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Earth nutation influence on system dynamics of Northeast Arctic cod

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This paper reports a correlation between the time series of Northeast Arctic cod population estimates and the Earth's nutation of 18.6 years. In the Barents Sea harmonic temperature cycles of 3*18.6=55.8 years, 18.6 years, and 18.6/3=6.2 years are correlated to the growth rate of cod and will cause long-term biomass fluctuations. Harmonic temperature cycles of 18.6/3=6.2 years cycle are correlated exponentially to time series of the recruitment cycles of cod. The influence of the Earth's nutation is explained by a General Systems theory where temperature cycles are a forced oscillator on the biological system in the Barents Sea. The system dynamics of the cod biomass are synchronized to the temperature cycle and amplified by a biological stochastic resonance to the supply of food.

Key words: Northeast Arctic cod, the Earth's nutation, stationary cycles, forecasting cod.

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Introduction

The Northeast Arctic cod is the largest stock of true cod in the world. Over the centuries it has been of vital importance for settlement and economic growth in the western part of Norway. In some years cod is abundant but in others there may not be enough to meet the demand. People dependent on fishing have always known that the stock has short- and long-term fluctuations. These have been explained to date by the onset of "herring periods" as opposed to "cod periods", the introduction of new fishing equipment, etc. When Norwegian marine research started at the beginning of this century its main aim was to discover how nature influenced the stock of cod and, if possible, to lessen the impact of the fluctuations on those who depended on fishing for their livelihood (Rollefsen, 1949). Better forecasting over the time span of 5–10 years, has always been crucial to better planning of the economical and sustainable utilization of the cod biomass.

Early scientific explanations of fluctuations of the stock were changes in food availability, mortality, hydrographic conditions in general, sea temperature fluctuations in particular, and positive feedback in recruitment (Rollefsen, 1949). More recently the fluctuations of the Northeast Arctic cod stock have been described in more detail (Jørgensen, 1992; Nakken, 1994), but the fundamental explanations are much the same: firstly the relation between the sea temperature and cod recruitment (Sætersdal and Loeng 1987; Nakken and Raknes, 1987; Eilertsen *et al.*, 1989; Nakken, 1994; Ottersen *et al.*, 1996), secondly the impact of predators like birds, marine animals, and cannibalism (Haug *et al.*, 1991; Gabrielsen and Ryg, 1992), and finally the amount of food *per se* (Ajiad *et al.*, 1992).

There may, however, exist a more fundamental cause of these fluctuations. In 1938 Petterson explained the fluctuations of herring by a tidal cycle of 112 years period and those of North Arctic cod by a 20–25 year cycle (Rollefsen, 1949). In historical records of cod landings in Norway, Ottestad (1942) reported 11, 17.5, 23, and 57 year cycles of cod. Later, Wyatt *et al.* (1992, 1994) found a correlation between cod landings and the 18.6 year cycle of the Earth's nutation. Yndestad *et al.* (1994) and Yndestad (1996b) has reported a correlation between historical records of Northeast Arctic cod and harmonic cycles of the 18.6 year Earth nutation.

This paper suggests the fundamental cause of fluctuations in the biomass of Northeast Arctic cod is an exponential relation between a stationary temperature cycle of 18.6/3=6.2 years and new recruitment of the Northeast Arctic cod population. The cycles of 18.6 years and 3*18.6=55.8 years, seem to influence the growth rate and the maximum level of cod biomass. The cycles are explained by a General Systems theory where the temperature is a forced oscillator to the biomass and the systems elements in the Barents Sea have a stochastic resonance close to the temperature cycles.

Materials and methods

All the time series on Northeast Arctic Cod that are used here appear in reports that are in the public domain (ICES, 1995; NIMR 1995).

Systems theory

Systems theory is a means of understanding abstract organizations independent of time and space. A system is a set of subsystems working together to give an effect. This may be expressed as:

$$S(t)=\{B(t),\ S_N(t)\}=\in w, \tag{1}$$

where S(t) is the system, $S_N(t)$ is a set of subsystems, B(t) is a dynamic binding between the subsystems, and w is the common system purpose. According to the General Systems Theory, systems are time varying, structurally unstable, and mutually state dependent. In this case the Barents Sea may have the General System architecture

$$S_B(t)=[B_B(t),\ \{S_T(t),\ S_D(t),\ S_P(t),\ S_S(t)\}]\in w, \tag{2}$$

where $S_T(t)$ is the temperature system, $S_D(t)$ is a detritus system, $S_P(t)$ is a plankton system (phyto, microzoo, mezozoo, macrozoo, predatoryzoo), $S_P(t)$ is a predator system (seabirds, cod, seal, and whale) $S_F(t)$ is the food system (cod, capelin, herring, redfish, shrimp), and $B_B(t)$ is an interaction or the binding between the Barents Sea systems.

