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# The intensity of the climatic signal in the dynamics of the increment of Scots pine (Pinus silvestris L.) of the Khrenovskii forest (Voronezh region, Russia)

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**Abstract** Our research was carried out in the center of the Voronezh Region, Russia, in the pine forest "Khrenovskoy forest", located in the forest steppe zone of the Russian Plain. The samples for dendrochronological analysis were collected from 30 trees (1 core per tree). The climatic characteristics are taken from the data of the weather stations "Khrenovskoy forest", for the period 1936-1996 and Voronezh for the period 1862-2015. In accordance with the goal of the research, we identified high correlation coefficients (up to 0.42) and dispersion (up to 0.66) between the radial increment of Scots pine and the climatic limiting growth factors (sum of atmospheric precipitation, hydrothermal coefficient Selyaninova). We revealed a significant positive effect of the sums of atmospheric precipitation in May-August on pine growth (correlation coefficient up to 0.39) and a weak effect of air temperatures. The prevailing cyclic components of the time series studied are established: a high-frequency cycle (about 3 years) and a Brikner cycle (about 33 years). We have constructed mathematical models by the method of singular-spectral analysis (SSA). In the mathematical models constructed by us, due to the use of combined time series of climatic factors (the sum of precipitation, hydrothermal coefficient and indices of the radial increment of pine stands, for the first time a very high coefficient of similarity between actual and theoretical series was achieved: 78…90%.

## 1. Introduction

Forests play an important role in ecological systems, in the development of the economy, in improving the environment, and in improving the welfare of the people [1]. In addition, forests affect the global climate through physical, chemical and biological processes that affect hydrological, cyclical and atmospheric composition [2]. On the other hand, the effectiveness of forests under the influence of climatic conditions constitutes a complex loop of feedback between climate and forest [3, 4].

In many works of scientific researchers it is confirmed that forest ecosystems are at risk due to global climate change [5, 6]. Dendrochronology provides tools for establishing relationships between the growth of trees and the dynamic climatic variables over time [7]. Tree rings are important natural archives of climate information and are key environmental indicators of the state of the environment and climate change [7-16]. The growth of trees is affected by the interaction of biotic and abiotic factors [4]. Among the latter, precipitation, temperature, wind and humidity strongly influence the radial increment of trees [4, 17, 18]. In this case, tree rings can be used as witnesses of past climate changes, and in modeling climate variability in the future [19-23]. The aim of the study is to identify the climatic signal (atmospheric precipitation, air temperature) in the dynamics of the radial increment of Scots pine in the Voronezh Region, the establishment of the main cycles of the dynamics of both climatic factors and radial increment of pine, and the construction, based on the identified patterns, of adequate mathematical models of changes in the time of the studied characteristics (parameters).

## 2. Experimental part

Our research was conducted in the center of the Voronezh Region, Russia, in the island forest of the pine "Khrenovskii forest" (51º11,5´N, 40º13´E). Khrenovskii forest is located in the forest-steppe zone of the Russian Plain, on the southern boundary of the distribution of Scots pine (Pinus sylvestris L.). This forest is one of the largest island arrays (40.8 thousand hectares) in the forest-steppe of Eastern Europe.

The sampling area (PRP) was laid in the 7th stratum, quarter 258 in – Khrenovskii forest district, the natural site "Morozovs Grove" in June, 2015 (figure 1). PRP is located in the 240-year-old pine stand of natural origin, in the type of forest growth conditions (FGC) "Pine forest on the moderately moist sandy loamy soils" (B2 symbol on Pogrebnyak scale) [24]. Underbrush on the PRP: Russian broom, rough spindle tree, mountain ash, Tatarian maple. Herbal cover on the PRP: green mosses, Solomon's seal, wood bluegrass, May lily, bush grass, wood avens, herb Robert, ground ivy, and mountain parsley. The characteristics of stands, determined by the authors, are documented in the Table 1.

