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System dynamics of the Barents Sea capelin

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Abstract

The capelin (*Mallotus villosus)* has a northerly circumpolar distribution. In the Atlantic the capelin is located in the Barents Sea, Iceland, Greenland, Labrador and Newfoundland. The capelin stock in the Barents Sea is the largest in the world and has a key role in the Arctic food chain. The large fluctuations of the biomass have been poorly understood and collapses in the biomass have been registered. In the presented paper a system analysis of the capelin stock has identified a state dynamic model and a frequency dynamic model of the stock properties. The results show the capelin stock dynamics is adapted to the deterministic 18.6 yrs and 18.6/3=6.2 yrs Earth nutation cycles. The most important cycle is the 6.2 yrs cycle, which is identified in the recruitment, maturity and growth. A frequency transform of the estimated model shows a stochastic resonance at about the half of the 6.2 yrs cycle. The stochastic resonance shows that fluctuation of stock number is a natural adoption to the environment and a strategy for optimal growth and survival in the long run. In this stochastic resonance is timing between stock number fluctuation and the 6.2 yrs cycle of most importance.

Keywords: Capelin ecology; Capelin model; Capelin management; Stochastic resonance; 18.6 yrs nutation cycle

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1. Introduction

The capelin (*Mallotus villosus)* has a northerly circumpolar distribution. In the Atlantic the capelin is located in the Barents Sea (ICES areas I and IIa), Iceland, Greenland, Labrador and Newfoundland. The capelin stock in the Barents Sea is the largest in the world and has maintained a fishery with annual catches up to 3 million tones. The capelin population in the Barents Sea constitutes a separate management unit in the ICES management system.

This stock is of vital importance in the arctic food web. It is the main plankton feeder in the area and serves as an important forage fish for other fish stocks, seals, whales and sea birds. The capelin is therefore, not only influenced by its abiotic environment, but also by the abundance of food, predators and fisheries.

Because of high spawning mortality, the capelin stock consists only of few year classes. With only 5 cohorts and a fishery that influences most of the age groups, reliable estimates of year class strength are indispensable. The abundance of capelin in the Barents Sea is monitored annually during larval survey, 0-group survey and acoustic survey on individuals older than 1-year. Despite thorough oversee, the Barents Sea capelin stock has large fluctuations, with registered collapses in the biomass around 1985 and 1993 (Figure 1). A question to be answered is how we may prevent a new collapse of the biomass in the future.

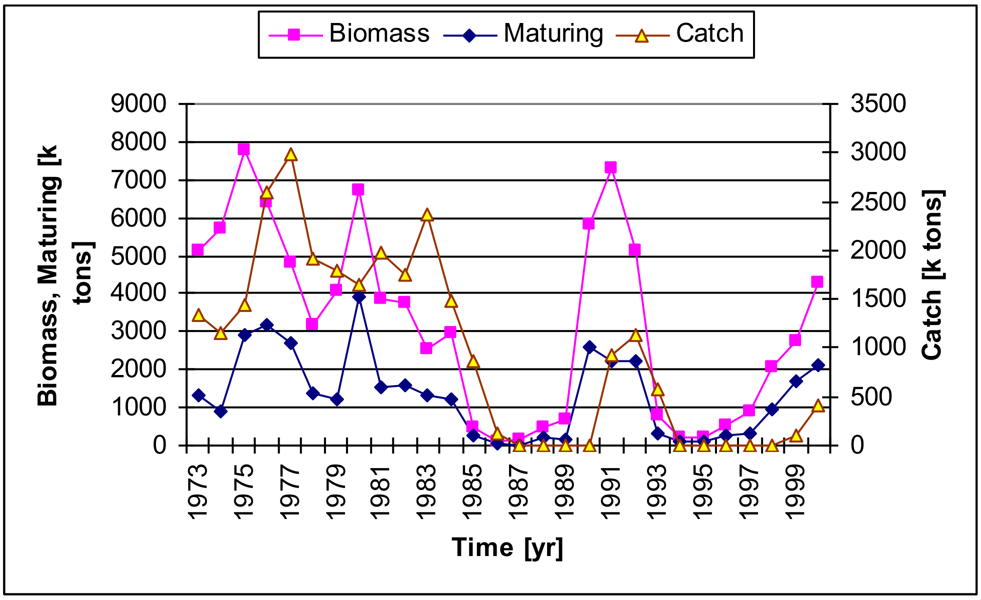

Figure 1 Time series of Barents Sea capelin biomass, maturing stock biomass and catch form 1973 to 2000 (1.October).

Variations in the biomass of any fish stock are dependent on the environmental temperature due to the thermal regulation of the individuals. Fluctuations in temperature will affect the stock characteristics, directly through effects on growth and recruitment or indirectly trough the variability of food and predators. Scientists have been aware of the trends in fisheries in relation to environmental variation in the past decades.

The environmental conditions in the Barents Sea are influenced by three water masses: Coastal Water in the south, North Atlantic Water extending over the western and central parts and the Arctic Water flowing in from north east. The temperature is therefore partly determined by the amount and the temperature of the water masses in the area.

Climatic variations are reckoned to be unpredictable, but some investigations have related such fluctuations to a nodal tide of 18.6 yrs. The oceanic response to this nodal tide is documented by Maksimov and Smirnov, 1965; Royer, 1989 and Royer, 1993. It is also reported a correlation between the Earth nutation and the temperature in the Barents Sea (Yndestad, 1999a). In addition the fluctuations in North Atlantic fish species have been related to the 18.6 yrs Earth nutation cycle (Izhevskii, 1964; Wyatt, 1984; Wyatt et al. 1994; Yndestad, 1996a, 1999b).

The aim of this study is to identify some basic system dynamic properties of the capelin stock related to growth, maturity, recruitment, and the response to environmental condition. In this investigation the environmental conditions in the Barents Sea are an estimated deterministic temperature cycle related to the Earth nutation. If the nutation cycle is active in the area, it will affect the sea temperature and dynamic properties of the capelin stock through growth, recruitment and mortality. This system dynamics can be used to predict when the capelin population has the best conditions for growth and survival and when this stock is more vulnerable to exploitation. This would make long time management possible and could be a method to prevent further collapses of the Barents Sea capelin.

2. Materials and methods

2.1. Materials

This investigation is focused on the Barents Sea capelin (*Mallotus villosus)*. Official monitoring of this capelin stock started in 1972. The results in this study are therefore limited to the periods from 1972 until today, where actual statistics of the capelin stock are obtainable from ICES reports. Growth, maturity and recruitment are used as parameters in capelin model identification. Data on growth and recruitment dates back to 1972. Registration of maturity did however not start until 1988, giving rather short time series. Data on stock numbers and weight are from measured in October. Estimates of January and April data started in 1990. This may introduce an overestimate of the catch rate to landing. The catch is the sum of catch in spring and autumn.

The capelin is the main plankton feeder in the Barents Sea. Zooplankton abundance was used as a parameter to find a possible binding between the capelin stock and the Barents Sea food system. The ICES registration of zooplankton in the Barents Sea did not start until 1987. The

Barents Sea zooplankton biomass is measured from the "multispecies" region 2 to 8 and the sum of 180-1000µm, 1000-2000µm and >2000µm and covers bottom to 0 m (ICES, 2001a). Missing data are region 2, 3, 4, 6 and 8 in 1988 and region 6 in 1989.

The Barents Sea capelin serves as an important forage fish for other fish stocks, seals, whales and sea birds. Reliable time series on stock characteristics are easiest to obtain for commercial fish species. Since young Northeast arctic cod (*Gadus morhua*) prey heavily on the mature capelin and the young Norwegian spring spawning herring (*Clupea harengus*) is believed to prey on the early capelin stages, these species were chosen as predator models to find possible binding between capelin and the Barents Sea predator system. The time series of the Norwegian spring spawning herring stock are based on ICES, 2001b and Northeast Arctic cod on ICES, 2001a.

