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Periodicity of climate conditions and solar variability derived from dendrochronological and other palaeoclimatic data in high latitudes

O.M. Raspopov[a,*], V.A. Dergachev[b], T. Kolström[c]

[a] SPbF IZMIRAN, P.O. Box 188, 191023 St. Petersburg, Russia
[b] Ioffe Physico-Technical Institute, RAS, St. Petersburg, Russia
[c] Mekrijärvi Research Station, University of Joensuu, Joensuu, Finland

Abstract

The periodicity of climatic processes in the Barents Sea Region and along the Arctic Ocean coast during several hundred years has been studied by analyzing the tree-ring chronologies for the regions close to the northern timberline. In the Barents Sea region, cyclicities of climatic processes with periods of around 90, 30–35, 22–23, 18 and 11–12 years have been established by spectral analysis of the data for the Kola Peninsula. Wavelet analysis of annual series of conifer tree-rings generalized for 10 regions along the northern timberline, from the Kola Peninsula to Chukotka, for the period 1458–1975 has revealed the same periodicities for the vast areas of northern Russia. Climatic cyclicity with a period of about 35 years is known as the Brückner cycle. Climatic cycles with periods of around 90, 22–23 and 11–12 years correlate well with the corresponding solar activity cycles. A possible solar forcing of periodic climatic processes and its nonlinear influence on the atmosphere–ocean–continental system are discussed.

Keywords: Solar activity; Solar irradiance; Climate change; Dendrochronology; Non-linear system; Brückner cycle

1. Introduction

At present, a considerable warming of climate has been detected both at the global scale and in the Northern Hemisphere. This warming does not, however, demonstrate a uniform character. In particular, cycles of relative warming and cooling may be observed in polar regions. The climate of the Barents Sea region is rather specific. Due to the impact of Gulf Stream, this region is to some degree warmer than other areas at the same latitudes of the Northern Hemisphere. Even with small displacements of Gulf Stream and related thermohaline circulation, changes in the climate of the Barents Sea region can exert a strong influence on the climate in the Arctic and Northern Hemisphere as a whole. Prediction of possible climatic changes and their consequences can be made only on the basis of analysis of past climatic changes in connection with natural and anthropogenic forcing factors. This, in turn, requires a more intensive research into long-term climatic variability.

A direct and systematic air temperature record for the Kola Peninsula, in the vicinity of Murmansk, is available for about 120 years. For this period, the temperature record demonstrates periodic changes on

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* Corresponding author. Fax: +7-812-310-50-35.
E-mail addresses: oleg@OR6074.spb.edu (O.M. Raspopov), v.dergachev@pop.ioiffe.rssi.ru (V.A. Dergachev), Taneli.Kolstrom@joensuu.fi (T. Kolström).

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the quasi-decadal and also longer scales. In addition, a general increase in temperatures during the past century may be observed. The main goal of the present work was to reveal periodic climatic oscillations in the Barents sea region by using dendrochronological data for the last 350 years collected from living trees at the northern timberline in the coastal zone of the Barents Sea on the Kola Peninsula. In this paper, we also

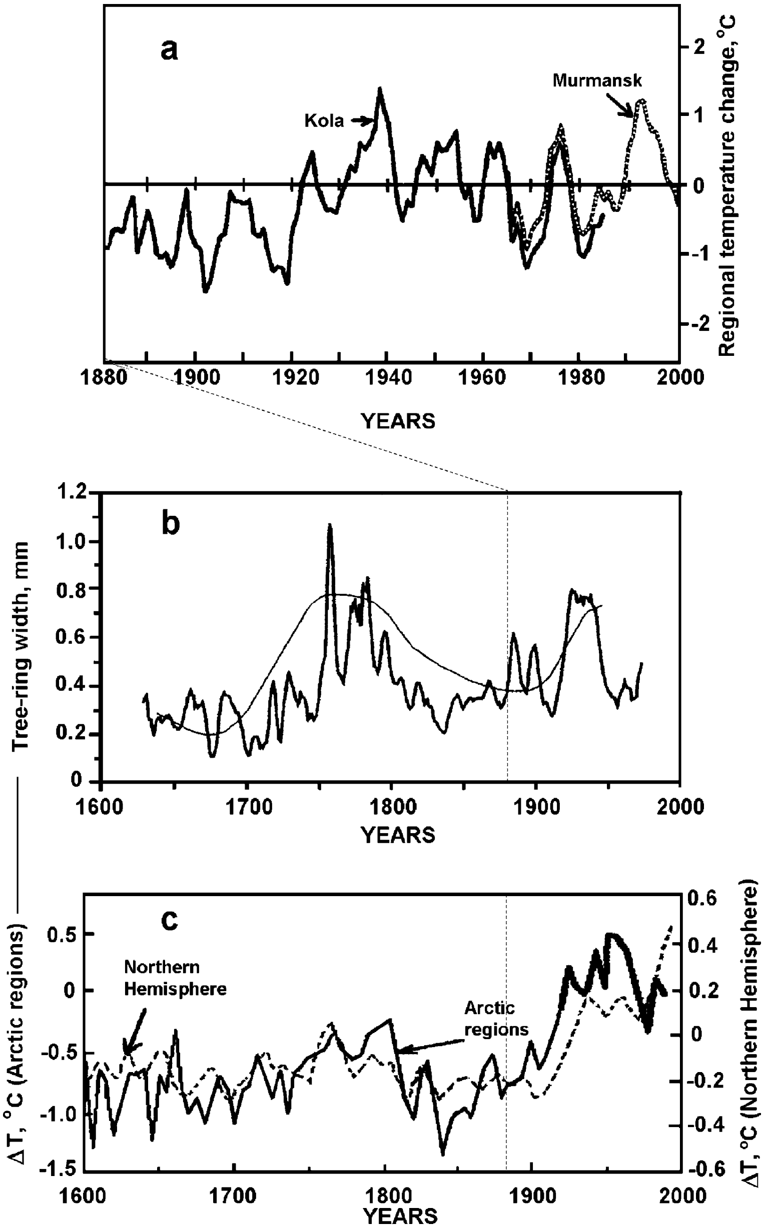

Fig. 1. (a) (top) Record of temperature variations on the Kola Peninsula (Kola-Murmansk) from 1880 to 2000 (5-year running mean); (b) (middle) variations in tree-ring widths (*Pinus sylvestris* L.) at the northern timberline on the Kola Peninsula for the past 400 years (5-year running mean); (c) (bottom) comparison of 10-year smoothed temperature anomalies for the Arctic region (Overpeck et al., 1997), with the dashed line showing instrumental data, and for the Northern Hemisphere (Mann et al., 1999) over the past 400 years derived from proxy and instrumental sources.

discuss the result of wavelet analysis of annual series of conifer tree-rings generalized for 10 regions along the northern timberline, from the Kola Peninsula to Chukotka, for 517 years, which give information on major specific features of climatic changes in the region of the northern coast of Eurasia.

