate provides good recruitment of herring and cod, but the herring entail mass death of capelin fry. These interrelations and the predation of immature cod on mature capelin when the capelin stock is depleted, are the most powerful dynamic factors in the system. This paper summarises the main evidences, which support the hypothesis of the model, describes the model structure and presents some preliminary results of model runs.

The concept

The physical conditions in the Norwegian Sea - Barents Sea region are governed by the inflow of Atlantic water through the Faroe-Shetland Channel (Figure1). The interface between the warm Atlantic water and the cold Arctic water, provides upwelling and the physical basis for two highly productive areas, one in the Norwegian Sea along the Polar front, and one in the marginal ice zone of the Barents Sea. Most of the plankton production is harvested by the Norwegian spring-spawning herring *Clupea harengus* in the Norwegian Sea, and the capelin (*Mallotus villosus)* in the Barents Sea (Figure 2). Herring and capelin are the main food sources for a large variety of stocks, but the northeast Arctic cod *Gadus morhua* is the largest predator and plays a decisive role in the balance of predators and prey (Bogstad and Mehl, 1987). The stocks spawn on the Norwegian coast, and the spawning migrations of the plankton feeders transfer huge quantities of fish biomass from distant waters to the Norwegian continental shelf and to the southern parts of the Barents Sea. These processes make this shelf area to one of the most profitable fishing grounds in the world.

Two large semipelagic stocks occur in the region, blue whiting and polar cod. The semipelagic stocks are however of marginal importance as prey species in this system because they spawn in other areas.

Details on stock distributions and interactions are illustrated in Figures 2 and 3. The adult herring feed along the Polar front in summer and spawn in spring on the western Norwegian coast. The cod spawn on the northern Norwegian coast in spring and feed in the southern part of the Barents Sea. During summer the capelin feed in the marginal ice zone and accumulates in front of the south moving ice boarder during autumn. In winter the maturing stock migrates towards the coast for spawning, and becomes available to the immature cod in the Barents Sea in spring. In the southern part of the Barents Sea the distribution of juvenile herring overlaps the distribution of the capelin larvae, which affects the survival of the capelin fray in warm periods when herring is abundant. The temperature varies periodically, with 8 to 15 years between warm periods (Figure 4) and a warm climate coincides with strong year classes of herring and cod. (Marty and Federov, 1963; Sætersdal and Loeng, 1984). These stock and climate interactions are the most powerful conceptual factors of the system and determine the dynamics of the model. A technical version of the model was published in a paper by Hamre and Hatlebakk in 1998, and a brief description of the model structure is outlined below.

Model structure

The model consists of three single species stock models (Beverton-Holt type) modelled as parameter dependent. The model is length-based, and the growth in length is modelled by the equation (von Bertalanffy, 1938):

$$dL(t) = l(t+T) - L(t) = (L_\infty - L(t)) \cdot (1 - e^{-KT}) \cdot M(t)$$

where t is a time variable and T an interval of fixed length. L_∞ is the maximum length of the fish. M(t) distributes the yearly growth on the different months, and K is the growth parameter, determined by the following equation for herring and capelin:

$$K = (a + b \cdot e^{-d \cdot B(t)}) \cdot g$$

B(t) is the stock abundance at time t, and regulates a density dependent growth. For cod the parameter K is computed according to the equation:

$$K = a(2.2 - 0.4 \cdot \frac{CCODC}{COD}) + b \cdot \frac{CCOD}{COD}$$

CCOD is the modeled food consumption for cod, CCODC the consumption of capelin, and COD the stock biomass. The a-parameter represents growth related to other food.

g is a function to regulate the growth according to environmental factors.

The juveniles are recruited to the stock in January at age 1. To describe the relation between the spawning stock in the springtime and the number of recruits in January the following year, the Beverton-Holt function is used:

$$R = \frac{M \cdot B}{H + B} e^{a \cdot T}$$

where R = recruitment; M = maximum recruitment; B = spawning stock biomass; H = the half- value; T = temperature anomalies. Two levels of M, high and low, are used for simulating recruitment when T exceeds a given value.

The effects of juvenile herring on the survival of capelin fry is modeled by a reduction factor proportional to the abundance of the age groups 1 to 3:

$$R = R_o \cdot (1 - (a_1 \cdot HER_1 + a_2 HER_2 + a_3 \cdot HER_{3+}))$$

The maturity ogive is computed from a logistic function (Tjelmeland, 1987):

$$M(l) = \frac{1}{1 + e^{4P_1(P_2 - l)}}$$

where l denotes mean length in the length groups. P_1 and P_2 are parameters.

