Probabilistic-statistical models of the dynamics of climatic changes in the Altai Mountains

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Abstract. A probabilistic-statistical parameterization of time series characterizing geological and climatic processes allows determining some regularities by an autocorrelation analysis of signals which differ in nature. The use of the autocorrelation method for analyzing data related to solar and tectonic activity and characterizing the level of stratospheric ozone (total ozone content), hydrothermal regimes (De Martonne aridity index), and wood structure (maximum density of annual rings) allows us to find regularities in time series of various natural processes. Data on the maximum density of Siberian larch trees growing in the Altai Mountains made it possible to calculate the past changes in total ozone content and the aridity index in the Altai Mountains from 1900 to 2014 based on some similarities in the series and a separation of a dendrochronological signal into its main components.

1. Introduction

The current studies have linked the changes in the ozonosphere to the solar activity and tectonic changes in the lithosphere [1-3]. Ozone changes (the characteristic is the total content of ozone, TOC) in the atmosphere cause both growth and decrease in the number of extreme climatic events [4]. If the ozone concentration in the atmosphere decreases, some extreme weather conditions become more frequent and significant in amplitude. For example, heat waves are longer and hotter, heavy precipitation and floods are more often, drought is more intense and more widespread. The extensive research on this subject is related to the mountain territories of Europe and America and, to a lesser extent, to the territory of Altai Mountains (Russia). According to the results of single studies in Altai after 1998 there was a change in the phase of the temperature fluctuation. At the same time, an essential tendency to changes in the quantity of atmospheric precipitation was not recorded. For certain regions of Altai, a delay of the rates of warming together with a cold snap tendency were noted. [5]. The same trend was observed for the nearby territory of Western Siberia [6].

In the geochronology of each individual territory, one can read a long history of the geological processes, including those associated with the accumulation of sedimentary rocks. Identification of synchronous changes in the composition of sedimentary rocks in similar or different conditions of their formation allows us to establish regularities in changing of the types of sedimentary rocks, changing of their sedimentation regimes associated with climate change. Analysis of the original data collected at the study points on the Earth's surface allows us to find the same regularity occurring in different time cycles. For example, the climate changes from heat to cold. When considering the evolution of sedimentation, one can suppose that the periods of warming and growth of the mean temperatures should correspond to the phases of volcanic activity in a zone with sufficiently large heat expenditure on volcanic activity leading to a decrease in the temperatures. This explains cooling after the periods of volcanic activity and the reciprocating course of climatic changes [7, 8].

A key factor of modeling of mountain region climate is the assessment of the functions of forests and the relations between the beginning, culmination, and cessation of tree growth under the influence of external factors. The growth of trees at different heights of a mountainous territory is more or less simultaneously limited by the following three factors: 1) air temperature; 2) amount of precipitation; 3) ultraviolet-B radiation (UV-B). The ratio between the temperature and precipitation can also be considered as a separate factor. Thus, if the air temperature is raising and the amount of precipitation is decreasing, then, in general, the climate change will be unfavorable for the growth of trees. Recently, in the climatic research the integrated influence of moisture and temperature on plants has been estimated using several indicators: the Selyaninov hydrothermal index, the Palmer drought index, and the De Martonne aridity index (IDM). The index characterizing weather conditions is the De Martonne aridity index. It estimates the ratio of the total amount of precipitation to the average temperature during the growing season or the whole year. The lower values of the index correspond to the drier climate and, consequently, to less favorable conditions for the growth of trees.

UV-B radiation passing through the stratospheric ozone layer and reaching the Earth's surface penetrates the photoreceptors of plants and has an impact on many processes of growth of trees and vegetation in a complex functional chain. The main effects of UV-B radiation are manifested in a decrease in the photosynthetic activity and productivity of the green mass of plants. The studies show that the effect of UV-B radiation on vegetation is enhanced under conditions of a decrease in the air and soil moisture during the era of rising air temperatures and ozone depletion in the stratosphere [9, 10].