2. Experimental data

Fig. 1a presents mean annual variations in air temperatures in the coastal zone of the Barents Sea (Kola-Murmansk, lat. 69°N, long. 33°E) for the period of systematic observations since 1878. The temperature variations (ΔT) demonstrate the presence of quasi-decadal variations for the whole observation period. Long-period oscillations (80–90 years) are seen to be characteristic of this region. To properly reveal the periodicity, however, proxy data on temperature variations for longer time intervals are needed. For this purpose, dendrochronological information was collected.

The tree-ring chronologies indicate that the climatic response is most pronounced under critical climatic conditions, i.e., at alpine and arctic timberlines. For this reason, the region at the northern boundary of pine-tree vegetation (*Pinus sylvestris* L.) in the Tuloma River valley (lat. 68.8°N, long. 32.8°E) was selected for the study. The topography of the region is flat, and the climate is influenced by the warm Gulf Stream all year round. A high humidity promotes intense pine growth, otherwise unexpected at the polar circle. The presence of 250–350-year-old trees is common here. Because of high humidity, temperature is most likely to be the main factor governing tree growth. This has been found in a number of studies (Lindholm et al., 1996, 2000; Jacoby and D'Arrigo, 1989; Jacoby et al., 2000). It is important to emphasize that the chosen region borders Northern Finland with similar climatic conditions. The tree-ring chronologies for northern Finland, covering nearly the last two millennia, are based on trees that grew in Northern Fennoscandia at the latitude belt that extends from 68°N to 70°N (Lamb, 1972; Lindholm et al., 1996, 2000; Ogurtsov et al., 2002a).

Fig. 1b shows the data on the average annual pine growth, i.e., tree ring widths (in millimetres), from 1629 to 1974 for the Tuloma River region. The cores of 10 trees more than 300 years old, collected by Lovelius (1997), were analyzed. We determined the width of each tree ring and calculated then the average growth value for the entire data set. The tree ring widths were found to vary periodically. As can be seen from Fig. 1b, the periods of about 20–30 and 80–90 years are most pronounced.

Fig. 1c shows variations in mean 10-year temperatures for the Arctic region (Overpeck et al., 1997) and the Northern Hemisphere (Mann et al., 1999). The correlation coefficient between the annual growth in the Tuloma River valley and annual temperature variations in the Northern Hemisphere is 0.309 ± 0.002. Such a correlation coefficient is rather high because the regional features of the temperature regime in the Barents Sea region differ considerably from the behaviour of the Northern Hemisphere temperatures.

Analysis of the correlation between regional monthly temperatures and annual pine growth (*Pinus sylvestris* L.) on the Kola Peninsula shows that the annual growth has a strong response to the regime of summer monthly temperatures (June to August) and to the temperatures in January (Raspopov et al., 2002). This means that the tree-ring growth variations contain information on not only summer temperatures but also mean annual temperatures.

Fig. 1 demonstrates that the widest tree rings and, hence, highest summer temperatures were recorded on the Kola Peninsula during the periods 1750–1780 and 1920–1950. At the same time, the minimum tree rings (and temperatures) were observed around 1650–1700

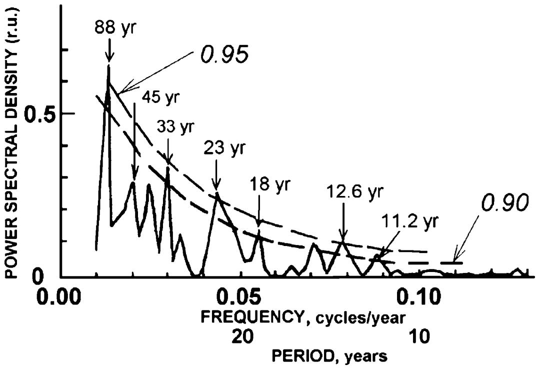

Fig. 2. Spectral density of tree-ring widths (*Pinus sylvestris* L.) for the Kola Peninsula. Dashed lines are confidence levels (0.9 and 0.95).

and 1840. This result agrees well with the temperature variations observed in Scandinavia and the Northern Hemisphere (Lindholm et al., 1996, 2000; Jacoby and D'Arrigo, 1989; Overpeck et al., 1997; Kalela-Brundin, 1999; Mann et al., 1999; Jacoby et al., 2000). Thus, the pine tree-ring data for the northern tree line of the Kola Peninsula contain palaeoclimatic information that is consistent with the general pattern of variations in climatic conditions at high latitudes of the Northern Hemisphere in the past centuries.