In computing mortality per month the following variables are used:

$$N_{i,t+1} = N_{i,t} \cdot (1 - G) \cdot (1 - M) \cdot (1 - P_i) \cdot (1 - F_i)$$

- spawning mortality (G) (capelin only)
- fishing mortality (F)
- predation (P)
- natural mortality (not including predation) (M)

The monthly predation is computed by species:

For capelin: $\qquad P_i = K \cdot (a_0 \cdot COD_{im} + a_1 \cdot COD_m)$,

for Barents Sea herring: $\qquad P_i = K \cdot COD/(1 + b_1 \cdot CAP)$,

for cod: $\qquad P_i = K \cdot COD/(1 + b_1 \cdot CAP + b_2 \cdot HER_{im})$,

where

P_i - predation mortality rate for length group i

$a_i(COD)$ - weighted sum of the predator stock (m/im = mature/immature)

$b_i(CAP, HER)$ - reduction in mortality rate due to preference of prey species

The impact of changes in the climate is modelled by a sine curve fitted to observed temperature anomalies in the Kola section (Figure 4). The recruitment parameters of capelin are determined by comparing modelled numbers of 2 years old to acoustic estimates of the age group in autumn, and the parameters of herring and cod by comparing modelled numbers of 3 years old to the corresponding VPA-estimates of the stocks. The stock in numbers is converted to stock biomass by observed weight by length-groups.

The predation parameters of cod are derived from estimates of the yearly consumption of cod, available from 1984 onwards (Bogstad and Mehl, 1997). These parameters are of basic importance and the period after 1982 is selected for fitting the model results to data (Figure 6). The fits are reasonably good whether the sine curve or the observed temperature anomalies are used, even in the period 1994-1996, when the deviation between observed and simulated temperature is significant. This is due to cod cannibalism (Figure 7), when the capelin stock is

depleted. Assuming a cyclic change in the ocean climate, the model is used in analysing the impact of different fishery management strategies on stock and yield.

Management strategy analysis

The catch is modelled by fishing mortality (F) and by catch quotas by season and year, the fishery being closed if and when the quota is taken. The capelin winter fishery is closed when the maturing stock is reduced to a predetermined lowest acceptable level.

The stock estimates as of 1 January 1982 are chosen as terminal stocks, and the runs cover periods of 40 years. Prior to 1999 the model uses historical data on catch and temperature. Warm periods with a cycle of 8-9 years are observed in recent years and a sine curve with corresponding amplitude and frequency is chosen as prognosis for the further development of the climate. The strategy chosen for the period after 1999 is similar to the exploitation pattern of the stocks in the 1990's, and is for capelin: no autumn catch and a winter catch limit of 800 000 tonnes, allowing at least 500 000 tonnes to spawn; for cod: a F of 0.7 and a catch limit of 900 000 tonnes; for herring: a F of 0.2 and a catch limit of 1.2 mill. tonnes. Output files of catch and stock biomass are processed on spreadsheet and illustrated in Figures 8 and 9 (read lines).

The capelin catches fluctuate between 0 and 0.8 mill. tonnes, with an average catch of 0.4 mill. tonnes (Figure 8). The cod catches fluctuate between 0.3 and 09 mill. tonnes with an average of some 0.55 mill. tonnes, whereas the herring may yield a constant catch equal to the yearly catch limit of 1.2 mill. tonnes. The corresponding development in stocks (Figure 9) reflects the effects of the basic hypothesis that a warm climate is favourable for recruitment of herring and cod, but bring about collapses in the capelin stock. The alternation in stock size between the cod (the predator) and capelin (its prey) illustrates the well-known phenomenon of the Lotka-Volterra predator-prey relationship, with a frequency of 8 years.

The most important question of fishery management policy in the Barents Sea is concerned with the management of the cod stock. The fisheries industry wants stability, and in order to test the effect of constant cod catches on stocks and yield, the model has been run with a yearly catch limit of 600.000 tonnes of cod from 1993 onwards, keeping the other parameters unchanged. The results show (Figures 8-9, black lines) that this strategy may create a new cycle in the predator-prey relationships between cod and capelin with a frequency of 16 years. Stability in the yearly catches of cod may thus not be achieved by reducing fishing mortality when the stock is abundant, and an accumulated cod stock may reduce the obtainable catch of the other stocks significantly. A large immature stock of cod may prevent rebuilding of the capelin stock, which in turn may reduce the food supply for cod for a whole period (8 years), and a new cycle of 16-years may occur.

The effects of the capelin fishery on the yield of cod, and prolonged time lags between warm periods have also been tested by model runs. The results show that the gain in the catch of cod is about 10 percent of the corresponding loss in the capelin catch, provided that the capelin is caught during winter and that at least 500 000 tonnes of capelin are allowed to spawn. The capelin fishery has insignificant effect on the herring stock, but prolonged time lags between warm periods reduces the yield of herring considerably. This is however favourable for capelin recruitment and biomass production of the capelin stock.