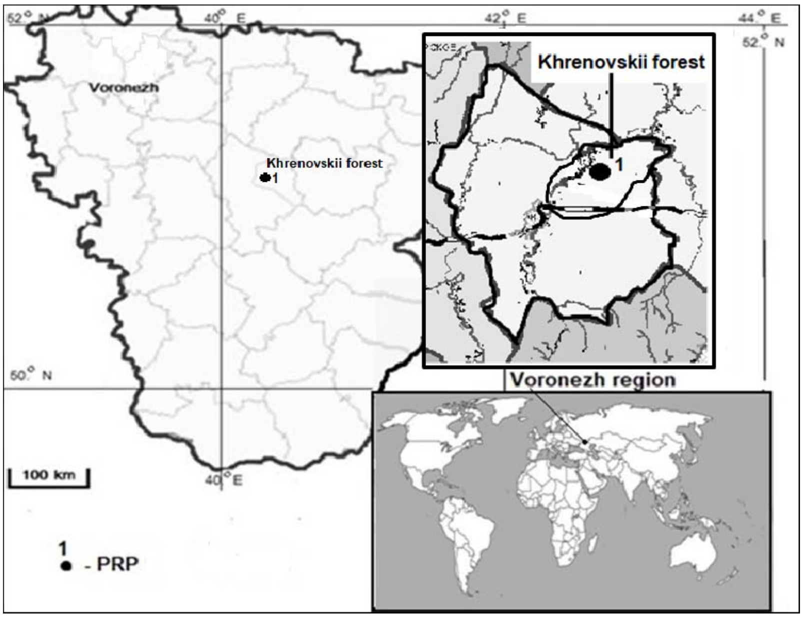


**Figure 1.** Geographical location of the research object.

**Table 1.** Characteristics of the stand in square meters 258 the 7th Khrenovskii forest

| Quarter / Stratum | Composition of tree species, % | Age, years | Growth class | h (m) | dbh (cm) | f |
|---|---|---|---|---|---|---|
| 258/7 | 100% Scots pine<br>100% Scots pine<br>+ Scots pine | 240<br>40<br>80 | I | 34<br>16 | 68<br>16 | 0.4<br>0.3 |

Note: h – mean height; dbh – mean diameter on the height breast; f – density of tree placement in the PRP (corresponds to the density of the canopy).

The cores for dendrochronological analysis were selected in accordance with the generally accepted method [25, 26]: cores were collected from 30 trees (1 core per tree). Dating and tree ring width measurement was carried out on the measuring complex LINTAB-6 using specialized software package TSAP-Win (Professional version) [27]. Calculation of the relative indices of the growth was made in TREND program [28]. Program STATISTICA-6.0 [29] was used for performing calculations of the basic statistical characteristics of tree-ring series: annual values of the coefficient of variation, standard deviation, probable error, calculated from time series of the width of annual rings. Correlation and variance analysis is made to determine the strength of relationship, and calculation of influence force of climatic factors on the radial increment of species under consideration.

The reflected population perception signal (expressed population signal - EPS), reflecting the representativeness of the chronology and Standard statistical characteristics of tree-ring series include signal-to-noise ratio (SNR) - is an indicator of intercorrelation of individual chronologies used to build a generalized chronology (formula 1).

$$SNR = \frac{N \times r}{1 - r}\ , \tag{1}$$

where N – selection scope, r – average interseries correlation coefficient.

The climatic characteristics are taken from the data of the weather stations " Khrenovskii forest" (51°07'N, 40°17'E, altitude above sea level 136 m) for the period 1936-1996 (the weather station stopped working) and Voronezh (51°40'N, 39°13'E, altitude above sea level of 149 m) for the period 1862-2015 (distance from the research object is 90 km.) [30].

Hydrothermal coefficient (HTC), an important characteristic about frequency of the atmospheric droughts, for the first time proposed by climatologist G.T. Selyaninov [31, 32], index demonstrated the connection between the air temperature and precipitation during the period with active plant growth, and calculated using the following formula 2:

$$HTC = \frac{\sum P}{0.1 \sum T^{*}}\ , \tag{2}$$

where P is the precipitation (mm), and T* is the mean temperature for the months with daily temperature above 10° C. In the city of Voronezh and Voronezh region, the period with average monthly temperature above 10° C extends from May to September, which was used for HTC calculations here.

To determine the cyclicity of the radial growth dynamics, STATISTICA-6.0 [29] performed a spectral analysis of the time series of Scots pine. Modeling of the studied characteristics (radial increment of pine, atmospheric precipitation, HTC) was carried out by the method of singular-spectral analysis (SSA) "Caterpillar" - a time series analysis method based on converting a one-dimensional time series into a multidimensional series, with subsequent application to the obtained multidimensional time series method main components [33]. The construction of the model based on the method of singular-spectral analysis (SSA) assumes a qualitative analysis of the time series: the structure of the series, the estimation of the random component, etc. The basis of this method is a model characterized by the equation:

$$X_t = T_{rt} + S_t + E_t (t = 1, 2, ...., n)\ , \tag{3}$$

where Tr – is the trend, a smoothly varying component describing the net effect of long-term factors, i.e. long-term trend of change in the trait under study; S – cyclic component, reflecting the frequency of the processes under study for a certain period; E – is a random component reflecting the influence of random factors that are not amenable to registration and registration [34].