System dynamics

The system dynamics of a Barents Sea element $S_e(t)$, may be modelled by the state space equation:

$$\dot{x}_e(t)=A_e(t)\cdot x_e(t)+B_e(t)\cdot u(t)+C_e(t)\cdot v_e(t)$$

$$y_e(t)=D_e(t)\cdot x_e(t)+w_e(t), \tag{3}$$

where $x_e(t)$ represents system element state vector, $A_e(t)$ a time varying growth rate binding matrix on the autonomous system, u(t) a state vector on an external system, $B_e(t)$ the dynamic binding matrix to the external system. $V_e(t)$ a disturbance vector from an unknown source, $C_e(t)$ the dynamic binding matrix to the unknown source, $D_e(t)$ the measure matrix, $y_e(t)$ the measured state vector, and $w_e(t)$ the measurement noise vector.

Forced oscillator on the biomass

In this case the temperature system $S_T(t)$ is expected to be a stationary cyclic process related to the Earth's nutation (Yndestad, 1996a, 1999). Since most energy is related to the cyclic temperature system $S_T(t)$, the Barents Sea system may be modulated as a forced oscillator non-linear ecological sea system. This forced oscillator temperature system has the property (Yndestad, 1999):

$$x_e(t)=\sum_{k=1/M}^{1}\sum_{k=1}^{M} a_k\cdot\sin[k\omega_n t+\varphi_k(t)]+v_e(t), \tag{4}$$

where a_k represents a cycle amplitude, M is the number of cycles, $\omega_n=2\pi/18.6$ (rad yr^{-1}) is the Earth's nutation angle frequency and $v_e(t)$ is a disturbance from an unknown source. The total temperature dependent system is a sum of the elements

$$x_{tot}(t)=\sum_{e=1}^{N} x_e(t_1)=\sum_{e=1}^{N}[x_e(t)+v_e(t)], \tag{5}$$

where $x_e(t)$ is the stationary cycle dependent element, N is the number of elements, and $v_e(t)$ is the non-correlated stochastic process. Each stationary cycle dependent element $x_e(t)$ is correlated to the Earth's nutation cycles and will be accumulated in the total biomass. The disturbance element $v_e(t)$ is not correlated and will not be accumulated. The cyclic temperature cycle is then expected to influence the biomass maximum potential.

Biomass resonance between bio systems

The biomass has a mutual relation $S_B(t)=\{B_B(t), [S_P(t), S_F(t)]\}$ where $S_P(t)$ is the predator system, $S_F(t)$ is the food system, and $B_B(t)$ is a mutual binding between the systems. A mutual relation between systems is a feedback system. Such a system may have the frequency transfer function:

$$M_B(j\omega)=\frac{H_F(j\omega)\cdot e^{j\tau_S(t)\omega t}}{1+[H_F(j\omega)H_P(j\omega)]e^{j[\tau_F(t)+\tau_P(t)]\omega t}}, \tag{6}$$

where $H_F(j\omega)$ represents an energy transfer function of the food system, the $H_P(j\omega)$ transfer function of the predator system, $\tau_F(t)$ the phase delay in the food system, and $\tau_P(t)$ the phase delay in the predator system.

Such a dynamic will have the following important results:

(1) A forced temperature oscillator will synchronize a cycle response and introduce a set of sub-harmonic cycles in the biomass (*Forced oscillator*).
(2) The frequency transfer function (6) has a resonance property. This means there may be a biological stochastic resonance between the food system and the predator system. Such a resonance, will be tuned to the temperature cycle and this will amplify the fluctuation property. In this case we have a biological resonance when maximum biomass density is matching maximum recruit rate of 6–7 years (*Biological resonance*).
(3) The frequency transfer function (6) has a time-dependent phase property. This means the biological resonance is structurally unstable. Such a system may be chaotic and deterministic, but the same dynamic interactions between the food system and the predator system will never be repeated (*Structural stability*).

