Wavelet transform as applied to analysis of natural and climatic systems

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Wavelet analysis is applied to investigation of oscillation structures in interannual variability of the temperature series (T) in Omsk, Tomsk, Krasnoyarsk, Irkutsk, Blagoveshchensk, and Petropavlovsk-Kamchatsky. The scales revealed are grouped near 5, 11, 22, 30, and 50 years. The same analysis was applied to the time series of South Oscillation Index (SOI), Wolf numbers (W), and geomagnetic index (Ap). The correlations were investigated between both initial T, SOI, W, Ap series and periodicity of different scales. Significant correlation (at the level of 99%) has been revealed only between the temperature series for the cities situated in the continental zone. On the scale of 30 and 50 years, a significant negative correlation has been revealed between SOI of certain periodicity and temperature series, while a significant positive correlation was found between W, Ap, and temperature series.

Introduction

Investigation of the peculiarities in modern nature and climate variations is an unavoidable stage of modeling and forecasting of the development of such multifactor, multilevel, multifunctional systems as natural climatic systems of the global or regional scale. Sufficiently long series of uniform observations of many parameters characterizing the state of different geophysical fields have been accumulated to date. Analysis of these data, which are the result of instrumental observations during more than one hundred years, can be considered as time series of modern natural climatic variations.

Time series of the characteristics describing different geophysical fields correspond to the non-stationary random processes. They contain the components describing the long-term trend, oscillation of different scales about the trend, as well as the random component. Different methods have been developed now for the analysis of these components. To obtain the long-term trend, two mathematical procedures are mainly applied: approximation of the whole time series by polynomials of different power and moving average. Analysis of the oscillation structure of time series is often based on the Fourier transform procedure. In spite of all its indisputable advantages, the Fourier transform method is not free of drawbacks. The main of them is that, although the Fourier transform keeps comprehensive information about the frequency structure of the signal, it does not enable one to analyze the local properties, because the basis functions of the Fourier transform are defined on the entire time axis.

To remove this drawback, the windows Fourier transforms are applied, in which the signal is analyzed only inside a window on the time axis. However, the difficulties arise related to the fact that one should use the windows of different size for analysis of oscillations of different scale. These difficulties can be effectively removed if applying the method of wavelet transform excellently described in recently published reviews.[1,2]

Then let us investigate some natural climatic characteristics, related in some way to the problem of climate change, by means of the wavelet transform. We will mainly consider the absolute values of the wavelet transform coefficients, though sometimes we will deal with the corresponding power spectrum.[3] Let us consider the series of annual average near-ground air temperature in the following cities as the objects under study:

Omsk (TO)	55.0°N	73.4°E
Tomsk (TT)	56.4°N	85.0°E
Krasnoyarsk (TK)	56.0°N	92.7°E
Irkutsk (TI)	52.3°N	104.3°E
Blagoveshchensk (TB)	50.3°N	127.6°E
Petropavlovsk-Kamchatsky (TP)	54.8°N	169.2°E

These cities from the Asian part of Russia in the 50° to 56°N latitude zone were chosen in order to select the general regional oscillations of climate on the background of the local ones. The South Oscillation Index (SOI) also was analyzed because its length is comparable with the temperature series. The periodicity structure of the Wolf numbers W and the geomagnetic index Ap characterizing to some extent the level of solar activity was revealed. The problems of correlation between both initial series and different scales of the wavelet transform coefficients W will be considered.

1. Methodical basis of the wavelet transform

The idea of the wavelet transform is as follows.[1] If a continuous function $f(t)$ has been set, it can be represented in the form of a series expansion:

$$f(t) = C_{\psi}^{-1} \iint W(a, b)\, \psi_{ab}(t)\, \frac{da\, db}{a^2}\,. \qquad (1)$$

Here $\psi_{ab}(t) = a^{-1/2}\,\psi\,[(t-b)/a]$ is the basis of the expansion obtained by means of continuous scale transformations and transfer of the "mother" wavelet $\psi(t)$ with arbitrary values of the basis parameters, the scale coefficient a, and the shift parameter b. The mother wavelet $\psi(t)$ is a soliton-like function, the choice of which depends on the specific features of the problem to be solved and is discussed in detail in Ref. 2. Then we will use the Morle wavelet[4] well localized in time and space:

$$\psi(t) = e^{is_0 t}\, e^{-t^2/2}, \tag{2}$$

the use of which enabled authors of Ref. 4 to correctly reproduce the oscillation structure of paleoclimatic data. The parameter s_0 in Eq. (2) determines the quantity of wavelet oscillations and, as a rule, is selected to be equal to $\pi(2/\ln 2)^{1/2} = 5.366$.