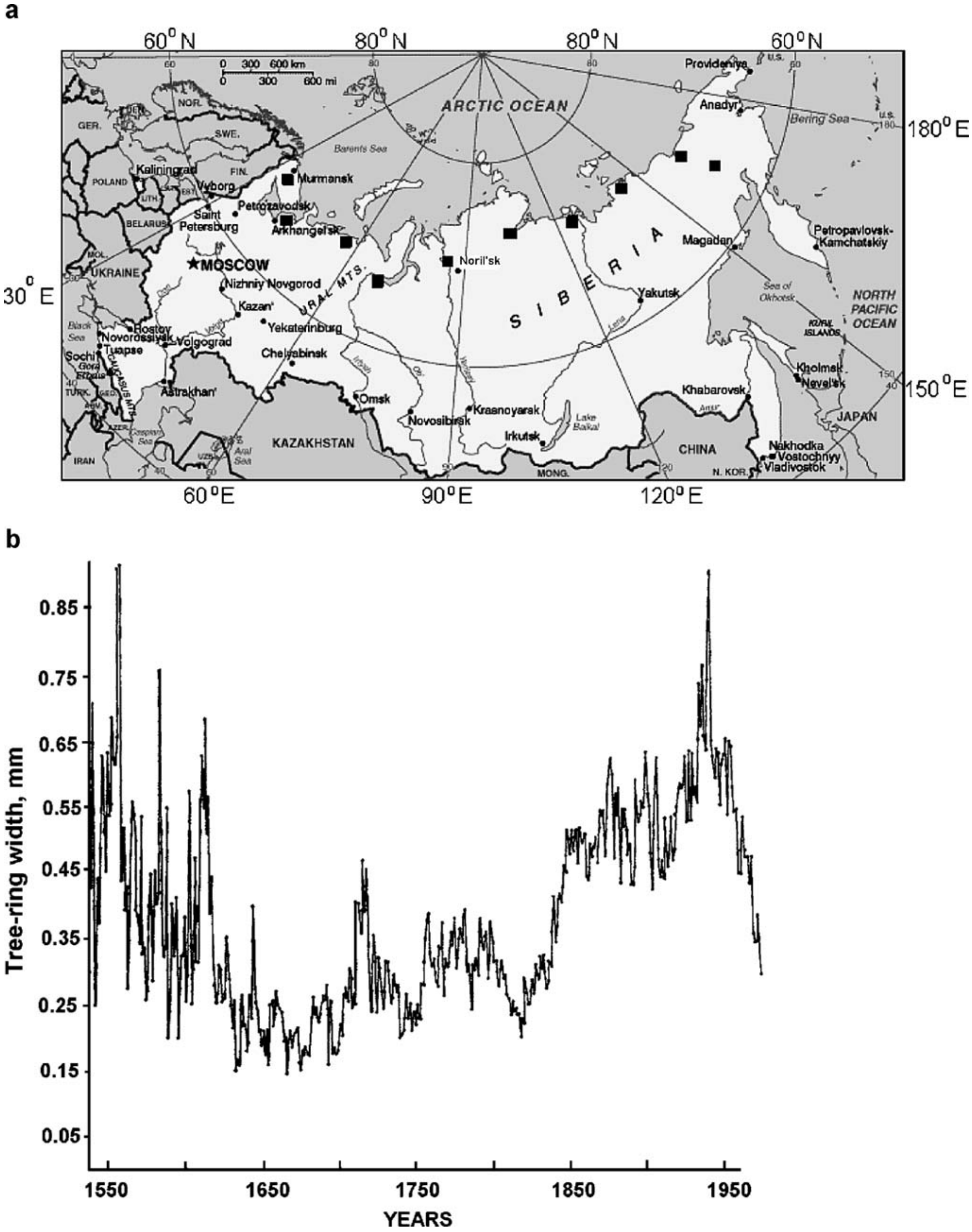

Fig. 3. Location of the sites near the northern timberline along the Arctic Ocean coast, from the Kola Peninsula to Chukotka, where the tree-ring samples were collected (a) and averaged coniferous tree-ring growth series for 10 northern regions of Eurasia (b).

Fig. 2 shows the results of spectral analysis of time variations in the pine tree-ring widths in the Tuloma River valley for the period from 1629 to 1974. The spectrum demonstrates the presence of periods of 88, 33, 23 and 12.6 years at a confidence level higher than 95% and periods of 18 and 11.2 years at a confidence level higher than 90%. Note that the results of spectral analysis of tree-ring growth in Finnish Lapland for the period from 1463 to 1960 reported by Lamb (1972) demonstrate the presence of similar spectral peaks of about 90, 30, 23, 18 and 11.2 years. The coincidence between both spectra indicates that the climatic conditions in Northern Scandinavia and on the Kola Peninsula changed similarly in the past 400–500 years.

The harmonic spectral analysis does not allow one to trace the dynamics of basic periodicities. Wavelet analysis should be used for this purpose. The wavelet transformation of a signal is a multiparametric function in the general case. In case of Fourier transformation, the signal is analyzed only in the frequency range, whereas the wavelet transformation (wavelets) allows analysis of the signal in both the frequency and time ranges. In other words, the wavelet transformation is localized in the time and frequency ranges.

By using wavelet analysis, we tried to reveal general climatic features at high latitudes, including the Barents Sea region, reflected by tree-ring growth. To this end, we carried out analysis of annual tree-ring series generalized for 10 regions (Lovelius, 1997) along the northern timberline, from the Kola Peninsula to Chukotka, for the period 1458–1975 in the longitude range from 30°E to 170°E. Fig. 3a shows the location of the sites where the tree-ring data were collected, and Fig. 3b presents variations in tree-ring growth averaged over the longitudinal interval mentioned above for 1458–1975. The results of wavelet analysis are presented in Fig. 4. One can see short-

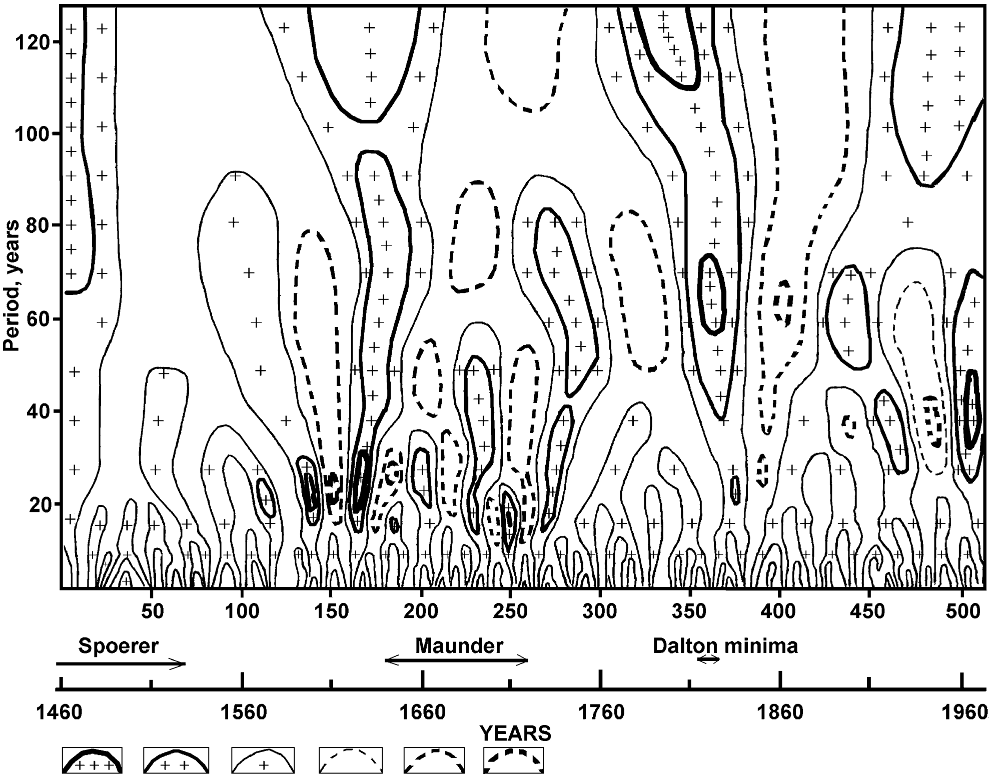

Fig. 4. The result of Morlet wavelet transformation of annual series of conifer tree-rings generalized for 10 regions along the northern timberline, from the Kola Peninsula to Chukotka, for the period 1458–1975. The *X*-coordinate shows the time interval (years) and the *Y*-coordinate the oscillation period (years). Density values from maximum to minimum are marked 1–6.

and long-period cycles and their temporal dynamics. The wavelet spectrum contains periodicities obtained by Fourier analysis of tree-ring data for the Barents Sea region (see Fig. 2).