System dynamics of Northeast Arctic cod

The system dynamics of Northeast Arctic cod may be modelled by the discrete difference equation:

$$x_c(nT+T)=A_c(nT)\cdot x_c(nT)+u_c(nT)+v_c(nT)$$

$$y_c(nT)=D_c(T)\cdot x_c(nT)+w_c(nT), \qquad (7)$$

where $x_c(nT)$ represents a year-class vector at the year n, T sample the time of one year, $A_c(nT)$ represents a time varying growth rate binding matrix on the autonomous system, $u_c(nT)$ represents the quota vector, $v_c(nT)$ represents a disturbance vector from an unknown source, $D_c(nT)$ is the measure matrix, $y_c(nT)$ is the measured state vector, and w(nT) is the measurement noise vector. A growth rate element $a_{ci}(nT)$ in the growth matrix $A_c(nT)$ at age index i is:

$$a_{ci}(nT)=x_{ci}(nT+T)/x_{ci}(nT), \qquad (8)$$

The estimated number of cod at age 3 is $yn_{c3}(nT)$, the estimated biomass $y_{c3+}(nT)$ is the vector sum from age 3, and the spawn biomass $y_{c8+}(nT)$ is the vector sum from age 8.

According to this theory, the Earth's nutation of 18.6 years is introducing a set of harmonic temperature cycles in the Barents Sea (Yndestad, 1999), the temperature cycles are a forced oscillator that introduces biomass cycles and biological stochastic resonance in the Barents Sea. These cycles are expected to be reflected in the growth matrix $A_c(t)$ of Northeast Arctic cod.

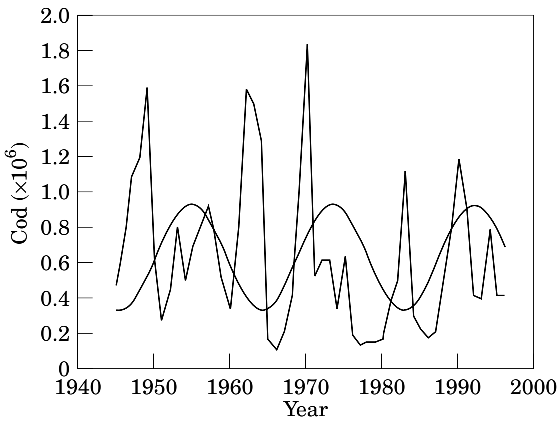

Figure 1. Time series of 3-year cod recruitment and the 18.6-year temperature cycle.

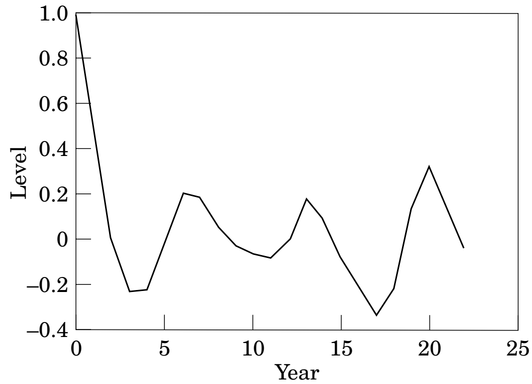

Figure 2. Autocorrelation of 3-year cod recruitment time series from 1945 to 1995.

Results

Identification of the Earth's nutation cycle

Figure 1 shows the time series $yn_{c3}(nT)$ of the number of 3-year Northeast Arctic cod since 1946 and the estimated 18.6 year temperature cycle in the Barents Sea (Yndestad, 1999). A visual inspection of Figure 1 indicates that the recruitment of 3-year cod has a low frequent component correlated in frequency and phase to the lower frequency temperature cycle of 18.6 years. This means that the growth matrix has a relation $A_c(t)=f(\omega_n)$ where $\omega_n=2\pi/18.6$ (rad yr^{-1}).

Figure 2 shows the autocorrelation function $R_{y3y3}(mT)$ of the recruitment $yn_{c3}(nT)$. The peaks in interval of about 6 years indicate a stationary cycle at about 6 years in the time series.

