ICES Journal of Marine Science, 56: 381–387. 1999
Article No. jmsc.1999.0469, available online at http://www.idealibrary.com on IDEAL

Earth nutation influence on the temperature regime of the Barents Sea

H. Yndestad

Yndestad, H. 1999. Earth nutation influence on the temperature regime of the Barents Sea. – ICES Journal of Marine Science, 56: 381–387.

A General System theory of the influence of the Earth's nutation on the temperature of the Barents Sea is presented. According to this theory, the Earth's axis behaves dynamically as a forced oscillator on a non-linear sea system that modulates a set of harmonic and subharmonic low-frequency temperature cycles.

A spectrum analysis of the Kola meridian sea temperature time series indicates a correlation between it and the Earth nutation cycles of 18.6 yr, 18.6/3=6.2 yr, and 18.6 × 3=55.8 yr. The 55.8 yr cycle seems to follow a moving average in the temperature series.

If the theory is confirmed by the analysis of other data sets it will open new perspectives in the forecasting of future temperature, ecological, and biological changes not only in the Barents Sea but also worldwide.

Key words: system theory, Earth nutation, temperature cycles, Barents Sea.

Received 20 March 1998; revised 28 September 1998; accepted 18 February 1999.

Harald Yndestad: Aalesund College, Box N-5104 Larsgaarden, 6021 Aalesund, Norway. Tel: +47 70 16 12 00; fax: +47 70 16 13 00; e-mail: harald.yndestad@hials.no

Introduction

Aristotle explained the dynamics of objects in nature by the four causes, namely the efficient cause, the material cause, the structure cause, and predestined fate. The latter was decided by the "cause of causes"; the positions of the Sun, the Moon, and the stars. Does this doctrine have any relevance today?

In 1543 Copernicus associated the change of star positions with a changing direction of the rotational axis of the Earth. Isaac Newton explained in "Principia" (Chandrasekhar, 1995) that the Earth is a spinning object where the axis describes a circle about the North Pole. This motion is called "precession" and proceeds, in about 25 800 yr, along a cone with a half-apex angle of 23.439 degrees and moves along the elliptic by 50.291 arc s yr^{-1}. In 1754 Kant predicted that friction with tidal forces on the Earth would cause a deceleration of the Earth's rotation. Euler predicted in 1758 that the rotation of the Earth's axis would show the Earth's motion with respect to an Earth-fixed reference frame (polar motion). Some years later in 1776 Laplace made theoretical tidal modelling involving periodic hydrodynamics on a rotating sphere. In the eighteenth century the English astronomer Bradley discovered that the Earth's rotational axis wobbled around the precession cone. This change was called the "nutation". Better instrumentation slowly modified the view of the movement of the Earth as a stable, dynamic process.

Earth axis dynamics are now described by the four components precession, nutation, celestial pole offset, and polar motion. The nutation has an amplitude of 9.2 arc s and a 18.6 yr cycle caused by the Moon. By new high-precision measurements more than 100 frequency components in the nutation have been discovered. The four dominant cycles of the nutation are 18.6 yr (precession period of the lunar orbit), 9.3 yr (rotation period of the Moon's perigee), 182.6 d (half a year), and 13.7 d (half a month). New geodetic techniques now make it possible to detect Earth displacement influenced by the tide, the Earth core and mantle, and from atmospheric disturbance. These cycles seem to influence global ecological changes. A worldwide correlation between the 18.6 yr Earth nutation and rainfall, tree-rings, air temperatures, and dates of wine harvests has been reported (Currie, 1991; Wyatt *et al.*, 1992). In historical records of cod landings in Norway a correlation has been reported between cod landings and the 18.6 yr Earth nutation (Wyatt *et al.*, 1994). A correlation has also

1054–3139/99/030381+07 $30.00/0

been reported between historical records of cod and nutation harmonics 18.6/3 yr, 18.6 yr, and 3 × 18.6 yr (Yndestad, 1996b).

In the Barents Sea the inflow of warm North Atlantic water meets a stream of cold Arctic water from the north and cool, mixed water circulates back to East Greenland. These currents may vary in intensity and slightly in position and cause biological changes in the Barents Sea. Since the first analysis by Helland-Hansen and Nansen (1906), changes in their patterns have been explained by variability in average wind and climatic conditions (Loeng *et al.*, 1992; Dyke, 1996). There is, however, no clear understanding of how meteorological and oceanographic conditions influence each other (Loeng *et al.*, 1992).