3. Discussion

Spectral analysis of the chronologies of living Scots pines for northern parts of the Kola Peninsula and wavelet analysis of tree rings for the Arctic Ocean coast region demonstrate the presence of pronounced decadal and multidecadal periodicities in the tree-ring growth and, hence, mean summer and annual temperatures in the Barents Sea region and northern part of Eurasia.

There are different opinions about sources of these variations. On the one hand, spectral density peaks at intervals of about 11, 23 and 88–90 years correspond to the periodicities of solar activity: Schwabe cycle (~ 11–12 years), Hale cycle (~ 22 years) and Gleissberg cycle (~ 80–90 years). Since solar influence is one of several possible reasons for climate changes, this issue is widely discussed in the scientific literature. A number of authors (Lean et al., 1995; Crowley and Kim, 1999; Lawrence and Ruzmaikin, 1998; Mann et al., 1999; Damon and Peristykh, 1999; Drijfhout et al., 1999; Dergachev and Raspopov, 2000; Bond et al., 2001; Douglass and Clader, 2002; Waple et al., 2002 and others) have discussed solar forcing by using both direct measurements of characteristics of climate and solar activity and proxy data, including radial tree-ring growth, and demonstrated its efficiency on the decadal to century time scales. On the other hand, it has been shown that internal instabilities in the atmosphere–ocean system can lead to generation of climatic variations on the multidecadal time scale in different regions of the Earth, including the North Atlantic (Delworth et al., 1993; Schlesingwer and Ramankutty, 1994; Mann et al., 1995; Timmermann et al., 1998; Delworth and Mann, 2000). In this paper, we attempt to provide arguments indicating that periodicities of about 21–29 and 65–100 years revealed in the spectrum of tree-ring growth (and, hence, temperature variations) in the Barents Sea region and also in the wavelet analysis of the generalized series of tree-ring growth at high latitudes of Russia can result from solar forcing.

By comparing dendrochronological data on tree-ring growth in Northern Finland (lat. ~ 68–70°N, long. ~ 20–30°E) for the period AD 8–1991 with variations in solar activity derived from direct measurements and proxy data, Ogurtsov et al. (2002a) demonstrated with high confidence that 65–140-year climatic cycles in the Northern Fennoscandia are associated with solar forcing. The site on the Kola Peninsula where the dendrochronological data used in the present work were collected is only 250–400 km to the east from the site of collection of the data used by Ogurtsov et al. (2002a). We should bear in mind that the spectrum of the tree-ring growth obtained in our work (Fig. 2) is very similar to the spectrum of tree-ring growth for Northern Lapland (Lamb, 1972), i.e., the region where the dendrochronological data used by Ogurtsov et al. (2002a) were collected. Thus, it can be stated with a high confidence that the spectral peak with a period of around 90 years (Fig. 2) results from the influence of solar Gleissberg cycles on climatic parameters at high latitudes. This result is also confirmed by comparison of the dynamic characteristics of the spectrum of Wolf numbers for the period of visual observation of sunspots with the results of wavelet analysis of tree-ring growth (actually, variations in summer temperatures) in the Arctic region (Fig. 3). Fig. 5 shows a local wavelet (Morlet basis) spectrum of Wolf numbers for the period from 1700 to 1990 (Ogurtsov et al., 2002b). It can be seen that from 1720 to 1850 the spectrum of Gleissberg cyclicity has periodicities with a period of about 60–65 years and, beginning from 1770 to the present, it exhibits periodicities with a period of about 90 years. A similar dynamic change in cyclicity can be traced in the wavelet spectrum of tree-ring growth for the Arctic region (Fig. 4): from the early 1700s to 1850 variations with a period of 60–65 years predominate, and the succeeding years are characterized by variations with a period of 90–100 years. This is an additional proof of the relationship between spectral peaks in the tree-ring growth and solar activity with periods of ~ 65–100 years (Gleissberg cyclicity). Note that the solar influence on climate parameters in the North Atlantic on the centennial time scale was confirmed by Bond et al. (2001).

A periodicity of about 22–23 years is pronounced in both the spectrum of tree-ring growth on the Kola Peninsula (Fig. 2) and in the wavelet spectrum of tree-

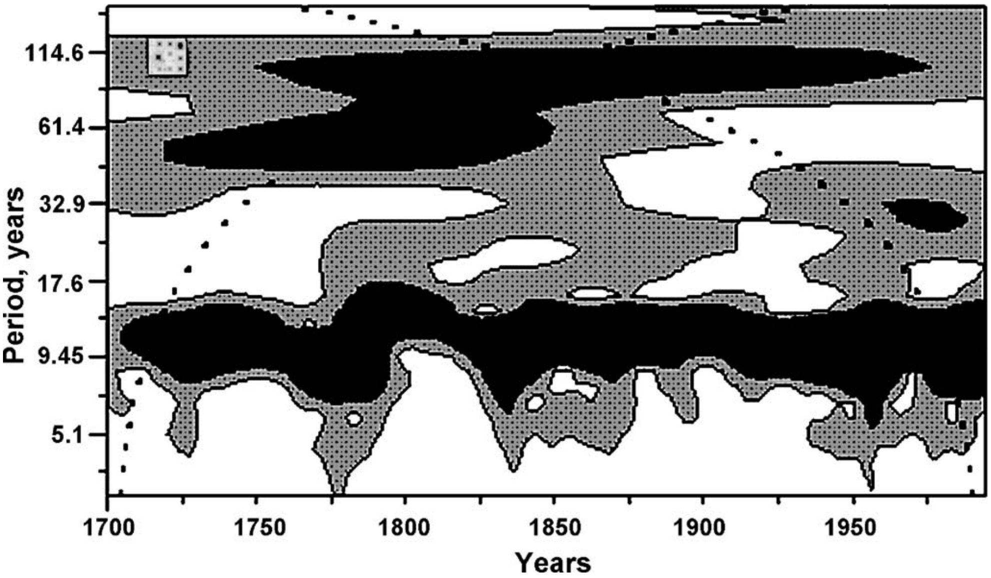

Fig. 5. Local wavelet (Morlet basis) spectrum of Wolf numbers (modified from Ogurtsov et al., 2002a).

ring growth in the Arctic region of Russia (Fig. 4). This periodicity corresponds to the periodicity of solar activity, i.e., Hale cycle. Solar activity with the periodicity of the Hale cycles was considered in detail by Cook et al. (1997) for drought rhythm in the Western United States, as an example. Cook et al. (1997) revealed periodicities of 22.2 and 18.6 years with a high statistical confidence. The former was regarded by Cook et al. (1997) as resulting from the influence of Hale cycles on climate. It is evident from Fig. 2 that both periodicities mentioned above are present in the tree-ring growth in the Barents Sea region. The possible nature of a periodicity of about 18 years will be discussed below.

