Relationship between long-period variability of the atmospheric ozone layer and UV-B induced variability of wood density

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Correlation between dendrochronological time series of conifers from International Tree-Ring Data Bank and chronology of total ozone at Arosa station, Switzerland, are analyzed. The strongest correlation is observed for such a characteristic as wood density. The negative correlation between chronologies of the mean density and total ozone, such as for Stone Pine, exceeds 0.6 in the absolute value. Ozone absorbs UV radiation in the same wavelength range as the molecules of living cells. The thinner the ozone layer, the higher the level of solar UV radiation reaching the Earth's surface. The UV B radiation causes plant shock depressing the growth of plant cells. This process has biological consequences in the tree rings, thus allowing the use of dendrochronological series for qualitative reconstruction of the total ozone in the vegetation season (April–September).

Introduction

Prediction of the ozone layer evolution in the Earth's atmosphere is still a subject of a wide discussion. As known, the tendency to ozone depletion observed since the late 1970's through the early 1990's was associated with the production and atmospheric emissions of ozone-destroying substances, first of all, freons. As a result, the Montreal Protocol of 1987 prohibited production of such substances. Because of the long lifetime of freons in the troposphere, the consequences of this prohibition could be seen not earlier than in the second quarter of the XXI century (in Russia, for example, the production of ozone-destroying substances has been completely terminated only in December 2000). However, after a long ozone depression lasting more than four years after Mt. Pinatubo eruption (June 1991), in 1996 the content of the tropospheric ozone began to increase, achieving the level of the 1970's during two years as quickly.[1]

It is impossible to relate that quick growth of the stratospheric ozone to realization of the measures declared by the Montreal Protocol. It is obviously caused by some other, most likely dynamic factors. However, the change in the stratospheric circulation can be caused by both natural and anthropogenic factors, for example, the effect of greenhouse gases. In this relation, the problem on predicting the future behavior of the ozone layer is similar to prediction of the climate changes.

As known, one of the approaches to investigation of the future climate is in the study of paleoclimate. The statistical prediction of the total ozone content (TOC) in the atmosphere, as well as prediction of any other climatic parameters, can also consist in judging the behavior of the ozone layer based on the statistical characteristics in the past. One of the stages of statistical prediction is selection of predictors. Unfortunately, the relatively short period of observations over the ozone layer does not allow us to track the long-period global atmospheric processes connected with long cycles of solar activity. The longest series of TOC observations in the atmosphere since 1926 is obtained at Arosa, Switzerland (46°78′ N, 9°68′ E). The satellite monitoring of TOC was started only in 1978. Therefore, it is interesting to find characteristics of longer time series connected implicitly with the TOC observations.

It is generally accepted that dendrochronological series contain a lot of information on natural ecological systems. The series of data available in the Internet form an extensive information network and are statistically reliable. For different sorts of wood species, time series are available for such characteristics, as the width of an annual ring of a tree, width of an annual ring of early wood, width of an annual ring of late wood, and maximum and minimum wood density. The width of an annual ring is widely used as a predictor of climate changes. Thus, numerous publications on paleoclimate studies are devoted to reconstruction of temperature and the amount of precipitation from the dendrochronological data series. It is clear, because just the temperature and the amount of precipitation are the main limiting factors in the formation of a tree annual ring. Meanwhile, these factors are not the only ones. The tree growth rate is also affected by biological and genetic features, age of a tree, the level of incoming solar radiation, and many other factors. Thus, the questions arise: on what is the effect of the ozone layer on the dendrochronological characteristics and which of them can be used as predictors of changes in TOC?

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The aim of this paper is to answer these questions and to justify selection of the predictor of TOC changes from characteristics of the dendrochronological series. For this purpose, let us consider the relationship between the long-term variability of the atmospheric ozone layer and the variability of characteristics of the tree radial increase due to UV-B radiation.

Statement of the problem

We should differentiate the effects of tropospheric and stratospheric ozone on the growth and productivity of plants. Tropospheric ozone has a direct effect on a plant by penetrating inside it through respiratory stomas and changing biochemical and physiological processes in cells. It is well known, in particular, that the annual growth of pines decreases, as the concentration of ozone in the near-ground atmosphere increases.[2] The effect of stratospheric ozone on the plant growth is certainly implicit and connected with the stress induced by the UV-B radiation controlled just by the ozone layer. This stress causes a decrease in the green biomass (decrease of the tree conifer, increase of needle density in conifers, etc.). It should be emphasized that the increase in the level of UV-B irradiation can provoke the increase in the tropospheric ozone[3] due to excess generation of the very strong oxidant – OH hydroxyl, which plays a key part in the tropospheric ozone cycles. Thus, the stress effect on plants may be even doubled, as the UV-B radiation increases.

