Functional Model of Influence of UV-B (TOC) and Climate on Tree Responses

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Abstract. In the framework of the functional model of the influence of atmospheric parameters on the growth of conifers, it is shown how changes in the level of UV-B radiation, indirectly related to changes in stratospheric ozone, affect the density of annual rings. Phytohormones initiate tree adaptation mechanisms by regulating the growth rate of tree cells. The simulation results showed that there is a strong relationship between the rates of changes in density and total ozone content.

1. Introduction
Since the 1980s, areas of coniferous forests that once occupied large areas in Europe have been declining. Today, with the increasing rate of climate change, the competitiveness of conifers may be weakened due to the abnormal impact of several factors at the same time. Responses of coniferous trees in long periods of background and active changes of UV-B radiation and climate were considered.

The choice of the territory of Switzerland is due to the statistical availability of environmental monitoring data of this area [1]. The responses of the trees were evaluated by tree-ring characteristics for the territory of Switzerland, and the level of UV-B radiation was evaluated according to the total ozone content (TOC). It has been shown statistical methods that climate changes and UV-B (TOC) affect the maximum density of the annual rings (MXD) [2], which may be related to the rate of cell growth in the annual ring.

Under favorable weather conditions for tree growth, the relationship between trunk respiration, crown photosynthetic activity and wood growth is well represented. Some empirical regularities of growth and nutrition of wood cells when changing the phytomass of the crown do not give a complete picture of the influence of physiological processes in needles on the annual growth of wood. Experimental studies, which describe the hormonal regulation and growth of plant cells in response to environmental influences, suggest that one of the Central functions of phytohormones is the adaptation of trees to stress [3].

The purpose of this work is development of a functional model of the influence of atmospheric parameters on the density of annual rings of coniferous trees and its applications.

2. Materials and methods
The dendrochronological method of studying the ozonosphere was contained in the monograph [4, 5], which provides a description of the method of reconstruction and prediction of TOC changes by the responses of conifers to the impact of the total ozone content [6, 7]. The considered scheme of bioindication: "the less TOC, the more UV-B, the greater the maximum density of the annual rings", is the basis of the reconstruction of 250-year changes in TOC for the Subarctic territory, while the functional model: "the influence of the atmosphere on plant growth" is associated with the processes of
photosynthesis in the crown and is reflected in the change in the density of the annual rings. This is proved by a stable significant correlation of MXD and TOC for the selected territory.

Data mining includes well-known statistical methods of time series research: correlation, cluster, factor analysis, principal component method, singular spectral analysis (Caterpillar-SSA) \[8\]. The instrumental data are built, filtered and grouped into time series, taking into account that the rings density data contains both climatic and UV-B signals. In the new functional model, phytohormones are the signal link between the root system, trunk and crown. At the same time the rate of cell division under the influence of atmospheric factors determines the density of wood and can be associated with the amount of hormonal substances in wood tissues. A priori: the rate of density changes of annual rings is related to the rate of decline and recovery of total ozone in the atmosphere.

Data were used:

- Dendrochronological data MXD of F. Schweingruber for cedar pine, spruce, fir and larch \[9\];
- Average monthly data of TOC for the growing season of the Swiss Arosa Observatory from 1926 to the present \[10\];
- Average monthly temperatures and precipitation of the Davos weather station since 1870. Calculated data of the De Martonne aridity index \[11\] of climate.

**Formulas and assumptions:**

- Index UVB-\(I\) is introduced to describe the dose UVB in the indexes TOC. \(UVB-I(t) = -TOC-I(t)\).
- Normalizing of indices \(Index(t) = [X(t) - mean] / STD\), where \(Index(t)\) is an index, \(X(t)\) is a parameter value in the time series, \(mean\) is the average value and \(STD\) is a standard deviation.
- As the rate of change in the density of the annual ring and the rate of decline of the CCA, the rate of change in the physical quantity is considered.
- The formulas for calculating velocities are obtained as derivatives from the trends of the initial processes \[12\]. In fact, trends of changes of the velocities are obtained. Themselves formulas of the trends of changes of velocities are shown directly below the graphs in table 1.
- The De Martonne aridity index (IM) is calculated according to the formula: \(IM = \Sigma P / (T + 10)\), where \(\Sigma P\) (mm) is the total monthly precipitation and \(T\) (°C) is the average monthly air temperature. According to IM data, it is clear that the aridity of the climate is gradually increasing. A decrease in climate aridity caused by a decrease in temperature and precipitation sometimes coincides with a decrease in TOC, which increases the response of trees. The amplitude of the density of the annual rings increases significantly.

