# Cyclic variations of gas components in tree-ring chronologies as response to climatic cycles

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**Abstract**. Vacuum-extracted gas samples from tree-ring wood of stems and large roots of some conifer species (of Tomsk oblast) are studied using a photoacoustic laser gas analysis. The retrieved $CO_2$, ($CO_2$+$H_2O$) chronologies are analyzed by spectral and cross-spectral analysis methods. A quasi-cyclic character of variations of the chronologies has been revealed, which is probably due to changes in climatic conditions and solar activity.
Keywords: ($CO_2$ +$H_2O$), $CO_2$, disc tree-ring wood, cyclicity.

## 1.Introduction

Forests are unique integral bioindicators of the processes occurring in the environment. Any tree possesses a unique feature characterizing the past year by growth of an annual ring formed under the influence of the habitat temperature and precipitation. Analysis of long chronologies of tree-ring widths allows one to establish a correlation between tree-ring widths and climatic parameters and, in some cases, even reveal the effects of solar activity variations on the tree-ring growth. The first results of search for the "solar signal" in the tree-ring chronologies were obtained in the fundamental works of astronomer A. Douglass. He believed that the solar activity variations influence the climate, especially the quantity of precipitation, and since the tree-ring chronologies retain the climatic signal, they could be used to reconstruct the characteristics of the solar cycles [1-3]. However, the mechanisms of influence of the solar activity variations on the earth climate are still debatable in many respects [4]. The influence of the Sun can be via the interaction of the earth atmosphere with the electromagnetic and corpuscular solar radiation, as well as through the solar wind modulation of the galactic cosmic rays.

The solar radiation intensity is changeable. Its greatest variations are related to the 11-year cycle of solar activity (the Schwabe-Wolf cycle). The maximum variation falls within the short-wave range of the solar spectrum. However, the radiation flux integral over the spectrum (the solar constant) changes little, by a value of ~0.1 % [4, 5]. The solar activity level is often characterized by the number of sunspots (the Wolf number). It correlates well with the short-wave solar radiation flux [4] as well as, at a statistically significant level, with the solar constant [16]. Sunspots were observed as early as 1610 [7]. In 1947, instrumental measurements were started of the flux of radio-frequency emission of the Sun at a 10.7-cm wavelength (the corresponding frequency is 2800 MHz), which depends on the solar activity level, and correlates with the sunspot number and the fluxes of short-wave radiation of the Sun [4]. In spite of the small changes in the solar constant, they are supposed to have a modulating influence on the local (regional) climate [8, 9], which can be more sensitive to changes in the solar activity [4, 10].

Annual rings, with their exact dating, show year-after-year changes in climatic conditions. Application of spectral, cross-spectral, and wavelet analysis methods to long chronologies of the ring widths allows revealing cycles that can be related to solar cycles [11]. However, the formation of annual tree rings and the cell growth are inseparably linked with the growth cell respiration, i.e. with the release of $CO_2$, whose main source is believed to be the respiration of the inner cells of the tree bark, cambium and xylem (although an experiment on the addition of the isotope C $^{13}$ to the transpiration flow has shown that the major part of $CO_2$ arrives from the root system [12]). Our experiments showed that a part of the $CO_2$ or ($CO_2$+$H_2O$) respired by the trees remained in the porous ring wood and, thus, there actually existed the pattern of the year-by-year distribution of the gases that remained in the tree stem (or a disc) [13]. We showed that the distribution of the stem $CO_2$ in the annual rings was related to the climatic parameters [14]. The variations of the solar activity could be manifested in the $CO_2$ chronologies via the modulation of the climatic parameters and/or the direct influence on the plant photosynthesis. Therefore, it is possible to expect a solar signal in the $CO_2$ and the ($CO_2$+$H_2O$) chronologies.

We believe that the disc porous wood can keep a fraction of the transpiration water and, in it, a part of the $CO_2$ respired by the plant. The subject of this paper is to study the ($CO_2$+$H_2O$) chronologies. The article shows the results of an investigation of the ($CO_2$+$H_2O$) chronologies and compares them to the earlier results for the $CO_2$ chronologies. This work can be interesting to specialists dealing with the problems of the atmosphere-biosphere exchange. It can also be useful for dendroecologists, dendrochronologists, and experts engaged in the estimation of the climate effect on large forests.