Ozone absorbs solar UV radiation in the same wavelength region as molecules of living cells. It is commonly known that the thinner the ozone layer, the higher the level of solar radiation reaching the Earth's surface. The mean intensity of the solar UV-B radiation and its variability strongly depend on the latitude and the angle of sun elevation. Therefore, the UV-B-induced change in the plant growth is directly connected with the place of inhabitancy. For example, the maximum TOC fluctuations are observed in the middle and polar latitudes. Dendrochronological studies (imitation model from Ref. 4) usually deal with the effect of irradiation on plants in the visible spectral region, and spectral variations of radiation are ignored. Nevertheless, just the changes in the spectral composition of the incident radiation, especially, in the UV-B region affect the annual growth of plants.

For most investigations of the effect of UV-B radiation on plants, the experimental data were obtained under laboratory conditions largely for green biomass (for leaves or needles). It is absolutely clear that to find changes in the ecosystem caused by long-term fluctuations of the UV-B irradiation, one- or two-year cycles of observations are insufficient, and at least decade- or century-long studies are needed. Dendrochronological series give a material, which was collected for an interval longer than 200–400 years. However, it should be kept in mind that, as follows from the literature, not all sorts of plants are equally sensitive to UV-B radiation. For example, among all conifers, a pine is most sensitive to the UV-B radiation.[5] The effect of UV-B radiation consists mostly in the change of the wood density.[6]

When analyzing dendrochronological series, we should consider physical and geographical factors as well. The seasonal growth of trees occurs in different periods at different latitudes. These periods start from different dates, but terminate roughly at the same time. Moreover, in the same geographic region, the date of beginning of the seasonal growth and its duration depends on the height above the sea level and the terrain.[4] Therefore, dendrochronological series for comparison with TOC data should be taken for the same place. For analysis, we took chronologies of conifers from International Tree-Ring Data Bank.[7]

Results and discussion

For Switzerland, the dendrochronological series are represented mostly by conifers. For example, for the place near the Arosa resort, these representatives are Norway Spruce, Stone Pine, European Fir, and European Larch. The vegetative period for trees in Arosa is since April through September.

Standardized chronologies of conifers for this place include the following wood characteristics: width of an annual ring, ring width for early and late wood, maximum and minimum wood density. It is usually assumed that the biological response of conifers to the UV-B radiation is delayed for 1–2 years,[8] therefore the analysis was performed for time series smoothed over two years. In the time series selected for analysis there is no autocorrelation (the effect of tree age) and the trend is subtracted.

The results of the correlation analysis are given below in the Table. The relation between TOC and the mean wood density is most pronounced, especially, for the stone pine. The larch is more sensitive to fluctuations of temperature and humidity than other conifers analyzed. Therefore, the less pronounced factor affecting larch did not find a significant response.

Table. Results of correlation analysis

File name in data bank	Time boundaries of chronologies, year	Sort	Geographic coordinates (N – E)	Ozone/ mean wood density correlation
Swit107.....dat	1690–1975	Norway spruce	46°48′ – 9°41′	–0.42
Swit109.....dat	**1788–1974**	**Stone pine**	**46°24′ – 8°01′**	**–0.63**
Swit111.....dat	1792–1974	European larch	46°24′ – 8°01′	–0.15
Swit113.....dat	1822–1980	European fir	46°18′ – 7°37′	–0.4

The density of a wood cell is estimated as the ratio of the cell wall area to the area occupied by the cell in the cross section. The characteristic "wood density" is a sum of densities of all cells. The density of annual rings is less subjected to age changes than the ring width; however, it also depends on both internal and external factors. There are some physiologically unclear results indicating toward the correlation between the maximum density and temperature for five-day periods. If such years are excluded from the series, the correlation with temperature becomes insignificant. Experimental studies show that the number of cells of late wood and the thickness of cell walls are affected by irradiation and photoperiod.[4] The wood density of conifers has a negative correlation with the ring width. The tree growth accelerates due to widening of the early wood layer, what causes the decrease in density.[9]

It follows from Fig. 1 that the mean TOC values for April–September correlate most closely with the mean density of the angular ring. The absolute value of the negative correlation between the chronologies of the mean density of the stone pine and TOC exceeds 0.6, while similar correlations are 0.46 for series with the maximum wood density and 0.58 for the series with the minimum wood density.

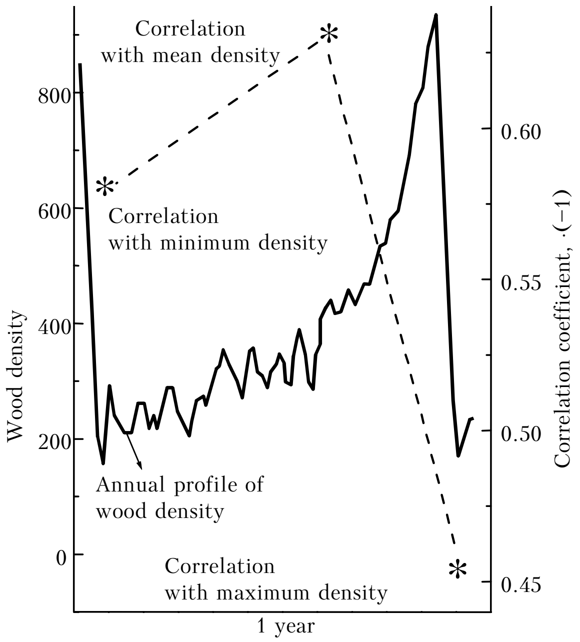

Fig. 1. Correlation of mean TOC for April–September with wood density. Annual profile of wood density is plotted according to Ref. 10.