**3. Results and discussion**

**Classification of responses of trees**

Based on the correlation analysis of MXD, UV-B and IDM, two categories of coniferous tree responses were identified:

- **Group I.** responses of trees sensitive to UV-B. Let's call them UV-B sensitive trees. Correlations between MXD and UV-B in April are significantly positive. The average response \(R = 0.55\) and \(R = 0.41\) at \(p < 0.05\) in April and in March-September, respectively.
- **Group II.** Responses of trees sensitive to climatic changes. Let's call them climate sensitive trees. Correlations between density and aridity index values are significantly negative. The average response \(R = -0.51\) at \(p < 0.05\).

There are small groups of trees whose adaptation to environmental changes is associated with other mechanisms. The chronologies of such trees were not used for bioindication. Figure 1 shows the distribution of responses of trees by group for Switzerland.
Figure 1. Correlation coefficients in the sample of UV-B sensitive trees on the left: MXD and UV-B (TOC); in the sample of climate-sensitive trees on the right: MXD and IDM.

Analysis of the variance of the studied characteristics in the data sample

- 46% of the sample from 160 time series MXD had a positive significant correlation with the average for April values of the level of UV-B radiation. The reaction of trees is observed throughout the growing season.
- The correlation of MXD with UV-B for 6% of the series was negative.
- 36% of the MXD sample with a significant negative correlation to climate change (CC) (March-September) did not respond to changes in UV-B in April.
- The rest (12%) had either no climate signal or it was weak.

In figure 2 on the right is a 3-dimensional visualization of the rotation of the main components of the MXD time series. The values of the main components [13] in each group approximate the surface. For group I, the maximum variance is observed in the direction of the component associated with the influence of the first main factor (UV-B). The second factor temperature (T) increases the effect of UV-B and the effect of the third factor, which is the amount of precipitation (P). As a result, the parameters T and P can be combined into one factor, estimated by the de Morton index, assigning it the cumulative % of the explained variance. In the fig. 2 the shape of the ellipse is determined by the correlation coefficients between the main components of the studied factors, such as the more extended the ellipse, the higher the correlation. The relationship of UV-B and CC in group I for the period 1940-1952 and the period 1953-1964 indicate an enhancing of the UV-B factor by the temperature factor. During the period of synchronous changes in CC and UV-B, the influence of both factors leads to an increase in the density of the annual rings.
Figure 2. Scattering and 3-D diagrams that visualize the relationship between UV-B and climatic parameters in responses of group I and group II.

Functional model

The functional model (figure 3) is based on the materials of experimental, field and model works close to the subject under study, as well as statistical analysis of data of global monitoring [14]. Thus, research in the Pamir mountains has shown that plants can adapt to stress due to hormonal regulation. Hormones are thought to be responsible for the process of cell expansion in the plant. At low temperature and drought, the concentration of abscisic acid (ABA) increases. The growth rate of plants susceptible to changes in UV-B increases, while the growth rate of UV-B resistant plants remains unchanged. Under high doses of UV-B inhibited growth processes of division and stretching of wood cells due to: 1) reduced synthesis of auxin and gibberellin; 2) increased production of abscisic acid, called the stress hormone.

Generalized MXD data for a large area (figure 4), contain fluctuations related to individual growth conditions, so the MXD time series was smoothed by a 3 - point FFT filter. The period of 1946-1960 (1) of background changes demonstrates a stable relationship between the TOC and the ring density with a correlation coefficient $R = -0.85$. The period 1961-1978 (2) has for numerous anomalous climate deviations, so the climate factor more often limits the growth of conifers than changes in UV-B (TOC). The TOC and MXD relationship is weaker, $R = -0.46$. The period 1979-1995 (3) is characterized by a catastrophically rapid decline in TOC in the atmosphere. The TOC and MXD relationship is strong $R = -0.82$. The period 1996-2006 (4) is the period of ozone recovery in the atmosphere. This period is associated with an increase in the climate factor. It is characterized by the absence of a significant effect on UV-B changes.
Figure 3. Functional model of influence of UV-B (TOC) and climate on tree responses.

Figure 4. MXD and TOC indices for Switzerland. 1, 2, 3, 4 are time periods. Rate of change of TOC and density

During the season there is an increase in early and late wood of the annual ring. An increased rate of density change means an extension of the boundaries of early wood, a decrease in the rate of density change, on the contrary, reduces and prolongs the growth time of late wood. Modeling has shown that the rate of changes in the density of annual rings can be related to the rate of decrease and recovery of TOC in the atmosphere. The relationship between the speeds of different processes is cyclical. The alternation of correlation signs indicates the alternation of growth-limiting factors.
Figure 5. Correlation R on the Y axis between the rate of change MXD and the rate of change TOC. There are 6 intervals on the X-axis: 1932-1943; 1944-1955; 1956-1967; 1968-1979; 1980-1991; 1992-2006 years.