Discussion

In a context of multispecies interactions with a large number of mutually dependent parameters, no unique solution exists in fitting model results to data. The parameter estimates used in this study are moreover preliminary, because some are only roughly estimated and not systematically tuned to data. However, the trends of development in stock and yield reflected by this model are probably more dependant on the validity of the concept on which the model is built than the accuracy of the parameter estimates. Provided that the concept is valid, the model should be a valuable tool to quantify the dynamic processes of the system. With this reservation in mind, some details of the model results will be commented on and discussed.

The impact of the climate on herring recruitment and the effect of juvenile herring on the capelin fray are the most powerful dynamic element in the model. The good herring recruitment takes place in warm periods when the fits of the sine curve to data are reasonably good. The strong herring year classes are triggered by high-temperature anomaly (T), and the model selects a high maximum recruitment level (M in the recruitment formula), when T exceeds a predefined value (0.4). When 3 strong herring year classes are simulated, the first one is reduced by 80%. For herring the high recruitment level is determined to be 20 times higher than the low M value, and the exponential factor in the recruitment formula is found to be negligible. Since the observed T in 1995 is below 0.4, the model estimates of recruitment for herring will be the same whether based on the sine curve or the observed values.

The recruitment relationship of cod to climate is different. The recruitment figures of 1-group cod is closely related to the temperature and less dependent on the peak value which triggers a strong herring year class. This is modelled by a relative high parameter value of the exponent in the recruitment formula for cod, and less differences in the levels of M. This will simulate good recruitment of cod in 1994-1995 as 1- group, but due to cannibalism in the subsequent years, these age groups are depleted as 3-year olds. The cod cannibalism in 1995 and 1996 is estimated to 0.4 and 0.6 mill. tonnes of young cod, respectively (Anon. 1998), and the cod predation parameters are tuned against these data. When the recruitment of cod as 3-group is modelled in this way, the final results of recruitment to the stock will be approximately the same whether the sine curve or the observed values of temperature are used in the simulation. The simulated food supply of cod from own progeny will however be lost when using the sine curve, and should be born in mind when using the model for prognostic purposes.

The ecological interpretation of the cod cannibalism indicates that the cod has adapted to the cyclic recruitment pattern of capelin by eating its own progeny when the capelin stock is depleted and is in a state of rebuilding. It seems obvious that if the 1 mill. tonnes of young cod eaten by older brothers and sisters in 1995-1996 had survived, this would have delayed rebuilding of the capelin stock in the subsequent years and thus threatened the food supply for the coming generations of cod. This form of cannibalism for regulating stock abundance when the prey species are scarce is a well known phenomenon among bird of prey and the ornithologists have termed it the Kain - Abel phenomenon (Newton, 1979)

The above interpretation of the role of cod cannibalism in the system supports the findings that a constant yearly catch-quota regulation of cod may fail in managing these fisheries on an optimal sustainable basis. It also explain the reason why the record catch of cod was obtained in the 1950's and 1960's, when the immature cod was heavily fished when the stock was

abundant (3 to 6 years after recruitment of strong cod year classes). The trawlers fished at that time with small meshes in the cod end, and large quantities of the smallest cod were discarded. In this way the trawlers increased the Kain-Abel effect in the system. The yearly catches fluctuated between 0.4 and 1.2 mill. tonnes, but the average catch obtained is the largest on record.

In conclusion, the present study indicates that the biomass production of capelin is the most important factor for the obtainable yield of cod, the former being governed by the recruitment and life pattern of the herring. The superior steering factor of the system is linked to the ocean climate, which may alternate with warm and cold periods. Most of the production takes place in the warm periods, and has to be harvested when the stocks are large in order to obtain an optimal sustainable catch. This refers especially to capelin and cod, which cannot be accumulated in their most productive phase for the benefit of increased catches when the biomass production is low. This is due to the short life span of capelin and to the stock interrelationship between mature capelin and immature cod. The sustainable yield of herring seems to be more dependent on climate changes than on the stock interrelationships and may be harvested with constant yearly catch quotas when the time lags between warm periods are short. A high frequency of warm periods is favourable for the herring, but has a negative effect on the obtainable yield of capelin and cod.