In Fig. 2 we can see how the plant response to variations in the stratospheric ozone changes from month to month during the vegetative period. Thus, considering the possibility of reconstructing TOC changes from April to August, the correlation is stronger than –0.66, and TOC variation from June to August is reconstructed best of all from time series of minimum wood density (–0.648).

It is clear that the physiologically explainable level of UV-B effect on the dendrochronological signal cannot exceed the total effect of humidity and temperature. Therefore, this effect is most pronounced in remains. To resolve the time series of wood density into simple components, we used the Caterpillar method (Russian analog of Singular Spectrum Analysis).[11] This method is based on transformation of a one-dimensional series into multidimensional one with the use of a one-parameter-shifted procedure. The method allows the time series to be resolved into the components and reconstructed based on selected basic components. In our case, a good result can be obtained from the sum of the first (31.2%) and third (10.96%) components, when the series is resolved into 21 components.

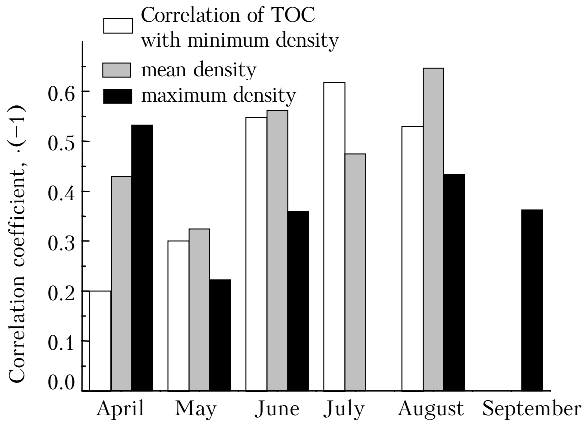

Fig. 2. Correlation of TOC with wood density for different months of the vegetative period.

When preparing data for analysis, trends were excluded from time series by the method of linear regression, and the absolute values of parameters were transformed into dimensionless indices for comparison of parameters having different variability ranges. For this purpose, we used the Statistica program, which includes a standardization procedure consisting in calculation of the values of time series by the following equation:

$$X(t) = (X(t) - \text{MEAN})/\text{STD},$$

where $X(t)$ is the value of a series variable; MEAN is the mean value of the series; STD is the standard deviation.

Figure 3 depicts the relation between time series of TOC indices for the vegetative period from April to September and the indices of the 43-% component separated from the dendrochronological signal: the level of correlation is –0.79. For the years, when the level of radiation increased in annual tree rings, the mean wood density increased markedly. Unfortunately, the time scope of the correlation analysis is limited, because the dendrochronological series for Arosa are published in the Internet only until 1974, while the data on TOC are available until 1997. Therefore, the studies should be continued for a wider data sample and for different geographic locations. The results obtained already now allow the dendrochronological data on the wood density to be used for qualitative reconstruction of the total ozone from year to year in the period of biological activity of trees.

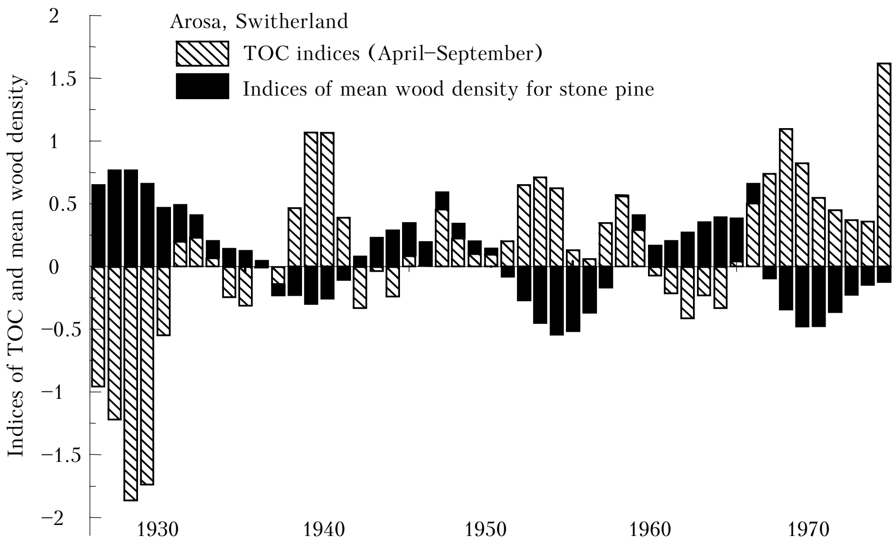

Fig. 3. Correlation of the mean TOC for April–September with 43-% component of wood density for the period from 1926 to 1974.

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