Russian scientists at the PINRO institute in Murmansk have provided monthly temperature values from the upper 200 m in the Kola section along the 33°30′E meridian from 70°30′N to 72°30′N in the Barents Sea (Bockov, 1982). The data series has quarterly values from the period 1906–1920 and monthly values from 1921, partly measured and partly interpolated. Loeng, *et al.* (1992) have studied this time series and found dominant coefficients at 3.3, 7.2, 8.8, 11.7–13.6, and 17.5 yr cycles in the Fourier spectrum. Latterly a more complete monthly data series from 1900 to 1994 has been compiled (Tereshchenko, 1996).

In 1994 a modelled projection of the lifetime earning capacity of a Norwegian trawler was carried out as an item of contractual research (Yndestad *et al.*, 1994). By chance, one of the findings was that the time series of North Atlantic cod catches has a dominant 6–7 yr cycle in the Fourier amplitude spectrum. The same dominant cycle was found in cod recruitment. After more research the same cycle, as an harmonic relation to the Earth's nutation, was found in the Kola series (Yndestad, 1996a). This paper presents a more detailed spectrum analysis of the Kola meridian temperature time series. The analysis detects harmonic and subharmonic periodic cycles related to the Earth's nutation of 18.6 and the 1 yr seasonal variation. The cycles have been analysed according to a General System theory and the concept of forced oscillators. According to this theory the Moon represents the "cause of causes" behind the low-frequency temperature cycles in the Barents Sea. Gravity from planetary forces causes changes of the Earth's rotation axis. In the long run this generates a set of harmonic and subharmonic energy cycles that modulate the current amplitudes. Some cycles may be amplified by resonance and some of them are depressed by energy loss. According to the General System theory, the cycles are phase sensitive. High-frequency cycle changes will be recorded as noise and influenced by local conditions. Low-frequency cycles will be recorded as climatic change.

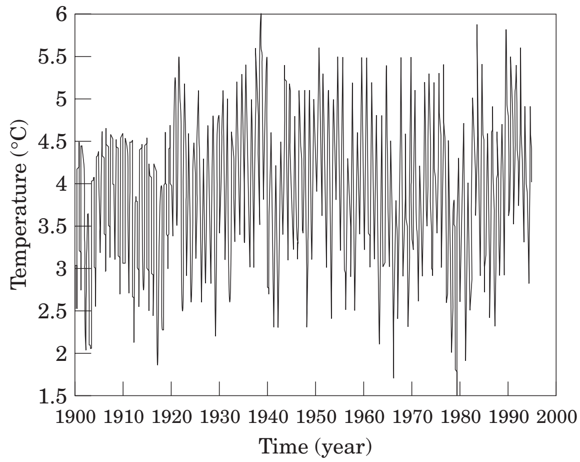

Figure 1. A yearly average temperature in the Barents Sea from the year 1900.

Materials and methods

Materials

Figure 1 shows the temperature series taken from the Kola section (Y. A. Bockov, pers. comm.). The data are measured along 33°30′E from 70°30′N to 72°30′N and have a sampling time "T" of 1 month from 1900 to 1994. According to the Shannon sampling theorem (Phillips and Harbor 1989) we may investigate planetary forced cycles up to about 50 yr. The figure shows that the temperature oscillates rapidly about 1°C from a mean value of about 3.7°C. To understand the more fundamental aspects of this temperature series we will relate the data series to a General System theory.

General System theory

"General System theory" is a means of understanding abstract organizations independent of time and space. A system is a set of subsystems cooperating to a common purpose. This may be expressed as:

$$S(t) = \{B(t), S_N(t)\} = \{B(t), \{S_1(t), S_2,(t) \ldots, S_n(t)\}\} \varepsilon w, \qquad (1)$$

where $S(t)$ is the system, $S_N(t)$ is a set of subsystems, $S_1(t)$ is a subsystem, $B(t)$ is a dynamic binding between the subsystems, and w is the common system purpose. According to the general theory, systems are time varying, structurally unstable, and mutually state dependent.

In this case we have the planetary system: $S(t) = \{B_p(t), \{S_e(t), S_m(t), S_s(t)\}\}$ where $S_e(t)$ represents the Earth system, $S_m(t)$ the Moon system, $S_s(t)$ the Sun system, and $B_p(t)$ is the mutual dynamic binding. In this case the planetary system represents a stable periodic system.