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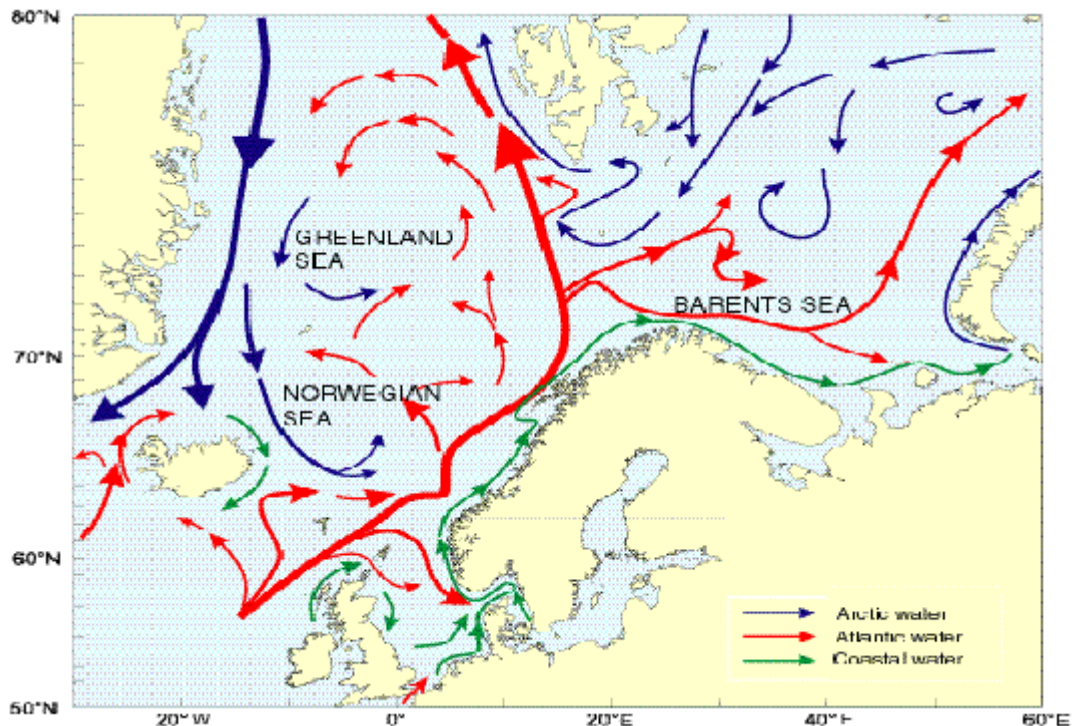
Figure 1. The circulation of the Norwegian- and Barents Sea.
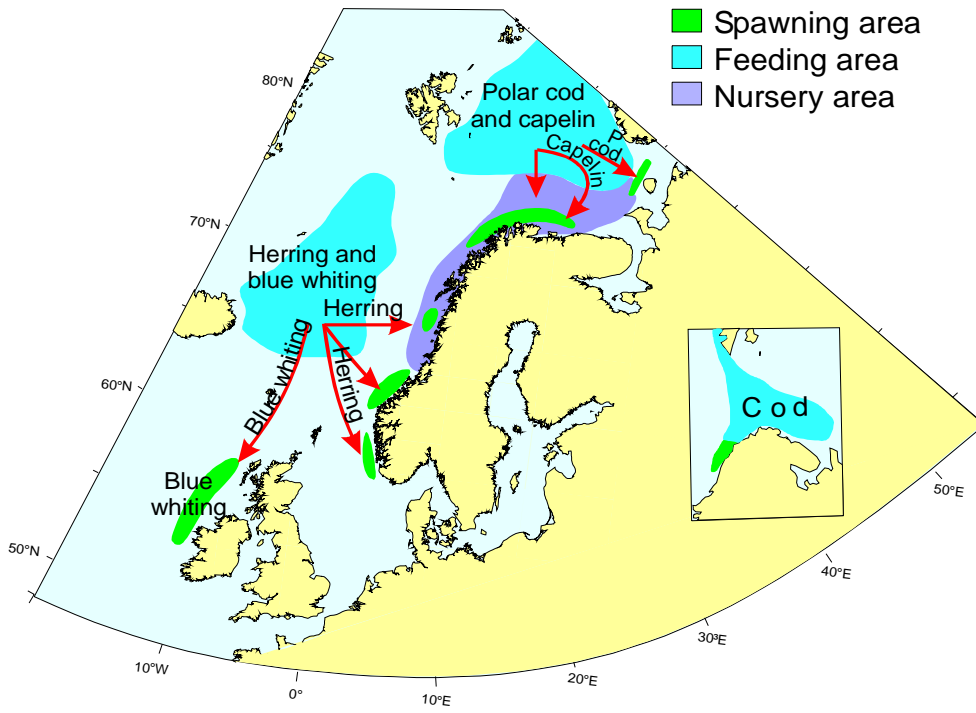
Figure 2. Distribution areas of main stocks in the Norwegian Sea-Barents Sea.　　.
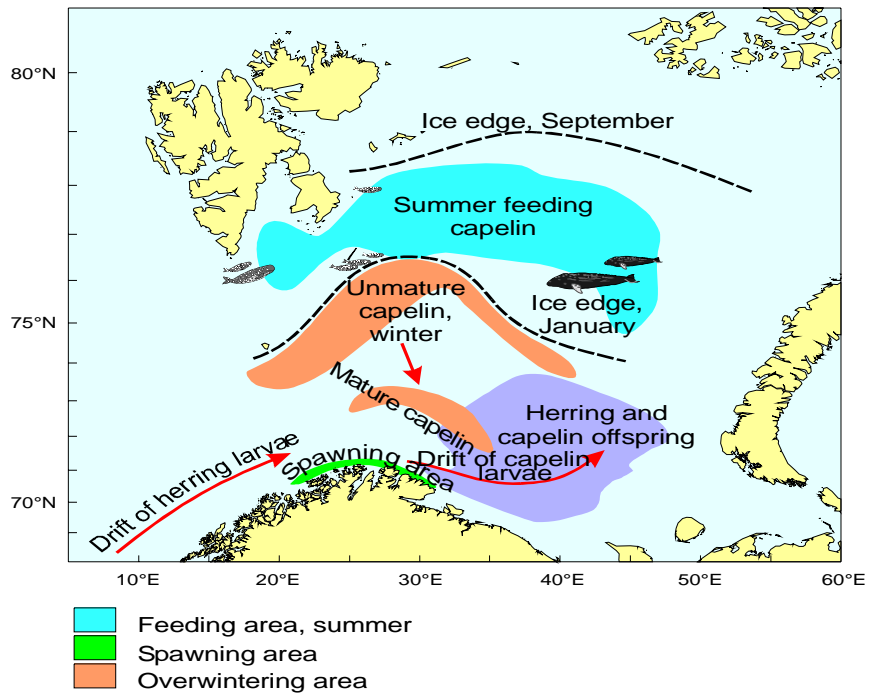