The wavelet transform of the signal $f(t)$ is defined as a transform inverse to (1):

$$W(a, b) = \frac{1}{\sqrt{a}} \int\limits_{-\infty}^{\infty} f(t)\, \psi^*_{ab}(t)\, dt. \tag{3}$$

The coefficients $W(a, b)$ are small in the ranges where the function $f(t)$ is smooth and take great values in the ranges of extremes.

Actual series of observations are often discrete in time. The discrete variant of the wavelet transform of the signal X_n can be written in the following form[5]:

$$W_k(s) = \sum_{n}^{N-1} X_n\, \psi^* \left[\frac{(k-n)\,\delta t}{s}\right], \tag{4}$$

where $W_k(s)$ are the wavelet transform coefficients, s is the scale (frequency), k is the displacement on the time axis, δt is the interval between neighbor measurements, ψ is the wavelet function, and * is the sign of complex conjugation.

The following equivalent expression can be written instead of the Eq. (1):

$$W_k(s) = \sum_{n}^{N-1} \hat{X}_n\, \hat{\psi}^*(s\omega_n)\, e^{i\omega_n k}, \tag{5}$$

where $\hat{\psi}(s\omega_n) = \left(\frac{2\pi s}{\delta t}\right)^{1/2} \hat{\psi}_0\,[s\omega_n]$, $\int\limits_{-\infty}^{\infty} |\hat{\psi}_0(\omega)|^2\, d\omega = 1$;

the sign (^) means the Fourier image; N is the quantity of points in the series, and ψ is the basis wavelet function (2).

The following estimates were used for the joint analysis of series X_n and Y_n: the scale average spectrum $|\overline{W_k(s)}|$, which is the weighted sum of the wavelet spectrum from the scale s_1 to the scale s_2, the wavelet cross-covariation function $C^{XY}_\tau(s)$, and the wavelet cross-correlation function $R^{XY}_\tau(s)$ for the scale s and the shift (lag) τ (Refs. 1 and 6):

$$\overline{W_k(s)} = \frac{1}{(j_2 - j_1)} \sum_{j=j_1}^{j_2} \frac{|W_k(s_j)|}{s_j}; \tag{6}$$

$$C^{XY}_\tau(s) = \mathrm{cov}\{W^X_k(s)\; W^Y_{k+\tau}(s)\};$$

$$R^{XY}_\tau(s) = C^{XY}_\tau(s) / (C^{XX}_0(s)\; C^{YY}_0(s))^{1/2}. \tag{7}$$

The scale-average wavelet spectra enable us to determine the modulation of one time series by another series, or the modulation of one selected frequency (scale) by another frequency (scale) both between different series and inside the same series.

The confidence interval of the calculated spectrum power of wavelet transform was determined (analogously to the Parseval theorem) as the probability of the event when the true wavelet spectrum at the given shift t and the scale s lies inside the interval with the estimated wavelet power spectrum:

$$\frac{2}{\chi^2_2\,(p/2)}\, |W_k(s)|^2 \le W^2_k(s) \le$$

$$\le \frac{2}{\chi^2_2\,(1 - p/2)}\, |W_k(s)|^2, \tag{8}$$

where $W^2_k(s)$ is the true wavelet spectrum, p is the level of significance ($p = 0.01$ for the 99% confidence interval); $\chi^2_\nu(p/2)$ is the χ^2 distribution with ν degrees of freedom.

The significance of the obtained estimates of the power wavelet spectra was examined based on the comparison of the boundaries of the confidence probability of the calculated energy density (8), and confidence intervals of "white" and "red" noise at the confidence probability of 99%. The "red" noise was simulated by the process of autoregression of the first kind $X_n = 0.7X_{n-1} + Z_n$, where $X_0 = 0$, Z_n is the "white" noise. According to the obtained estimates, the values of the local extremes are significant even on the scale of 8–16 years.