2.2. Systems theory

The biomass of Barents Sea capelin is related to a complex system. In this case the Barents Sea system $S_B(t)$ has the general simplified system architecture

$$S_B(t) = \{B(t), \{S_{ca}(t), S_c(t), S_f(t), S_p(t), S_o(t), S_e(t), S_v(t)\}\} \in w \qquad \text{Eq. 1}$$

Where B(t) is a time varying mutual binding between the all subsystems of $S_B(t)$. Then the dynamics of a subsystem $S_i(t)$ is dependent on its autonomous dynamics, the mutual binding to the other subsystems and the autonomous dynamic of each system. To understand the dynamics of a capelin system, we need to understand the fundamental properties all systems and their dynamic mutual relations to the capelin system. In this simplified system architecture, $S_{ca}(t)$ is the autonomous capelin system, $S_c(t)$ is the system of catch of capelin to landings, $S_f(t)$ is the plankton food system, $S_p(t)$ is the predator systems which are mainly herring and cod, $S_e(t)$ is the Earth dynamic system represented by the 18.6 yrs nutation cycle, $S_o(t)$ is the temperature in the Barents Sea that influences the capelin system, $S_v(t)$ represents a disturbance from an unknown source and w is the common purpose.

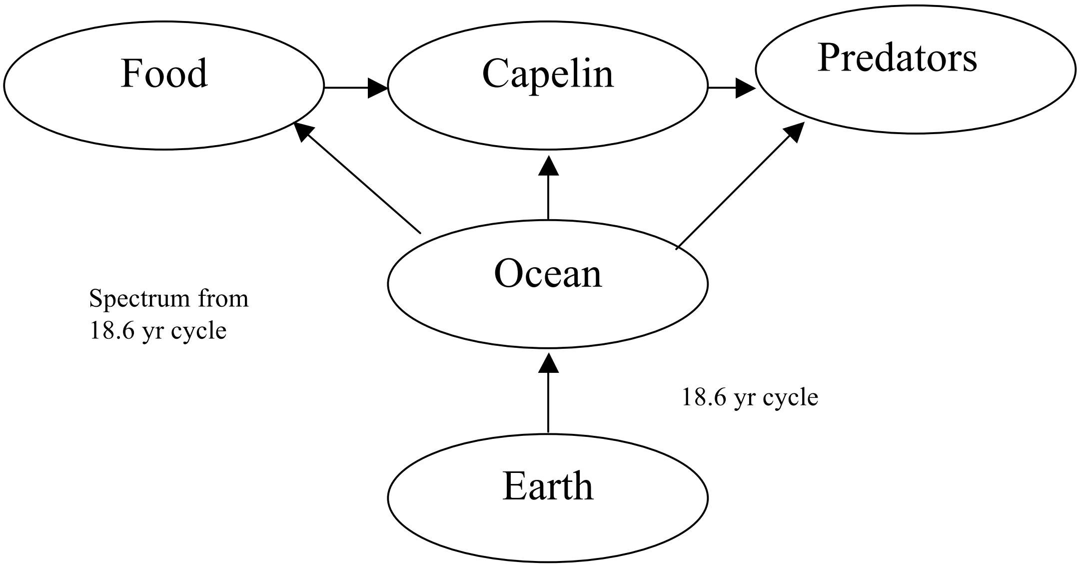

Figure 2 The Barents Sea system architecture

The Barents Sea system consists of a set of different abiotic and biotic factors. In this case the Earth system $S_e(t)$ represents a cyclic process that influences all the others. The theory of this investigation is based on the deterministic 18.6 yrs Earth nutation cycle, causing fluctuations in the water temperature in this area. These fluctuations will, directly the or indirectly, lead to fluctuations in the capelin stocks.

System state dynamics

The system dynamic state is described by a set of first order differential equations

$$\begin{aligned} \dot{x}(t) &= f(x(t), u(t), v(t), t) \\ y(t) &= g(x(t), w(t), t) \end{aligned} \qquad \text{Eq. 2}$$

where x(t) represents the state vector on a system element S(t), u(t) the state on an external system, v(t) the state on an unknown system, y(t) the measured state and w(t) measured error. A linear time variant dynamic system is described by the differential equation

$$\begin{aligned} \dot{x}(t) &= A(t)x(t) + B(t)u(t) + C(t)v(t) \\ y(t) &= Dx(t) + w(t) \end{aligned} \qquad \text{Eq. 3}$$

where A(t) is the system matrix, B(t) the binding to a known source u(t), C(t) a binding matrix to an unknown source v(t), D is the measurement matrix and w(t) is measurement error.

Frequency response

Frequency functions represents a shift from the time domain to a frequency view of system dynamic properties. The Fourier transform of the state dynamic model (Equation 3) is

$$X(j\omega) = (j\omega I - A)^{-1} BU(j\omega) + (j\omega I - A)^{-1} V(j\omega) \qquad \text{Eq. 4}$$
$$Y(j\omega) = D \cdot X(j\omega) + W(j\omega)$$

where I is an identity matrix, j is a complex operator, ω represents the angle frequency, A is the mean of the growth system matrix A(t), B is the mean of the binding matrix B(t), X(jω) the state spectrum vector and U(jω) the state spectrum vector from a known source. The stationary frequency transfer function H(jω) from a known source U(jω) to the state X(jω) is from Equation 4.

$$H_u(j\omega) = \frac{X(j\omega)}{U(j\omega)} = (j\omega I - A)^{-1} BU(j\omega) \qquad \text{Eq. 5}$$

where $H_u(j\omega)$ is a complex function. This transfer function H(jω) describes in the frequency domain how the capelin biomass responds to stationary cycles from the source U(jω).

$$H_v(j\omega) = \frac{X(j\omega)}{U(j\omega)} = (j\omega I - A)^{-1} V(j\omega) \qquad \text{Eq. 6}$$

where $H_v(j\omega)$ is a complex function. This transfer function H(jω) describes in the frequency domain how the capelin biomass responds to stationary cycles from the source V(jω).

The time series v(t) on the Barents Sea system $S_B(t)$ is influences by mutual dynamics in all systems of S(t) in Equation 1. According to Parseval theorem the energy E_v has the property

$$E_v = \int_{-\infty}^{+\infty} | v(t) |^2 = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left| V^*(j\omega) \right|^2 d\omega \qquad \text{Eq. 7}$$

If the spectrum V(jω) is white noise, the energy E_v is infinitive. A more realistic distribution of energy from the mutual interaction is a red shift frequency non-correlated spectrum. Low frequent cycles of this spectrum is climatic change. If we are able to identify the source of the low frequent cycles, we are able to forecast future climatic change.

Frequency response in the system chain

When a known stationary Earth nutation cycle $u_{18.6}(t)$ has a binding B(t) to a system element $S_i(t)$, the response X(jω) from known cycle $U_{18.6}(j\omega)$ is expected to be

$$X(j\omega) = H_i(j\omega) \cdot U_{18.6}(j\omega) \qquad \text{Eq. 8}$$

where $H_i(j\omega)$ is the frequency transfer function of the system element $S_i(t)$. If the systems element $S_i(t)$ is non-linear, it is known from the theory of non-linear systems that the response X(jω) will have introduced harmonics and sub harmonic frequency cycles of $U_{18.6}(j\omega)$. When there are n systems elements in the system, the total frequency response is expected to be the total product.

$$X(j\omega) = H_1(j\omega) \cdot H_2(j\omega) \cdot H_n(j\omega) \cdot U_{18.6}(j\omega) \qquad \text{Eq. 9}$$

In this system the total response X(jω) will keep the Earth nutation cycle $U_{18.6}(j\omega)$, but each transfer function $H_1(j\omega)$,,,, $H_n(j\omega)$ will influence the amplitude and the phase of Earth nutation frequency $U_{18.6}(j\omega)$.

Stochastic resonance

The eigenvalues of a mean system matrix A(t)=A has information on the fundamental stability and oscillating properties of the capelin system. The eigenvalues the system matrix A is computed by

$$\det[\lambda I - A] = 0 \qquad \text{Eq. 10}$$

Where I is an identity matrix and the eigenvalues is a diagonal matrix $\lambda I = \Lambda$. The dynamic system is asymptotical stable if, and only if, $\mathrm{Re}[\lambda] < 0$ for all eigenvalues λ in Λ. The system has an oscillating property when eigenvalues of Λ has complex values.