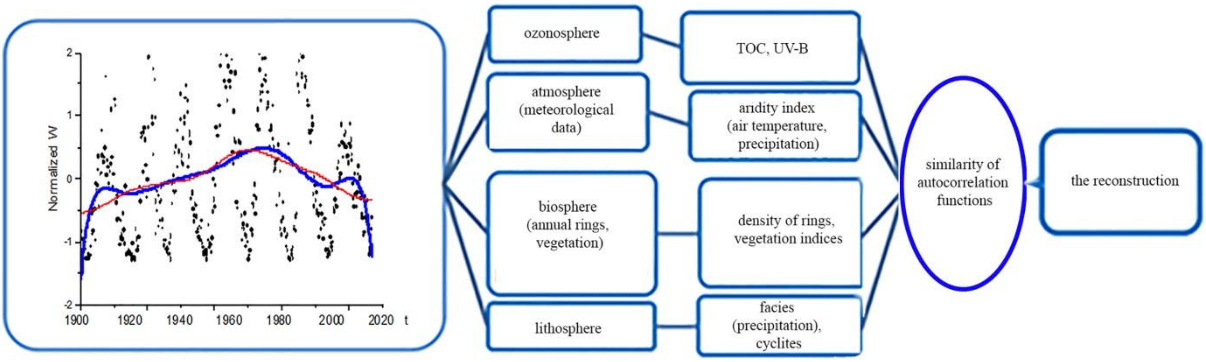


Figure 1. Scheme of the probabilistic-statistical parametrization of climatic changes within the solar activity cycle for reconstruction of the past.

The probabilistic-statistical parameterization of the time series characterizing the geological and climatic processes is based on the assumption that the effects of micro and mesoscale ozone changes (the total content of ozone, TOC) on the dynamics of interactions between the geosphere and biosphere can be related to the parameters of the predicted fields of other geospheres. This allows us to establish new patterns. The De Martonne aridity index (the hydrothermal regime determined by the temperature and the amount of precipitation) and the structure of wood (the density of the annual rings (MXD) of coniferous trees) are also in this chain. With some degree of probability, we can judge about the similarity in climate changes and the ozonosphere on annual growth rings. This similarity can be used to reconstruct past changes of the parameters. Long-term climate change causes a response in the trees. A quantitative value that can be measured, estimated, and interpreted is the annual tree rings (their particular alternation) and their physical characteristics (e. g. density). Using the autocorrelation function (ACF) in the time series of the investigated parameters one can find identical periods. For e preliminary search for regularities in the time series of the TOC (UV-B) and the density of annual rings, a method of reconstructing the changes in the TOC (UV-B) from the density of the annual rings of coniferous trees is used. Long-term climate change and the UV-B (TOC) affect the functioning of forest ecosystems, triggering a response in the form of reducing their resilience [11]. This increases the density of annual rings of coniferous trees [8, 12].

The aim of the study is to develop a methodology for probabilistic statistical parameterization of cyclic changes in time series characterizing the geological and climatic processes of the Altai Mountains.

