Tree-ring isotope chronologies of the Baikal region and their connection with ice isotope chronology of Greenland

V.I. Voronin,[1] V.A. Tartakovskii,[2] Yu.V. Volkov,[2] G.H. Schleser,[3] G. Helle,[3] and B.D. Nesvetailo[2]

[1]Siberian Institute of Plant Physiology and Biochemistry, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia
[2]Institute for Monitoring of Climatic and Ecological Systems, Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia
[3]Research Center Juelich, Isotope Geochemistry and Paleoclimate Research, Juelich, Germany

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Long series of paleodata describing environmental and climatic changes create an objective basis for forecasting. The problem of correlation between oxygen isotope chronologies from atmospheric precipitations fixed in ice cores and from cellulose molecules of tree rings. It is concluded that current ideas on these processes, in particular, the presented new results do not contradict the hypothesis on the presence of a natural mechanism of synchronization of isotope chronologies, which may be caused by the global character of the forcing action. Within this hypothesis, the use of the new "compression–extension" algorithm is justified and the possibility of correcting ice core chronologies using tree-ring isotope chronologies is shown.

Introduction

Long-term series of experimental data characterizing environmental and climatic changes create an objective basis for prediction of such changes. Because of the absence of direct measurements of traditional climatic characteristics until such measurements became possible, it is important to consider data having the time reference, connected with climate elements, and fixed in the unchanged form. In this sense, it is promising to consider the $^{18}O/^{16}O$ oxygen isotopic ratio, which is fixed in tree rings and in ice core, and depends on the air temperature. The isotopic data are used in the form $\delta^{18}O = 10^3(R_p - R_{SMOW})/R_{SMOW}$ ‰, which reflects their ratio in a wood sample $R_p = (^{18}O/^{16}O)_p$ with respect to SMOW (Standard Mean Ocean Water; $R_{SMOW} = (^{18}O/^{16}O)_{SMOW}$.

The enriching of plant cellulose with the ^{18}O isotope results from fractioning having both the physical and biochemical components. The oxygen from atmospheric carbon dioxide and water is involved in this process. The isotopic composition of soil moisture is determined by that of atmospheric precipitation. Dansgaard [Ref. 1] separated seasonal, latitudinal, continental, and vertical peculiarities in the distribution of the isotopic composition of precipitation. The common property of these distributions is the decrease of $\delta^{18}O$ in precipitation far in land and in high latitudes, as well as with increasing altitude and decreasing temperature. Thus, $\delta^{18}O$ of oceanic water as SMOW is equal to 0.0‰, while in Northern Eurasia the annual average values of $\delta^{18}O$ in atmospheric precipitation range from −10 to −24‰ [Ref. 2].

Investigations of aquatic and terrestrial plants have shown that the values of $\delta^{18}O$ for cellulose were by 27.3‰ higher than for water at a place of cellulose synthesis.[3,4] This result of isotopic fractioning is determined by the photosynthesis and respiration processes. Temperature conditions at the time of cellulose synthesis affect significantly the isotopic composition of cellulose, because they determine the isotopic equilibrium in the system $CO_2 \leftrightarrow H_2O$; at 25°C the coefficient of isotope separation in this system is 1.0412 [Ref. 5].

Among physical factors of isotope fractioning, the most significant one is weighting of oxygen of intracellular water at increasing temperature, as compared to soil moisture, because the light oxygen isotope is removed first from the water contained in plants in the transpiration process.

The migration and fixation of stable oxygen isotopes in animate and inanimate nature are poorly studied. Nevertheless, it is commonly accepted that the isotopic composition of plant cellulose is determined, first of all, by the composition of the initial water, and the most significant factor affecting this composition is temperature, which determines the conditions of proceeding of both physical and biological fractioning processes. In its turn, the isotopic composition of atmospheric precipitation, which forms the plant water and glaciers, depends on the evaporation and condensation processes, which are determined by the temperature and weight of molecules.

Material and technique

We have obtained the following isotopic chronologies of larch (*Larix sibirica Ledeb.*): IRK

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(near Irkutsk; 52°14′N, 104°11′E, 450 m asl, period of 1682–1998); OLC (Olkhon Island; 53°17′N, 107°38′E, 530 m asl, period of 1659–2001); DAV (Baikal Ridge; 55°51′N, 108°55′E, 1400 m asl, period of 1388–2000).