The stochastic resonance is a symmetric bistable stochastic process where the stock numbers x(t) are changing between recruitment and stock numbers. The process are driven by a external random process v(t) and an external stationary cycle u(t). The resonance frequency is dependent on the eigenvalues of the A system matrix.

2.4 Binding to climate cycles in the Barents Sea

According to Equation 1 the zooplankton system $S_z(t)$ has a binding to the general system $S(t)=\{B(t),\{S_z(t),S_c(t),S_f(t),S_n(t)\}\}$. Since this is a very complex system, there is need for simplifications. Long-time series of the plankton-feeding system $S_f(t)$ are unknown. A first step to reduce complexity is to introduce the hypothesis that the dynamic of the food system, follows the climate system $S_c(t)$. The climate system $S_c(t)$ may be represented by a set of indicators such as the sea temperature, pole ice extension and the NAO winter index. It is confirmed that there is a correlation between the 18.6 yr Earth nutation spectrum and the Kola-section temperature series (Yndestad,1999a), extension of ice in the Barents Sea, extension of ice north of Iceland and the NAO winter index (Yndestad, pers.comm.). The estimated Earth nutation spectrum from the Kola section may then be used as climate reference cycle in the analysis. A next step is to introduce the hypothesis that there is a dynamic binding $B_e(t)$ between the Earth nutation cycles $u_e(t)$ and the zooplankton biomass dynamics. A binding between the Earth nutation the zooplankton biomass is modeled by the differential equation

$$\dot{x}(t) = A(t)x(t) + B_e(t)u_e(t) + v(t) \qquad \text{Eq. 11}$$

where v(t) is an unknown source and the $u_e(t)$ is the Earth nutation spectrum

$$u_e(t) = \sum_{k,m} B_{k,m} \sin(k\omega_0 t / m + \varphi_{k,m}) \qquad \text{Eq. 12}$$

where the nutation angle frequency $\omega_0 = 2\pi/18.6$ (rad/yr), m the sub-harmonic index, k the harmonic index and φ the phase delay. The autonomous growth matrix A(t) is unknown. The system dynamic model (Equation 3) has a complex property, therefore it is introduced the hypothesis that the external environment relation $B_n(t)$ is the most important factor in a one yr sample time.

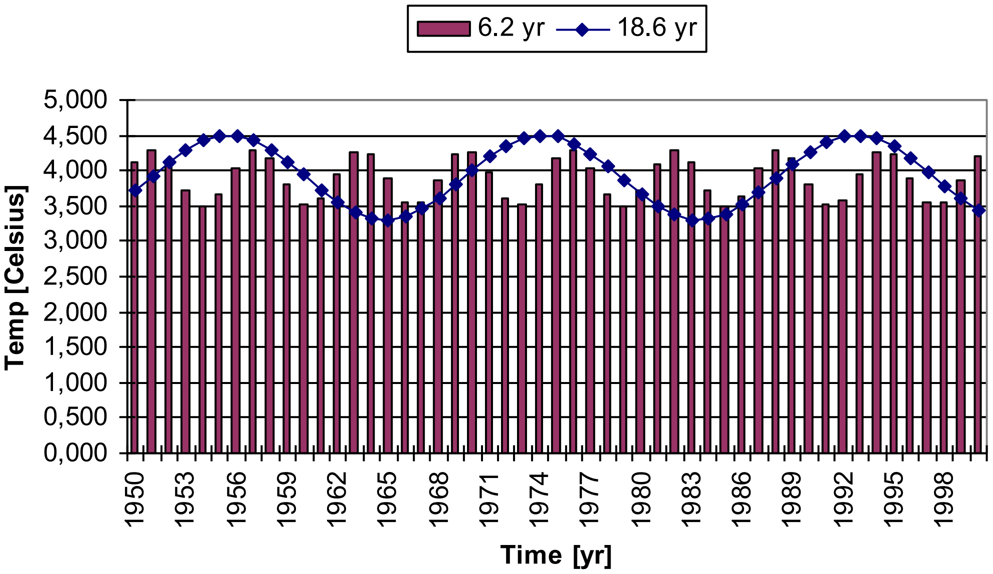

Figure 3 Stationary reference cycles of 6.2 yr and 18.6 yr from the Kola data temperature data series.

The estimated binding to a stationary nutation cycles in the Barents Sea, based on Kola temperature data series is estimated (Yndestad, 1999a) to the stationary temperature cycles

$$x_t(nT) = 3.9 + 0.4\sin(3\omega_0 nT - 0.29) + 0.6\sin(\omega_0 nT + 1.52) \qquad \text{Eq. 13}$$

where sample time T= 1 yr, n=1900…2000, the angle frequency $\omega_0=2\pi/18.6$ (rad/yr). These estimated stationary cycles from the Kola section are used as stationary reference climate model in this paper.

2.3. Capelin biomass dynamics

The capelin system $S_{ca}(t)$ has stock numbers of age where the dynamics is represented by the state differential equation

$$\dot{X}(t) = A(t)X(t) + B(t)U(t) + V(t) \qquad \text{Eq. 14}$$

Where X(t) represents the state vector of the capelin year class numbers, A(t) is the internal growth system matrix, U(t) represents all known state vector in subsystems of Equation 1, B(t) represents the binding matrix from the U(t) vectors and V(t) is a disturbance from an unknown source $S_v(t)$. In the system growth matrix A(t) of Equation 3

$$A(t) = \begin{bmatrix} R(t)Ma(t) \\ I - M(t) \end{bmatrix} \qquad \text{Eq. 15}$$

Where R(t) is the recruitment rate, Ma(t) the maturing vector, I is an identity matrix and M(t) the mortality matrix. The system matrix A(t) is a time varying process modeled by

$$A(t) = A + B_A(t) \cdot U_A(t) + V_A(t) \qquad \text{Eq. 16}$$

Where A is the mean growth system matrix, $U_A(t)$ a known external sources that influences the system matrix A(t), $B_A(t)$ is the binding form $U_A(t)$ to the system matrix A(t) and $V_A(t)$ is a disturbance from an unknown source.

3 Results

The Barents Sea system $S_B(t)$ may be modeled by the simplified general system model $S_B(t)=\{B(t),\{S_e(t),S_c(t),S_Z(t),S_f(t)\}\}$ (Equation 1) where $S_e(t)$ represents the Earth nutation system, $S_c(t)$ thr climate system, $S_Z(t)$ the zooplankton system and $S_f(t)$ the fish biomass systems. According to the general systems theory, changes in one system element will influence all the others. In this case the Earth system $S_e(t)$ has a stationary 18.6 yrs climatic cycle and is the expected to be identified in the time series of the other biotic systems.

3.1. Binding to food system

It has been a common knowledge for years that there is a relation between zooplankton biomass fluctuations and environmental conditions. According to Equation 1 the Barents Sea system $S_B(t)$ may be modeled by the simplified general system $S_B(t)=\{B(t),\{S_e(t),S_c(t),S_Z(t)\}\}$ where B(t) represents a binding between the Earth nutation system $S_e(t)$, the climate system $S_c(t)$ and zooplankton system $S_Z(t)$. According to the hypothesis in this paper, the cycle property of the Earth nutation in $S_e(t)$ will influence all other system elements. In this case the time series of zooplankton is measures only from 1987.