The Earth system has the subsystems $S_e(t)=\{B_e(t), \{S_b(t), S_g(t), S_w(t), S_c(t), S_v(t)\}\}$ where $S_b(t)$ is the Barents Sea system, $S_g(t)$ the Earth axis system, $S_w(t)$ a warm Atlantic flow system, $S_c(t)$ a cold-water stream system, $S_v(t)$ an unknown disturbance system, and $B_e(t)$ the dynamic binding between the systems. Since all subsystems are dynamic mutually dependent we have to understand some fundamental dynamic properties of each system.

System state dynamics

The temperature state dynamics in the Barents Sea system $S_b(t)$, may then be modelled by the state space equation:

$$\ddot{x}(t)=A(t)\cdot x(t)+B(t)\cdot u(t)+C(t)\cdot v(t);$$
$$y(t)=x(t)+w(t), \tag{2}$$

where x(t) represents a temperature state vector, A(t) represents a time varying internal binding, and u(t) represents a state vector from planetary system as a forced oscillator. B(t) represents the dynamic binding from the planetary objects to the Barents Sea, $S_w(t)$ is the warm-water system, $S_c(t)$ the cold-water system, v(t) is a disturbance vector, C(t) the dynamic binding from disturbance, D(t) is the measure matrix, y(t) is the measured temperature, and w(t) is noise in measurement.

Wiener spectrum

The energy E_v from an unknown system state v(t), may be estimated by Parseval's theorem:

$$E_v=\int_{-\infty}^{+\infty}|v(t)|^2=\frac{1}{2\pi}\int_{-\infty}^{+\infty}|V^*(j\omega)|^2 d\omega. \tag{3}$$

If the spectrum V(jω) is white noise, the spectral density is:

$$S_{vv}(j\omega)=|V^*(j\omega)|^2=V^2{}_0, \tag{4}$$

where $V^2{}_0$ is the noise variance. In this case the integrated energy will be infinite. Since this is impossible, the temperature spectrum must be coloured. Such process may be modulated by the first order process:

$$\dot{v}(t)=-a\cdot v(t)+n(t), \tag{5}$$

where n(t) is non-correlated white noise. The autocorrelation of this process (5) is:

$$R_{vv}(\tau)=E[v(t)\cdot v(t+\tau)-E[v(t)]^2]=\frac{V_0^2}{2a}\cdot e^{-a|\tau|} \tag{6}$$

where τ is a time displacement. This indicates that the autocorrelation function of the time series v(t) is expected to fall exponentially. The frequency transform of the first order process (5) is a Wiener spectrum:

$$V(j\omega)=\frac{N_0}{a+j\omega}. \tag{7}$$

This indicates that spectrum of the measured time series is expected to fall by N_0/ω, or 20 dB/decade, when $\omega>a$.

Periodic properties

The planetary system S(t) is a stable system generating periodic states u(t). These states can be represented by the Fourier series:

$$u(t)=\sum_{n=0}^{\infty}u_n\cdot e^{jn\omega_i t}, \tag{8}$$

where u_n represents amplitude series and the angle frequency $\omega_i=2\pi/T_i$. In this case the most important cycles are the Earth's seasonal frequency $\omega_s=2\pi/1$ (rad yr^{-1}), the Earth's nutation $\omega_n=2\pi/18.6$ (rad yr^{-1}) and the precession $\omega_p=2\pi/26\,800$ (rad yr^{-1}). The autocorrelation of the periodic u(t) has the property:

$$R_{uu}(\tau)=E[u(t)\cdot u(t+\tau)-E[u(t)]^2]=\frac{u_0^2}{2}\cos(\omega_i\tau), \tag{9}$$

where τ is the time displacement. This means that if the measured time series y(t) has a periodic property, it will be reflected in the autocorrelation function.

Forced oscillators on non-linear systems

In this case the Earth's axis dynamics is a forced oscillator on a non-linear sea system. Such a system may be modelled by the Duffing equation:

$$\ddot{x}(t)+A\cdot\dddot{x}(t)\times F[x(t)]=B\cdot\cos(\omega t), \tag{10}$$

where F[x(t)] is the non-linear system. It is well known that such a system has chaotic behaviour and generates a set of harmonic and subharmonic frequencies (Moon, 1987).