2. Wavelet analysis of the temperature series and the South Oscillation Index

Distributions of the absolute values of the wavelet transform coefficients $|W_k(s)|$ for the considered temperature series are shown in Fig. 1. It follows from the shape of the distribution that they both have common peculiarities and differences. For a convenience of the statement, let us consider the scales of oscillations of 5, 11, 22, 30, 40, 50, and 100 years keeping in mind that the true scales lie within the limits shown in Table 1. Perhaps, the most general peculiarity is the presence of large-scale oscillation structure centered at the scales of 50–60 years. The problem of existence of oscillations of such a scale as a global climatic sign was discussed in Ref. 7. Analyzing the long-term temperature series for Northern Europe, authors of this paper did not find a convincing confirmation of the supposition of a pronounced periodicity (with the period of ≈ 60 years) of air temperature variations in Europe. In our case, periodicity of such a scale is seen in all cases, however, significant (up to the level of 45 years) displacement of the scale of low-frequency oscillations for Krasnoyarsk (Fig. 1*c*) casts some doubt on its universal character. A smaller (up to the level of 52 years) displacement is observed for Blagoveshchensk (Fig. 1*e*). The existence of such displacements is evidence of the effect of local conditions. A greater variety of distributions is observed in the range of intermediate scales. The periodicity with the scale of 28–40 years is well seen for Omsk (Fig. 1*a*), the values $|W_k(s)|$ within these scales increase from the beginning to the end of the analyzed period.

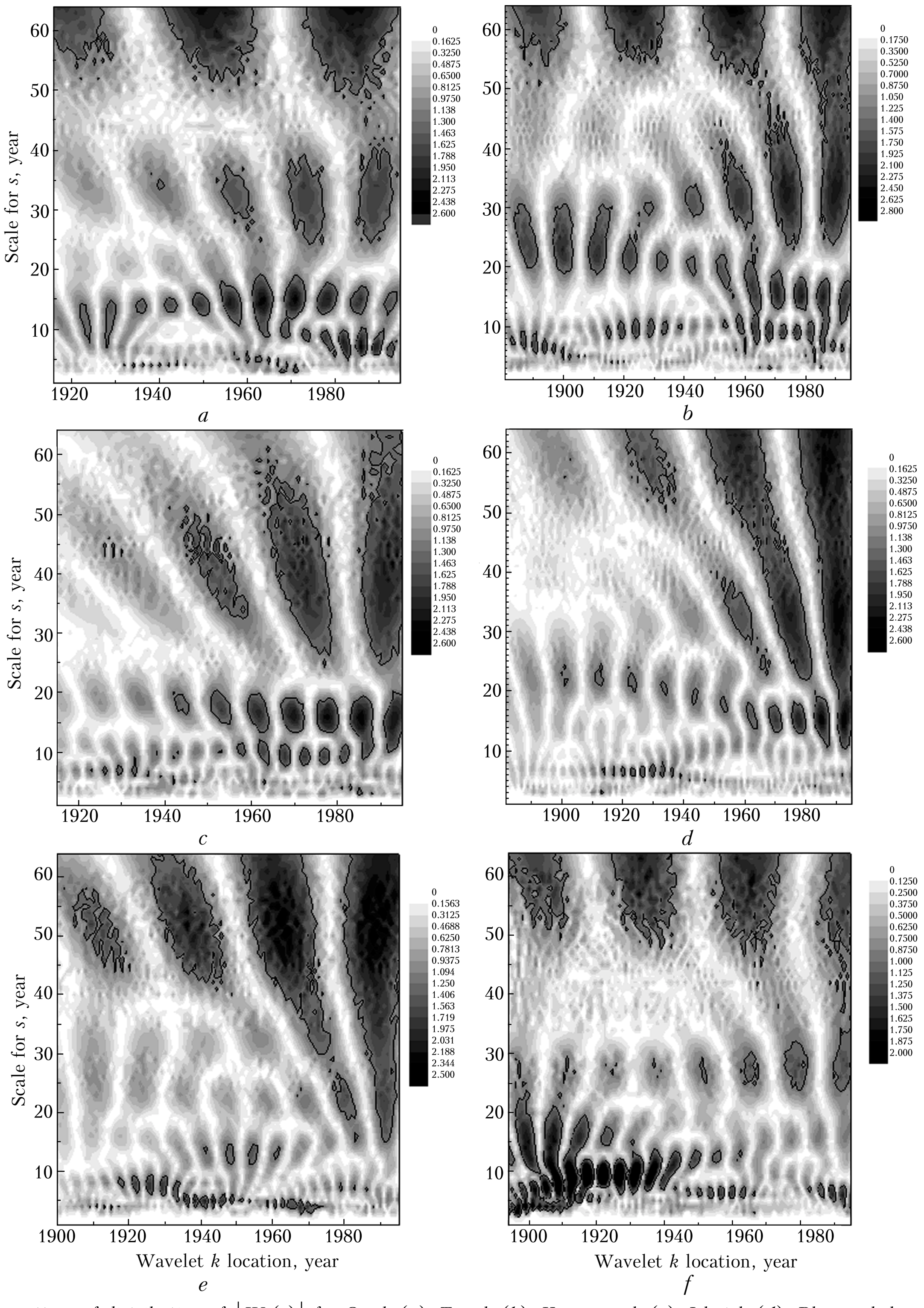

Fig. 1. The pattern of distribution of $|W_k(s)|$ for Omsk (*a*), Tomsk (*b*), Krasnoyarsk (*c*), Irkutsk (*d*), Blagoveshchensk (*e*), and Petropavlovsk-Kamchatsky (*f*).