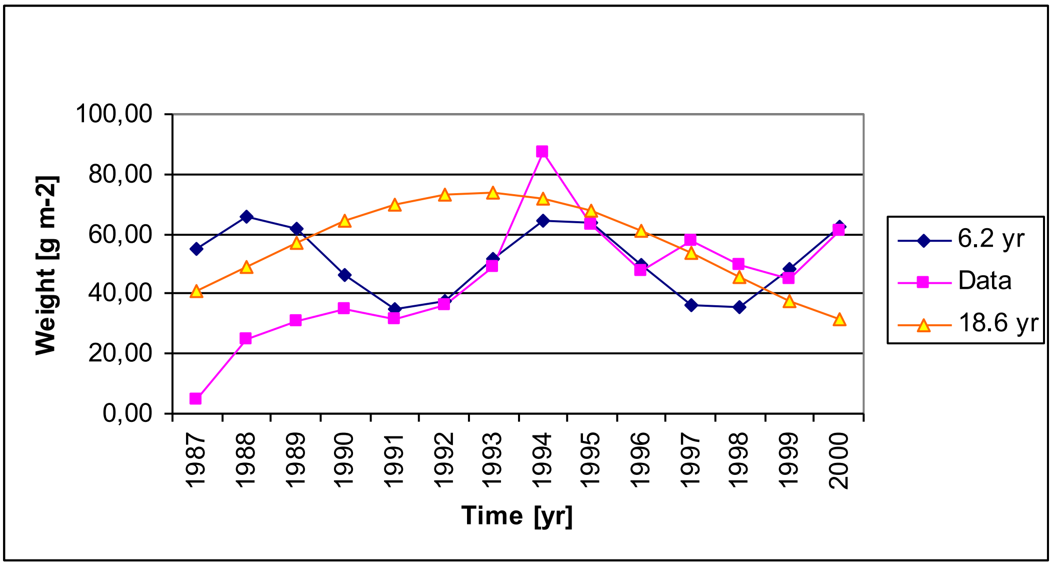

Figure 4 Zooplankton abundance in the Barents Sea (1987 until 2000) and estimated deterministic cycle of 18.6 yr and 6.2 yr.

Figure 4 shows the sum of zooplankton biomass from region 2 to 7 in the period for 1987 to 2000 (ICES, 2001). The zooplankton biomass has a maxim at about the yrs 1990 and 1994. This is the same period the Kola section 6 yr wavelet cycle has a maximum and the 6 yrs cycle of ice extent has a minimum. From this short time series, it is estimated deterministic a 6.2 yrs and a 18.6 yrs cycle of zooplankton based on the stationary Kola climate cycles (Equation 13) by the model

$$x_{z6.2}(nT) = 50 + 40\sin(3\omega_0 nT - 0.29)$$

Eq. 17

$$x_{z18.6}(nT) = 50 + 40\sin(\omega_0 nT + 1.52)$$

where sample time T=1 yr, n=1900…2000, the angle frequency $\omega_0=2\pi/18.6$ (rad/yr). The estimated cycles are shown on Figure 4. The estimated 6.2 yr cycle $x_{z6.2}$(nT) has a maxim in 1998, 1994 and 2000 which is close to the total maximum in zooplankton data set and the $x_{z18.6}$(nT) cycle estimate follows the general trend of the biomass. The correlation is week during the warm period around 1988. This may be due to the lack in data from region 2, 3, 4, 6 and 8 in this period.

3.2. Capelin model identification

To maintain a fish stock, the portion of the population removed through fishery and predation must be replaced through individual growth and recruitment of new individuals. Important subjects to be analyzed in this study of stock dynamics, are the direct and indirect effects of the climate temperature cycle on growth, recruitment and mortality.

Growth

Due to their thermal regulation, different fish species and year classes have a general temperature preference for optimum growth. Growth is however also dependent upon food and activity. The ambient temperature of the capelin may therefore vary with non-thermal components like zooplankton abundance and stock size. Growth rate is used as parameter to analyze the effect on growth in relation to the temperature climate cycle, stock densities and food.

The different age groups do not grow synchronously (Figure 5). As expected, the capelin growth rate is highest early in life. The growth rate will decrease when body size is increasing and during sexual maturity when energy is diverted into reproductive activities. It is also large fluctuations in growth rate between different years and age groups in growth conditions in the investigated period.

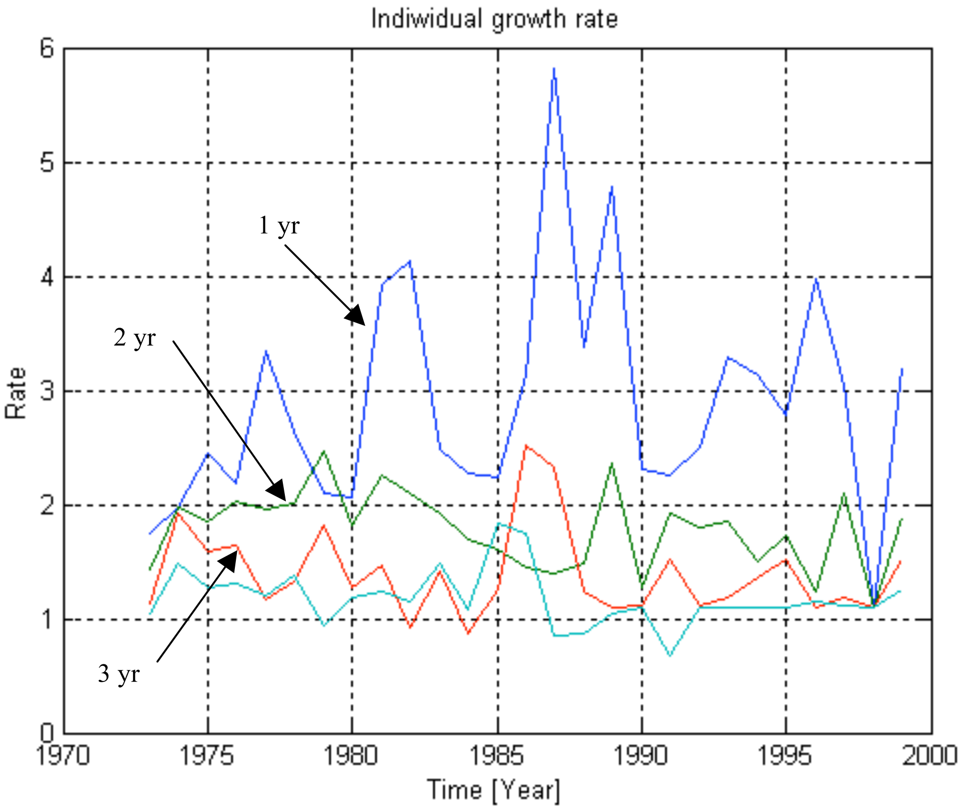

Figure 5 Growth rate of different age groups from 1973 until 2000.

The mean growth rate of weight is $A_w(nT)$ (Equation 16) in this short time series is estimated to

$$A_w(nT) = 1.8 + 0.5\sin(\omega_o nT / 3 - 0.29) \qquad \text{Eq. 18}$$

where sample time T= 1 yr, n=1900…2000 and the Earth nutation angle frequency $\omega_0=2\pi/18.6$ (rad/yr). The mean individual growth of weight $A_w=1.8$ and the mean influence from the 6.2 yrs cycle has a maximum amplitude $A_{wA}= 0.5$.

The growth rate of the one-year old had a maximum around 1977, 1982, 1988 and 1996, close to the maximum of the 6.2-yrs climate cycle. The growth rate maximum of this age group does also correlate to the maximum zooplankton abundance. The growth rate of the 3 yrs old is more negatively correlated to the climate cycle with growth rate maximum around 1973, 1979, 1986, 1991 and 1997. The growth rate of the 2 yrs old does not fluctuate to the same degree as the other age groups. Different correlation to the climate cycle may be due to different temperature, food preference and differences in food abundance, but it may also be related to the stock size and size of the year class.

Stock density

Intra specific competition is generally believed to have major influence upon growth if other environmental conditions are stable. Time series of number in different age groups of capelin are illustrated in Figure 6.