The habitats, in which wood was sampled for isotopic analysis, differ in the basic climatic characteristics. Near Irkutsk, the amount of precipitation is 300–400 mm/yr, the annual average temperature in the last decade is +1.1°C. On Olkhon, these parameters are 200 mm/yr and +1°C. The most moistened region is the Davan Pass of the Baikal Ridge, where the amount of precipitation exceeds 1000 mm/yr, and the corresponding temperature ranges from –0.3 to 0°C.

The isotopic composition of wood was determined in Research Center Juelich (Juelich, Germany) at the Institute of Chemistry and Dynamics of the Geosphere (ICG-V) on the IRMS mass-spectrometer (OPTIMA). Under the microscope, drill wood cores were prepared into annual layers. For every year, a wood sample was concentrated for five cores. As a result, the needed mass of a weighted sample was achieved, and an average sample for an individual tree was obtained. Soda pulping was used to separate cellulose, which was then used in the isotopic analysis. For each habitat, the isotopic composition of wood cellulose for five trees was determined.

Results and discussion

Although isotopic tree-ring chronologies have been obtained for very contrast habitats (southern taiga, forest-steppe, and uplands) far spaced from each other (max > 600 km), they are rather synchronous (as to the sign of their derivatives). Along with the highly synchronous behavior, the chronologies are characterized by significant correlation at the period of three hundred years (Table, Fig. 1).

	IRK	DAV	OLC
IRK		0.47/67	0.74/100
DAV	0.57/62		0.33/80
OLC	0.57/81	0.61/64	

N o t e . Correlation (numerator) and synchronism (denominator, %) coefficients of the $\delta^{18}O$ chronologies are given to the right from the diagonal for the period of 1980–2000 and to the left for the period of 1682–2000.

Of particular interest is the jointly observed significant correlation of the chronologies and their synchronism for the droughty, sultry, steppe habitat on Olkhon Island (OLC) and the overmoistened, cool, high-mountain habitat on the Davan Pass (DAV) for the period of 1682–2000. In the last decades, the coefficient of synchronism increased up to 80%. This coefficient reflects the degree of action of common external factors on the compared time series,[6] that is, annual average variations of $\delta^{18}O$ in larch cellulose in all habitats. According to the theory of isotopic fractioning, the common factor should be the isotopic composition of precipitation, which transforms under the action of temperature, acquiring a local feature, namely, different values of $\delta^{18}O$. Thus, in the forest-steppe habitat on Olkhon Island (OLC), these values are naturally lower than in the high-mountain, cooler habitat of the Baikal Ridge (DAV). At the same time, synchronism keeps between the $\delta^{18}O$ chronologies in the different far spaced habitats with contrast climatic conditions.

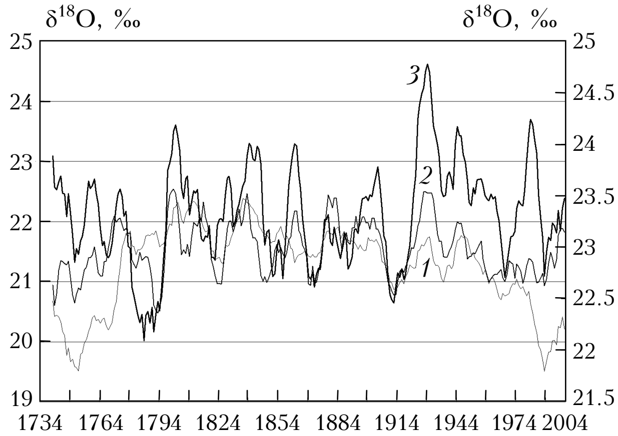

Fig. 1. Fragments of $\delta^{18}O$ isotopic tree-ring chronologies IRK (*1*), DAV (*2*), and OLC (*3*). Series *1* and *2* are plotted on the left axis, and series *3* is plotted on the right axis.

Analysis of data of the WMO/IAEA Global Network "Isotopes in Precipitation" (GNIP)[7] has shown that the relation between the annual average values of $\delta^{18}O$ in precipitation and the temperature of the surface air layer for high-latitude regions is the same as between the annual average values of $\delta^{18}O$ in the larch wood in the Baikal region and the corresponding temperature. At both places, $\delta^{18}O$ varies from 0.7 to 0.9‰ per 1°C.

It should be also noted that according to the GNIP data, the annual average values of $\delta^{18}O$ in precipitation for Greenland and North Baikal vary in a rather narrow range: from –10 to –14‰ [Ref. 8].