Pudovkin and Lyubchich (1989) demonstrated, with high statistical confidence, that there is a relationship between variations in winter temperatures in St. Petersburg (Russia) and solar Hale cycles. They found out that there is a 1–2-year lag between the Hale cycles and 22–23-year temperature variations. A similar periodicity was revealed for temperature variations in Stockholm (Ol’, 1969). Peristykh and Damon (1998) analyzed changes in the periods of Hale and Schwabe (~ 11 years) cycles before the Maunder solar minimum (AD 1540–1630), during it (AD 1630–1720) and after the minimum (AD 1715–1805) (Fig. 6). As can be seen from Fig. 6, before the Maunder minimum the Hale cyclicity was represented by a period of 22.9 years. During the minimum, the maximum is split into periods of 24 and 15.8 years, and after the minimum the period of Hale cyclicity increases to 26 years. If we turn to Fig. 3, it becomes apparent that just the same changes in the climatic parameters determining the tree-ring growth in the Arctic region of Russia occurred during the period from 1540 to 1805. Thus, the dynamics of changes in the periodicity of Hale cycles and climatic changes at high latitudes in the Barents Sea region and along the Arctic ocean coast in Russia are in good agreement. This is an additional argument indicating that the peak in the tree-ring growth of about 23 years can be interpreted as a result of solar influence.

The arguments in favour of interpreting spectral peaks of ~ 90 and ~ 22–23 years in climatic changes (tree-ring growth) in the Barents Sea region and along the Arctic ocean coast as resulting from the influence of solar cyclicity do not exclude the interpretation of these periods as resulting from internal instabilities in the atmosphere–ocean–continental system. In this respect, attention should be paid to recent publications that reconcile these conflicting points of view. These works consider the effects of a weak external signal on a system having internal

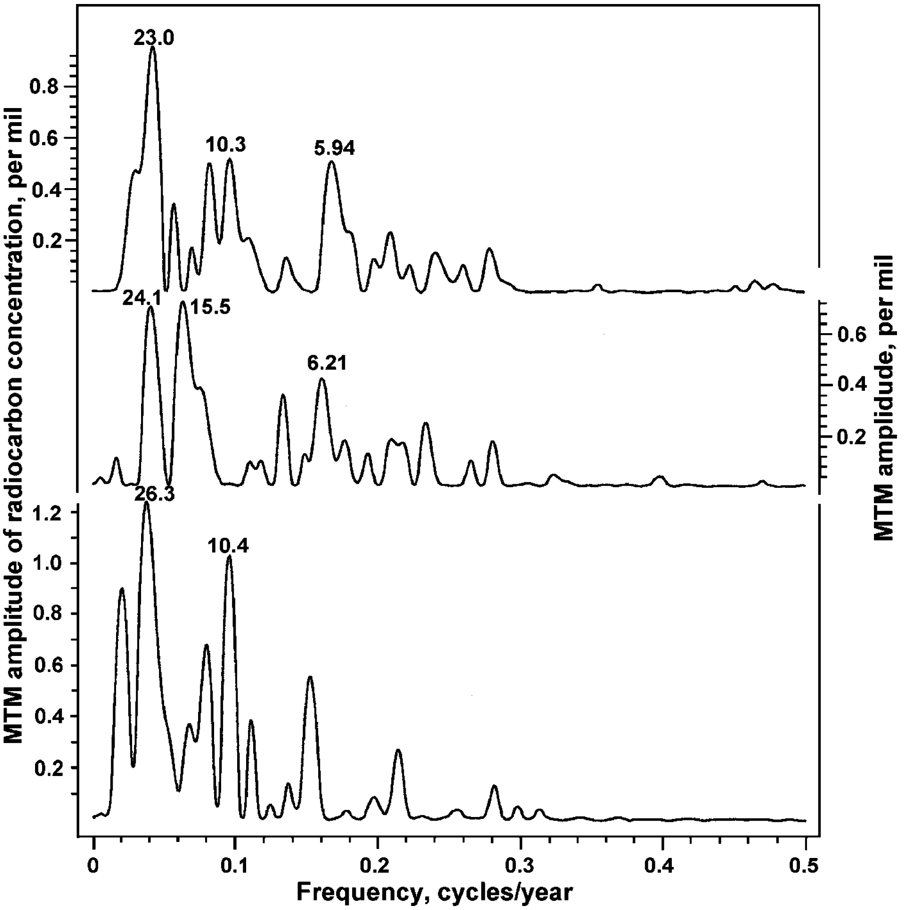

Fig. 6. Multi-taper method (MTM) spectra of Δ^{14}C series: AD 1540–1640—before Maunder Minimum (top spectrum), AD 1630–1720—during Maunder Minimum (middle spectrum) and AD 1715–1805—after Maunder Minimum (bottom spectrum). The peaks labelled by their periods are significant at the 95% confidence level (modified from Peristykh and Damon, 1998).

noise. Under certain conditions, the system is able to fall in resonance with the external signal thereby considerably amplifying it. Using this concept, Lawrence and Ruzmaikin (1998) treated a simple model utilizing “stochastic resonance” and demonstrated a unique effect involving the significant amplication of a weak, periodic signal by a noisy, nonlinear system, as applied to decadal solar cycles. Drijfhout et al. (1999) carried out a series of experiments in which a variable solar irradiance is imposed for a range of frequencies and amplitudes in a simplified coupled General Circulation Model. They showed that weak 22-year irradiance variation excites a significant spectral peak, whose amplitude is comparable to the amplitude of the 70-year periodicity associated with internal processes in the atmosphere–ocean system. By using a highly simplified climate model and analysis of experimental temperature data, Douglass and Clader (2002) demonstrated that the solar signal is approximately twice as high as that expected from a no-feedback Stefan–Boltzman radiation balance model. White et al. (1997) revealed that the global-average upper ocean temperature anomalies fluctuate in fixed phase with decadal signals in the Sun’s irradiance over the past 100 years, but its amplitude is two to three times that expected from the transient Stefan–Boltzman radiation balance (White et al., 2000). This supports the hypothesis that the decadal signal in the Sun’s irradiance excites the internal decadal mode in the Earth’s ocean–atmosphere system and explains its quasi-periodicity. White et al. (2000) showed that there is a lag between decadal temperature variations and variations in solar activity of the order of 1–1.5 years. This is close to the lag between these signals obtained by Pudovkin and Lyubchich (1989) for temperature variations in St. Petersburg (Russia).