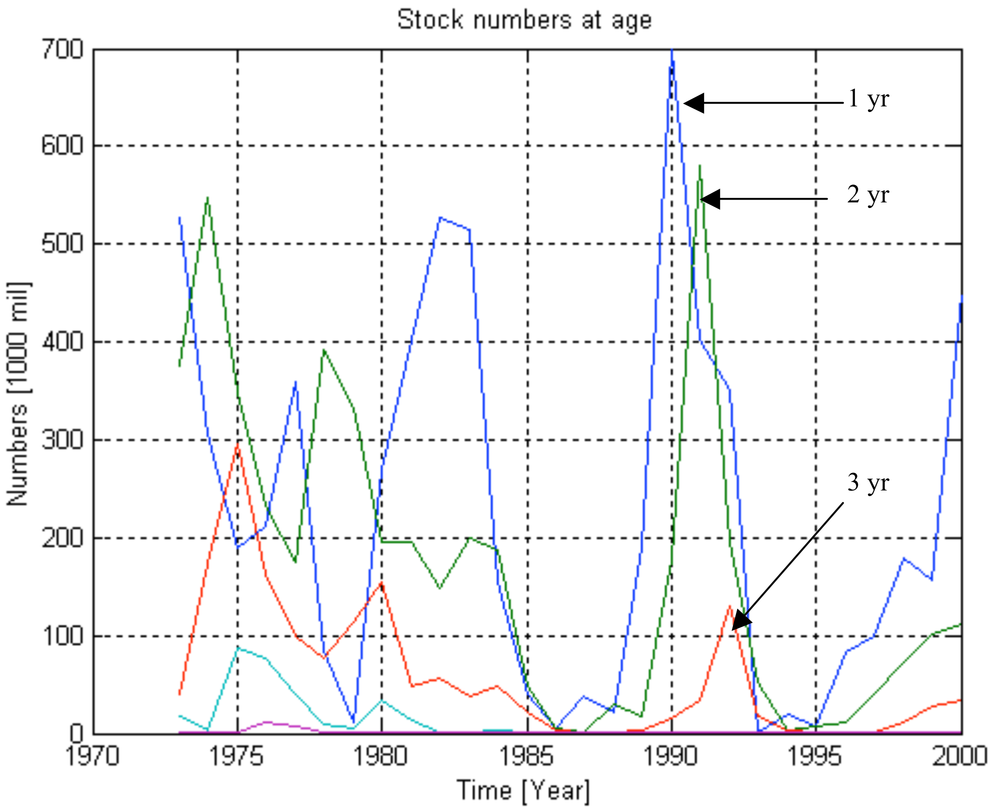

Figure 6 Variations in number of individual age groups from 1973 until 2000

By comparing the variations in number of individuals with variation in growth-rate, density-dependent effects may be identified. When the number of individuals in each year class is low, the increase in growth rate is high. One exception is the maximum growth rate and number of the one-year old capelin around 1982. Most prominent is the growth rate maximum of all age groups in the late 80`s and mid 90`s after the collapses in the stock. The increased growth rate in this period is followed by an increase in number. An increase in numbers of individual is directly related to changes in recruitment rate and the spawning stock numbers.

Recruitment

The maturity rate has a maximum at about the years 1991 and 1997-8. This short time series indicate that the maturing rate may be negatively correlated to the 6.2-yrs cycle. The fluctuations in the maturing rate are mainly caused by the varying maturing rate of the 3-yrs old capelin. ICES-data shows that the weight of this age group was at its maximum in 1991 and 1997, indicating weight dependent maturity.

The mean maturing (Equation 15,16) is, in this short time series, estimated to

$$Ma(t) = 0.46 + 0.1\sin(\omega_o nT/3 - 0.29) \qquad \text{Eq. 19}$$

Where sample time T= 1 yr, n=1900…2000 and the Earth nutation angle frequency $\omega_0=2\pi/18.6$ (rad/yr).

The recruitment rate is an estimate of reproductive success of the individual in the spawning stock.

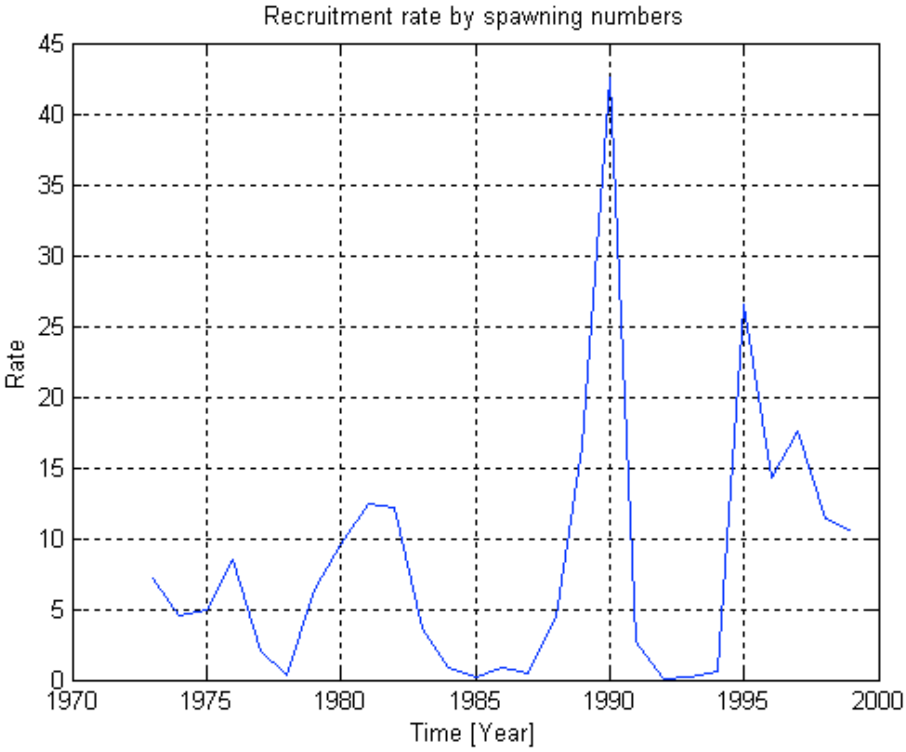

Figure 7 Number of 1-yr old capelin produced per spawning individual.

Figure 7 shows the computed 1-yr recruitment rate $Rr_1(nT) = x_1(nT-T)/x_{3+}(nT)$ where $x_{3+}(nT)$ is the spawning stock numbers and $x_1(nT)$ is the one year recruitment. The recruitment rate and the growth rate of the 1-yr old capelin had maximum around 1982, 1990 and 1995. These years are closely correlated to the maximum of the 6.2 yrs cycle. The two last years also correlate to the maximum in zooplankton abundance in the Barents Sea registered by ICES. High recruitment rate seems associated with periods of good conditions for growth and survival for 1-yr old capelin.

The growth potential in a fish stock is mainly a function of recruitment or addition of new individuals to the population. Yearly recruitment is dependent on the size and condition of the spawning biomass, but also on the environmental conditions for growth and survival. In this investigation age at first reproduction and an estimated recruitment rate is used to identify variations in recruitment.

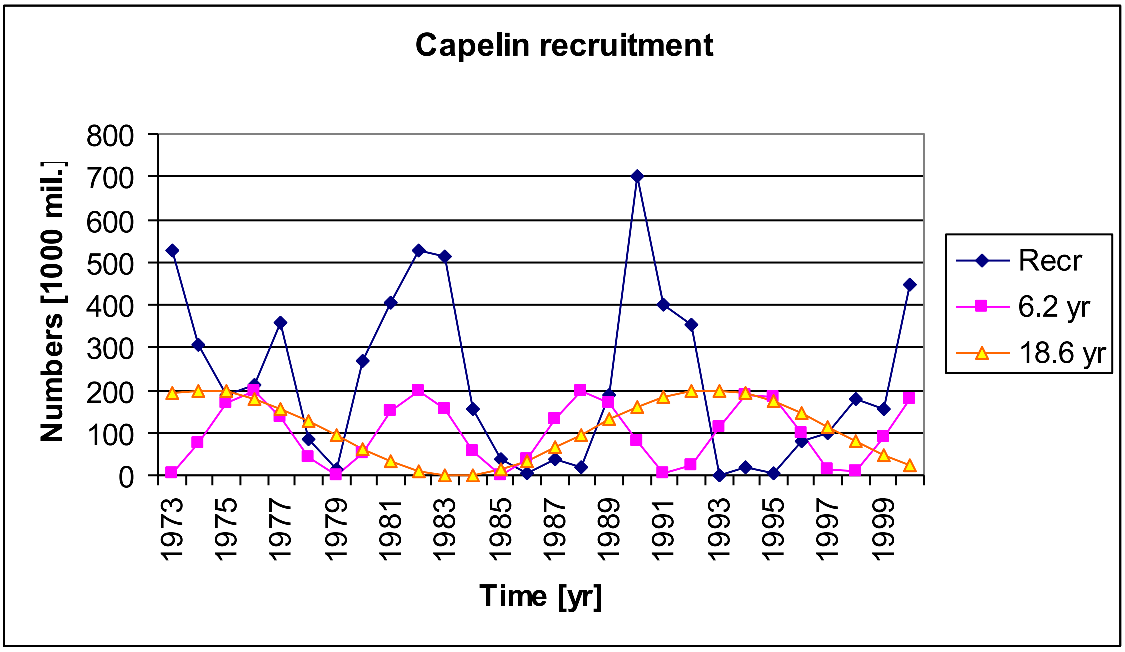

Figure 8 One yr recruitment of capelin (10 mill) and deterministic cycles of 6.2 yr and 18.6 yr.