Table 1. Periodicities of temperature and geophysical indices

Periodicity, years	SOI	T_O	T_T	T_K	T_I	T_B	T_P	Ap	W
5	4–10	3–7	3–7	3–7	3–7	3–8	3–7		
11	10–16	8–12	8–12	8–12	8–12	10–16	8–12	7–13	7–14
22	18–28	13–24	13–24	13–24	13–24	18–28	14–20	14–20	
30	–	28–40	28–40		28–40	28–40	23–35	23–46	22–40
40	–	–	–	28–55	–	–	–	–	–
50	30–60	50–64	50–64	–	50–64	45–60	50–64	–	40–60
100	–	–	–	–	–	–	–	–	85–115

The periodicity of 20–30 years is characteristic of Tomsk (Fig. 1*b*) from the beginning of the last century. Since approximately 1930 it is divided into ascending and descending branches. The first one forms the oscillations of 28- to 40-year scale by the end of XX century, and the second one forms the oscillations of 13- to 24-year scale. Stable oscillations of 13- to 24-year scale are observed in Krasnoyarsk (Fig. 1*c*) on the whole time axis. Besides, the 11-year periodicity is well seen for this city. Oscillations with 28- to 40-year scale have been formed in Irkutsk since approximately 1940. The periodicity of 20- to 30- year scale observed in the beginning of the century is transformed according to the well pronounced linear law to the periodicity of 13- to 24-year scale by the end of XX century. Oscillations of intermediate scales in Blagoveshchensk (Fig. 1*e*) are weakly pronounced. The 23- to 35-year periodicity is well pronounced in Petropavlovsk-Kamchatsky (Fig. 1*c*). Besides, the well formed structure of approximately 10-year scale is observed in the first half of the century. As to the scales less than 10 years, the corresponding quasi-periodic structures are observed in each considered case. However, as has correctly been noticed in Ref. 1, analysis of oscillations of such scales requires monthly average temperatures as input data, but not annual average.

It was noted in Ref. 8 that El Niño/South Oscillation (ENSO) observed in the tropical zone approximately every 2 to 7 years makes the greatest contribution to the interannual climate variability and causes the statistically significant response in different regions of the Earth. Different ways for selecting indices describing ENSO are discussed in details in Ref. 8. In this paper we use the South Oscillation Index denoted as SOI. This index is the difference of normalized pressure anomalies at the station Taiti (17°N, 15°W) and Darwin (12°N, 150°E) and describes the anomalies of the near-ground atmospheric pressure along the tropical zone. The series of annual average values of this index during 1882–2000 is shown in Fig. 2*a*, and the distribution of its absolute values of the wavelet transform $|W_k(s)|$ is shown in Fig. 2*b*.

Analysis of the last figure shows that the periodic structure is observed, the scale of which linearly decreases from 40–60 years in the beginning of the century to 30–50 years by its end. The weakly pronounces periodicity in the intermediate scale range is divided in 1940 into ascending and descending branches, the latter is most pronounced in 1960–2000. The quasi-periodic structure of 4- to 10- year scale is observed in the small scale range. Its strengthening is observed in 1900–1920, i.e., in the time interval when the most sharp oscillations of temperature and SOI index are observed.