Waple et al. (2002) provided a detailed statistical analysis of both the decadal and multidecadal patterns of surface temperature response to solar irradiance variations based on analyses of long-term surface temperature reconstructions during the period 1650–1850. The authors estimated the surface temperature response for solar irradiance variations (SRV) with a period of more than 40 years and for SRV with a period of 9–25 years. In the former case, the forcing factor was identified with the Gleissberg cyclicity of solar activity and, in the second case, it was identified with the Hale and Schwabe cyclicities. The estimates revealed that in the case of Gleissberg cyclicity, the atmosphere–ocean–continental system, which determines surface temperature, exhibits the highest sensitivity to a solar signal with a lag of about 15 years. For the Hale and Schwabe cycles, the lag is about 1.5 years, which is consistent with experimental data of White et al. (2000) and Pudovkin and Lyubchich (1989). The response of surface temperatures to a solar signal demonstrates a high spatial inhomogeneity. For instance, the regions of Scandinavia and Siberia are characterized by a strong positive response to increasing solar irradiance, while the region of Western Greenland exhibits a negative response. Thus, a pronounced climatic response to solar activity on the Kola peninsula is consistent with the work of Waple et al. (2002).

The lag of the climatic response of the atmosphere–ocean–continental system to solar signals (which is different for different signal frequencies) and also the spatial inhomogeneity of the response point to the nonlinear character of the processes in the system and its interaction with solar forcing. If several external periodic signals (in our case, different solar cycles) affect a nonlinear system, generation of combinatory frequencies and also of signal harmonics (Burroughs, 1994) can occur in the system. In the case of Gleissberg and Hale cycles ($\nu_G \sim 1/88$ year^{-1} and $\nu_H \sim =1/23$ year^{-1}), the first combinatory frequencies are $\nu_+ = \nu_H + \nu_G = 1/23 + 1/88 = 0.055$ year^{-1} and $\nu_- = \nu_H - \nu_G = 1/23 - 1/88 = 0.032$ year^{-1}, which corresponds to periods of 18.2 and 31.2 years, respectively. As shown by Raspopov et al. (2001), because of a high variability in durations of the Gleissberg and Hale cycles, the periods of combinatory frequencies associated with them can vary in fairly wide limits. As follows form the work of Waple et al. (2002), the manifestation of signals at generated combinatory frequencies must be spatially inhomogeneous because of different responses of the system to multidecadal and decadal solar variations. Thus, the physical nature of climatic oscillations in the range of periods of 30–35 and 17–18 years can be interpreted in this context. This interpretation is confirmed, in our opinion, by the results of spectral analysis of tree-ring growth in Northern Patagonia (South America, Chile) (Roig et al., 2001).

Fig. 7 shows spectral characteristics of living *Fitzroya curpessoides* woods from the Northern Patagonia region (Roig et al., 2001). The tree-ring growth of *Fitzroya*, similar to that of *Pinus* in the Barents Sea region, responds in general to summer temperatures (December to March in the Southern Hemisphere) (Villalba, 1994; Lara and Villalba, 1993). Comparison of the spectrum of climatic changes in the Barents Sea region (Fig. 2) and climatic changes in the Pacific Ocean region (Fig. 6) demonstrates a striking identity of the spectra. In all the spectra, oscillations with periods of 82–95, 45–51, 30–35 20–24, 17–18 and 9–12 years are present. Such a similarity points to the global character of the forcing factor influencing the nonlinear ocean–atmosphere–continental system. The source of such climate changes may be solar forcing. The distribution of the frequencies of tree-ring width variations corresponding to periodicities of solar activity (ν_G,ν_H) and their combinatory frequencies ($\nu_H - \nu_G$) and ($\nu_H + \nu_G$) are shown in the Fig. 7.

Climatic oscillations with a period of 30–35 years have been known for more than 100 years and are called Brükner cyclicity (Brückner, 1890). The physical nature of this cyclicity still remains unclear. Of course, Brückner cyclicity can be interpreted from the point of view of development of internal processes in the atmosphere–ocean–continental system. However, no direct proofs of this interpretation have been suggested so far. Therefore, in our opinion, the hypothesis that Brückner cyclicity is generated under the action of solar activity on the nonlinear atmosphere–ocean–

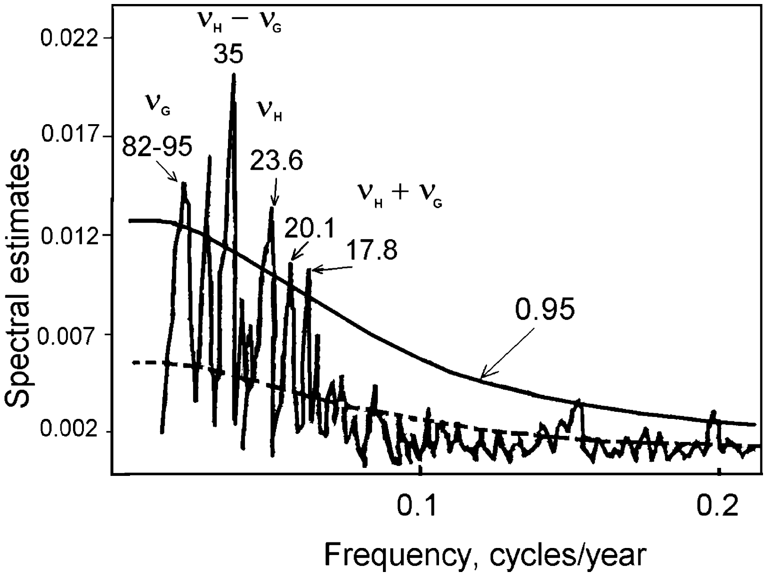

Fig. 7. Spectral characteristics of living *Fitzroya cupressoides* tree-ring growth and distribution of frequencies of tree-ring width variations corresponding to the periodicities in solar activity (ν_G,ν_H) and their combinatory frequencies ($\nu_H - \nu_G$ and $\nu_G + \nu_H$). Periods are given in years for each individual peak. The confidence level (0.95) is shown (modified from Roig et al., 2001).

continental system and subsequent signal amplification resulting from interaction of this cyclicity with internal processes in the system is more justified. The signal amplification was demonstrated, for instance, by Drijfhout et al. (1999) for the 22-year solar cycle.