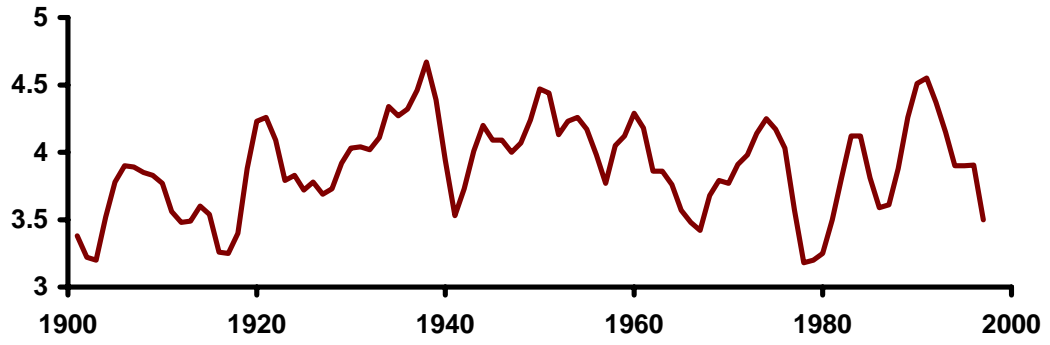Figure 3. Interactive feeding and competition of stocks in the Barents Sea.

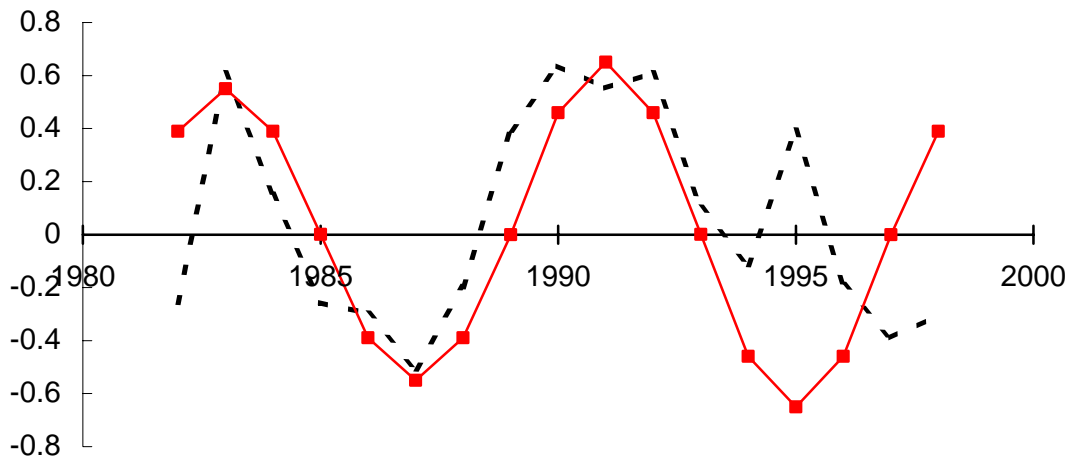Figure 4. Temperature in the Kola section (smoothed).