Table 1. Functions the rates of change of TOC and MXD.

| Interval   | Function TOC          | Function MXD          |
|------------|-----------------------|-----------------------|
| 1946-1960  | $y = 0.0072x^2 - 0.0316x - 0.4152$ | $y = 0.0324x^2 - 0.8266x + 4.5516$ |
| 1961-1978  | $y = -0.005x^2 + 0.123x - 0.657$   | $y = -0.0156x^2 + 0.1902x - 0.0526$ |
| 1979-1995  | $y = -0.0018x^2 + 0.0324x + 0.112$ | $y = -0.0696x^2 + 1.1174x - 4.6044$ |
| 1996-2006  | $y = 0.0036x^2 - 0.1414x + 0.6632$ | $y = 0.1269x^2 - 1.9322x + 6.3999$ |

Table 2. The correlation coefficient of the rate of change of MXD and TOC.

|       | 1946-1960 | 1961-1978 | 1979-1995 | 1996-2006 |
|-------|-----------|-----------|-----------|-----------|
| $R$   | 0.73      | 0.86      | 0.91      | 0.90      |

Consider the functions of the rates of change of the TOC and MXD in the periods indicated in Fig. 4. The simulation results are shown in table 1. The first column contains graphs of the density change rate, and the second column contains graphs of the ozone change rate (on the Y scale). Years from the specified interval are postponed on a scale X, and on a scale Y values of rates of changes of physical quantities within the considered cycle are postponed. It can be seen
that during periods of active UV-B exposure with a decrease in the level of TOC in the atmosphere, the changes and growth rate of the annual rings occur synchronously with changes in the atmosphere. In table 2 the correlation coefficients of the MXD rate of change and the rate of change TOC are given. The speed functions show the increase, decrease, and the highest and the lowest values of the processes.

5. Conclusion

Thus, the rate of change in the TOC can be judged on the state of the atmosphere: there is the destruction of the ozone layer (1970-2003) or, on the contrary, its recovery (1953-1960), as well as how long these processes take place. The results obtained can be used for reconstruction [13] and prediction [14] of climate and atmospheric characteristics.

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References

[1] Staehelin J, Viatte P, Stübi R, Tummon F, Peter T 2017 Stratospheric ozone measurements at Arosa (Switzerland): History and scientific relevance/ journal Atmos. Chem. Phys. 1–24.
[2] Fritts H C 2001 Tree rings and climate (New York: The Blackburn Press) p 582.
[3] Bondarenko S L, Savchuk D A 2018 Global. J. Environ. Sci Manage 4 (3) 299–314.
[4] Zuev V V, Bondarenko S L. 2007 Ozonosphere Research by Dendrochronological Methods (Tomsk: Opt. Atm. Sib. Otd. Ross. Akad. Nauk Press) p 168.
[5] Methods of Dendrochronology. Applications in the Environmental Sciences 1990 (Eds. Cook E R, Kairiukstis L A Dordrecht; Boston: L.: Kluwer Acad. Publ.) p 394.
[6] Guiot J, Wu H, Garreta V, Hatté C, Magny M 2009 A few prospective ideas on climate reconstruction: from a statistical single proxy approach towards a multi-proxy and dynamical approach. Clim Past 5 571–583.
[7] WMO 2008 Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report, GCOS-117, WCRP-127, IGBP Report No. 58, WMO/TD No. 1418, Geneva: World Meteorological Organization.
[8] Glinsky V V, Ionin V G 2002 Statistical analysis (Moscow: INFRA-M Publ.) p 241.
[9] Schweingruber F N and Briffa K R 1996 Three ring density networks for climate reconstruction. Climatic variations and foring mechanisms of the last 2000 years. NATO ASI Series 141 43–66.
[10] Dütsch H U 1984 An update of the Arosa ozone series to the present using a statistical instrument calibration Q. J. 632 R. Meteorol. Soc. 110 1079–1096.
[11] De Martonne E 1923 Ariditéet indices d’aridité Académie des Sciences. Comptes Rendus 182 1935-1938.
[12] Bondarenko S L, Ustinova I G 2019 Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering 330 (3) 50–59.
[13] Bondarenko S 2005 Study of main components of long-period variations of stratospheric ozone according to reconstructed and instrumental data by Caterpillar method 6160 10.1117/12.675225.
[14] Loginov V F 2017 Izmeneniya klimata: trendy, cikly, pauzy (Minsk: Belaruskaya navuka) p 179 ISBN 978-985-08-2127-0.