## 3. Results and discussion

The statistical characteristics of the dendrochronological series under study confirm its suitability for the purpose of research, due to its high sensitivity to the influence of climatic factors (Table 2).

The expressed signal of the population (EPS) was 0.99 – the chronology is considered quite representative [35]. The calculated signal-to-noise ratio (SNR) was 68, i.e. the generalized chronology contains high variability due to the influence of climatic factors (the trees under study are sensitive to changes in climatic conditions).

**Table 2.** Statistical characteristics of the dendrochronological series.

| Object | Period | Duration, years | SD | Mean value CV | $i_{sr}$ | Standard error | $P_{sr}$ | EPS | SNR |
|---|---|---|---|---|---|---|---|---|---|
| Chronology "Morozovs Grove" | 1778-2015 | 238 | 0.75 | 42.3 | 1.107 | 0.045 | 5.1 | 0.99 | 68 |

Note: $P_{sr}$ – the average value of the probable error; $i_{sr}$ – average annual increment, mm.

Analysis of the response of radial increment of pine on the factors limiting the increment of trees: the sum of atmospheric precipitation for the year (P year), the sum of the precipitation of the warm period (P 4-9), the mean annual air temperature, the HTC by correlation analysis was performed for two meteorological stations: Khrenovskii forest" and "Voronezh" (Table 3).

**Table 3.** The matrix of values of correlation coefficient (r) of indices of radial increment of Scots pine and limiting factors.

| Significative | Indices of increment, I | HTC * 100 | P 4-9 «Voro-nezh» | P year «Voro-nezh» | T | P 4-9 "Khrenovskii forest" | P year "Khrenovskii forest" |
|---|---|---|---|---|---|---|---|
| Relative increment indices (I) | 1.0 | 0.42 | 0.26 | 0.36 | 0.18 | 0.28 | 0.38 |
| Hydrothermal coefficient (HTC) * 100 | 0.42 | 1.0 | 0.74 | 0.72 | 0.22 | 0.46 | 0.39 |
| Precipitation for April-September on the weather station "Voronezh" | 0.26 | 0.74 | 1.0 | 0.52 | 0.12 | 0.10 | 0.11 |
| Annual rainfall at the meteorological station "Voronezh" | 0.36 | 0.72 | 0.52 | 1.0 | 0.15 | 0.12 | 0.69 |
| Average annual air temperature at the weather station "Voronezh" (T) | 0.18 | 0.22 | 0.12 | 0.15 | 1.0 | 0.08 | 0.10 |
| Precipitation for April-September on the weather station "Khrenovskii forest" | 0.28 | 0.46 | 0.10 | 0.12 | 0.08 | 1.0 | 0.51 |
| Annual rainfall at the meteorological station "Khrenovskii forest" | 0.38 | 0.39 | 0.11 | 0.69 | 0.10 | 0.51 | 1.0 |

The coefficient of correlation (r) between the sum of atmospheric precipitations at the meteorological station "Khrenovskii forest" and at the "Voronezh" meteorological station is quite high and is 0.69 (Table 3, line 4, 7), and the correlation of the increment indices with precipitation by the named meteorological stations is almost the same (0.38 and 0.36 respectively) (Table 3, line 4, 7), which allowed us to use the data of a longer series of observations of the "Voronezh" meteorological station in further analysis and in the construction of mathematical models.

The analysis of the obtained results showed that the correlation of the indices of radial increment of wood with limiting factors varies from weak (0.18-0.28) (Table 3, line 5, 3, 6) to moderate (0.36-0.42) (Table 3, line 4, 2). The correlation coefficient of the increment indices is the highest with a complex indicator of the effects of droughts - HTC.

Figure 2 presents the results of the analysis of the influence of climatic factors (the sum of precipitation and average air temperature at the weather station "Voronezh") on the radial increment of Scots pine by months of the hydrological year (from October of the previous year to September of current year).