## 2. Materials and methods

Pine forests are most widely spread in Tomsk oblast where Siberian stone pine and larch are codominants. Practically all ripe and overmature plantations of all types of forest are 120-150 years old [15, 16]**.** Our investigations are presented by results for discs of pine (*Pinus sylvestris* L.), spruce (*Picea obovata* Ledeb.), larch (*Larix sibirica* Ledeb.), and Siberian stone pine (*Pinus sibirica* Du Tour), i.e. the main representatives of coniferous trees of the region. By the present time, 2000 vacuum-extracted gas samples from the wood of stem and root discs have been investigated. They were kept under laboratory conditions for a period of 3 months to several years. To analyze the content of the residual gases in the roots, large roots of the pine and Siberian stone pine stumps were separated. We investigated 47 (out of 59) tree rings of the pine root (the diameter is ~8 cm, the length is ~22 cm) and 21 (out of 28) tree rings of the Siberian stone pine root (the diameter is ~ 11 cm, the length is ~30 cm). It should be noted that our method is applicable even to very old discs, since it was found that the tree-ring wood can retain bound water with the $CO_2$ dissolved in it for a long time irrespective of the storage conditions of a disc.

The experimental procedure is described in detail in [13, 14, 17]. The wood of each tree ring was planed and placed in an exposition chamber, and a short-term vacuum was created for the gases sorbed by the wood to get into the chamber. At the same time, the pressure of the extracted gas sample was measured. The variations of the composition of the extracted samples were investigated using a laser photoacoustic (PA) spectrometer, with a frequency-controlled $CO_2$ laser as the source. The measurement results were collected in a file, in which a PA signal was recorded by the absorption at four laser lines: 10 ***P*** (20, 16, 14) coinciding with the $CO_2$ absorption lines and 10 ***R*** (20) coinciding with the $CO_2$ and $H_2O$ absorption lines. Measurements at the ***R*** (20) line allow recording the signal from the sum of the gas components ($CO_2$ +$H_2O$). In this case, the PA signal is stronger than in the case of detecting only $CO_2$. Since we believe that the wood retains a part of the transpiration water together with a part of $CO_2$ respired by the plant, the aim of this article is to investigate the ($CO_2$+$H_2O$) chronology. As the need arises, it is possible to obtain data of the year-by-year variations of water vapor in the annual tree rings by subtracting the $CO_2$ signal from the ($CO_2$+$H_2O$) signal at the line 10 ***R*** (20). It should be noted that preliminary calibration of the detector allows determining the partial pressure of the gases under study.

The article also presents the results of the isotope analysis of carbon in $CO_2$ extracted from the tree-ring wood to prove that the $CO_2$ under study did not get from the atmosphere. It is well known that in plants like a conifer, $\delta^{13}C$ varies within (–22) – (–32) ‰ [18], whereas in the atmosphere the average value of $\delta^{13}C$ = –8.5 ‰ [19]. The relation of the stable isotopes ($\delta^{13}C$) of wood $CO_2$ was measured

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with an accuracy of 0.5‰ (at a 0.95 confidence interval) with the help of mass-spectrometer DELTA V Advantage in the Laboratory of the Isotope Methods (Tomsk, Russia).

In roots it may be hard to accurately separate the wood of a current year from the wood of the previous year because of narrowness of the annual tree rings (as in the pine root) or the light color of the late wood (as in the Siberian stone pine root). Therefore, the error of dating of the root tree rings is taken equal to 1 year.

The $CO_2$ and ($CO_2$+$H_2O$) chronologies were studied using the methods of spectral, cross-spectral, and wavelet analysis. In a number of cases, the fast Fourier transform from the ORIGIN graphic software was used.

We used the sunspot numbers as an index of solar activity (http://sidc.oma.be/sunspot-data/).