2. Method of probabilistic-statistical parameterization of time series

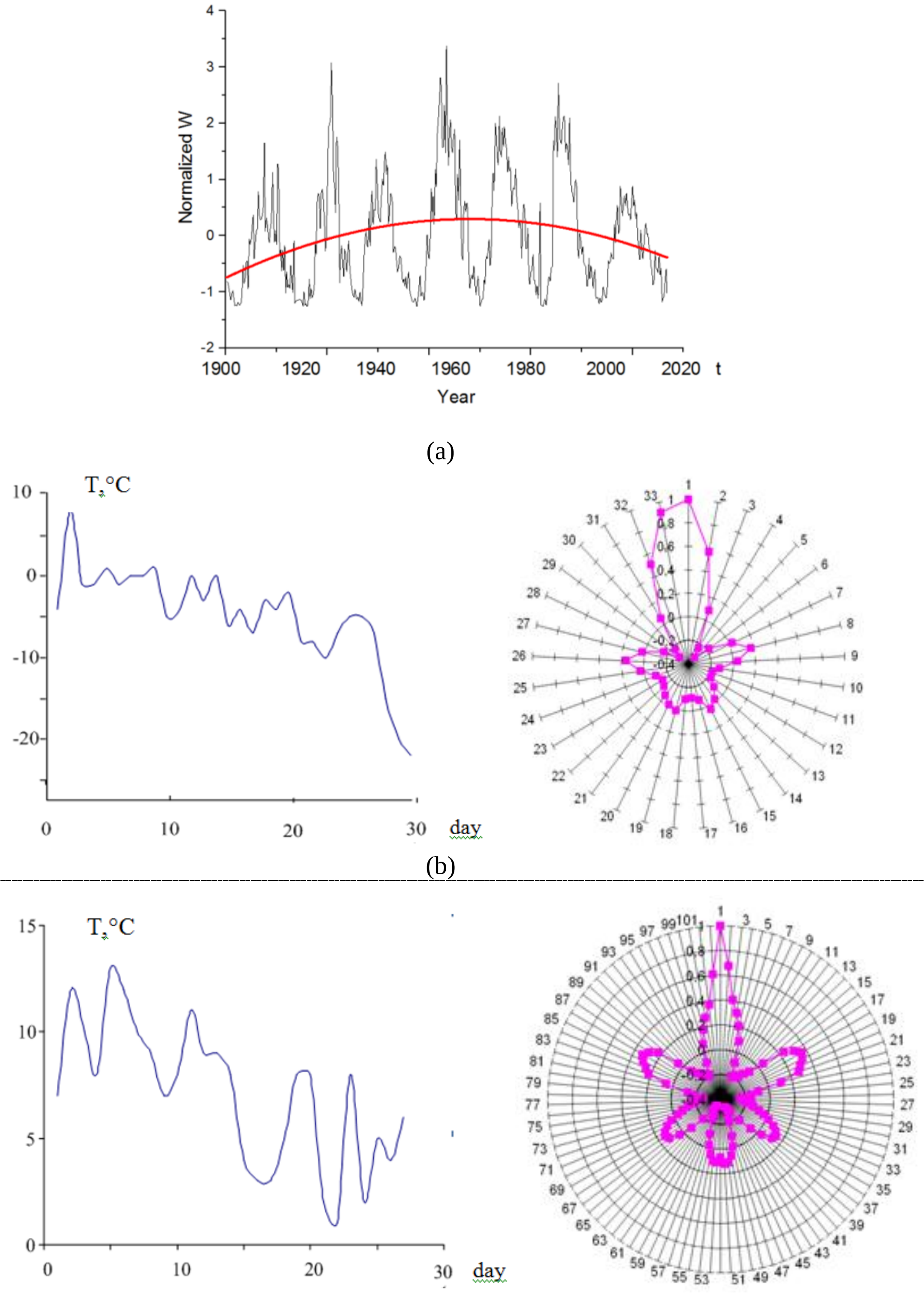
Climate modeling is mainly based on the analysis of two factors, such as temperature and precipitation. However, for a mountainous area changing UV-B radiation is also a significant factor. The use of the integral climate indicator (the De Martonne aridity index) makes it possible to simplify the modeling. The polynomials characterizing the reconstruction of the changes in the TOC (UV-B) and the aridity index from the density of the annual rings of coniferous trees describe the past climate changes in the dynamics and allow predicting future changes.

Solar activity determines the cycling of many climatic and atmospheric processes [13]. Significant 30- and 60-year cycles are observed in the 100-year cycle of the solar activity according to observations of the number of spots on the Sun (Wolf numbers) (Figure 2 (a)). Approximation of the solar activity data by a polynomial of the second degree shows that since the 1960s the solar activity has decreased. Within the last 30-year cycle from 2000 to the present, a decrease in the solar activity is also observed, which should affect the climate.

There could be similar patterns with a tendency of reciprocating course of growth in the different time series. To transfer the parameters such as temperature, solar activity, sedimentation from the sample under investigation to another sample (TOC, IDM, MXD), one or more assumptions about the correlation of characteristics are necessary. These assumptions should be based on the corresponding probabilistic model.

Let us consider the variability patterns of the paleostructure, such as paleo-temperatures and sedimentation during the Holocene on short time intervals. It is also possible to identify short-period variations that will have a reciprocating course associated with the cyclic nature of the natural processes in climatic, hydrothermal, and radiation data.

The principle of reciprocating course as of October 2008 temperature changes in the southeast region of the West Siberian Plate (WSP) is given in Figure 2. The temperature curves indicate the direction to decrease in the temperatures. Figure 2 (b) demonstrates the trend of the nighttime temperature changes. Figure 2 (c) demonstrates the curve of the daytime temperature variation. The last illustration better reflects the reciprocating nature of the temperature changes (the period of oscillations is approximately 7 days).



(a)

(b)

(c)

Figure 2. Red line: approximation of solar activity (W, in conventional units) by curve $y = -0.75 + 0.009x - 0{,}00002x^2$ (a). The average daily temperature (T° C) as for October 2008 for the south-east of the WSP and ACF of temperature variations: (b) during night time, (c) during daytime.