Figure 8 shows the 1 yr recruitment number (1.oct.) of Barents Sea capelin and the estimated 6.2 yr and 18.6 yr cycles. The figure shows that the recruitment is well correlated to the 6.2 yr cycle and the trend of the 18.6 yr cycle in the 1970's. In 1984-85 there was a collapse in the biomass and the recruitment did not recover before the 6.2 yr and the 18.6 yr cycle had a maximum in 1989-91. In 1993 there was a new collapse in the biomass, partly caused of the first collapse, and the 6.2 yr cycle had no effect on the recruitment. In 2000 the 6.2 yr cycle again had a maximum and again there was a new strong year class of recruitment.

An analyses of the computed recruitment R(nT) indicates there is an exponential relation between the recruitment rate and the Earth nutation cycles by the estimated model

$$\hat{R}(nT) = R_0 \exp(B_{18.6} \sin(\omega_0 nT + \varphi_{18.6}) + B_{6.2} \sin(3\omega_0 nT + \varphi_{6.2})) \quad \text{Eq. 20}$$

where the sample time is T= 1 yr, n=1900…2000, the Earth nutation angle frequency $\omega_0=2\pi/18.6$ (rad/yr). In this short time series the parameters are estimated to $R_0= 4.9$, $B_{6.2}=-0.35$, $B_{18.6}=-0.30$, $\varphi_{6.2}= -0.29$ and $\varphi_{18.6}= 1.52$.

Frequency response

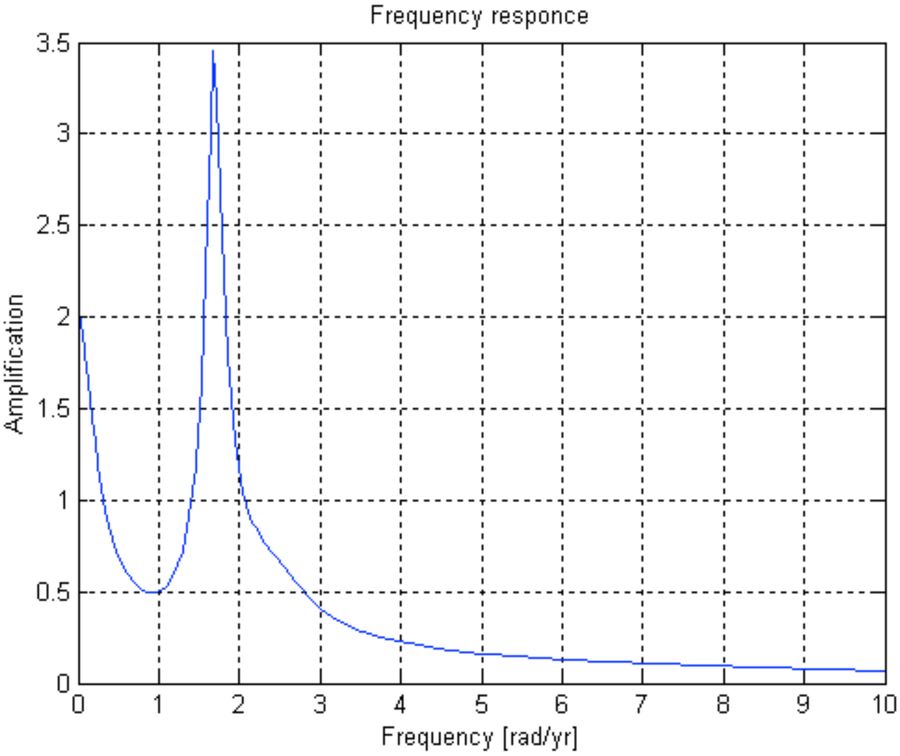

Figure 9 Frequency properties of the capelin stock

Figure 9 shows the computed mean frequency transfer function H(jω) from Equation 5. The transfer function shows the total capelin stock has a stochastic resonance at the angle frequency $\omega_0=1.8$ (rad/yrs) or at the cycle time $T_0=2\pi/1.8= 3.4$ yrs which is close to half of the Earth nutation reference cycle 18.6/3=6.2 yrs. This means that the capelin system has adapted a stochastic resonance where the phase will be synchronized to the 6.2 yrs cycle in periods of about 6 yrs.

A good recruitment starts during optimum condition from the 6.2 yrs temperature cycle, after a delay of 3 yrs the biomass has maximum recruitment from the stochastic resonance. At this time the climate cycle is at its minimum level, making conditions for growth and survival less optimal. When the recruited year class is mature in the next 3 yrs, again there is a new optimum condition from the 6.2 yrs climate cycle. In this dynamics of recruitment it is of most importance for the year class strength that there is a synchronization between the 6.2 yrs cycle and the biomass cycle. This means large fluctuations are an important strategy for of long time existence.

Long-term growth of capelin stock is when the angle frequency ω=0. The computed long-term amplification is $|H(j\omega=0)|=2$ (Figure 9). This indicates that the mean capelin recruitment is twice of its need for population growth in the long run. The stock numbers will then grow in the long run when the catch rate to landings is less then about $F(nT)=0.5$ (catch numbers/stock numbers).

3.3. Binding to predator system

Young Northeast Arctic cod prey heavily on the mature capelin and the young Norwegian spring spawning herring is believed to prey on the early capelin stages. The development in the biomass of cod (3-7 yrs) versus the biomass of 3+ capelin is illustrated in Figure 10, while the biomass of herring (0-4 yrs) and 1 yrs capelin is illustrated in Figure 12.

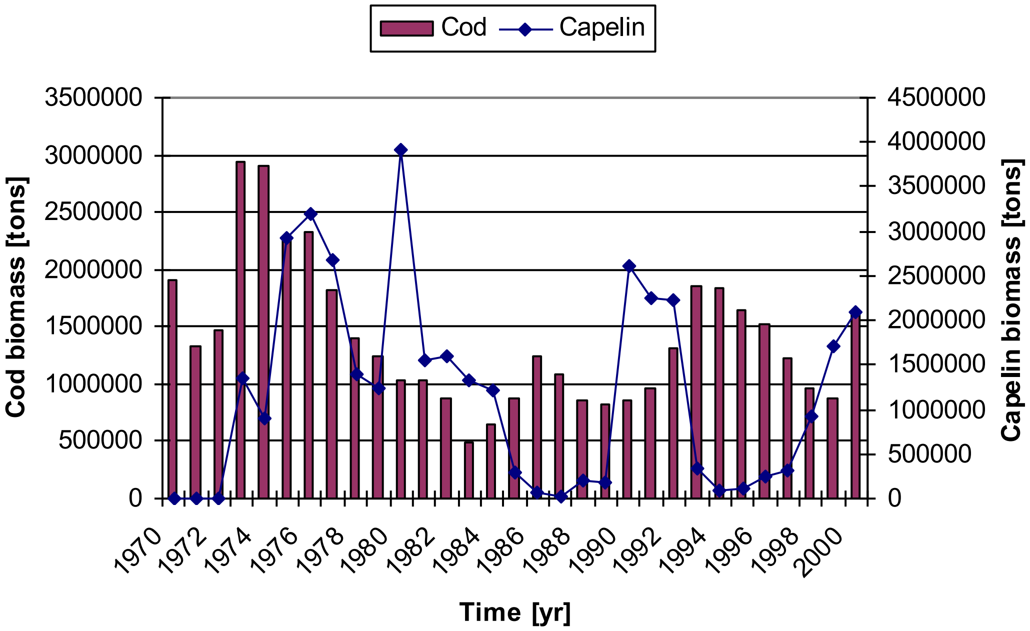

Figure 10 Development in the biomass of Northeast Arctic cod (3-7 yrs) and Maturing capelin from 1970 until 2000.

