Complex studies of significant responses in annual rings of coniferous trees to the effect of solar UV-*B* radiation

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Institute of Atmospheric Optics has developed a method of reconstruction of total ozone (TO) from dendrochronological data, which makes it possible to trace the TO behavior for a few centuries back to thousand years. In treatment of biospheric effect of the UV-*B* radiation at the wavelengths shorter than 310 nm, the data of TO measurements can be considered adequate and more efficient replacement of data of radiation measurements. In this paper we present some results the sensitivity of wood plants to long-term enhancement of UV-*B* radiation, search for significant bioindicators of stratospheric ozone in annual rings of coniferous trees, and also consider the possibilities of accounting for the effect of UV-*B* radiation and tropospheric ozone in the existing models of growth and structure of annual rings.

Introduction

The ozone layer absorbs shortwave portion of UV solar radiation, dangerous for the Earth's biosphere. It is not surprising, therefore, that the steady decreasing total ozone (TO) content in recent decades stirred much discussion not only in the scientific community but also in the mass media. However, for a long time this debate had no appropriate scientific substantiation of the observed tendencies in the ozone layer, primarily because the period of instrumented TO observations, performed on a global scale for less than half-century was too short.

The developed method of TO reconstruction from dendrochronological data[1,2] makes it possible to trace the TO behavior during several hundred years back to one thousand years. This method is based on the significant correlation between TO and dendrochronologic parameters revealed,[3] caused by the effect of UV-*B* radiation on the growth of wood plants.

1. Statement of the problem

It is accepted to determine the UV-*B* radiation in the spectral interval 290–315 nm. Most biologically active part of UV-*B* radiation has wavelengths shorter than 310 nm, where there are the absorption bands of the main macromolecules, albumens, and nucleic acids. At the wavelengths shorter than 310 nm all deviations from the normal level of UV-*B* radiation reaching the Earth's surface are almost totally determined by TO variations.[4]

Table 1 presents the coefficients of correlation between variations of TO and UV-*B* radiation at the wavelengths 300, 305, and 310 nm, obtained from the measurements at two sites in midlatitude belt of the Northern Hemisphere (Edmonton and Kagoshima). It is seen that the level of correlation coefficients is significant in all cases with 0.95 (and in most cases even with 0.99) confidence probability.

It is worthy to note the efficiency of using TO time series as an adequate replacement of UV-*B* radiation series to account for the biospheric effect of UV radiation at the wavelengths shorter than 310 nm in comparison with direct radiation measurements, because the errors of TO measurements are an order of magnitude smaller than that of UV radiation measurements.

Figure 1 presents the scheme of UV-*B* radiation action on photosynthetic system (PSS) of plants. It shows both the direct effect via absorption of high-energy UV photons by the main macromolecules and indirect effect owing to the key role of UV-*B* radiation in photochemical generation of tropospheric ozone, the strongest ecotoxicant. It is noteworthy that both the absorption of UV photons and the effect of tropospheric ozone lead to intensification of similar oxidizing biochemical processes causing stress of the plants. Thus generated additional tropospheric ozone can be considered as an intensifier of negative effect of UV-*B* radiation on the plants.

It should be noted that, evolutionarily, at the genetic level, the plants have adapted to the normal behavior of variations of UV-*B* radiation, occurring in a wide range daily, annually, as well as in the cycles of solar activity modulating, primarily, the UV solar radiation. Therefore, it is quite natural to inquire if the natural TO deviations from normal behavior quite significantly influence the parameters of annual tree ring.

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Table 1. Correlation coefficients R and confidence intervals $\Delta r_{0.95}$ of the series of relative deviations for the dose of UV-*B* radiation D and TO