The analysis of autocorrelation functions of the temperature variations showed that practically on any segments we observe patterns of growth or decrease of the investigated parameters. These patterns are identical to those found in the paleo-structure. If the trend changes smoothly, then the temperature variations are also smooth and frequent. If the temperature swings in the longer period increase, then not only the amplitude of the temperature fluctuations, but also their period increases. The oscillations of other processes (series), such as TOC, IDM, and MXD could be treated in the same way. For example, we matched the time series of TOCs of different durations and compared their autocorrelation functions.

3. The method of autocorrelations

The autocorrelation function is one of the most important second- order characteristics of a stationary random process [8, 14], since it allows one to solve the following practical problems:

- evaluation of the correlation properties of signals and noise;
- calculation of the weight functions and frequency characteristics of optimal filters based on the knowledge of ACF signals and noise [14, 15];
- separation of the observed process into homogeneous regions according to the statistical characteristics;
- check of the stationarity of the observed process.

According to the ACF, the interval or correlation radius of the initial data $r\Delta$ is determined. This interval is the distance where the observed values y_i and y_{i+r} are no more correlated. To determine the correlation interval, one can use the estimate from [16]. For a given value of ε changing in the interval from $0.1R(0)$ to $0.3R(0)$, we find the initial value r of the ACF argument for which the inequality $|R(m)|<\varepsilon$ holds for all $m>r$. For example, for a number of ozone in April for $\varepsilon = 0.3$, $r = 5$, and for $\varepsilon = 0.1$ there are no such values. Therefore, reconstruction of the signal by the ACF in this case is not possible.

To compare the autocorrelation functions obtained from the initial data and from the reconstructed data, we use the nonparametric Mann-Whitney test. This criterion is used in the present paper because it is a rank criterion. It is free from assumptions about the type of distribution [17] and, therefore, it is not guaranteed that the values of the found autocorrelation functions belong to some parametric family of distributions because of too small sample size.

The essence of the Mann-Whitney test can be expressed as follows. Let $x_1, x_2, ..., x_n$ be a random sample of the observed values of the random variable X, with the distribution function $F(t)$ which is unknown. Let $y1, y2, ..., y_m$ be another random sample of the random variable Y, which is independent of X. Let $G(t)$ be the distribution function of the random variable Y. The problem is to verify the null hypothesis H_0 that the distribution functions of these two random variables coincide, i. e., H_0: $F(t) = G(t)$.

Assume that the data of the second sample $y_1, y_2, ..., y_m$ have mostly greater values than $x_1, x_2, ..., x_n$. Then the alternative hypothesis states: H_1: $F(t)>G(t)$, i.e. there is a significant shift of the second distribution to the right (the median of the distribution of the random variable Y is greater than the median of the random variable X). Let $x_1, x_2, ..., x_n$ be the values of the autocorrelation function calculated from the initial ozone data in April. Let $y_1, y_2, ..., y_m$ be the values of the autocorrelation function calculated from the reconstructed data. The numbers of values in the samples are $n = 10$, $m = 19$. Thus, we have $n + m$ independent random variables. Now they should be sorted in ascending order and then ranked. The lowest data value is assigned to rank 1, the next one is assigned to rank 2, and so on, and the largest value is assigned to the rank $n + m$. If there are the same values in a combined sample, then the arithmetic mean of their ranks should be assigned to them [18]. Let us find the sum of the ranks of the first sample $x_1, x_2, ..., x_n$, denoted by R_x. The sum of the ranks of the second sample $y_1, y_2, ..., y_m$ is denoted by R_y.

$$R_x = r_1 + r_2 + ... + r_n = \sum_{i=1}^{n} r_i = 140.5,$$

$$R_y = s_1 + s_2 + ... + s_m = \sum_{k=1}^{m} s_k = 294.5.$$

Next, the number of inversions of the sample Y with respect to X should be found: $U_y = n \cdot m + \frac{m \cdot (m+1)}{2} - R_y$. Here the value U_y=85.5. The equation $U_x = n \cdot m + \frac{n \cdot (n+1)}{2} - R_x$ describes the number of relative inversions of X and Y, which is 104.5. The inequality $U_y<U_x$ shows that the values of the autocorrelation function of the reconstructed series are less than those of the autocorrelation function of the original series. The significance of this distinction is checked by the Mann-Whitney test. The significance level α = 0.05 yields the critical value $U_{cr}(n, m, \alpha) = 58$ according to the table [19]. Similarly, the significance level α = 0.1 gives $U_{cr}(n, m, \alpha) = 66$. Since $U_y = 85.5 > U_{cr}(n, m, 0{,}1)$, the hypothesis H_0 on insignificance of the differences between the values of two autocorrelation functions is adopted. Consequently, we can consider that the obtained autocorrelation functions have insignificant differences.