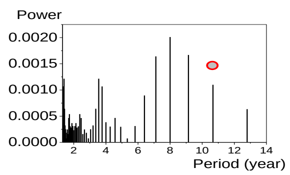
## 3. Experimental results

### *3.1. Isotopic analysis*

By now, the isotope carbon composition of more than 80 samples desorbed from tree rings of the discs of different conifers has been investigated. The results show that the gas samples desorbed from the discs of the stems of Siberian stone pine, pine, larch, and spruce are enriched with the light isotope, $^{12}C$. The $\delta^{13}C$ values approach −25.3‰ for the spruce disc, vary between −25‰ (1894) and −36.4‰ (1986) for the stone pine discs, between −25 ‰ and −30‰ for larch, and between −25 ‰ and −34‰ for pine [13]. The value of $\delta^{13}C$ equals to − 27‰ for the Siberian stone pine root and varies within (−33.5) ‰ ÷ (− 27) ‰ for the pine root [17]. Therefore, the investigated $CO_2$ has biogenic origin and did not get into the wood of the trees from the atmosphere.

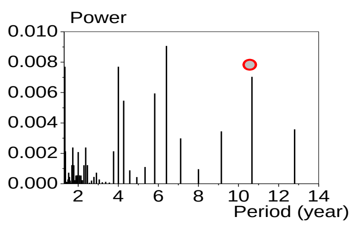
### *3.2. Fourier analysis of the chronologies*

Figure 1 presents the Fourier spectra of the ($CO_2$+$H_2O$) chronologies for the pine (a, b, c, d, e, f) and spruce (g, h, i, j) discs (N is the sample number equal to the tree number). The polynomial trend of the 6th order was first removed from the data.



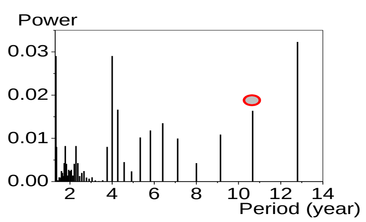

a)

N=36, 1979-2014



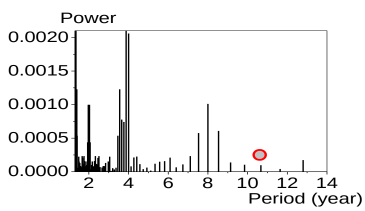

b)

N=48, 1968-2015




c)

N=55, 1956-2010 (alive pine)




d)