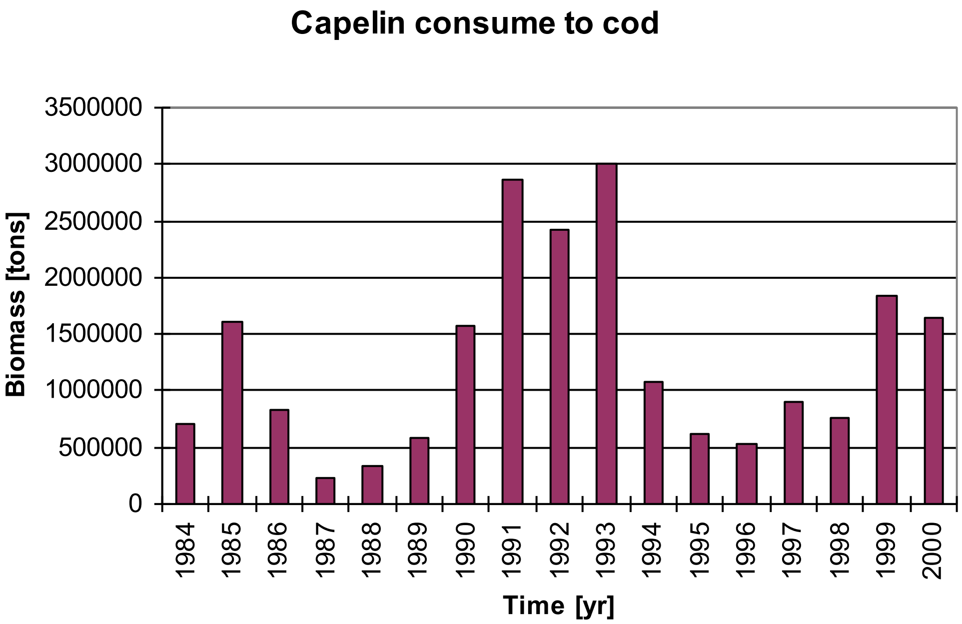

Figure 11 Consume of Barents Sea capelin to Northeast Arctic cod

The recruitment of Northeast Arctic cod has a fluctuation which correlated to the 6.2 yr and the 18.6 yr climate cycle in the Barents Sea (Yndestad, 1996b,1999b). This means that Barents Sea capelin and Northeast Arctic cod recruits good year classes at the same time in periods of about 6 years. A good year classes of cod, will after the next 3 year predate good year class of capelin. This explains the consume of Barents Sea capelin to Northeast Arctic cod shown on Figure 11.

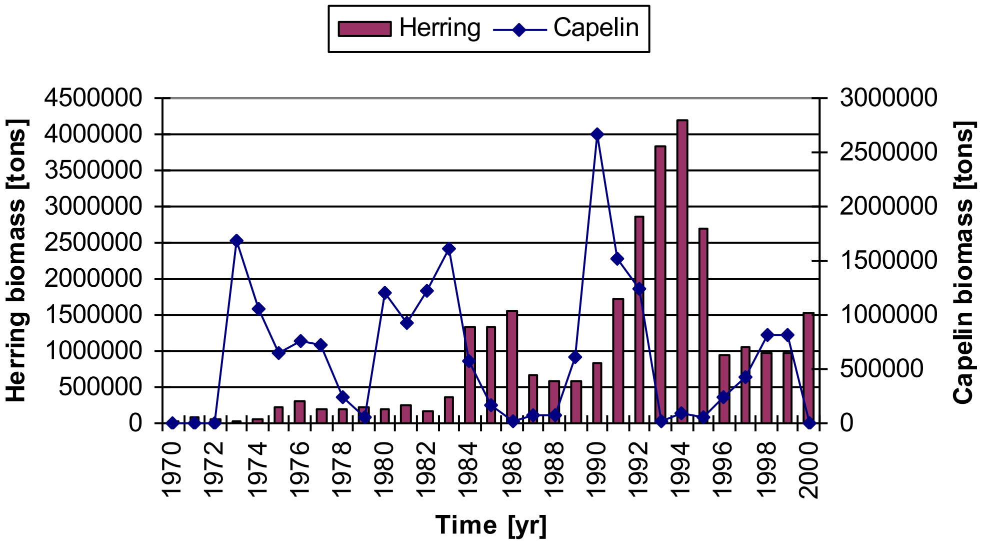

Figure 12 Development in the biomass of Norwegian spring spawning herring (0-3 yrs) and 1 yrs old capelin.

The results indicate an inverse relationship between the predator and its prey. Before 1978 juvenile herring was at a low level, the cod stock was decreasing and the capelin stock was at its highest level. After 1983 until 1987 and from 1990 until 1994 the juvenile herring and young cod was increasing while the capelin stock decreased to almost zero.

The predators were at their maximum level in 1987 and 1994. These periods are correlated to the warm periods of the 6.2 yrs climate cycle, indicating and increased food demand and increased consumption of capelin. By adding the fishing activity to predation, it seems *that mortality has contributed to the last phase of the collapses observed in the investigated period.

3.4. Binding to catch

Fishing activity is expressed as catch rate and computed by the relation

$$F_b(nT) = \frac{\| x_c(nT) \|}{\| x_b(nT) \|} \qquad \text{Eq. 21}$$

where $\|x_c(nT)\|$ is catch (in tons) to landings (spring plus autumn) at the time nT and $\|x_b(nT)\|$ is the total biomass (in tones). The landings rate $F_b(nT)$ (biomass catch/biomass) is computed from the biomass in October and catch in spring and autumn since stock numbers in January are unknown. This may cause an unexpected high catch rate when there is a an high mortality in the spring and $F_b(nT)$ is not exactly the same as the earlier described F(nT) (catch numbers/biomass numbers).

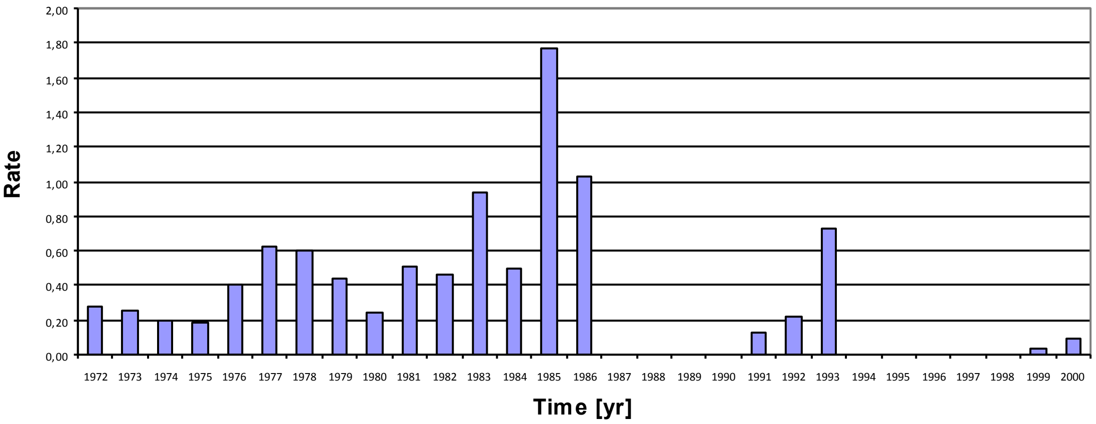

Figure 13. Catch rate of landing of capelin from 1973 to 1999.

The estimated frequency response has indicated that the stock numbers are expected to grow in the long run when the catch rate F(nT) < 0.5 (catch numbers/biomass numbers). The results show an increase in catch rate in 1977, 1985 and 1993. Until 1977 the catch rate to landings was about 0.3-0.4. In the early 1980's the catch rate passed the 0.5 limit to about 0.6 and increased to 1.78 in 1985. The combination of a cooled Barents Sea (Figure 3), reduced growth (Equation 16) and an increased catch rate of landings of the maturing stock (Figure 13), had negative effect on recruitment and caused a collapse of the biomass in 1985.