$R \pm \Delta r_{0.95}$ (*Edmonton*)				
Wavelength, nm	Full period (07.25.96–12.31.04)	10-day averaging (07.25.96–12.31.04)	Monthly averaging (08.1996–12.2004)	Annual averaging (1997–2004)
300	**–0.673** ± 0.020	**–0.734** ± 0.053	**–0.76** ± 0.08	–0.80 ± 0.29
305	**–0.666** ± 0.020	**–0.740** ± 0.052	**–0.68** ± 0.11	–0.81 ± 0.28
310	**–0.548** ± 0.025	**–0.639** ± 0.068	**–0.55** ± 0.14	–0.81 ± 0.28
N	2896	287	100	8
$(r_{\min})_{0.95}$	–0.094	–0.122	– 0.20	–0.70
$(r_{\min})_{0.99}$	–0.097	–0.152	– 0.26	–0.82
$R \pm \Delta r_{0.95}$ (*Kagoshima*)				
Wavelength, nm	Full period (01.01.91–12.31.01)	10-day averaging (01.01.91–12.31.01)	Monthly averaging (01.1991–12.2001)	Annual averaging (1991–1992, 1994–2001)
300	**–0.488** ± 0.025	**–0.720** ± 0.050	**–0.73** ± 0.08	–0.73 ± 0.31
305	**–0.310** ± 0.029	**–0.499** ± 0.077	**–0.50** ± 0.13	–0.69 ± 0.34
310	**–0.179** ± 0.032	**–0.296** ± 0.094	**–0.28** ± 0.16	–0.64 ± 0.41
N	3613	360	130	10
$(r_{\min})_{0.95}$	–0.092	–0.105	–0.17	–0.62
$(r_{\min})_{0.99}$	–0.096	–0.141	–0.23	–0.75

N o t e . N is the sample size; $(r_{\min})_{0.95}$ and $(r_{\min})_{0.99}$ are minimum significant values of correlation coefficients with 0.95 and 0.99 confidence probability.

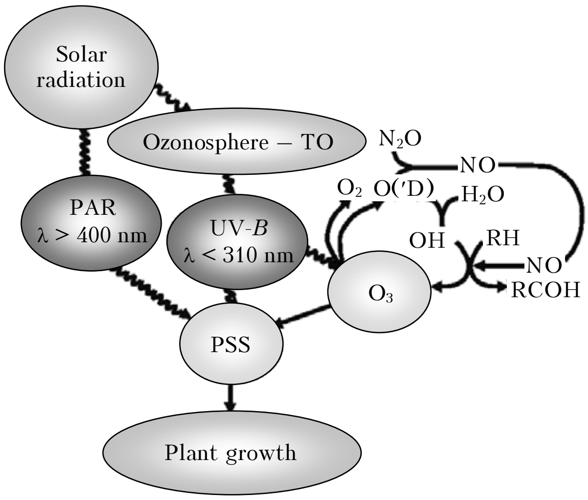

Fig. 1. Scheme of action of UV-*B* radiation on photosynthetic system of plants. PAR is the photosynthetically active radiation; and PSS is the photosynthetic system.

This issue has been the key problem in the integration project of SB RAS No. 95, performed for the three years (2003–2005) by research groups from five institutes of SB RAS: IAO, ISTP, IBP, Sukachev IF, and Budker INP. The results of this project have been summarized in a collective monograph "Bioindication of stratospheric ozone" edited by V.V. Zuev, corresponding member of RAS and, also, the project co-ordinator. The present paper considers the original results, obtained as part of this project in the study of sensitivity of wood plants to long-term intensification of UV-*B* radiation and searching for significant bioindicators of stratospheric ozone in annual rings of coniferous trees.

2. Numerical simulation of long-term effect of UV-*B* radiation and tropospheric ozone on tree system

One of the ways of solving the above-stated problem is to try to take into account the effect of UV-*B* radiation and tropospheric ozone in the existing models of growth and structure of annual rings. Figure 2 shows a block-diagram of the *TREERING* model.[5,6] In the models the environmental factors exert both direct and indirect effects on radial xylem growth.

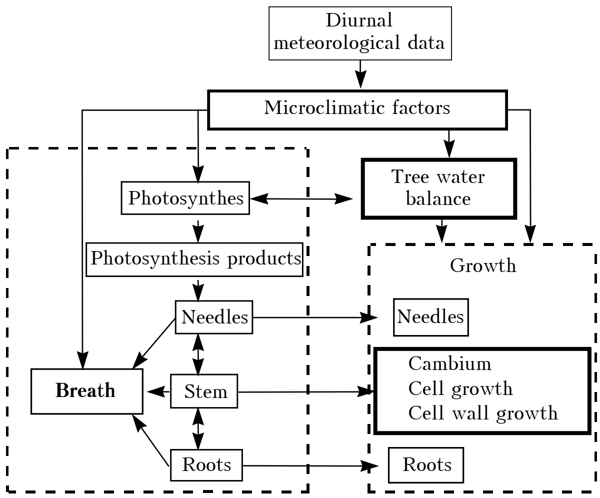

Fig. 2. Block diagram of the TREERING model.