The cyclic properties may also be estimated by computing the auto power density spectrum. This

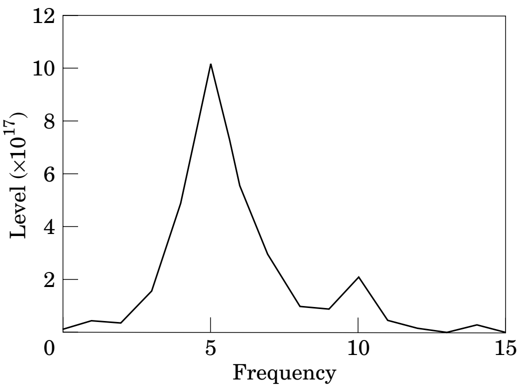

Figure 3. Power density spectrum of 3-year cod recruitment time series from 1946 to 1995.

spectrum is computed by the Fourier transform of the autocorrelation:

$$S_{y3y3}(k) = \sum_{n=0}^{N-1} R_{y3y3}(mT) \cdot e^{-jkmT/N}, \tag{9}$$

Figure 3 shows the power density spectrum windowed by 32 samples. Here there is a peak at the cycle $32/5 \approx 6$ years. This is close to the temperature cycle of 6.2 years. This analysis indicates that there is a close correlation between the recruitment of Northeast Arctic cod and the temperature cycles of 6.2 years and 18.6 years. The growth matrix then has a property $A_c(t) = f(\omega_n, 3\omega_n)$.

Ottestad (1942) has investigated landings in Lofoten from 1875 to 1940. He found maximum cycles of Northeast Arctic cod in intervals of 11, 17.5, 23, and 57 years but did not find any explanations. These cycles may be explained by the harmonic growth cycles of 18.6/3=6.2, 18.6, and 3*18.6=55.8 years. The 57 year cycle is close to the 55.8 year cycle and the 17.5 year cycle from Otterstad is approximately the same as the 18.6 year cycle. Otterstad found cycles of 11 and 23 years which are both about 6 years from the 17.5 year cycle. The 11 and 23 year cycles are counted because the nutation harmonic cycles are additive by nature. The growth rate is then expected to be influenced by the sum of three stationary temperature cycles. This indicates that the growth matrix has the property $A_c(t) = f(3\omega_n, \omega_n, \omega_n/3)$. The growth rate of each elements in the growth matrix $A_c(t)$ is then expected to be influenced by the sum of three stationary temperature cycles plus a random disturbance from an unknown source. The total growth rate $a_{ci}(nT)$ at age index i may be expressed as:

$$a_{ci}(nT) = a_{cia}(nT) + a_{cin/3}(nT) + a_{cin}(nT) + a_{ci3n}(nT) + a_{civ}(nT), \tag{10}$$

where $a_{cia}(nT)$ is the average growth rate, $a_{cin/3}(nT)$ is the growth rate influenced by the 6.2 year cycle, $a_{cin}(nT)$ is the growth rate from the 18.6 year cycle, $a_{ci3n}(nT)$ is the growth rate from the 55.8 year cycle and $a_{civ}(nT)$ is a growth rate from an unknown source. The next step is to estimate some of these parameters.

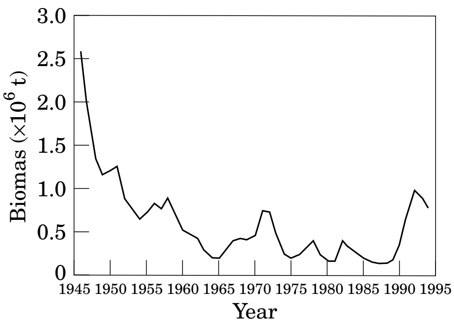

Figure 4. Spawning stock cod from 1946 to 1995.

Parameter identification

From known data (ICES, 1995) the growth rate $a_{cia}(nT)$ for each year class i=1.8 is estimated (3.33, 2.10, 1.95, 1.61, 1.55, 1.47, 1.35, 1.26.). The temperature dependent growth from the 6.2 year cycle $a_{cin/3}(nT)$ is estimated (4.00, 2.25, 2.33, 1.71, 1.56, 1.43, 1.35, 1.26). The parameters of $a_{cin}(nT)$ and $a_{ci3n}(nT)$ have not been estimated since there is a lack of data.

Figure 4 is the time series of the spawning stock biomass $y_{c8+}(nT)$ of cod from 1946 (ICES, 1995). The linear production rate $p_{cl}(nT)$ of cod may be defined as the relation between the number of first year cod and the spawning stock of cod biomass. This rate may be computed by:

$$p_{cl}(nT) = \frac{yn_{c1}(nT)}{y_{c8+}(nT)}, \tag{11}$$

where $y_{c8+}(nT)$ is the known spawning-stock biomass of cod. $yn_{c1}(nT)$ is the backward estimated recruited number of 1-year-old cod when $yn_{c3}(nT)$ and the mortality is known. In this case the discrete mortality rate M=0.2.