Figure 5. Temperature anomalies in the Kola section.
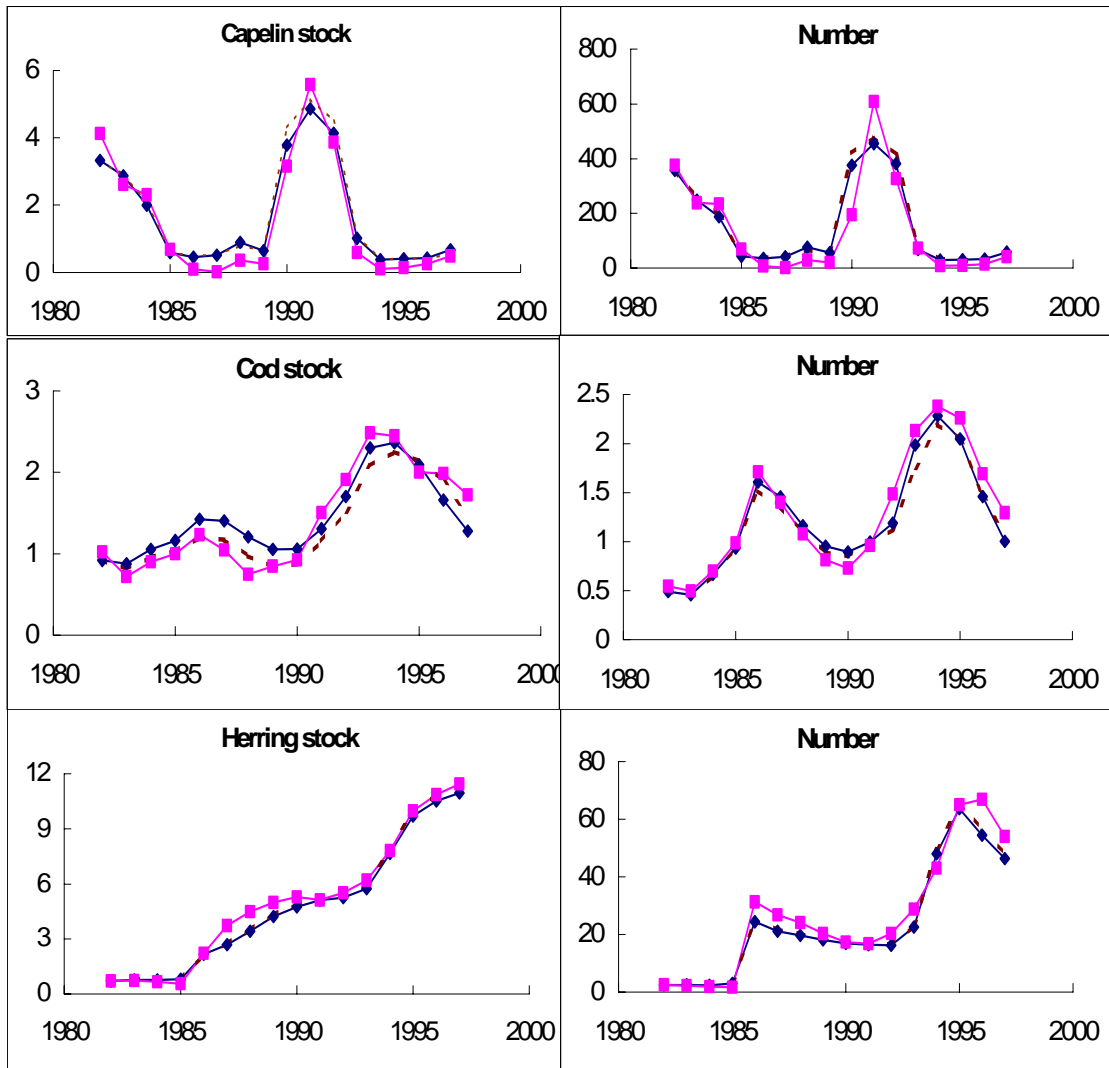red line = simulated, dotted line = observed

