New dendrochronological parameter – the result of optoacoustic measurements of CO_2 concentration in the annual rings of trees

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Using the vacuum technology, gas samples have been extracted from the annual fir tree rings and then CO_2 content has been measured in the samples by laser optoacoustic spectroscopy technique. The measured time series of CO_2 concentration were analyzed statistically and relations of thus obtained statistical characteristics with time series of the monthly mean air temperatures for the growing season and with total ozone content over Tomsk have been sought.

Introduction

Dendrochronological parameters reflect plant response to external impacts it underwent in the past. Traditionally, this data are obtained from measured size and density characteristics of an accurately dated annual ring and its elements. Thus obtained information on the tree growth cannot be regarded sufficient, for it does not cover the retrospective physiological-biochemical activity of the plant. In Refs. 1 and 2 it was revealed using laser optoacoustic spectroscopy that CO_2 content (ppm) (residual CO_2) in gas samples extracted from annual tree rings is higher than in the ambient air. We have supposed that this information could be used in dendrochronological research. This work aims at compiling successive yearly series of data on the content of residual carbon dioxide in the annual rings of trees and analyze their statistical characteristics to reveal the relationships between these series, ring width, and the external factors.

Methods and materials

We studied ten discs of the firs taken in a hundred-year old dead-litter fir forest 40 km to the east of Tomsk and three discs of Siberian stone pine taken from a mixed sparse growth of trees on the motley grass south-west slope of the Seminskii Range in Altai. The first discs were made at 70–80 cm above the soil. The width of the annual rings was measured on the disk surfaces by two radii using a semiautomatic LINTAB setup with an accuracy of 0.01 mm.

From every annual ring of these discs, corresponding to the last 24–29 years, we extracted and measured the residual CO_2 using a standard method (Refs. 1 and 2).

We have standardized all the individual tree-ring series by the negative exponent or by a linear function and by the auto-regression modeling in order to have finally the standard (Std) and residual (Res) series (chronologies). The first type of series had the age component minimized and the second one had the autocorrelation component minimized. These series were averaged to make up generalized chronologies. Here, the first order sensitivity and autocorrelation coefficients and the standard deviation were determined (Ref. 3). In a similar way, we processed the residual CO_2 chronologies. The correlation analysis was performed by the Spearmen rank correlation method using the Statistica package for Windows.

To compare the obtained CO_2 series with the external factors, we used the data of the total stratospheric ozone content, air temperature, and precipitation for Tomsk in the period from 1979 until 2004.

Results

In measurements of CO_2 content in the xylem rings it was necessary to understand if the content of residual CO_2 in the tree rings depends on 1) location of the discs on the stem; 2) on the radial orientation on the disc.

To answer the first question, we extracted the residual CO_2 from Siberian stone pine discs made at an 0.5 (*c*) 10.5 (*b*), and 18 m (*a*) height above the surface (the discs were stored at room temperature for six years). The obtained individual gas concentration series (Fig. 1) turned out to be

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synchronous (the synchronism coefficient was 60–76%) and well correlating with each other (the correlation coefficient R = 0.63–0.75).

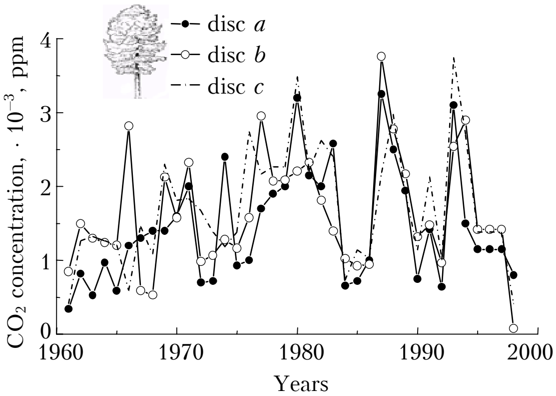

Fig. 1. Variability of CO_2 concentration in Siberian stone pine rings depending on disc location on the stem.

When answering the second question, we chose at random a fir disc hp15 and extracted the residual CO_2 from each of its rings along four radial directions (Fig. 2). Here again the yearly values of gas concentrations are highly synchronous (76–85%) and correlated (R = 0.30–0.70).