Climatic cyclicity of 17–18 years was revealed for the first time in a study of the periodicity of droughts in North America (Currie, 1981; Cook et al., 1997). O'Brien and Currie (1993) put forward a hypotheses that this cycle is a result of the influence of the lunar nodal cycle on atmospheric processes. On the other hand, modelling results by Latif and Barnet (1994, 1996), using only the physics of the coupled ocean–atmosphere system, were able to produce a bidecadal cycle in their model runs that extends from the western North Pacific Ocean eastward over the North American continent. Their model does not require any external forcing to generate this cycle in climatic parameters. The analysis performed in our work suggests that even a weak signal generated at a combinatory frequency in the decadal and bidecadal period range (including the 17–18-year periodicity) due to the influence of Gleissberg and Hale cycles on the nonlinear system can be appreciably amplified in the system through the mechanisms discussed by Lawrence and Ruzmaikin (1998), Graham and White (1988), Drijfhout et al. (1999) and Waple et al. (2002). Thus, the spectral peak of about 17–18 years in climatic processes can also be interpreted in the context of the nonlinear effect of solar signals on the atmosphere–ocean–continental system.

In this paper, we did not pursue the goal of discussing a possible physical mechanism responsible for the influence of variability in solar irradiance and solar activity, including modulation of cosmic rays fluxes, on climatic changes. This mechanism is still unclear and is a subject of discussion. Our aim was to give additional experimental arguments speaking in favour of the idea that solar variability and activity affect climatic processes. We also tried to show that the most promising direction of the research is a combined consideration of the response of the atmosphere–ocean–continental system to solar signals and of the internal oscillation processes in the system.

4. Conclusions

Spectral analysis of the dendrochronological data for the coastal zone of the Barents Sea region on the

Kola Peninsula has revealed climatic oscillations with periods of about 90, 45, 33, 23, 18 and 11–12 years. These periodicities of climatic processes in the Barents Sea region turned out to be nearly identical to those of climatic processes in the Pacific Ocean region obtained by using dendrochronological data for Northern Patagonia (South America, Chile). The same frequency characteristics were revealed in analysis of tree-ring series of conifer trees generalized for the northern timberline of Russia. Such identical characteristics demonstrate the global nature of the impact on the climatic ocean–atmosphere–continental system. Variations in solar activity seem to be a plausible source of such global forcing phenomena. In addition, the mechanism of the impact of solar activity on the ocean–atmosphere–continental system seems to be different for different frequency ranges. In the case of long-term variations of solar activity (Gleissberg cycles), the solar influence on the atmosphere–ocean system can result from long-term changes in solar irradiance (Lean et al., 1995; Waple et al., 2002) and variations in cloud cover under the influence of long-term changes in galactic cosmic ray flux intensities associated with solar activity variations (Pudovkin and Raspopov, 1992; Pudovkin and Veretenenko, 1995; Pallé Bagó and Butler, 2000; Marsh and Svensmark, 2000). For the Hale (22–23 years) and Schwabe (11–12 years) cycles, the effect of variable solar irradiance on the atmosphere–ocean–continental system possessing internal noise can lead to enhancement of a signal. Generation of climatic oscillations with periods of about 30–35 and 17–18 years can be associated with the effect of solar variability in the range of Gleissberg and Hale cyclicities on the atmosphere–ocean–continental system that exhibits a pronounced nonlinearity and, therefore, can generate combinatory frequencies of these cycles and lead to their subsequent amplification, as shown experimentally and in model experiments for the Hale and Schwabe solar cycles. Thus, the generation of climatic oscillations with periods of 18 and 30–45 years can also be regarded as a result of solar forcing. Generation of combinatory frequencies also provides a possible physical interpretation of the Brückner climatic cycle (30–35 years). The Brückner cycle was discovered more than a hundred years ago, but its physical nature is still unclear.

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References

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 21–36.

Brückner, E., 1890. Klimaschwankungen seit 1700. Geographische Abhandlungen, 14.

Burroughs, W.J., 1994. Weather Cycles. Real or Imaginary? University of Ontario Press, Cambridge.

Cook, E.R., Meko, D.M., Stockton, C.W., 1997. A new assessment of possible solar and lunar forcing of the bidecadal drought rhythm in the western United States. Journal of Climate 10, 1343–1356.

Crowley, T.J., Kim, K.-Y., 1999. Modeling the temperature response to forced climate change over the last six centuries. Geophysical Research Letters 26, 1901–1904.

Currie, R.G., 1981. Evidence for 18.6 year MN signal in temperature and drought conditions in North America since AD 1800. Journal of Geophysical Research 86, 11055–11064.

Damon, P.E., Peristykh, A.N., 1999. Solar cycle length and 20th century Northern Hemisphere warming: revisited. Geophysical Research Letters 26, 2469–2472.

Delworth, T.L., Mann, M.E., 2000. Observed and simulated multidecadal variability in the Northern Hemisphere. Climate Dynamics 16, 661–676.

Delworth, T.L., Manabe, S., Stouffer, R.J., 1993. Interdecadal variations of the thermohaline circulation in a coupled ocean–atmosphere model. Journal of Climate 6, 1993–2011.

Dergachev, V.A., Raspopov, O.M., 2000. Long-term processes on the Sun controlling trends in the solar irradiance and the Earth's surface temperature. Geomagnetism and Aeronomy 40 (3), 9–14.

Douglass, D.H., Clader, B.D., 2002. Climate sensitivity of the Earth to solar irradiance. Geophysical Research Letters 29 (16) (10.1029/2002GL015345).

Drijfhout, S.S., Haarsma, R.J., Opsteegh, J.D., Selten, F.M., 1999. Solar-induced versus internal variability in a coupled climate model. Geophysical Research Letters 26, 205–208.

Graham, N.E., White, W.B., 1988. The El Niño cycles natural oscillator of the Pacific ocean–atmosphere system. Science 240, 1293–1302.

Jacoby, G.C., D'Arrigo, R., 1989. Reconstructed Northern Hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. Climatic Change 14, 39.

Jacoby, G.C., Lovelius, N.V., Shumilov, O.I., Raspopov, O.M., Karbainov, Ju., Frank, D., 2000. Long-term temperature trends and tree growth in the Taymir region of northern Siberia. Quaternary Research 53, 312–318.

Kalela-Brundin, M., 1999. Climatic information from tree-rings of *Pinus sylvestris* L. and a reconstruction of summer temperatures back to AD 1500 in Femund-marka. Eastern Norway, using partial least squares regression (PSL) analysis. Holocene 9, 59–69.