4. Results

Let us make a comparison of the time series of TOCs in different geographic locations. Figure 3 demonstrates those for Arosa region in Switzerland (red line, left top) and Aktru region in Altai Mountains (blue line, left top). It is easy to see that the minimum of long-term TOC fluctuation is in 1994, and then a slow reciprocating course of the ozone layer recovery begins (Figure 3 (a)). Also there was a gradual decline in IDM, which started in 1994 and ended in 2010. The time series of IDM (Figure 3) can be considered as a part of the thirty-year climate fluctuation, since the autocorrelation functions (ACFs) of the time series are identical.

The analysis of the autocorrelations of the time series of the mean monthly values of the TOC for the Altai Mountains (Figure 4 (a)) shows that the presence of quasi-biennial oscillations reduces the significance of the correlation coefficients for the subsequent lags. This makes it difficult to detect other patterns. A possible solution is elimination of these quasi-two-year oscillations from the time series (Figure 4 (b)). In addition, Figure 4 (b) illustrates the presence of further fluctuations in the average monthly values of the TOC for July and September.

For the reconstruction of the TOC data we used the maximum density of the annual rings of Siberian larch trees that grew in the Altai Mountains at the WSP border. These magnitudes make it possible to indirectly evaluate and interpret the conditions for the growth of trees in the past centuries. In the sample under investigation one can distinguish two groups of density chronologies, which reflect the changes in the climate and UV-B response of the trees (Figure 4 (c)). The data of past changes in the TOC can be obtained by inverting the time series of the UV-B signal and normalization on the value of the calibration period [9].

Approximation of the IDM data has the form $y = -7.50 + 0.01x - 2.73E\text{-}6x^2$. Approximation of the UV-B data has the form $y = 52.39 - 0.05x + 1.348E\text{-}5x^2$.

Approximations of the reconstructions of the IDM and UV-B are represented by polynomials of the 9th degree. This submission for IDM is $y = -1.71E11 + 6.85E8x - 1.18E6x^2 + 1144.31x^3 - 0.66x^4 + 2.28E\text{-}4x^5 - 3.84E\text{-}8x^6 - 4.59E\text{-}13x^7 + 1.22E\text{-}15x^8 - 1.38E\text{-}19x^9$. The approximation of reconstruction of the UV-B is $y = -2.97E11 + 1.079x - 1.57E6x^2 + 1127.38x^3 - 0.28x^4 + -1.6E\text{-}4x^5 + 1.59E\text{-}7x^6 - 5.82E\text{-}11x^7 + +1.05E\text{-}14x^8 - 7.69E\text{-}19x^9$.