Temperature and moisture regimes of the plant immediately influence cambial cell division and the possibility of the cell differentiation and growth into mature tracheides. Indirectly, through the change of concentration of photosynthesis products, these factors, together with the radiation regime in the PAR range, influence the radial growth. The model incorporates the following processes: seasonal growth of needles, stem, and roots; seasonal dynamics of photosynthesis; breath of the living tissues; water regime of the plant; seasonal dynamics of carbon content in needles, stem, and roots; seasonal rate of xylem growth, cell division rate in the cambium, the rate of tracheide tension and the rate of formation of cell wall for all cells in annual ring during the entire season.

One of the continuous effect of UV-*B* radiation, like that of the tropospheric ozone, may be decrease of the stomatal conductance. In the simulation, the maximum stomatal conductance decreased linearly from one year to another. Figure 3 shows the calculated results in conditional units; they are based on the method of Vaganov and Shashkin[6] and use the data of Turukhansk meteorological station.

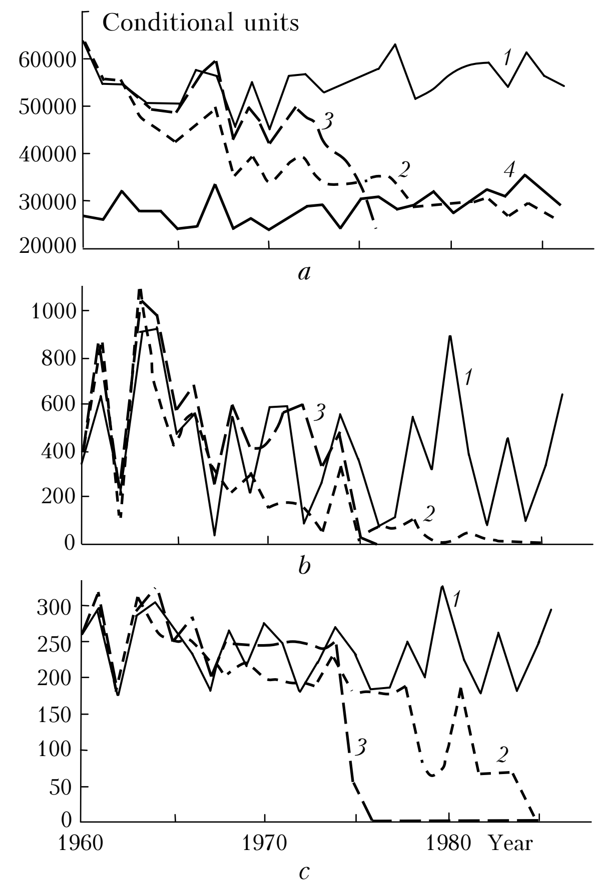

Fig. 3. Dynamics of photosynthesis (*a*), variations of radial growth (*b*), and maximum area of tracheide walls of latewood (*c*) as functions of the following factors: only climatic conditions (curve *1*); climate plus stomatal damage (curve *2*); climate plus decrease of the mass of the root system (curve *3*); and intensity of breath (curve *4*).

It is seen that the main effect of the stomatal conductance is manifested in the value of photosynthesis (Fig. 3*a*, curves *1* and *2*). Marked decrease of photosynthesis took place during third year. This delay is associated with the fact that under these climatic conditions of Turukhansk, the conductivity rarely reaches minimum values, and only when maximum conductivity considerably changes, the photosynthesis decreases. Even more delayed response is exhibited by annual ring width (Fig. 3*b*, curves *1* and *2*). Significant decrease of the growth takes place only in the seventh year. The maximum annual ring density in this model version was found to be less sensitive than the annual ring width (Fig. 3*c*). Change of the stomatal properties is not the only mechanism of destructive effect of UV-*B* radiation. However, change of only this parameter already shows high sensitivity to long-term effect of UV-*B* radiation.