N=90, 1916-2005

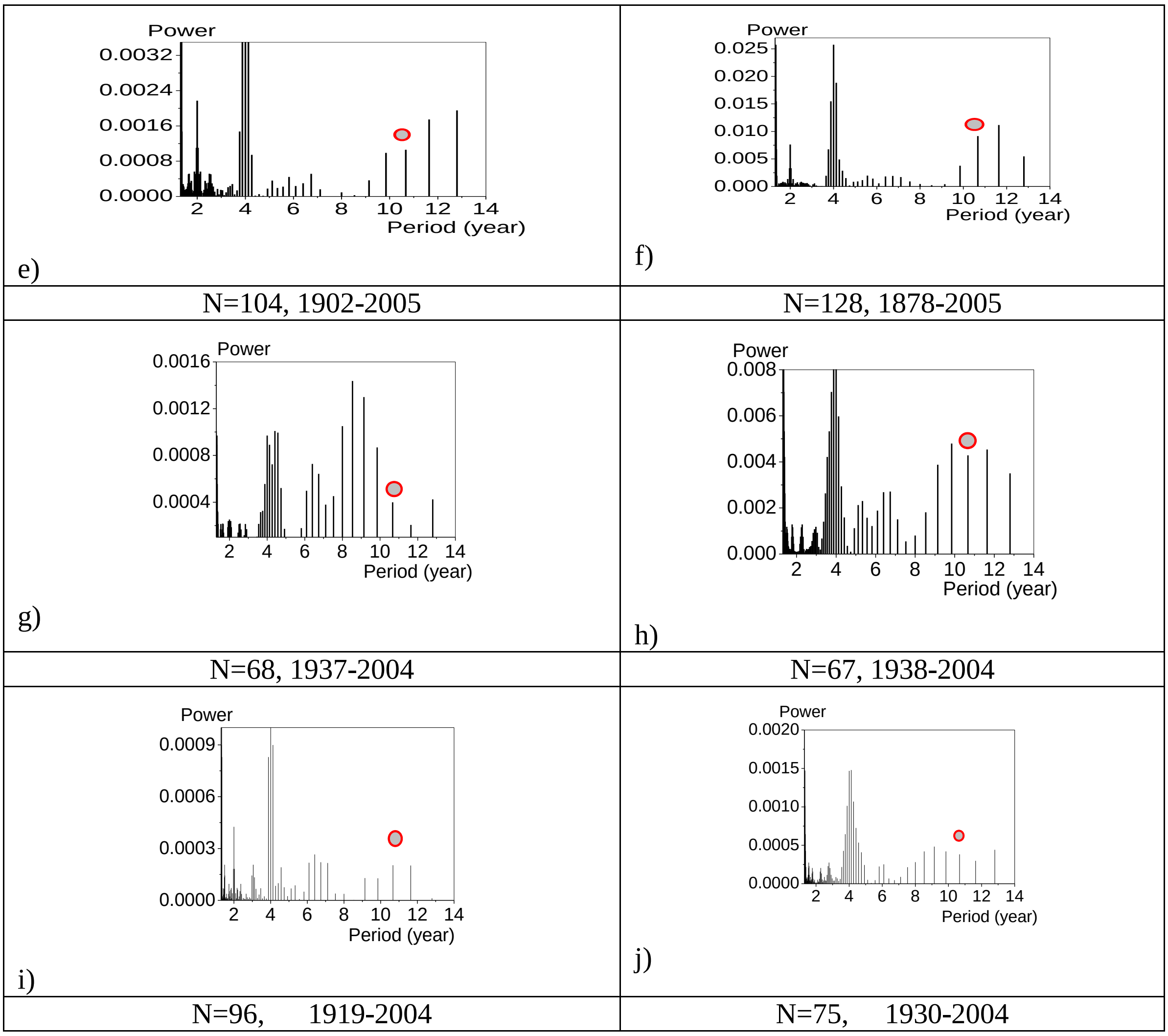



**Figure 1.** Fourier spectra of the ($CO_2$+$H_2O$) chronologies for the annual tree ring wood of the pine and spruce discs. N is the ring number.

The figure shows that the Fourier spectra of the ($CO_2$+$H_2O$) chronologies of the annual rings of conifers growing in the same region (West Siberia, Russia) are characterized by maxima with a period of ~4 years and often by maxima in periods of 2 and 6-8 years. Besides, some spectra have maxima with a period of ~10 years. Earlier ($CO_2$+$H_2O$) chronologies for the Siberian stone pine discs (*Pinus sibirica* Du Tour) and larch discs (*Larix sibirica* Ledeb.) were obtained for the same region [14, 20]. The Fourier spectra of these chronologies are shown in Figure 2. They have the same maxima as in Figure 1.