The warm Atlantic inflow and the cold Arctic water in the Barents Sea are parts of a complex global hydrodynamical system. Each of them may be modulated as a forced oscillator u(t) on the feedback systems. The warm-water stream system may be modulated as $S_w(t)=\{B_w(t), \{S_f(t), S_b(t)\}\}$ where the feed forward system $S_f(t)=\{B_f(t), \{p_{f1}(t), p_{f2}(t) \ldots p_{fn}(t)\}\}$ and a feedback system $S_b(t)=\{B_b(t), \{p_{b1}(t), p_{b2}(t) \ldots p_{bm}(t)\}\}$. Each subpartner $p_i(t)$ may have a local circular stream of water and each subsystem p(t) will have an energy loss h(t) that has the frequency transfer function H(jω). From the theory of feedback dynamic systems, the frequency transfer function of a circular system of water flow is:

$$\frac{V_{fb}(j\omega)}{U(j\omega)} = \frac{H_{f1}(j\omega)\ldots H_{fn}(j\omega)\cdot e^{j[\tau_{f1}(t)+\tau_{fn}(t)]\omega t}}{1+[H_{f1}(j\omega)\ldots H_{fn}(j\omega)]\,[H_{b1}(j\omega)\ldots H_{bm}(j\omega)]\, e^{j(\tau_{f1}(t)+\tau_{fn}(t))\omega t} e^{j(\tau_{b1}(t)+\tau_{bm}(t))\omega t}}, \quad (11)$$

where $H_i(j\omega)$ represents an energy transfer function, $\tau_i(t)$ represents a time-dependent transport delay, $U(j\omega)$ the input energy to the sea, and $V_{fb}(j\omega)$ the output energy to the Barents Sea. From the theory of feedback system dynamics this type of system has some fundamental properties:

(1) The forced oscillator u(t) will modulate a set of harmonic and subharmonic temperature cycles into the Barents Sea;
(2) The feedback property will introduce a set of harmonic cycles related to the total transport delay. Changes in this transport delay will influence the phase dependent cycles;
(3) The feedback system (11) may have resonance, and thus be able to absorb energy. This explains why a small movement of the Earth's nutation can be amplified and cause a significant force oscillator to the Barents Sea;
(4) The system is structurally unstable. Changes in binding B(t) between subpartners may force changes in the cycle phase and thus introduce a disturbance and major state changes in the system;
(5) The temperature in the Barents Sea will be disturbed by the sum of the warm-water feedback system and the cold-water feedback system.

The state dynamics of the forced oscillator system then will have the property:

$$y(t) = F^{-1}\{V_{fb}(j\omega)\} + v(t) + w(t) = y_u(t) + v(t) + w(t);$$
$$y_u(t) = \sum_{(n,m)=0}^{\infty} A_{(n,m)}\cdot \sin\left[\frac{n}{m}\cdot\omega_i t + \varphi_{(n,m)}(t)\right] \quad (12)$$

where ω_i is the periodic cycle, A_i the cycle amplitude, n the harmonic number, m the subharmonic number, $\varphi_i(t)$ the phase delay, v(t) a disturbance from an unknown source, and w(t) is measured noise.

According to this theory, there may be harmonic and subharmonic cycles from the precession, nutation, and from the polar motion.

Results

Figure 2 shows the power density spectrum periodogram of the Kola section temperature–time series y(t). This figure confirms some fundamental properties from the general system theory:

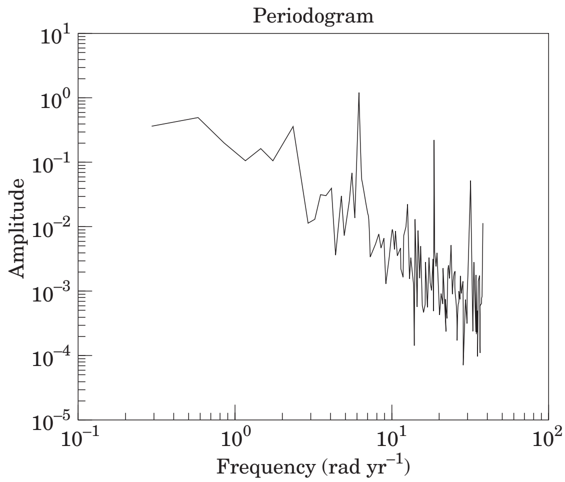

Figure 2. Power density spectrum of the temperature series y(t).