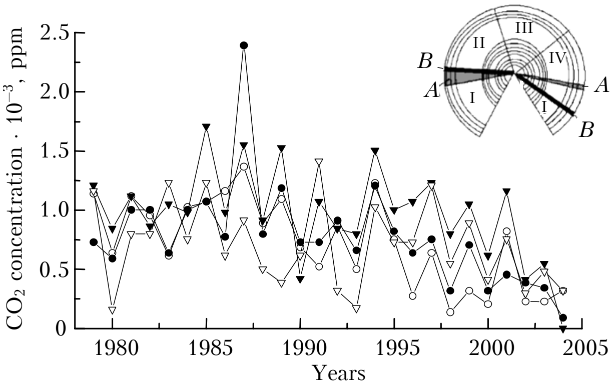

Fig. 2. Variability of CO_2 concentration in hp15 annual disc rings of fir along different radial directions: –○– (I), –●– (II), –▲– (III), –▽– (IV). A refers to the knot area; B is tree ring width measurement area.

Thus, the residual CO_2 content in the wood rings can be regarded independent of the disc location on the tree stem and radial direction on the disc. Therefore, the extraction of the residual CO_2 from the primary wood rings in fir discs was made in the same two radial directions as measurement of ring widths.

For each tree, we have compiled an individual series of measured annual CO_2 concentrations (ppm) (indicated as tree numbers hp11 to hp20 in the table). Then these series were converted to the standard and residual index chronologies for each tree. Thus, overall we have obtained 30 series, for which we calculated statistical characteristics represented in the table. For example, the standard deviations in the experimental measurement series vary from 0.086 to 0.674 and the sensitivity coefficients vary from 0.327 to 0.613 (sufficient is 0.2). The indices of the Std-series have a considerable autocorrelation component. The most apparent reason for this is physiological processes connected with supply, transport, and use of photosynthesis products (Ref. 4) as well as a long-term exposure to soil, phytocenotic, climatic, and other factors (Ref. 5). Using the autocorrelation data, we can suppose that CO_2 may diffuse from one ring to another (neighboring) one. In the individual Res-series as compared to standard ones variance is somewhat lower and the sensitivity is 8–25% higher. Thus, the individual gas concentration series, both the standard and the residual ones, may incorporate climatic signal.

Statistical characteristics of the individual series of the residual CO_2 content in the annual rings of fir

Series	Interval	Series length, years	Sensitivity	Standard deviation	First order auto-correlation
hp11	1977–2004	28	0.470	0.165	0.32
Std	1977–2004	28	0.469	0.476	0.34
Res	1978–2004	27	0.514	0.435	–0.02
hp12	1977–2004	26	0.357	0.086	0.05
Std	1977–2004	26	0.358	0.318	0.01
Res	1980–2004	25	0.320	0.295	0.01
hp13	1979–2004	26	0.327	0.178	0.38
Std	1979–2004	26	0.326	0.380	0.33
Res	1980–2004	25	0.378	0.365	0.05
hp14	1976–2004	29	0.613	0.674	0.46
Std	1976–2004	29	0.629	0.820	0.42
Res	1977–2004	28	0.787	0.561	–0.34
hp15	1979–2004	26	0.525	0.162	0.40
Std	1979–2004	26	0.530	0.426	–0.14
Res	1980–2004	25	0.487	0.430	0.00
hp16	1981–2004	24	0.459	0.405	–0.01
Std	1981–2004	24	0.455	0.803	–0.14
Res	1982–2004	23	0.490	0.813	–0.02
hp17	1979–2004	26	0.597	0.152	0.19
Std	1979–2004	26	0.596	0.480	0.18
Res	1980–2004	25	0.666	0.484	–0.06
hp18	1979–2004	26	0.465	0.122	0.18
Std	1979–2004	26	0.465	0.452	0.17
Res	1980–2004	25	0.502	0.450	0.05
hp19	1979–2004	26	0.557	0.132	–0.26
Std	1979–2004	26	0.557	0.544	–0.27
Res	1981–2004	24	0.386	0.432	–0.04
hp20	1979–2004	26	0.335	0.321	0.41
Std	1979–2004	26	0.333	0.383	0.23
Res	1980–2004	25	0.367	0.370	–0.10

Of interest are the statistical characteristics of the fir tree numbered as hp14 (see the table). In its residual individual series, it has a high autocorrelation (–0.34) at a high sensitivity (0.787) and standard deviation (0.561). For the last 25 years, this tree has grown by 134 mm (on average for this period, the rings show a yearly growth of 5.4 mm). It is the highest growth rate among the considered trees. We analyzed the growth history of this tree by studying the diagram of transverse stem diameter growth on a semi-logarithmic scale (Ref. 6) and found that until the 1980 its growth was extremely suppressed, probably, by the neighboring trees. From about the 1980, the phytocenotic situation around the fir must have sharply improved and let it quickly pick up in stem biomass. Strong growth promoted an intensive surge of plastic substances to the growth points, which disbalanced the distribution of the emergency plastics and the current photosynthesis products among different metabolites (Ref. 7). This resulted in an inadequate response of the tree organism to external factors during this period.