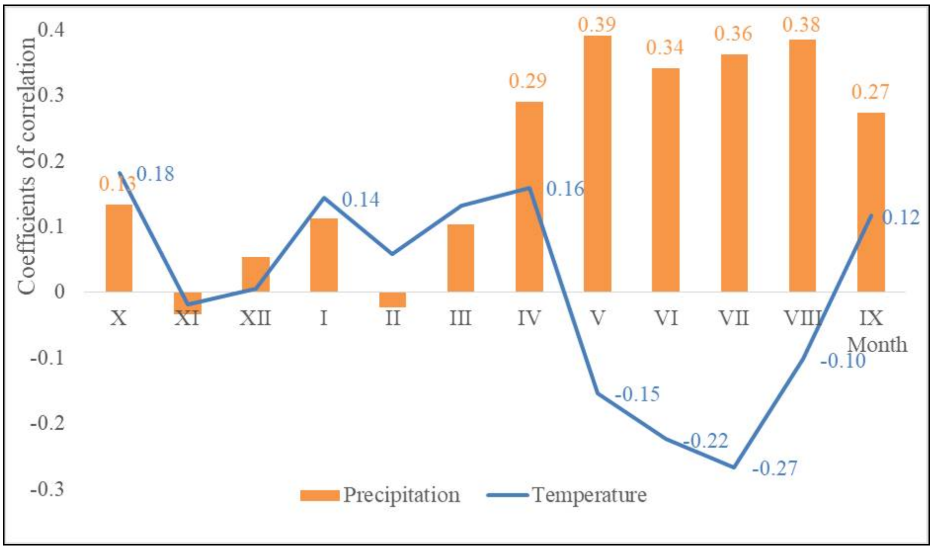


**Figure 2.** Significant correlation coefficients between the tree ring indices of Scots pine, the sum of atmospheric precipitation and average air temperatures by the months of the year (weather station "Voronezh").

Analysis of the response of Scotch pine on climatic factors showed that the dominant influence on the radial increment of the pine is caused by the precipitation of the warm period of the current year. A moderate positive correlation is observed between the indices of tree increment and the amount of precipitation in the spring-summer period (from May to August): from 0.34 to 0.39 (figure 2). Rainfall in September of this year also has a significant effect on increment (r = 0.27) (figure 2), which indicates their importance in preparing trees for the rest period - lignification of wood cells. Precipitation of the winter period, and especially of March-April, obviously has significance in the accumulation of the moisture reserve contained in the soil at the onset of cambial activity.

The increase in Scots pine shows a negative response to the temperatures of May and summer months (from -0.27 in July to -0.10 in August) (figure 2). Temperatures of the remaining months of the year have a slight positive impact on pine increment.

Arsalani et al. [22] noted positive correlations of precipitation of May, June and August with the tree ring indices (up to 0.40). Many researchers [6, 9, 15, 16, 20] note that there is a significant relationship between the tree ring indices and precipitation, the air temperature of the summer months shows a negative correlation with the tree ring indices.

Data on the influence of climatic factors on the radial increment of the pine are confirmed by the results of the variance analysis (Table 4). The greatest influence on the radial increment of the pine is exerted by the complex indicator of the effect of droughts - HTC ($\eta 2 = 0.66$) (Table 4, line 1).

**Table 4.** Dispersion analysis of the influence of climatic factors on the increment of Scots pine.

| Factor of influence on growth | Index forces of influence $\eta^2 \pm m$ | Fishers actual test ($F_f$) | Fishers standard criterion ($F_{st}$) |
|---|---|---|---|
| HTC | 0.66±0.018 | 10.4 | 3.9 |
| Annual amount of precipitation | 0.49±0.102 | 5.9 | 3.9 |
| Amount of precipitation for April-September | 0.51±0.043 | 9.1 | 3.9 |
| Average annual air temperature | 0.20±0.054 | 5.5 | 3.9 |

Analysis of the cyclicity of the relative indices of the increase in the pine of the ordinary tract "Morozovs Grove" (Figure 3) showed the presence of cycles of different lengths in a series of relative indices of pine growth in calendar years: the cycles shown in ascending order (with rounding to whole years): 2-3, 5- 6, 8-9, 11-12, 15-18, 20-24, 33-36, 55, 60, 125-150. With the amplification or weakening of geophysical processes, high-frequency cycles appear (2-3, 5-6 years). The most pronounced of high-frequency cycles in the investigated stand is a cycle with a frequency of 5-6 years.