(1) The power density spectrum of y(t) is falling by k/ω^2. This confirms the theory of energy distributions (7);
(2) Most power density is concentrated at the 1 yr seasonal angle frequency $\omega_e = 6.28$ (rad yr^{-1}) forced from the Sun;
(3) The seasonal 1 yr cycle from the Sun generates the harmonics $2\omega_e$ and $3\omega_e$ and there is a trace of the subharmonics $\omega_e/2$ and $\omega_e/4$. This is according to the modulation theory (10) and (11);
(4) At the lower end of the spectrum there are some indications of the nutation harmonics frequency $\omega_e/2 = 0.6$ (rad yr^{-1}) or 9.3 yr, $\omega_e/3 = 1.1$ (rad yr^{-1}) or 6.2 yr, and at $\omega_e/4 = 1.3$ (rad yr^{-1}) or at 4.6 yr. This confirms the modulation theory (10) and (11).

The time series y(t) is dominated by the 1 yr seasonal cycle. The next step is to look more closely for cycles related to the Earth's nutation.

Filtered time series

Figure 3 shows a low pass filtered temperature series. In this case the 1 yr cycle is suppressed by the linear phase, moving average filter:

$$y_{lp}(nT) = \frac{1}{2M+1}\sum_{m=-M}^{m=M} y(nT+mT), \quad (13)$$

where M is 12 months. The filtered time series now seems to be dominated by state changes. The fundamental properties of this time series have been analysed more closely by looking at the phase-space, the

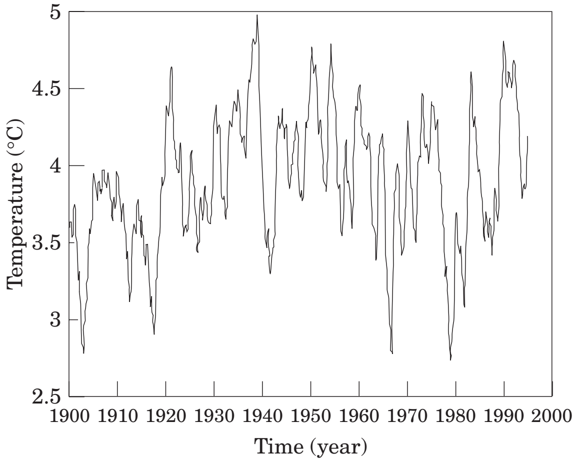

Figure 3. The Kola section temperature–time series.

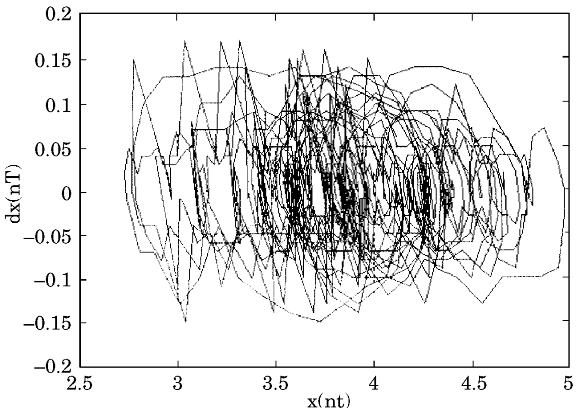

Figure 4. Phase-space analysis of dx(nT) and x(nT) (°C).

autocorrelation, and a number of spectrum estimation methods.

Phase space analysis

Figure 4 shows a phase-space analyses of the time series. The x-axis shows the time series y(nT) and on the y-axis and we have the velocity:

$$dx(nT) \approx \frac{x(nT) - x(nT - T)}{T}. \tag{10}$$

Figure 4 indicates a chaos attractor in the phase-space at the temperature x = 3.73°C. This attractor in the phase-space supports the theory that there are deterministic periodic cycles in the 100 yr temperature–time series.

Correlation analysis

Figure 5 shows the computed normalized autocorrelation function $R_{yy}(\tau)$ of the filtered time series $y_{lp}(nT)$.