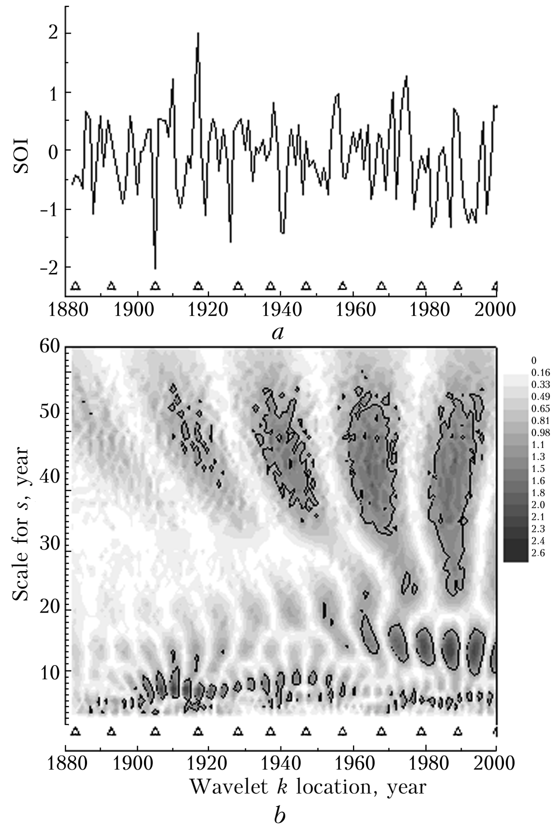

Fig. 2. Year-to-year variability of the South oscillation index (SOI) (*a*) and the amplitude spectrum of the wavelet transform $|W_k(s)|$ (*b*). Arrows show maxima of the Wolf numbers in the 11-year cycle.

Table 1 shows the summary of the scales of periodicities in the series of the parameters under study. The minimum scale of 3 to 7 years is observed in the variations of the near-ground temperature over cities, and the scale of 4 to 10 years is observed in the variations of the SOI series. Periodical structures of the scale of 11 and 22 years are observed in all temperature series and in the SOI series. Periodical structures of the scale of 30 years are observed only in the temperature series. The exception is Krasnoyarsk, which is characterized by the presence of the 40-year periodicity. Periodical structures of the scale of 50 years are observed in the SOI series and temperature series of all cities except for Krasnoyarsk.

We tried to estimate the correlation between temperature series and the considered direct and indirect indices of geophysical activity. In order to determine the significance of the obtained estimates, the confidence boundaries of the calculated correlation functions and single correlation of the white noise[9] were found. The analyzed series were preliminary normalized. The formula for the standard deviation of the sample correlation coefficient which has the normal distribution $(1 - R^2)/\sqrt{N}$ was used for determination of the standard deviations of the sample correlation functions. The standard deviation of the sample estimate of the single correlation coefficient was assumed to be equal to $1/\sqrt{N}$. The confidence boundaries were estimated using the Student coefficient at the confidence probability of 99%.

The sample correlation coefficients of the near-ground temperature series of Omsk, Tomsk, Krasnoyarsk, Irkutsk, Blagoveshchensk, and Petropavlovsk-Kamchatsky with each other and the ENSO series are shown in Table 2.

Table 2. Correlation coefficients of the initial series

Characteristics	T_O	T_T	T_K	T_I	T_B	T_P
SOI	−0.08±0.59	−0.11±0.49	−0.18±0.58	−0.22±0.48	0.03±0.54	0.06±0.52
T_O	1	**0.85±0.38**	**0.71±0.44**	**0.60±0.41**	**0.55±0.46**	0.29±0.50
T_T		1	**0.89±0.36**	**0.69±0.38**	**0.54±0.46**	0.17±0.52
T_K			1	**0.86±0.31**	**0.65±0.47**	0.30±0.57
T_I				1	**0.69±0.42**	0.15±0.52
T_B					1	0.39±0.50
Ap	0.10±0.67	0.04±0.67	0.13±0.67	0.11±0.67	0.13±0.67	0.09±0.67
W	0.03±0.60	0.05±0.49	0.02±0.59	0.11±0.49	0.18±0.53	0.20±0.51