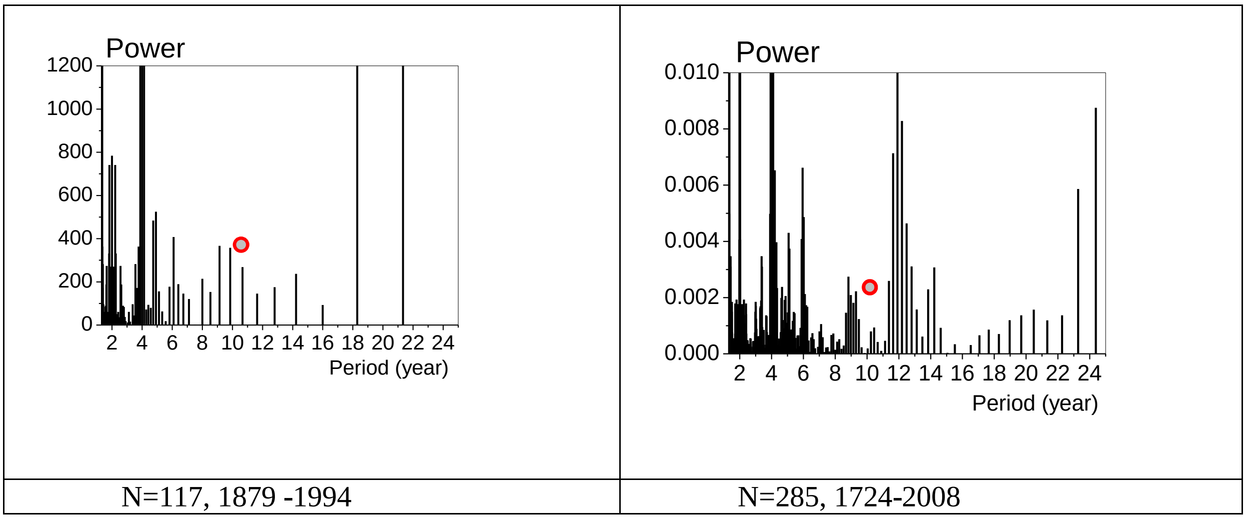



**Figure 2.** Fourier spectra of the ($CO_2$+$H_2O$) chronologies for Siberian stone pine (a) and larch (b).

The results of analysis of the cyclic behavior of the ($CO_2$+$H_2O$) chronologies of the discs of the tree stems can be supplemented by the results of analysis of the ($CO_2$+$H_2O$) root chronologies. Figure 3 presents the Fourier spectra of the ($CO_2$+$H_2O$) chronologies for the discs of the pine and Siberian stone pine roots. The polynomial trend of the 3rd order was first removed from the data. On the whole, the characteristic features of the spectra (the spectral maxima) agree with the results for the tree stems.

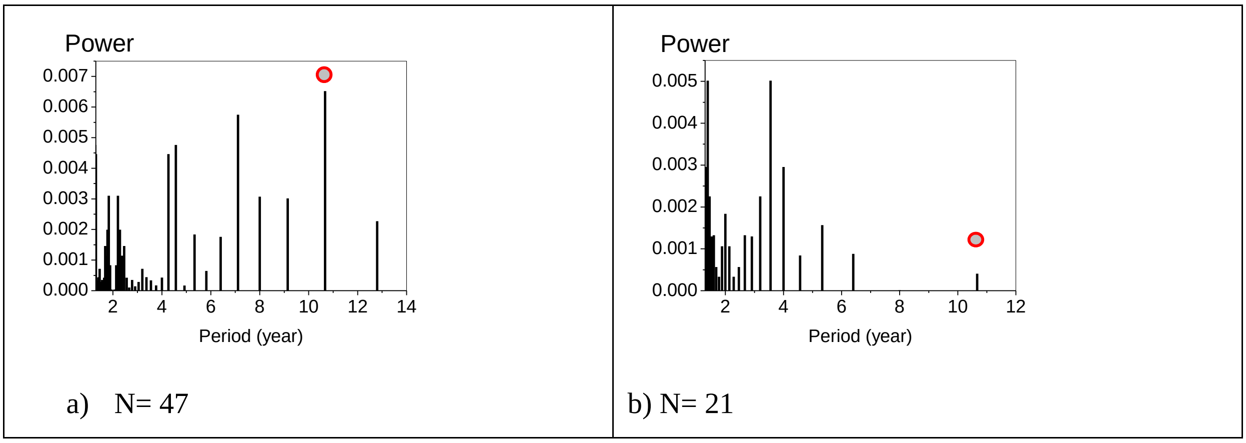



**Figure 3.** Fourier spectra of the ($CO_2$+$H_2O$) chronologies for the pine root (a) and the Siberian stone pine root (b).

In our paper [17] related to a study of variation of pressure in wood-ring root samples it was found that the concentration of the residual (retained) $CO_2$ in the root wood of pine and Siberian stone pine varied in the annual rings within (400-2000) ppm, and in the $CO_2$ chronologies, as well as in the pressure chronologies, there were spectral maxima with periods of ~ 4 and ~10 years. A cross-spectral analysis of the ($CO_2$+$H_2O$) chronologies for the Siberian stone pine root showed that the 4-year variations were coherent with the similar variations of pressure and were approximately in anti-phase to them.