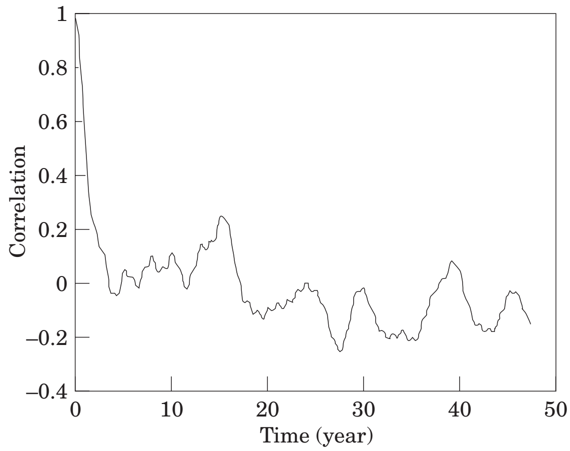

Figure 5. Autocorrelation function.

The rapidly falling autocorrelation indicates there is a significant amount of noise v(t) from an unknown source in the time series $y_{lp}(t)$ (6). The periodic variations in the autocorrelation indicate periodic cycles in the temperature series (9). The next step is to estimate the cycle parameters of $y_u(t)$ (12).

In this case the data series is corrupted with noise v(t) and w(t). To suppress the noise a closer spectrum analysis has been done by analysing the power density spectrum of the time series. The time series is short compared to the nutation cycle and the power density spectrum loses the phase information. The phase is estimated by a cross-correlation between the time series $y_{lp}(nT)$ and harmonic nutation cycles. The estimated harmonic nutation related cycles were the third harmonic cycle $y_{m,3}(nT)$ of 6.2 yr, the nutation test cycles $y_{1,1}(nT)$ of 18.6 yr, and the subharmonic cycle $y_{3,m}(nT)$ of 55.8 yr.

$$\begin{aligned} y_{m,3}(nT) &= 3.9 + 0.4 \cdot \sin\left(\frac{3 \cdot 2 \cdot \pi}{18.6} \cdot nT + 12T\right); \\ y_{1,1}(nT) &= 3.9 + 0.6 \cdot \sin\left(\frac{2 \cdot \pi}{18.6} \cdot nT + 9.6T\right); \\ y_{3,n}(nT) &= 3.9 + 0.4 \cdot \sin\left(\frac{2 \cdot \pi}{3 \cdot 18.6} \cdot nT + 336T\right), \end{aligned} \tag{14}$$

where n = 0, 1, 2, months from the year 1900, T is the sampling time of 1 month, and $\varphi_i = 12T$ is a phase displacement.

The power density spectrum analysis has identified a peak at about 18.6/2 or 10 yr and a significant peak at about 4 yr. The 4 yr peak seems to be the 4. harmonic of the seasonal 1 yr cycle. These cycles were not estimated.

Figure 6 shows the filtered time series $y_{lp}(t)$ and the estimated third subharmonic temperature cycle $y_{3,m}(nT)$ of 55.8 yr. The cycle has a maximum at about 1945 and

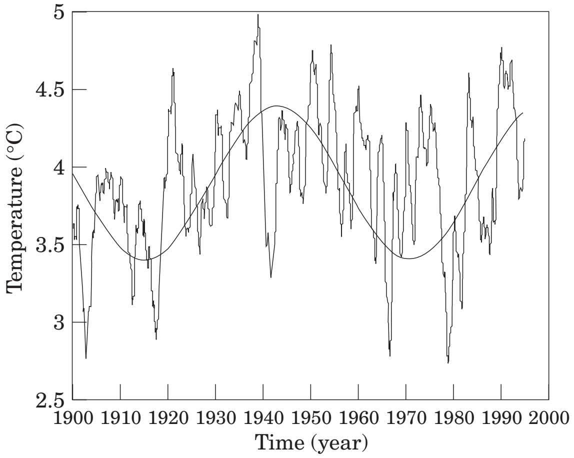

Figure 6. Temperature series $y_{lp}(t)$ and a 55.8 yr cycle $y_{3,n}(nT)$ (°C).

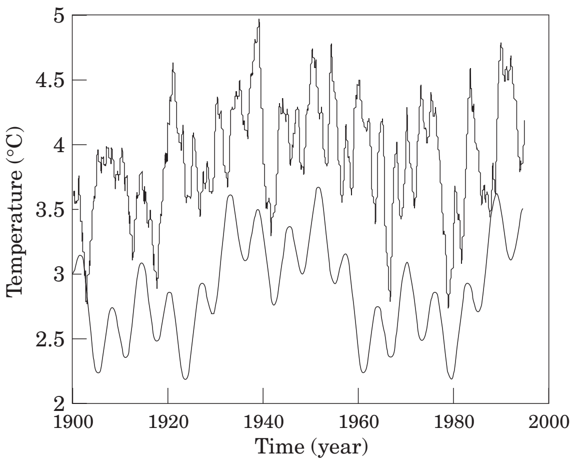

Figure 7. Temperature–time series $y_{lp}(t)$ and estimated cycles $y_u(t) - 1$ (°C).

will reach a new maximum around the year 2000. The figure shows that the temperature seems to follow this 3. subharmonic cycle as a moving mean temperature. This indicates that the Barents Sea has no stationary mean temperature.