The result is shown in Figure 5. A constant production rate indicates a linear biomass-dependent recruitment. In this case there is a strong periodic fluctuation in the production rate. The fluctuation is correlated in frequency and phase to the 6.2 year temperature cycle. This supports the theory of the influence of the Earth's nutation and introduces a 6.2 year temperature cycle in the recruitment of North Arctic cod.

The system element $S_e(t)$ is a temperature dependent food chain. In the Barents Sea the system elements in the food chain are temperature dependent. Since there is an additive correlation (5), we may expect there is an

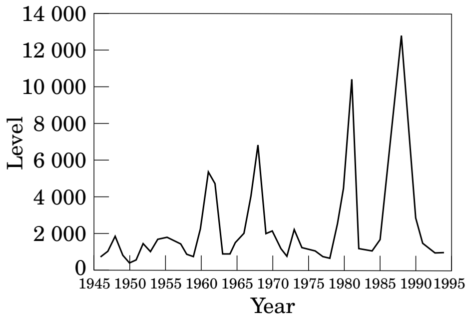

Figure 5. Linear production rate from 1946 to 1995.

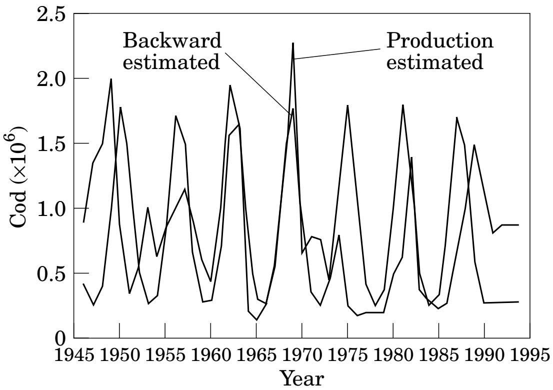

Figure 6. Backward estimated 1 year recruitment and forward estimated 1 year recruitment.

exponentially temperature-dependent recruitment in the biomass. Such a relation is expressed by the model

$$p(nT) = \bar{p} \cdot \exp[T_B(nT)], \tag{12}$$

where $T_B(nT)$ is an exponential relation to the nutation cycles of 6.2, 18.6, and 55.8 years and $\bar{p}$ is the mean production rate. The production rate is than estimated to the 6.2 year cycle. In this case:

$$\bar{p} = E[p(nT)] = 1600 \text{ fry/ton spawn cod}, \tag{13}$$

and the relation to the 6.2 year temperature cycle is estimated to be:

$$T_{Bn/3}(nT) = -0.38 + 1.0 \cdot \sin\left(\frac{3 \cdot 2 \cdot \pi}{18.6} nT + T\right), \tag{14}$$

where T is the sample time of 1 year and n is a number of years from the reference year 1900. Forward estimated recruitment of 1-year cod is estimated from known spawn biomass $y_{c8+}(nT)$ and known production rate. From (10) to (13) the forward estimated recruitment is:

$$yn_{c1f}(nT) = y_{c8+}(nT) \cdot \bar{p} \cdot \exp[T_{Bn/3}(nT)], \tag{15}$$

In this case only the 6.2-year cycle is used in the temperature binding $T_{Bn/3}(nT)$.

Figure 6 shows backward estimated, 1-year recruitment $yn_{c1}(nT)$ and forward estimated, 1 year recruitment $yn_{c1f}(nT)$. It shows a close correlation between the two estimates. If we introduce the temperature cycle of 18.6 years in the model the amplitude error will be further reduced. These estimates indicate that the recruitment is exponentially dependent on the temperature cycle and linearly dependent on the biomass.

Discussion

This paper shows that there is a correlation between the Earth's nutation and the time series of estimated annual stock recruitment of the Northeast Arctic cod. It supports the theory that the Earth's nutation of 18.6 years is introducing a set of harmonic and sub harmonic temperature cycles in the Barents Sea (Yndestad, 1999). The estimated temperature cycle of 18.6/3=6.2 years is correlated exponentially to the recruitment pattern. The temperature cycles of 3*18.6=55.8 years, 18.6 years, and 18.6/3=6.2 years are correlated to the growth rate. These estimates explain the time series of cod landing cycles in Lofoten from 1880 to 1940 (Otterstad, 1942). The 122 year cycle of herring (Rollefsen, 1949) may be explained by a sub-harmonic biomass cycle of 4*18.6=111.6 years periodicity. This theory will open a new perspective into forecasting short-time fluctuations of 6–7 years and long-time fluctuations of 50 years or more.