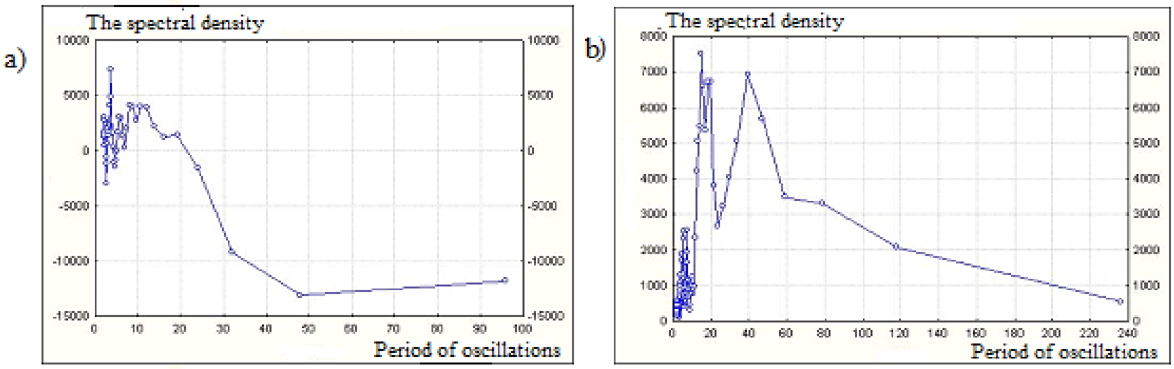


**Figure 3.** Periodograms smoothed by Hamming weights: a) the spectral density of a number of atmospheric precipitation; b) the spectral density of a number of relative increment indices of Scots pine.

The cyclicity with a duration of 20-24 years (Hale or magnetic cycle), as well as high density peaks of 40 and 46 years, 33-36 years (the Brikner cycle) prevails over the spectral density.

Among the values of sums of atmospheric precipitation, the most pronounced are high-frequency 2-3-year, 8-9-year cycles of oscillations.

The high values of correlation and dispersion coefficients, as well as the clearly expressed cyclicity of different orders, revealed during the research of time series of the radial increment of Scots pine and climatic factors allow us to proceed to the modeling of the time dynamics of these characteristics. For the subsequent modeling the program "Caterpillar" was used. With the help of the "Caterpillar" program (SSA method), the spectral components of time series were selected taking into account the amplitude and phase changes of the quasiperiodic radial gain signal, the HTC and the sum of annual precipitation. Taking into account the prevalence of the Brikner cycle in the dynamics of climatic factors and the significant variability of the amplitude of their oscillations, we applied a 33-year cyclic component in the construction of a combined mathematical model.

The basis for the choice of the 33-year simulation period for the radial increment model in the construction of the combined mathematical model, was the analysis of the cyclicity of the radial increment of the pine of the natural site "Morozovs Grove" and the earlier studies of the cyclic dynamics of droughts, solar activity and increment of stands of the Central forest-steppe. The frequency (recurrence) of repetition of strong, with catastrophic consequences, droughts in the Central forest-steppe region correlates with the Brikner cycle (the average recurrence interval is 33-35 years) [32].

The simulation results are shown in figures 4 and 5. With the chosen cyclicity parameters of time series, a high similarity of the actual oscillations and simulated series of both the HTC (78%) and the pine increment indices (82%) was obtained (figure 4). The model reflects both the cyclic component of the oscillation period and the nature of the amplitude of the oscillations.