The dependence of $\delta^{18}O$ in larch wood on the air temperature is demonstrated by comparison of the DAV isotope chronology with variation of the sulfate concentration in the GISP2 ice core.[9–11] The drastic increase of the sulfate concentration in ice layers is associated with powerful volcanic eruptions, which emitted giant amounts of dust and aerosol particles in the atmosphere and thus led to attenuation of solar radiation, which caused cooling, sometimes very significant and long.[12] For example, the temperature decreased considerable in 1600 (Huaynaputina eruption) and in 1815 (Tambora eruption). These periods are clearly seen in the DAV isotope chronology as a sharp decrease of $\delta^{18}O$. In general, the following tendency can be seen: as the sulfate concentration increases sharply, the values of $\delta^{18}O$ decrease in the same manner, inducing the decrease of temperature.

Thus, the tree-ring $\delta^{18}O$ chronologies obtained by us correspond to the known regularities: regardless of a habitat, tree-ring chronologies reflect the isotopic composition of atmospheric precipitation, in particular, formed by Greenland glaciers.

The isotopic characteristics of Greenland GISP2 ice cores are used to reveal climate changes in the Northern Hemisphere in the remote past.[13] The ice core chronologies are referenced to the official Meese/Sowers timescale. Cores were dated through calculation of the depth/age ratio with the aid of different methods and parameters: visual stratigraphy, calculation of the concentration of stable oxygen isotopes and main anions and cations, electric conductivity, radiocarbon dating, etc.[14,15] Nevertheless, the exact dating of ice core layers to calendar years is not established yet. According to the most optimistic estimates, the error in estimation of the age of ice layers is about 2% for the period of 0–11640 years until now.[14]

These errors can be removed by applying long paleochronologies for correction of ice chronologies.[16]

Tree-ring $\delta^{18}O$ chronologies have absolute dating and can serve as a reference for ice chronologies. The use of such a parameter as the tree-ring width from tree-ring chronologies of the Eurasian Subarctic for correction of Greenland ice isotope chronologies has shown reasonableness of this approach.[17] For this purpose, it is appropriate to use the tree-ring $\delta^{18}O$ chronologies, which were used by us for the Northern Eurasia for the first time.

Model and dating algorithm

Thus, it is necessary to compare the known ice $\delta^{18}O$ chronology obtained from GISP2 ice cores with the longest DAV tree-ring $\delta^{18}O$ chronology (650 years). It should be taken into account that the tree-ring chronologies have absolute calendar dating, whereas the ice chronologies have not actual year-by-year resolution. We start from the fact that the experimental data, described above, although fragmentary, do not contradict the hypothesis on the presence of a natural mechanism of synchronization of chronologies, which may be caused by the global character of the forcing action. It should be kept in mind also that the spatial averaging due to mixing of aqueous aerosol in the atmosphere and the time averaging due to mixing of ice core material suppress fluctuation.

The tree-ring and ice core isotope chronologies characterize variations of the same physical parameter: concentration of the ^{18}O isotope in time at two quite remote points on the Earth's surface (Fig. 2).

We will consider these chronologies as a mixture of useful climatic signal and noise. The latter is connected with natural local fluctuations of isotope concentrations, seasonal peculiarities of isotope fixation in ice and wood, and others. However, the most significant source of noise is the error in dating of ice core layers.[18] The model of this error can be represented as some transformation of the time scale through its compression and extension, but without breaks and shifts.

Within the model proposed by us, it is assumed that incorrect dating of ice cores leads to desynchronism of chronologies (Fig. 3). It is natural to suppress it by the inverse transformation of the time scale. Such approaches were discussed and applied earlier.[18–20]

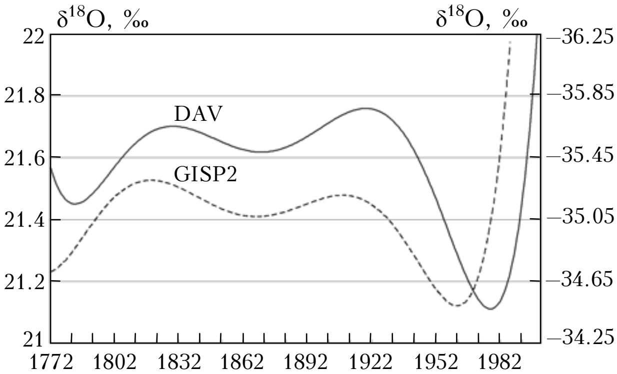

Fig. 2. Fragments of the tree-ring (left axis) and ice (right axis) $\delta^{18}O$ isotope chronologies smoothed by the sixth-order polynomial by the least-squares method. Desynchronism is observed.