Table 3. Correlation coefficients of the periodicities

Characteristics	Periodicity, years	T_O	T_T	T_K	T_I	T_B	T_P
SOI	5	0.19±0.59	0.07±0.49	−0.12±0.59	−0.21±0.48	0.09±0.54	0.37±0.49
	11	−0.16±0.59	−0.26±0.48	−0.24±0.58	**−0.45±0.44**	0.18±0.53	0.11±0.52
	22	−0.44±0.54	−0.40±0.45	−0.28±0.57	−0.43±0.45	**−0.50±0.47**	**−0.52±0.45**
	30	−0.28±0.57	−0.33±0.46		−0.39±0.46	**−0.64±0.43**	−0.01±0.52
	40			**−0.78±0.41**			
	50	−0.05±0.60	−0.24±0.49		**−0.47±044**	**−0.83±0.36**	**−0.66±0.41**
T_O	5	1	**0.85±0.38**	**0.61±0.49**	0.30±0.57	0.37±0.56	0.40±0.55
	11	1	**0.88±0.37**	**0.72±0.44**	**0.67±0.46**	0.23±0.58	−0.24±0.58
	22	1	**0.89±0.36**	**0.70±0.45**	**0.59±0.49**	0.04±0.60	**0.56±0.50**
	30	1	**0.97±0.32**	**0.74±0.43**	**0.95±0.33**	**0.90±0.35**	0.27±0.57
	50	1	**0.91±0.35**	−0.14±0.59	**0.84±0.39**	0.44±0.54	0.37±0.49
T_T	5		1	**0.81±0.40**	**0.51 ±0.43**	0.42±0.49	0.27±0.51
	11		1	**0.81±0.40**	**0.75 ±0.35**	0.04±0.54	−0.17±0.52
	22		1	**0.87±0.37**	**0.81 ±0.33**	0.24±0.53	0.18±0.52
	30		1	**0.79±0.41**	**0.95 ±0.27**	**0.91±0.32**	0.25±0.51
	50		1	0.13±0.59	**0.92 ±0.29**	**0.67±0.42**	**0.68±0.40**
T_K	5			1	**0.86±0.37**	**0.63±0.48**	0.30±0.57
	11			1	**0.90±0.35**	0.08±0.59	−0.11±0.59
	22			1	**0.90±0.35**	0.15±0.59	**0.79±0.41**
	30			1	**0.84±0.38**	**0.90±0.35**	0.34±0.56
	50			1	0.21±0.58	0.47±0.53	0.42±0.54
T_I	5				1	**0.59±0.45**	0.08±0.52
	11				1	0.06±0.54	−0.28±0.50
	22				1	**0.56±0.46**	0.35±0.49
	30				1	**0.91±0.32**	0.41±0.48
	50				1	**0.85±0.35**	**0.82±0.35**
T_B	5					1	0.43±0.49
	11					1	0.34±0.51
	22					1	0.05±0.54
	30					1	0.17±0.53
	50					1	**0.92±0.31**
Ap	11	0.12±0.67	−0.02±0.67	0.25±0.65	0.41±0.62	0.32±0.64	0.11±0.67
	22	−0.03±0.67	0.30±0.64	0.55±0.57	0.54±0.57	0.05±0.67	**0.66±0.53**
	30	**0.67±0.52**	**0.62±0.54**	**0.74±0.49**	**0.57±0.56**	**0.75±0.48**	−0.35±0.63
W	11	−0.25±0.58	−0.25±0.48	−0.23±0.57	−0.27±0.48	0.30±0.52	0.45±0.47
	30	**0.80±0.41**	**0.67±0.38**	**0.73±0.44**	**0.67±0.38**	**0.72±0.40**	0.18±0.52
	50	−0.41±0.55	−0.09±0.49	**0.89±0.36**	−0.04±0.49	0.27±0.52	0.18±0.52

The confidence boundaries of the calculated correlation coefficients are also shown in the cells. Analysis of Table 2 shows that no significant correlation between the series of near-ground temperature T and the ENSO series is observed. Significant positive correlation of 0.60–0.89 is observed between the series of near-ground temperature of four cities of Siberian region (the cities situated in the continental climatic zone) and insignificant one of 0.39 is observed for two cities of the Far East region. Also the insignificant correlation (0.15–0.39) is observed between Siberian cities and Petropavlovsk-Kamchatsky. Correlation between the temperature series of Blagoveshchensk and temperature series of Siberian cities is expressed more strongly (0.55–0.69).

The next stage of analysis was calculation of the wavelet correlation function $R_{\tau}^{XY}(s)$ (7) from the scale-average wavelets (6). The calculated results are presented in Table 3. The values of the correlation function at zero displacement are shown in the cells of the Table. The cells with the significant correlation at the confidence probability of 99% are marked by bold type.

The analysis of the results obtained shows the following.

1) mainly negative significant correlation is observed between periodicities of temperature series and periodicities of the ENSO series. The number of correlating periodicities increases from one (Krasnoyarsk) to two or three (Irkutsk, Blagoveshchensk, Petropavlovsk-Kamchatsky) while approaching the ocean.

2) one should pay due attention to high and significant values of the correlation function $R_0^{XY}(s)$ obtained for periodicities of the series of near-ground temperature. High significant correlation between almost all used periodicities for neighboring cities is observed for five cities – Omsk, Tomsk, Krasnoyarsk, Irkutsk, and Blagoveshchensk (the difference in geographical latitude less than 12° for Siberian cities-"neighbors" and 23° between Irkutsk and Blagoveshchensk). Relation of these cities to Petropavlovsk-Kamchatsky (41.6° of geographical latitude to Blagoveshchensk) is observed as existence of one correlation between periodicities: the 22-year periodicity for Omsk and Krasnoyarsk and 50-year periodicity for Tomsk, Irkutsk, and Blagoveshchensk.