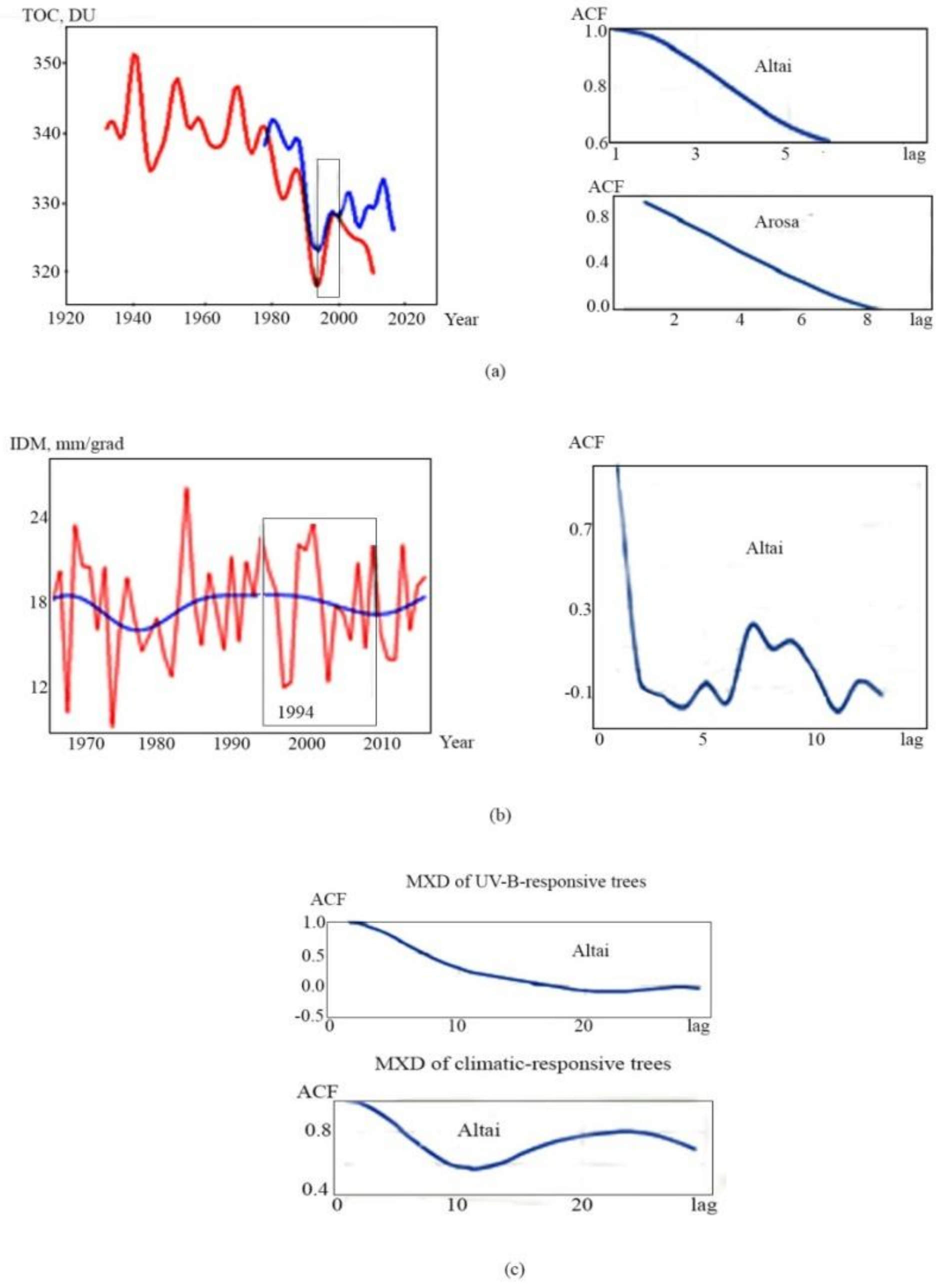


Figure 3. Autocorrelation functions of time series of average monthly TOCs for the warm period from April to September, for the Ust-Koksa aridity index (IDM), meteorological stations near Aktru and MXD (dendrochronological data of the maximum density of annual rings) of Siberian larch trees. There are regions of maximum coincidence of the TOC curves for Arosa and Altai in the square (a). There are IDM values during the ozone depression in the square (b).