The cycles of biomass are explained by a General Systems theory, temperature cycles as a forced oscillator on the ecological system, and a biological stochastic resonance that will amplify the cod biomass fluctuations. According to this theory the temperature cycles first influence the food system of the Northeast Arctic cod. The food system will then influence exponentially the recruitment rate and the mortality fluctuates exponentially since recruitment and mortality are dual aspects of the same process. The growth rate is estimated to be linearly dependent on the temperature cycle. The biomass of cod has a maximum recruitment rate and a maximum density at 6–8 years of age. This means the biomass has a biological stochastic resonance close to the temperature cycle.

References

Ajiad, A. M., Mehl, S., Korsbrekke, K., Dolgov, A. V., Korzhev, V. A., Tretyak, V. L., and Yragina, N. A. 1992. Tropic relationships and feeding-dependent growth in the Northeast Arctic cod. Proceedings of the Fifth PINRO-IMR Symposium, Murmansk, August 1991. Institute of Marine Research, Bergen.

Currie, R. G. 1991. Deterministic signals in tree-rings from Tasmania, New Zealand and South Africa. Annual Geophysics, 9: 71–81.

Eilertsen, B., Fossum, P., and Sundby, S. 1989. Relation between temperatures and survival of eggs and first-feeding larvae of Northeast Arctic Cod (*Gadus morhua* L). Rapports et Procès-Verbaux des Réunions du Council International pour l'Exploration de la Mer, 191: 209–219.

Gabrielsen, G. W., and Rygg, M. 1992. Sjøfugl og sjøpattedyr. *In* Økosystem Barentshavet, pp. 203–229. Ed. by E. Sakshaug. Mesne Trykk, Lillehammer, Norway (in Norwegian).

Haug, T., Krøyer, A. B., Nilssen, K. T., Ugland, K. T. I., and Aspholm, P. E. 1991. Harp seal (*Phoca groenlandica*) invasions in Norwegian costal waters, composition and feeding habits. ICES Journal of Marine Science, 48: 363–371.

ICES 1995. Report of the arctic fisheries working group. ICES Headquarters. Copenhagen. Denmark.

Jørgensen, T. 1992. Long-term changes in growth of Northeast Arctic cod (*Gadus morua*) and some environmental influences. ICES Journal of Marine Science, 49: 263–277.

Nakken, O., and Raknes, A. 1987. The distribution and growth of Northeast Arctic cod in relation to bottom temperatures in the Barents Sea in the period 1977–1984. ICES CM 1984/G:20.

Nakken, O. 1994. Causes of trends and fluctuations in the Arcto-Norwegian cod stock. ICES Marine Science Symposium, 198: 212–228.

NIMR 1995. Norwegian Institute of Marine Research. Ressursoversikt. Bergen. Norway.

Ottestad, P. 1942. On periodical variations on the yield on the great sea fisheries and the possibility of establishing yield prognoses. Fiskeridirektoratets Skrifter. Vol, VII. No 5. Bergen. Norway.

Ottersen, G., Michalsen, K., and Nakken, O. 1996. Ambient temperature and distibution of Northeast Arctic cod. ICES, Annual Science Conference. Reykjavik, Iceland, 27 September–4 October 1996.

Rollefsen, G., and Strøm, J. 1949. Norsk Fiskeri og Fangst Handbook. Bind 1. Alb. Cammermeyers Forlag. Oslo.

Sætersdal, K., and Loeng, H. 1987. Ecological adaption of reproduction in Northeast Arctic cod. Fisheries Research, 5: 253–270.

Wyatt, T., Currie, R. G., and Larraneta, M. G. 1992. Codstock recruitment problems, the nodal tide and sunspot cycles. ICES CM 192/L:17.

Wyatt, T., Currie, R. G., and Saborido-Ray, F. 1994. Deterministic signals in Norwegian cod records. ICES Marine Science Symposium, 198: 49–55.

Yndestad, H. 1996a. Stationary Temperature Cycles in the Barents Sea. The cause of causes. The 84'th international ICES Annual Science Conference. Hydrography Committee. Reykjavik, Iceland, 27 September–4 October 1996.

Yndestad, H. 1996b. Systems Dynamics of North Arctic Cod. The 84th international ICES Annual Science Conference. Hydrography Committee. Reykjavik, Iceland, 27 September–4 October 1996.

Yndestad, H. 1999. Earth Nutation Influence on the Temperature in the Barents Sea. ICES Journal of Marine Science, 56: 381–387.