Thus, the use of wavelet cross-correlation analysis has made it possible to reveal that correlation between temperature series and SOI has significant, greater than 0.5, anticorrelation for periodicities, the size of which is greater than 11 years. Relations of temperature series are characterized by positive correlation of almost all periodicities between neighboring cities situated in the continental climatic zone and the single correlation at the periodicities less than 22 years between Petropavlovsk-Kamchatsky situated on the coast of the Pacific Ocean and continental cities.

3. Wavelet analysis of the series of Wolf numbers and index of geomagnetic activity Ap

The series of annual average Wolf numbers during 1700–2000 and corresponding power spectrum of the wavelet transform are shown in Fig. 3.

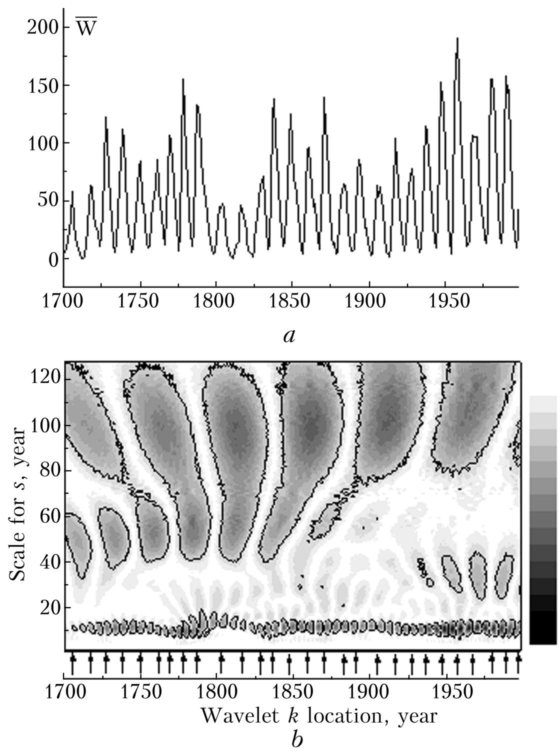

Fig. 3. Series of annual average Wolf numbers in the period from 1700 to 2000 (a) and distribution of $|W_k(s)|$ for the series of the Wolf numbers (b). Arrows show maxima of the Wolf numbers in the 11-year cycle.

It is seen that the 11-year cycle is well pronounced on the entire time axis. The well pronounced break of scales in this cycle is observed in 1775–1825, where the displacement to the greater frequencies is observed. The well pronounced periodicity with the mean scale of 55 years is observed in the period from 1700 to 1850. The existence of this cycle was revealed in investigating the hysteresis curves connecting the points of the neighboring 11-year cycles on the diagram Maximum Wolf number – cycle length.[10] After 1850 this periodicity is broken, and the periodicity of the scale of 30 years begins to be formed since 1925. The formation of this periodicity is accompanied by essential increase of the power of the wavelet transform in the 11-year cycle. One can say that the oscillations of greater scales (30 and 55 years) appear when the well pronounced breaks of the 11-year cycle have been observed. These breaks can be represented by both distance between the peaks and by the change of their amplitude. As to the 22-year periodicity, it is not observed for the series under consideration, as is with the 5.5- year periodicity revealed in some investigations.[11]

The series of observations of geomagnetic index Ap also were analyzed. The pattern of the Ap distribution is shown in Fig. 4. Break of the 11-year periodicity in 1960–1980 attracts our attention. The periodicity of the scale of 15 to 20 years is clearly seen though being weakly pronounced. Periodicity of the scale of 30 to 40 years is dominating, the maximum value $|W_k(s)|$ is observed between 1950 and 1960.