*3.3. Cyclicity of the climatic chronologies*

The results obtained show that the chronologies of the gas and pressure in the vacuum-extracted samples from the annual ring wood are characterized by quasi-cyclic variations. To interpret these results, we analyzed the chronologies of the habitat precipitation and air temperature. Earlier we found a relation of the $CO_2$ variations in the annual rings of the stem discs of Siberian stone pine to climatic parameters [16]. Figure 4(a, b) shows the power spectra of the vegetation-period mean precipitation and air temperature in Tomsk calculated with the maximum entropy method. The spectra contain maxima with periods close to 4 years, and the temperature spectrum also has a distinctive quasi-decadal maximum.

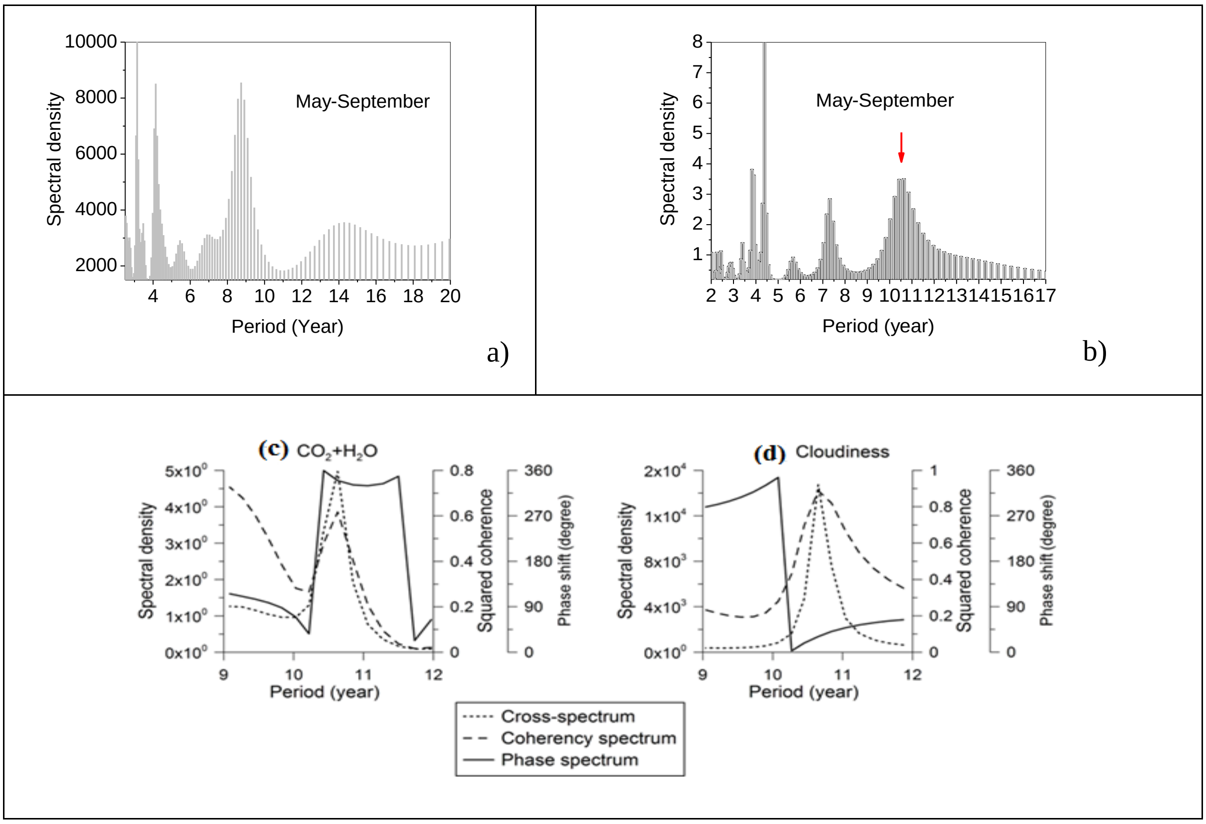



**Figure 4.** Power spectra of precipitation (a) and air temperature (b) in Tomsk for the vegetation period from May to September; results of cross-spectral analysis of the ($CO_2$+$H_2O$) content in the wood of the annual rings of the Siberian stone pine (c) and warm-period mean cloud cover over Tomsk (d), on the one hand, and the sunspot number, on the other hand.