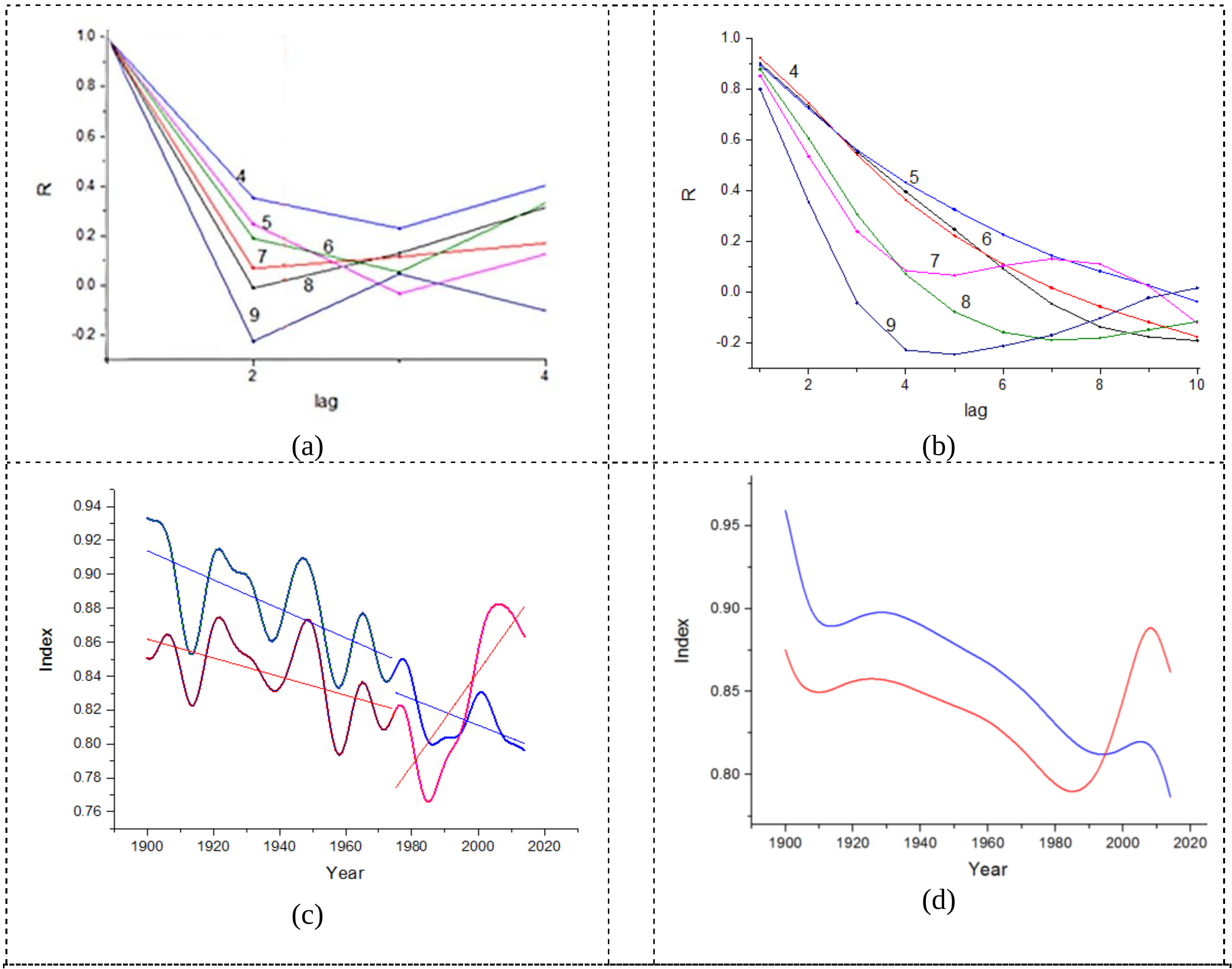


Figure 4. ACF of average monthly changes in the TOC, trends and models of the climatic (blue line) and UV-B signals (red line) for Aktru:
(a) There is a quasi-biennial fluctuation in ACF of the average monthly changes in the TOC from satellite data of 1979-2017.
(b) ACF of time series of TOC smoothed by a filter with a window of 2 years.
(c) Nonlinear trends of climatic and UV-B signals in the density of annual rings of larch.
(d) Model of changes in UV-B and IDM.
4-7: designations of the months April-September.

5. Discussion and conclusions

Some regularities in the dynamics of the parameters studied above for a territory in the Altai Mountains (Aktru) have been established with an analysis of autocorrelation functions. Using a probabilistic model, the properties established by the analysis of the temperature and solar activity samples were used for the general population of coniferous trees.

Previously, the method of multiple regression was used to reconstruct the TOC from dendrochronological data [8, 9]. Advantages of the method are the speed and simplicity of model development and easy interpretation of the model. Based on the regression coefficients obtained, one can judge how a particular factor affects the results. The method works well if the trend of changes in the time series is linear.

The increased amplitude of UV-B (TOC) oscillations from 1994 to the present time leads to great changes in the density of annual rings, significantly above the average (Fig. 4c). The trend of changes can be represented by a parabola, which makes the linear regression method unsuitable.

The MXD time series characterizing the climatic and UV-B signals were represented by the sum of oscillations of different periodicity and amplitude, inverted in the case of feedback parameters and unchanged with direct coupling. The decomposition components were analyzed by means of factor analysis. The technique for separating signals into climatic and UV-B sensitive ones is described in detail in [10]. The above constructed models (with a polynomial of the 9th degree) for the IDM and UV-B changes (Figure 4 (c)) show significant differences in the dynamics of time series characterizing IDM and UV-B.

Acknowledgments

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