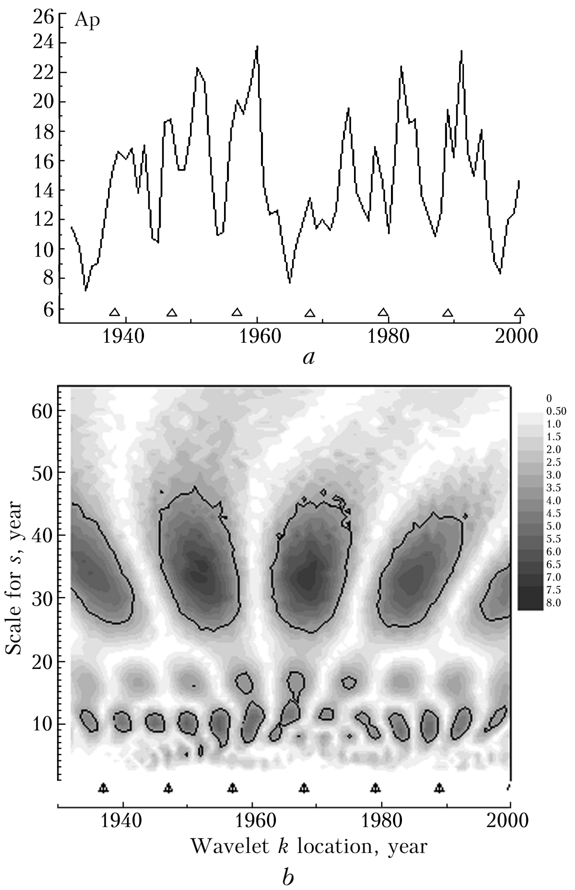

Fig. 4. Series of geomagnetic planetary index Ap in the period 1932–2001 (*a*) and distribution of $|W_k(s)|$ for the series of Ap (*b*). Arrows show maxima of the Wolf numbers in the 11-year cycle.

Analyzing Table 1, one can see that the minimum scale of 3 to 8 years observed in the temperature variations of some temperature series and series of SOI is absent in the series of the W and Ap indices. Periodical structures of the scale of 11 years are present in the W and Ap indices, and 22-year periodicity are observed only in the Ap structure. Weakly pronounced oscillations of this scale of the Wolf numbers are observed only in the limited time interval between 1775 and 1925. Wolf numbers and geomagnetic index Ap show the periodicity of 30 years. The scale of 50 years is observed in the series of W. At least the 100-year cycle is well pronounced in the series of W. Perhaps, the century cycle is characteristic of other indices, however, it can not be revealed because of the limited length of the corresponding time series.

We tried to estimate correlation between temperature series and the indices W and Ap considered using the technique described in previous section. Analysis of the results obtained (see Tables 2 and 3) has shown the following:

1) no significant correlation between the initial series of near-ground temperature series and the series of W and Ap is observed.

2) significant positive correlation at the level of 99% is observed between the periodicities of temperature series of all cities and periodicity of the Ap series. The 30-year periodicity correlates in the case if the cities are situated on the continent: Omsk, Tomsk, Krasnoyarsk, Irkutsk, and Blagoveshchensk. Correlation of 22-year periodicity temperature series and periodicity of the series of Ap is observed for Petropavlovsk-Kamchatsky.

3) significant positive correlation at the level of 99% characterizes the periodicity of temperature series of continental cities and periodicities of the Wolf numbers. Periodicity of temperature series of Krasnoyarsk and periodicity of W correlate on two scales, 30 and 50 years. The periodicity of the temperature series of Omsk, Tomsk, Irkutsk, and Blagoveshchensk correlate with periodicity of the series of W on the scale of 30 years.

Conclusion

The analysis performed above has shown that periodical structures of different scales of oscillation are present in the year-to-year variability of temperature series of the considered cities. Oscillations on the scale of 5, 11, and 22 years are present in all temperature series in one degree or another. As was mentioned above, analysis of oscillations of the scale of 5 years requires a different approach. As to the periodicity of 11 and 22 years, they are well pronounced on the entire time axis only for some cities, for example, approximately 14-year periodicity is observed for Omsk and 20-year periodicity is observed for Krasnoyarsk. In other cases we see either weakly pronounced periodicity of such scales or their fragments. The scales of 30, 40, and 50 years are present, as is seen in Table 1, only in some series or in groups of series.

It follows from the above stated that temperature oscillations of global scale or characteristic of the region under consideration are absent in the considered case. It could be an argument for the circumstance that the moving force of these periodicities is located inside the climatic system, and El Niño – South Oscillation could be one of the phenomena causing such a force. However, two facts make up an evidence against such an argument. First, as it follows from Table 2, significant correlation is absent between the initial series of SOI and temperature. Second, Table 3 shows that the significant (at the level of 99%) correlation between periodicity of different scales of temperature series and series of SOI is an exception rather than a rule. Let us note that the sign of correlation is negative in all cases. On the contrary, high positive correlation is observed between the 30-year periodicity of the geomagnetic series Ap and the series of Wolf numbers and corresponding periodicity of temperature series of all cities, except for Petropavlovsk-Kamchatsky. It is the case when the influence of heliophysical factors does not show universal character.

In general, the analysis has shown that oscillations are observed in the dynamics of the climatic system, which correspond to non-linear and non-stationary processes that are related to internal and external forcing, although additional investigations are needed to finally reveal the nature of these oscillations.

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