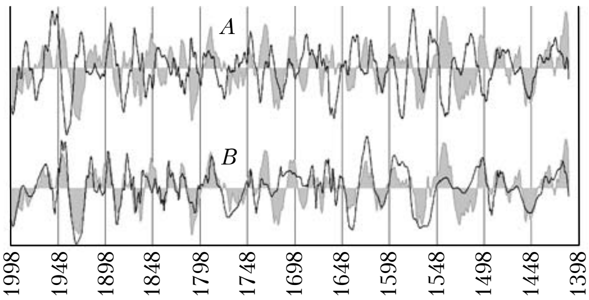

Fig. 3. 11-year normalized average values of $\delta^{18}O$ (DAV chronology is shown as a gray background, and GISP2 chronology is shown as a curve): initial chronologies, correlation coefficient of –0.07 (*A*); isotope content in ice core dated by the proposed method by the DAV chronology, the correlation coefficient is 0.66 (*B*). Years until now are plotted as abscissa.

In this paper, to solve the problem, we use a new computational procedure based on the "compression–extension" algorithm[20,21] implementing the single-valued, continuous, and invertible transformation of oscillations.

At the first stage of the procedure, two series of coordinates of significant extremes are determined automatically in the both chronologies. The option of interactive editing of these series is available. Then the both series are interpolated by splines, and the resultant functions have a meaning of phases of the chronologies as oscillation processes. For the phase functions obtained, the inverse functions are determined by rotating the initial phases around the bisector of the first quadrant of the coordinate system (Fig. 4). All these operations are possible, when the phase functions are a priori monotonic and have the upper-bounded derivative.

At the second stage of computations, the direct compression–extension operation of the ice chronology (GISP2) is executed with the use of the inverse phase. Then the inverse compression–extension operation is executed with the use of the phase for the tree-ring chronology (DAV). Thus, the both chronologies are synchronized.

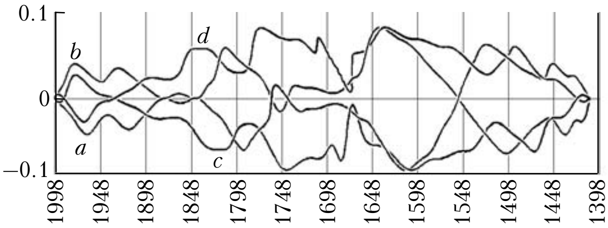

Fig. 4. Direct and inverse phase functions of isotope chronologies used in the compression–extension operation; quadrant bisector is removed: DAV (*a, b*) and GISP2 (*c, d*) chronologies. Years until now are plotted as abscissa; the shift measured in fractions of chronology duration is plotted as ordinate.

At the last stage of calculations, the curve of recalculation of the initial dates of the ice core chronology into new dates is obtained (Fig. 5). For this purpose, we used the phase of the ice core chronology for the direct compression–extension operation and the inverse phase of the tree-ring chronology for the inverse compression–extension operation.

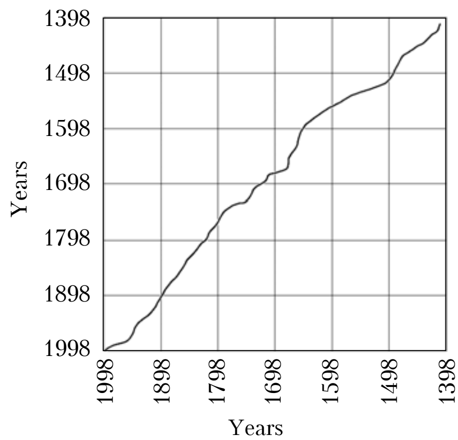

Fig. 5. Recalculation of the initial dates of the GISP2 chronology into new dates (using the DAV chronology). Initial dates are plotted as an ordinate, and new dates are plotted as an abscissa. The largest shift of the transformed GISP2 chronology with respect to the initial one was about 50 years.

After synchronization, the correlation coefficient of the ice core and tree-ring chronologies increased considerably from –0.07 to 0.66 (see Fig. 3) and approached the coefficients obtained for 318-years long chronologies of the Baikal region (see Table). This fact confirms that the correlation coefficient in this case can serve as a measure of the global forcing.

Conclusions

Thus, accepting the hypothesis on the presence of the natural mechanism of synchronization of chronologies and proposing the model of error dating, we have obtained justification for application of our compression–extension algorithm and showed the possibility of correction of ice core isotope chronologies against tree-ring isotope chronologies.

Now there are some absolutely dated tree-ring chronologies of several thousands years long for the Northern Eurasia.[18,22] Once the isotope characteristics of these chronologies is obtained, it becomes possible to refine the dating of Greenland ice cores for the Holocene period.

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