 Figure 6.   Simulated and observed (red line) stocks in weight and number. Dotted lines show the simulated stocks when the climate changes are expressed by a sine curve adjusted to the observed data.
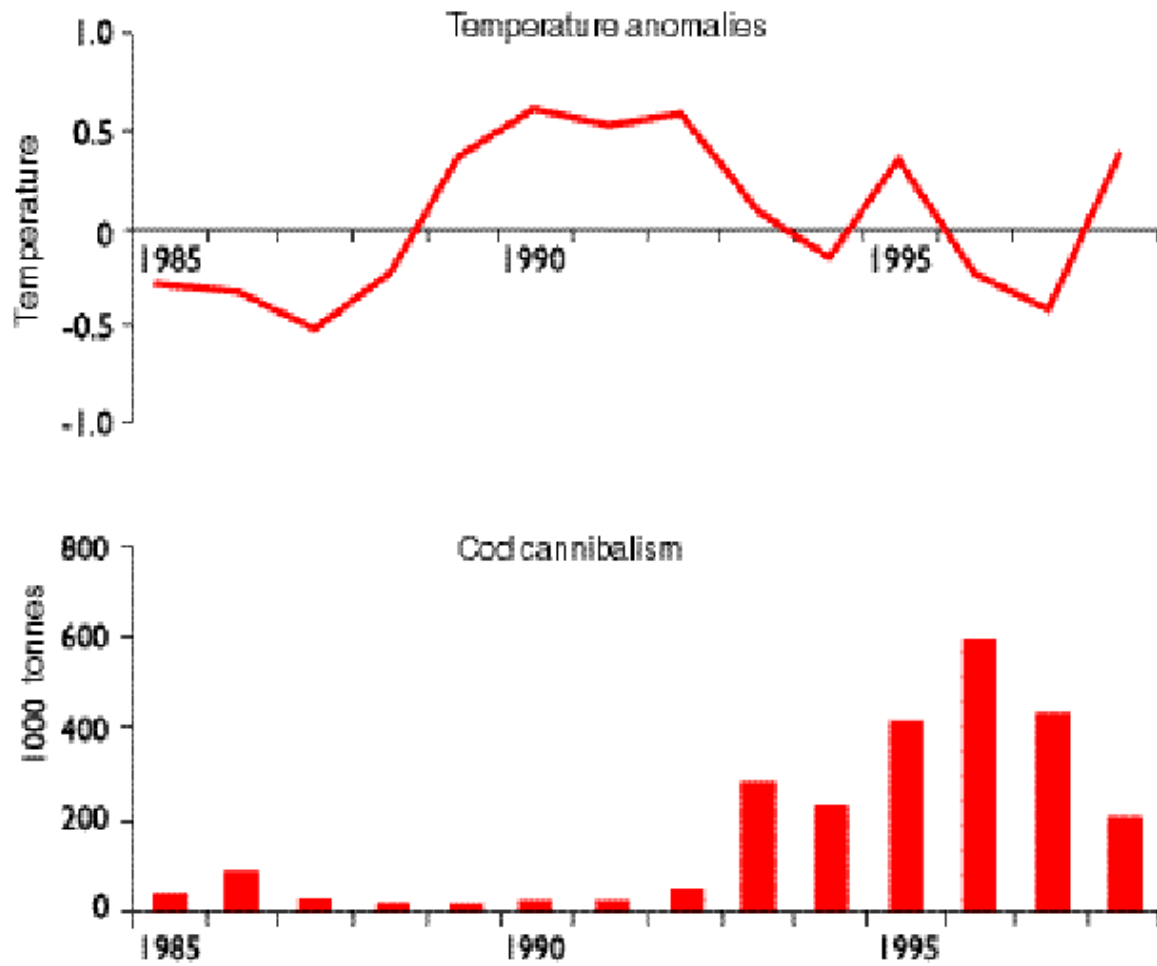