The growth and photosynthesis processes of conifers were also compared using another model constructed on the basis of biochemical photosynthesis model.[7] Analysis of this model shows that, with the decrease of stomatal conductivity, the year-to-year dynamics of photosynthesis does not change as a function of climatic conditions, and only the absolute value of the photosynthesis decreases. Therefore, the breakdown of stomatal conductivity may not alter the qualitative character of influence of climatic factors on photosynthesis. Then, the low-frequency trends may be caused already not by climatic signal but, possibly, by the effect of UV-*B* radiation and tropospheric ozone.

3. Search for new dendrochronological parameters, sensitive to TO variations

Institute of Forest SB RAS studied cell chronologies: cell wall thickness, cell density, roentgenographic density of the cell density, and index of roentgenographic density of the cell wall. Institute of Atmospheric Optics SB RAS studied CO_2 content in annual tree rings and Institute of Nuclear Physics SB RAS studied the chemical composition of annual rings.

Physical characteristics of cell wall

Cell parameters were measured across five radial cell rows in each annual ring using Axioskop 20 microscope (Carl Zeisse firm, Germany) equipped with a computerized video system of image analysis and processing. The measurements were carried out using original methods of the authors.[8] The densitometric data are obtained using densitometric complex DENDRO-2003 (Walesch Electronic, Switzerland). We chose as parameters of the cell structure the cell wall thickness *W*, the cell density, roentgenographic density of cell wall c_w, and index of roentgenographic density of cell wall *Ipw*. Figure 4 shows the main cell parameters of the annual rings measured.

Estimates by Silkin in 2004 and 2005 suggest that c_w and *Ipw* depend strongly on the presence of mineral spots in the composition of envelopes of cell wall. In different trees, growing in the same region, these roentgenographic parameters vary synchronously, thereby reflecting a certain external impact, common to all trees of a tree stand. We revealed interrelation between roentgenographic parameters of cell wall and the sum of monthly mean (May–August) TO of the current growing season (Table 2).

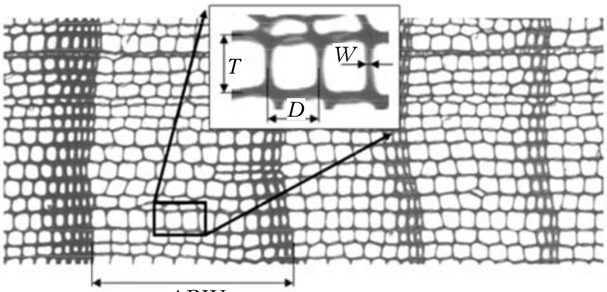

Fig. 4. Section of pine sample: ARW is the annual ring width; *D* and *T* are the radial and tangent cell sizes; *W* is the thickness of the doubled cell wall.

Table 2. Summary table of interrelation of TO and annual ring parameters

Tree species	Annual ring parameter	Significant values of coefficient of correlation with TO for $p < 0.05$	Delay of response, year
Pine	Cell wall density of early wood	0.54	2
	Cell wall density of transition wood	0.58	2
	Maximum density*	−0.5 ... −0.66	1 ... 3
Fir	CO_2	0.59	3
	Calcium	0.53	2
	Iron	0.55	2
Spruce	Calcium	0.48	2
	Iron	0.57	2
	Maximum density	−0.63 ... −0.73	1 ... 3
	Width*	0.55 ... 0.89	3 ... 5

* Observation series have been smoothed over two years.

Laser acousto-optic gas analysis of CO_2 in annual rings of coniferous trees

CO_2 is accumulated in vases, tracheides, and capillary system of the tree, most likely as a deposited plastic substance. From annual rings of fir stem cuts, we extracted the residual carbon dioxide, whose concentration was determined by the method of laser optoacoustic spectroscopy using a CO_2 laser with discretely tunable frequency. The analysis of thus obtained data has shown that the chronologies of residual carbon dioxide concentration in fir wood and TO are significantly interrelated[9] (see Table 2).