Figure 7 shows the low pass filtered time series $y_{lp}(t)$ and sum of harmonic cycles $y_n(t)=y_{m,3}(t)+y_{1,1}(t)+y_{3,m}(t)$ (displaced 1 degree down). The estimated cycles now have the same pattern. Some years, however, the 6.2 yr cycle seems to have a phase shift.

The correlation between the time series, $y_{lp}(t)$ and the three estimated cycles $y_n(t)$ is 0.5. The correlation is sensitive when changing cycle frequency or phase. This is a strong indication that the source of the basic cycle is Earth nutation. The non-linear sea system modulates a set of harmonic and subharmonic cycles in the Barents Sea.

Discussion

The Kola meridian temperature–time series has been analysed. The power density spectrum of this is falling by k/ω^2 as expected according to the General System theory. The important property of the estimated spectrum is that major low-frequency cycles are correlated with the harmonics and subharmonics of the Earth's nutation of 18.6 yr. Since these are known and simple deterministic cycles it opens a new perspective in the prediction of fundamental long-term changes in sea temperature, and associated environmental and ecological changes, not only in the Barents Sea but also worldwide. The analysis has estimated cycles of $18.6/3=6.2$ yr, 18.6 yr, and $18/6 \times 3=55.8$ yr. However there may be more subharmonic temperature cycles in the data from the Barents Sea.

The estimated harmonic cycles are explained by a General System theory and the theory of forced oscillators. According to this theory the dynamics of the Earth's axis behave as a forced oscillator that transfers low-frequency energy to the non-linear sea system. Limits of predictions may be more low-frequency cycles and non-stability in the cycle phase. This introduces an uncertainty in the prediction of future temperatures.

To confirm this theory by oceanographic measurements existing data sets should be examined for matches to the harmonics of the Earth's nutation.

Acknowledgements

The author is grateful to Mr Yu. A. Bochkov at PINRO, Murmansk, for his assistance in providing access to the Kola meridian temperature–time series.

References

Bochkov, Y. A. 1982. Water temperature in the 0–200 m layer in the Kola-Meridian in the Barents Sea, 1900–1981. Sb. Nauchn. Trud. PINRO, Murmansk, 46: 113–122 (in Russian).

Chandrasekhar, S. 1995. Newton's: Principia for the Common Readers. Oxford University Press Inc, New York.

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

Dyke, P. 1996. Modelling marine processes. Prentice Hall, London.

Helland-Hansen, B., and Nansen, F. 1909. The Norwegian Sea. Fiskeridirektoratets skrifter. Havundersøkelser, 2: 1–360.

Loeng, O. 1994. Statistical Modelling of Temperature Variability in the Barents Sea. ICES CM 1994.

Loeng, H., Blindheim, J., Ådlandsvik, B., and Ottersen, G. 1992. Climatic variability in the Norwegian Barents Sea. ICES Marine Science Symposium, 195: 52–61.

Moon, F. C. 1987. Chaotic Vibrations. John Wiley & Sons, New York.

Phillips, C. L., and Harbor, R. D. 1989. Feedback Control Systems. Prentice-Hall International (UK) Limited, London.

Tereschenco, V. V. 1996. Seasonal and year-to-year variations of temperature and salinity along the Kola meridian transect. The 84th international ICES Annual Science Conference. Hydrography Committee, Iceland.

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., Helgesen, Ø., and Walde, P. 1994. Livssyklusanalyse av tråler. Høgskolen i Ålesund. Ålesund (In Norwegian).

Yndestad, H. 1996a. Stationary temperature cycles in the Barents Sea. The cause of causes. The 84th international ICES Annual Science Conference. Hydrography Committee, Iceland.

Yndestad, H. 1996b. Systems dynamics of North Arctic Cod. The 84th international ICES Annual Science Conference. Hydrography Committee, Iceland.