Figure 7. Cod cannibalism as an adaptation mechanism to food supply governed by the climate.
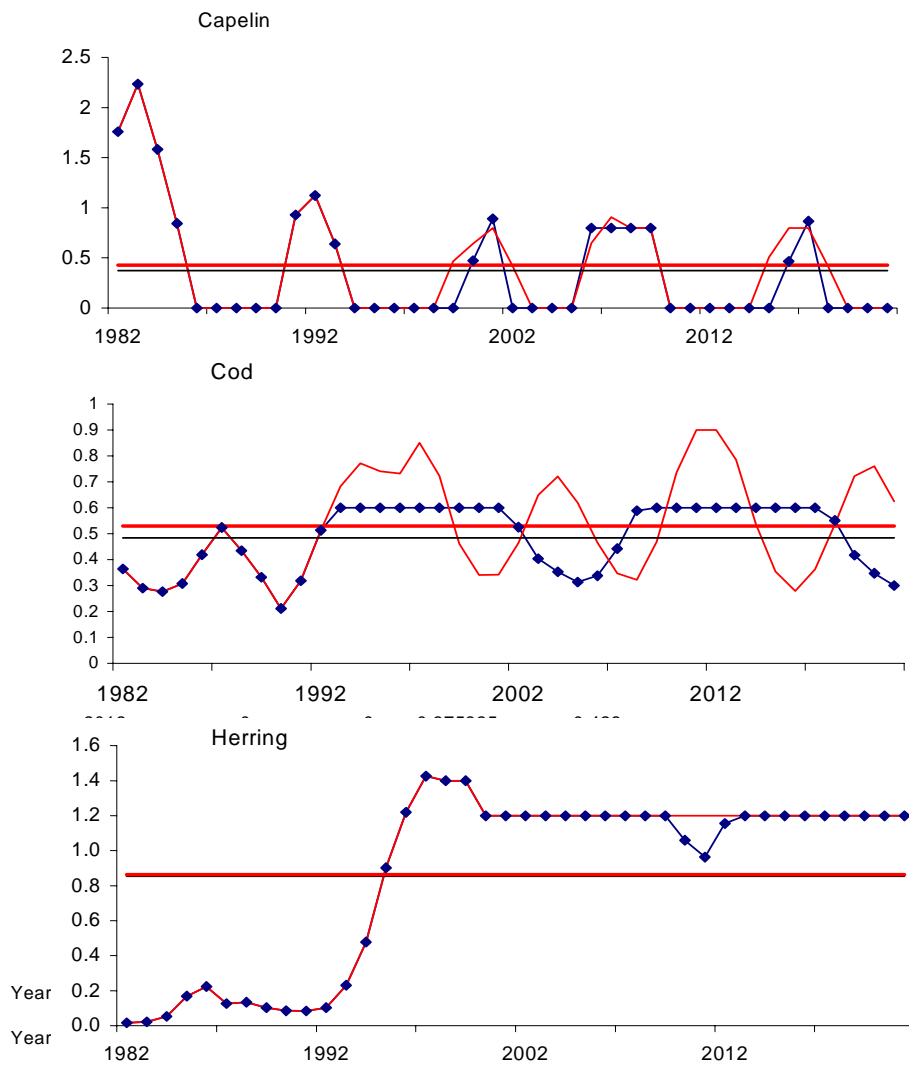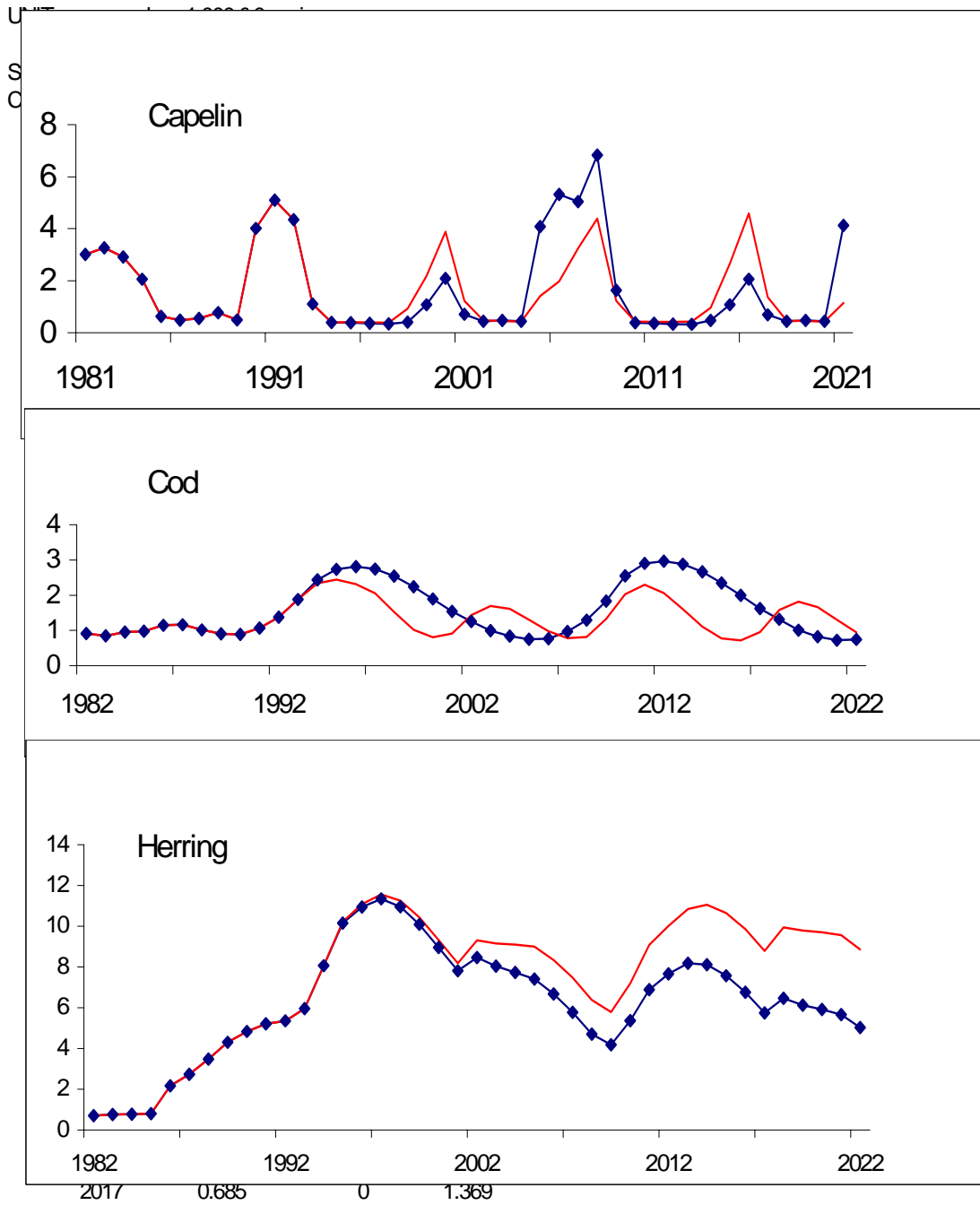
Figure 8. Simulated catches the next 20 years (see text.)

Figure 9. Simulated stocks the next 20 years (see text.)