Scanning roentgen-fluorescent analysis of annual rings of coniferous trees

Experiments on determination of microelement content in annual rings have been conducted in a scanning mode at the station of roentgen-fluorescent analysis using a beam of synchrotron radiation (SR) from a storage device VEPP-3 (electron energy is 2 GeV, and current of electron beam is up to 100 mA) at the Institute of Nuclear Physics SB RAS according to the scheme shown in Fig. 5.

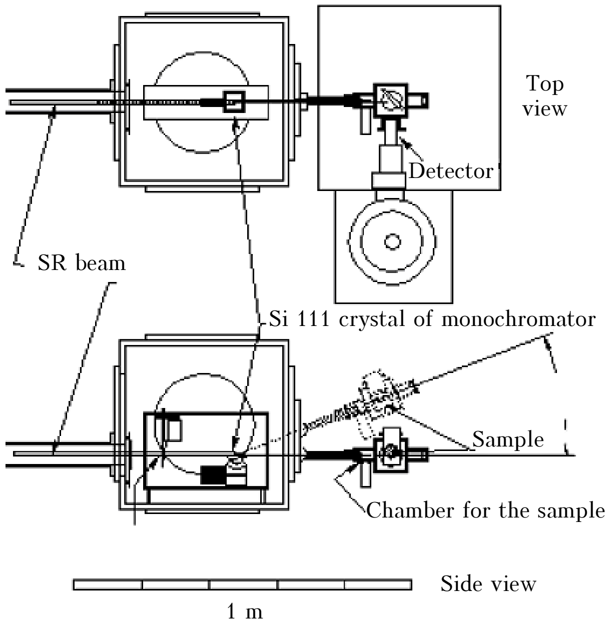

Fig. 5. Block-diagram of the setup for scanning roentgen-fluorescent analysis of annual rings of coniferous trees.

For excitation of fluorescence, we used an SR beam from wiggler with a 2*T* field. The station is equipped with a monochromator based on a Si (111) crystal, permitting generation of monochromatized SR beam with the photon energy in the range from 5 to 46 keV. For recording the fluorescence, we used a semiconductor Si(Li) detector by Oxford Instruments Co., with the resolution of 140 eV (at energy of 5.9 keV). The mass of the measured substance may be $10^{-4} - 10$ g. The detection limit for multielement analysis is $10^{-7} - 3 \cdot 10^{-8}$ g/g. The measurement time is $10–10^3$ s. The station is equipped with a special scanner making it possible to study the samples with length up to 400 mm using variable steps.

Data on the content of the elements were obtained in the wood samples taken in Khaldeevo village, Tomsk Region, where soils are enriched with Fe, Mn, as well as the system of microcomponents (Pb, Cu, Zn, etc.) in amounts not exceeding the background values. Based on the measurement data, we obtained the concentration profiles of the following elements: Cl, K, Ca, Ti, V, Mn, Fe, Ni, Cu, Zn, As, Br, Kr, Rb, and Sr over the entire sample length. The obtained results have made it possible to draw certain conclusions: under favorable conditions, the elements are preserved in the wood of annual ring, whereas under poor conditions at increasing UV-*B* radiation they, most likely, are trapped by the needles at the expense of reduced deposition in the annual rings. Therefore, the correlation between TO and content of the elements such as Ca and Fe is positive (see Table 2). Probably, the reactions of metabolic processes are most intense in the second-year rings, therefore, the shift of the series of analyzed parameters ranges from 1 to 2 years.

Conclusion

The studies we have conducted show that the long-term TO deviations from the climatic norm cause corresponding changes of the biologically active part of UV-*B* radiation at wavelengths shorter than 310 nm and thus noticeably manifest themselves in practically all parameters of the annual rings of trees, reflecting both photosynthesis and metabolism. Both in the measured parameters and in the model calculations, there is a delayed response to changes of TO (UV-*B* radiation), which is characteristic of the cumulative effect, typical for ever-green coniferous plants.[10] This property of coniferous trees makes it possible to obtain a response in annual rings to the effect of UV-*B* radiation, which is not less sensitive than the response to the impact of climatic factors.

Note that all correlation coefficients presented in Table 2 are sufficiently high; therefore, these parameters can be used for reliable bioindication of the stratospheric ozone. From a practical viewpoint, of course, most interesting are the main dendrochronological parameters (annual ring width and density), most widely presented in different databases.

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