Now, for analysis of the relations between the residual CO_2 in tree ring and other parameters, we use the chronologies of the residual CO_2 content obtained by averaging the individual series upon discarding occasional bursts and the hp14 fir with its inadequate response. In dendrochronology this is known to be the residual generalized chronology. The relations of the generalized CO_2 content chronology with the time series of temperature and precipitations for the vegetation period for Tomsk are statistically negligible (R varies from −0.10 to −0.27), but they get stronger in a two-year time shift. For example, the average temperature for the periods from February to March in the most recent two years is closely connected with the residual CO_2 in tree rings (R = −0.82). Probably, the higher the temperature, the more active the processes in a tree and the less amount of biologically active substances reserved.

We have compared the dependence of the residual carbon dioxide concentration in a tree ring on its width (Fig. 3). For this purpose, experimental data were converted into the relative indices.

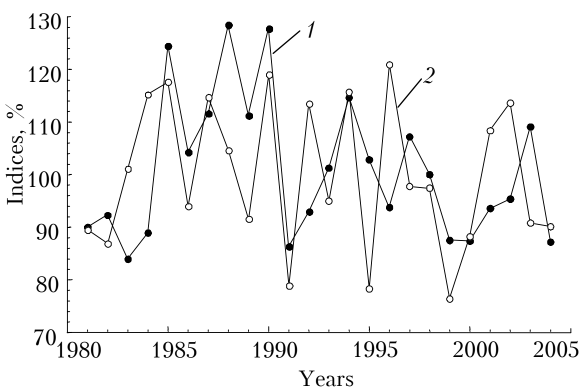

Fig. 3. Generalized Res-chronologies of CO_2 content and annual fir ring widths: CO_2 (*1*); widths (*2*).

The relationship (R = 0.40) between them is established to be weak. These parameters are of different nature and, probably, the extent of their dependence on external factors is also different. Nevertheless, gas concentration is connected with the width of the ring of the preceding two years of its growth. The highest value (R = 0.61) is fixed with a two-year shift between the series. Perhaps, the gas can partially spread within the two neighboring rings of the xylem. For example, the experiments with tagged carbon $C^{14}O_2$ have demonstrated that most of it is concentrated in the several rind-adjacent rings except the current-year ring (Ref. 8). Though in the experiments the authors dealt with a growing tree, we suppose that such CO_2 distribution may conserve in discs. Thus, we accept the viewpoint that CO_2 is actively transported to the other rings rather than over the current year ring.

Comparing the CO_2 concentrations with the total stratospheric ozone content for the vegetation period expressed in indices (Fig. 4), we see that the relationship between them is the same (R = 0.59 at a probable level of $p < 0.002$), but the time shift is now greater: three years.

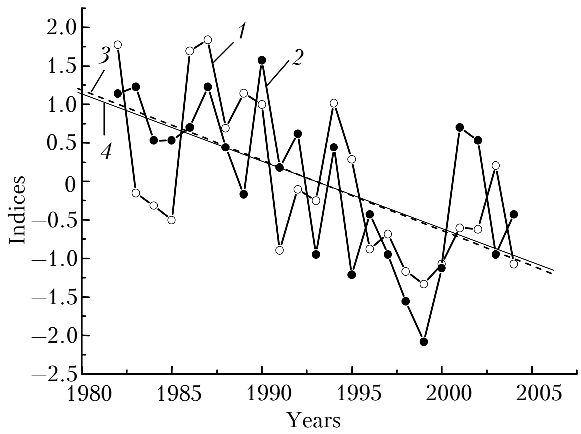

Fig. 4. The generalized chronology of CO_2 content in annual fir rings and a series of average (April-August) values of the total ozone content (TOC): CO_2 (*1*); TOC (*2*); TOC trend (*3*); CO_2 trend (*4*).

Probably, through the "stratospheric ozone – UV radiation – tropospheric ozone" chain this factor cumulatively affects the physiological–biochemical processes in a plant, which in its turn determine its CO_2 content as a storage plastic substance.

Conclusion

The statistics of measurement data allows us to consider the yearly variations of residual CO_2 in tree rings as a new dendrochronological parameter. Together with size and density characteristics of a ring, it will allow a more thorough study of the tree organism response to external factors, facilitate understanding of changes in plant states and its physiological–biochemical functions in the past.

The concentration of CO_2 in a xylem does not depend on location of discs on the stem and radial direction on the discs. The main statistical characteristics of individual gas content series bear a climatic signal. Temporal variation of carbon dioxide concentration is connected with the width of a certain ring as well as with the total ozone content.

Acknowledgments

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