By comparing the development of the capelin stock biomass with the development in catch rate, there seems to be increased landings when the stock biomass is decreasing. Maximum catch rate also correlates with the maximum level of predators. From 1983 until the first collapse in 1985 the catch rate increased from 0.45 to 1.78 and in 1993 the catch rate was again increased to 0.75 while the stock was rebuilding. The capelin stock needed more years to recover from the second collapse. This can be due a small spawning stock producing and few recruits in the period from 1985 to 1988 (Figure 10 and Figure 12) and increasing abundance of younger herring in the Barents Sea.

4. Discussion

In the current paper it has been estimated a model of the Barents Sea Capelin to analyze the stock dynamic properties. The results show that the stock-variations are due to dynamics in growth, recruitment, mortality and frequency property characteristic for this stock. The stock dynamics are also related to dynamics in the environment.

Zooplankton

The zooplankton abundance in the Barents Sea was increasing during periods of an estimated increase in water temperature, showing a correlation to the 6.2 yrs climate cycle. The time series of zooplankton abundance are short, and therefore just an indication of a probable relationship.

The spring bloom in arctic waters starts earlier in cold years and culminates a month or more earlier than in warm years. In cold years the zooplankton spawns later and copepodite stages do not reach a size, which allow them to fully utilize the early phytoplankton bloom (Melle and Skjoldal, 1998). This may explain the high zooplankton abundance in warm periods of the climate cycle. Yndestad (personal comm.) has identified a correlation between zooplankton, climate indicators and the Earth nutation spectrum in the Barents Sea and at north of Iceland.

Gjøsæter 1997 reported that the mean annual individual growth in weight of Barents Sea capelin is positively correlated to the average zooplankton density. The strongest relationship was found between 1-yr old capelin and the smallest zooplankton fraction, and between three years old capelin and the largest size fraction of plankton. Total zooplankton density (*Calanus finmarchicus)* is almost tree times higher in the Atlantic water, than in melt water (Hassel *et al* 1991, Melle and Skjoldal, 1998).

The 1 yr old capelin prefers the size fraction of food and the temperature related to the Atlantic water. This probably explains the high growth rate found during warm periods. The density of plankton in the largest size fraction is significantly higher in the colder Arctic water in the eastern areas of the Barents Sea (Melle and Skjoldal, 1998). The 3 yrs old capelin prefers the size fraction and the temperature related to the Arctic water. This may explain the high growth rate of this age group in periods of estimated low temperatures.

Recruitment

The growth rate in numbers of any population is influenced by age at maturity or when the individuals start to reproduce. This is often sex and size dependent. Differences in age at maturity of the capelin are registered only for 10 yrs, giving short time series for system dynamic analyses. The results did, however, indicate an inverse relationship to the climate cycle with a decreasing age at sexual maturity when the temperature in the 6.2 yrs climate cycle is increasing. Since sexual maturity is size dependent, the increased growth of 3+ capelin during cold periods will result in a related decrease in age at maturity.

The number of 1-yr old capelin produced per spawning individual had its maximum around 1982, 1990 and 1995. These years correlate to the maximum of the 6.2 yrs climate cycle. The growth rate maximum of the 1-yr old capelin and the maximum in zoo plankton abundance, indicating that warm periods gives good conditions for growth and survival of juvenile capelin.

Stochastic resonance

Stochastic resonance is an important source of stock number fluctuations. The frequency transfer function shows the stock number dynamics has a dominant 3.4 yrs resonance cycle, which is close to a half of the 6.2 yrs climate cycle. This is an optimal resonance cycle time. By this stochastic resonance, the stock numbers will have optimal recruitment in cycles of about 6 yrs when the 6.2 yrs climate cycle may change recruitment rate from about 0 to 40. By this view stock number fluctuation is an adaptation for existence in the long run. In this stochastic resonance timing between stock number fluctuation and the 6.2 yrs climate cycle is of most importance. A forced phase delay of fluctuation from predation or catch may cause a collapse of the capelin biomass.

Growth

Large fluctuations in growth rate between years and age groups were observed in this study. The growth maximum of the one-year old capelin corresponds to the maximum of the 6.2 yrs climate cycle. The growth rate of the 3 years old is however negatively correlated to the same cycle. Preference for colder water with increasing age, may explain the differences in growth rate between age groups and years. The growth rate maximum of the 1-year old found in this study is in accordance with the growth maximum of the total Barents Sea capelin stock found in other investigations (Gjøesæter, 1997). The correlation between the growth rate of the 1-year old and the total population must be due to the fast growth rate of the youngest age groups dominating the growth rate mean.

The growth of stock numbers is directly related to changes in recruitment rate and the spawning stock numbers. Most prominent is the growth rate maximum of all age groups in the late 80`s and mid 90`s. This may be a response to the collapse in the stock inducing good conditions for growth and survival. Optimal growth condition is resulting in a later increase in numbers as illustrated by the recruitment rate. Natural populations that suffer a major, rapid decline in abundance, usually display subsequent increase in growth rate (Ross and Almeis, 1986).

Mortality

The collapses in the capelin stock may be caused by factors like climate, predation and fishing activity. Norwegian and Russian investigations indicate a collapse in this stock in the 1950s and early 1960s, before commercial fishery of capelin started (Olsen, 1968; Ozhigin et al. 1996). This indicates that the stock fluctuation is dependent on climate conditions.

Recruitment failures has also been associated with presence of young herring in the nursery area of capelin (Hamre, 1994). There are however few observations of capelin larvae in herring stomach (Huse and Toresen, 2000). Presence of 0-group herring has little effect on capelin recruitment compared to significant amounts of 1-yr old and older herring in the Barents Sea (Gjøesæter and Bogstad, 1998). The results in this investigation showed an inverse relationship between the biomass of 1-yr old capelin and young herring 0-4 yr, also indicating a negative interaction between these to species.

Cod is interacting with the capelin through heavy predation on the spawning stock on its way south to the spawning grounds. Large year classes of cod (3 to 7 yrs) are believed to have important effect on the biomass of the maturing capelin stock (Hamre, 2000). Data analysis of the consumption to cod (ICES, 2000a) shows that the relative consumption had the highest level in 1985-87 and from 1993-95 when the biomass collapsed. The fisheries also exploit the maturing part of the stock. The results in this investigation indicate that increased landings appear simultaneously with increased predator abundance. If mortality exceeds recruitment over time, severe reduction in stock biomass is the result.

The analyses in this paper shows the growth in stock numbers is dependent on climate cycles and the stock will grow in the long run when the landing rate is about 0.5. From this analysis, 3 different phases of the stock collapses have been identified. First there was a negative climate shift from two climate cycles. The 18.6 yrs climate cycle shifted from a maximum value in 1974 to a minimum in 1983 and the 6.2 yrs and cycle from a maximum in 1982 to a minimum in 1985 and there was less growth in the biomass. In the same period there was an increase in the catch rate to landings from about 0.2 in 1974 to a level far above the sustainable level 0.5 in the period 1983-86. The biomass declined from about 600 in 1974 to about 300 thousand tons in 1984 and collapsed in 1985. In the third phase there was an increase in the biomass of interacting age groups of cod and herring from the mid-80`s. Consumption of capelin to cod (ICES, 2000a) shows that the relative importance of cod increased in the late third phase when biomass was collapsing from 1984-86. In the collapsed period 1985-89 there was a cooled climate from the 6.2 yrs climate cycle and new recruitment was at a minimum. In the years 1989 and 1990 there was optimal climate conditions. A new positive 18.6 yrs and a 6.2 yrs climate cycle that increased zooplankton biomass and the capelin stock numbers up to a level from the 1970's. When the biomass was mature in 1993 the 6.2 yrs climate cycle was at a minimum, again new recruitment was at a minimum and there were no new recruited year classes from the 1985 to 1989 period. The catch rate to landing increased from about 0.2 in 1991 to about 0.75 in 1993 and again predation from herring and cod increased in the late phase. The biomass collapsed a second time in 1993 and started recovering at about 1998 in a new positive period of the 6.2 yrs climate cycle.

Management is to control biomass dynamics. In a capelin stock climatic cycles and stochastic resonance are of most importance of long-time growth. The catch rate in management of the capelin stock therefore should be adjusted to according to state of the climate cycles and the stochastic resonance.

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