Lamb, H.H., 1972. Climate—Present, Past and Future. Methuen & Co., London.

Lara, A., Villalba, R.A., 1993. A 3620-year temperature record from *Fitzroya curpessoides* tree rings in Southern South America. Science 260, 1104–1106.

Latif, M., Barnet, T., 1994. Causes of decadal climate variability over the North Pacific and North America. Science 266, 634–637.

Latif, M., Barnet, T.P., 1996. Decadal climate variability over the North Pacific and North America: dynamics and predictability. Journal of Climate 9, 2407–2423.

Lawrence, J.K., Ruzmaikin, A.A., 1998. Transient solar influence on terrestrial temperature fluctuations. Geophysical Research Letters 25, 159–162.

Lean, J., Beer, L., Bradley, R.S., 1995. Reconstruction of solar irradiance since 1610: implications for climate change. Geophysical Research Letters 22, 3195–3198.

Lindholm, M., Timonen, M., Meriläinen, J., 1996. Extracting midsummer temperatures from ring-width chronologies of living pines at the northern forest limit in Fennoscandia. Dendrochronologia 14, 99–113.

Lindholm, M., Lehtonen, H., Kolström, T., Meriläinen, J., Eronen, M., Timonen, M., 2000. Climatic signals extracted from ring-width chronologies of Scots pines from the northern, middle and southern parts of the boreal forest belt in Finland. Silva Fennica 34/4, 317–330.

Lovelius, N.V., 1997. Dendroindication of natural processes. World and Family-95. St. Petersburg, 320 p.

Mann, M.E., Park, J., Bradley, R.S., 1995. Global interdecadal and century-scale climate oscillations during the past five centuries. Nature 378, 266–270.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1999. Northern hemisphere temperatures during the millennium: inferences, uncertainties, and limitations. Geophysical Research Letters 26, 759–764.

Marsh, N., Svensmark, H., 2000. Cosmic rays, clouds, and climate. Space Science Reviews 94, 215–230.

O'Brien, D.P., Currie, R.G., 1993. Observation of the 18.6-year cycle of air pressure and a theoretical model to explain certain aspects of this signal. Climate Dynamics 6, 287.

Ogurtsov, M.G., Kocharov, G.E., Lindholm, M., Meriläinen, J., Eronen, M., Nagovotsyn, Yu.A., 2002a. Evidence of solar variations in tree-ring-based climate reconstructions. Solar Physics 205, 403–417.

Ogurtsov, M.G., Nagovotsyn, Yu.A., Kocharov, G.E., Junger, H., 2002b. Long-period cycles of the Sun's activity recorded in direct solar data and proxies. Solar Physics 211, 371–394.

Ol', A.I., 1969. The 22-year cycle of solar activity in the Earth's climate. Trudy Arktičeskogo i Antarktičeskogo Naučno-Issledovatelskogo Instituta (Reports of Arctic and Antarctic Research Institute) 289, 116–128 (in Russian).

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., Zielinski, G., 1997. Arctic environmental change of the last four centuries. Science 278, 1251–1256.

Pallé Bagó, E., Butler, C.J., 2000. The influence of cosmic rays on terrestrial clouds and global warming. Astronomy and Geophysics 41 (4), 418–422.

Peristykh, A.N., Damon, P., 1998. Modulation of atmospheric ^{14}C concentration by the solar wind and irradiance components of the Hale and Schwabe solar cycles. Solar Physics 177, 343–355.

Pudovkin, M.I., Lyubchich, A.A., 1989. Manifestation of the solar and magnetic activity cycles in the variations of the air temperature in Leningrad. Geomagnetism and Aeronomy 29 (3), 359–366.

Pudovkin, M.I., Raspopov, O.M., 1992. The mechanism of solar activity impact on the state of the lower atmosphere and meteorological parameters. Geomagnetism and Aeronomy 32 (5), 593–608.

Pudovkin, M.I., Veretenenko, S.V., 1995. Cloudiness decreases associated with Forbush-decreases of galactic cosmic rays. Journal of Geophysical Research 57, 1349–1355.

Raspopov, O.M., Shumilov, O.I., Kasatkina, E.A., Turunen, E., Lindholm, M., Kolström, T., 2001. The nonlinear character of the effect of solar activity on climatic processes. Geomagnetism and Aeronomy 41 (3), 407–412.

Raspopov, O.M., Kolström, T., Shumilov, O.I., Kirtsideli, I.Ju., Dergachev, V.A., Lindholm, M., Meriläinen, J., Eggertsson, O., Kasatkina, E.A., Kuzmin, A.V., Matishev, G.G., Dzhenyuk, S.L., 2002. Global warming and regional tree-ring growth response in the Kola Peninsula, North-West Russia. In: Kankaanpää, S., Müller-Wille, L., Susiluoto, P., Sutinen, M.-L. (Eds.), Northern Timberline Forests: Environmental and Socio-economic Issues and Concerns. Finnish Forest Research Institute, Kolari Research Station, pp. 106–113.

Roig, F.A., Le-Quesne, C., Boninsegna, J.A., Briffa, K.R., Lara, A., Grudd, H., Jones, Ph., Villagran, C., 2001. Climate variability 50,000 years ago in mid-latitude Chile as reconstructed from tree rings. Nature 410, 567–570.

Schlesingwer, M., Ramankutty, N., 1994. An oscillation in the global climate system of period 65–70 years. Nature 367, 723–726.

Timmermann, A., Latif, M., Voss, R., Grotzner, A., 1998. Northern Hemispheric interdecadal variability: a coupled air–sea mode. Journal of Climate 11, 1906–1931.

Villalba, R., 1994. Tree-ring and glacial evidence for Medieval Warm Epoch and the Little Ice Age in southern South America. Climatic Change 26, 183–197.

Waple, A.M., Mann, M.E., Bradley, R.S., 2002. Long-term patterns of solar irradiance forcing in model experiments and proxy based surface temperature reconstruction. Climate Dynamics 18, 563–578.

White, W.B., Lean, J., Cayan, D.R., Dettinger, M., 1997. A response of global upper ocean temperature to changing solar irradiance. Journal of Geophysical Research 102, 3255–3266.

White, W.B., Dettinger, M.D., Cayan, D.R., 2000. Global average upper ocean temperature response to changing solar irradiance: exciting the internal decadal mode. Proceedings of 1st Solar and Space Weather Euroconference. The Solar Cycle and Terrestrial Climate Santa Cruze de Tenerife, Tenerife, Spain, pp. 125–133. ESA SP-463.