Thus, taking into account the results of [14], the 4-year variations of the ($CO_2$+$H_2O$) chronologies can be related to the 4-year variations of air temperature and precipitation. The mechanism of the relation was proposed in [14]. To this we can add that, apparently, a periodic increase in the summer precipitation produces an overpressure in a root, which, in turn, increases the pressure in the stem. The pressure in the stems was also determined in our experiment [21]. It is possible that a response to the overpressure could be increased cell respiration, i.e. an increase in the $CO_2$ release. However, in the precipitation chronology there is no cycle with a period close to 11 years. Therefore, the ~11 year cycle in the ($CO_2$+$H_2O$) chronology could be related to the solar cycle through the temperature variation, supposing that for the given region there is temperature modulation with a cycle close to the 11-year solar cycle.

*3.4. Possible relation to solar activity variations*

Quasi-decadal variations in some spectra in Figures 1–4 point to the possibility of their relation to the 11-year cycle of solar activity. Analysis of this relation requires time series of a length large enough to include at least several solar cycles. Some of our results in this field are presented in [13, 22]. Figure 4c shows the results of a cross-spectral analysis of the ($CO_2$+$H_2O$) content in samples of the annual rings of Siberian stone pine and the sunspot number. The analysis characteristics are the mutual spectral density (cross-spectrum), the squared spectral coherency, and the phase spectrum. Spectral coherency characterizes the correlation coefficient between two signals determined at a given frequency (period) under aligned signal phases. The phase spectrum determines the phase shift (in this case, the time shift) between two signals at a given frequency (period). Figure 4c shows distinct maxima of the spectral density and coherency with a period corresponding to the period of the solar cycle, which points to the statistical relation of the quasi-decadal variations of ($CO_2$+$H_2O$) in the annual rings of the Siberian stone pine to the 11-year solar cycle. The phase spectrum shows that the ($CO_2$+$H_2O$) variations are in phase with the solar cycle (the phase shift: ~360° = 0°).

Since the changes in the solar radiation intensity at the surface level during the 11-year solar cycle do not exceed 0.1% (see Introduction), it is unlikely that such small changes can influence the vital activity of a tree directly. However, the mechanism of the influence could be indirect. Figure 4d shows the results of the cross-spectral analysis of the summer cloud cover over Tomsk and the sunspot number. The cross-spectrum and the coherency spectrum point to the relation of the cloudiness to the solar cycle, with the variations in the cloudiness occurring, according to the phase spectrum, approximately in phase with the solar cycle. The cloudiness variations modulate the solar radiation intensity at the surface level by screening the direct and increasing the diffusive radiation, and it could be the reason for the ($CO_2$+$H_2O$) variations on the scale of the solar cycle period. Comparison of the phase spectra in Figs. 6a and 6b shows that the solar cycle-like variations of $CO_2$+$H_2O$ are approximately in phase with the variations of the cloud cover.

## 4. Conclusions

1. The ($CO_2$+$H_2O$) chronologies for all kinds of coniferous trees of the same habitat (the environs of Tomsk), i.e. for pine, larch, spruce, and Siberian stone pine, whose discs we studied, are characterized by variations with periods close to 4 years and, in some cases, with periods of about 10 years. The 4-year cyclicity of the ($CO_2$ +$H_2O$) chronologies and the pressure in the wood of the stem and root rings of conifers may be related to the 4-year variations of air temperature and precipitation. The quasi-decadal variations may be related to the 11-year cycle of solar activity (Schwabe-Wolf cycle).

2. We believe that the cyclic $CO_2$ variations in tree discs are a tree response to variations of climatic parameters with close period, including variations of precipitation.

3. The cyclic changes of pressure in tree roots and stems may result, in our opinion, in a cyclicity of $CO_2$ diffusion into the atmosphere. The $CO_2$ release from stems and roots of coniferous trees, depending on time of day and season, may have quasi-periodic multi-year changes which have not yet been taken into account in measurements of the $CO_2$ released by the biota.

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