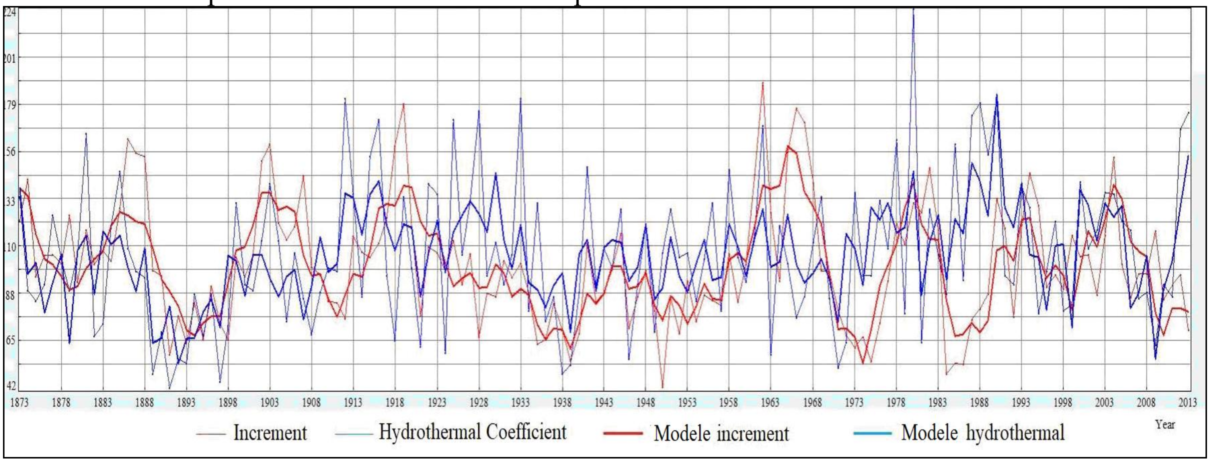


**Figure 4.** Models of radial increment and HTC using the "Caterpillar" program.

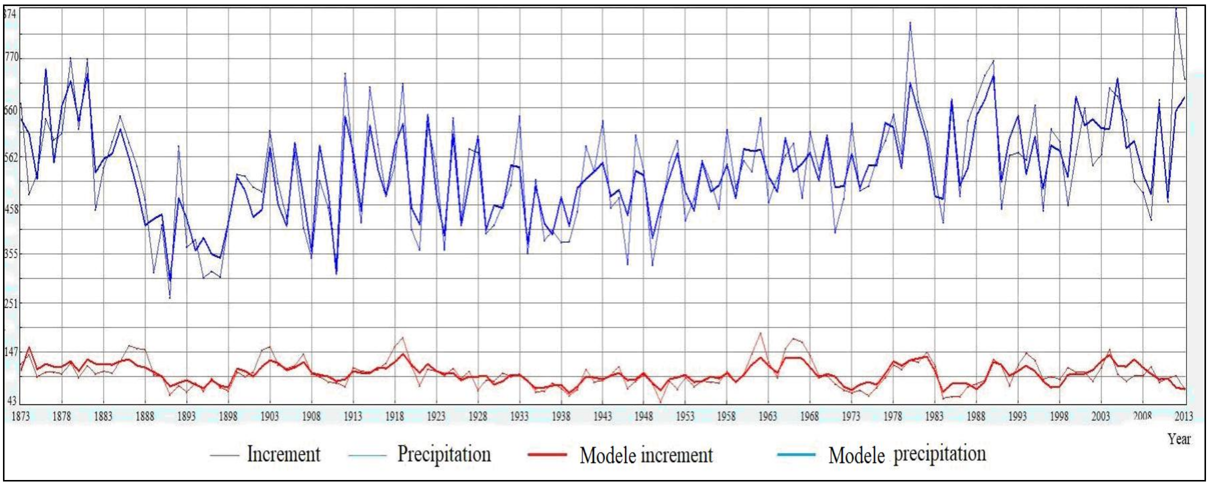


**Figure 5.** Models of radial increment and precipitation using the "Caterpillar" program.

Even more high similarity was shown by combined models of precipitation and pine increment indices: the correlation coefficient is 90% in both cases.

Simulation of the radial increment indices based on high correlation coefficients with climatic factors was also carried out by other researchers [13, 21, 23], the similarity of the obtained theoretical and actual series was not high enough. The approach we used (the SSA method, the selection of cyclical components, as well as the use of combined modeling of the radial increment indices and climatic factors allowed us to obtain a very high similarity between the actual and theoretical series (78-90%) for both the radial increment indices and climatic factors.

## 4. Conclusions

In accordance with the goal of the research, we identified high correlation coefficients-correlations (up to 0.42) and dispersion (up to 0.66), between the radial increment of the common pine of the Khrenovskii forest and climatic limiting growth factors (sum of atmospheric precipitation, HTC). The character of the seasonal dynamics (by months of the hydrological year) of the influence of atmospheric precipitation and air temperatures on the radial increment of Scots pine, is shown. A significant positive effect of the sums of atmospheric precipitation in may-august on pine increment (correlation coefficient up to 0.39) and a weak effect of air temperatures was revealed. The prevailing cyclic components of the time series studied are established: a high-frequency cycle (about 3 years) and a Brikner cycle (about 33 years). We have constructed mathematical models by the method of singular-spectral analysis (SSA). In the mathematical models constructed by us, due to the use of combined time series of climatic factors (the sum of precipitation, HTC) and indices of the radial increment of pine stands, for the first time a very high coefficient of similarity between actual and theoretical series was achieved: 78…90%. Our models can be used to predict the dynamics of the radial increment of pine stands, as well as climatic indicators.

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