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Section A

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Application of synchrotron X-ray fluorescent analysis to studies of the records of paleoclimates of Eurasia stored in the sediments of Lake Baikal and Lake Teletskoye

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Abstract

Multi-element SRXRF of sediments of Lake Baikal (East Siberia) with samples taken at 10 cm intervals from a core spanning the last 250 ky revealed nine peaks of "warm" signals like Sr/Ba(Rb,Cs) and U/Th corresponding to Oceanic Isotope Stages 1,3,5a,5c,5e,7 and 9, and six peaks of "cold correlator" corresponding to OIS 2,4,5d,6 and 8. A slab (1500–2200 mm below the sediment surface) taken from another core was studied by scanning SRXRF. This interval corresponds to the Siberian Karga interstadial (OIS3, 24–58 ky BP). It hosted two peaks of diatom algae frustulles, indicators of warmer climates. The scanning was performed at a temporal resolution of ca. 50 yr. Ratios of concentrations like Sr/Rb(Ba,Cs,Ti,Fe) (Nucl. Instr. and Meth. A 448(1–2) (2000) 384; Nucl. Instr. and Meth. A 448 (1–2) (2000) 400) appeared to be more sensitive proxies of warm climates, compared to total diatoms, and revealed at least six pronounced cycles of abrupt warming and cooling episodes, each lasting a few millennia. These fluctuations may reflect a response of the catchment basin of the Lake Baikal to abrupt global climate cycles recorded in the ice of Greenland and in the sediments of North Atlantic (Nature 364 (1993) 142; Science 278 (1997) 1257; Science 288 (2000) 128). SRXRF applied to the sediments of Lake Teletskoye (West Siberia, Altai Mountains) of the last 600 yr provided a temporal resolution of 1.2–1.8 yr. The profiles of a few elements like K, Ca, Ti, Fe, V revealed oscillations with a periodicity of 9.4 yr over the time interval between years 1400 and 1600. Oscillations faded out after the cooling of 1600–1700 (The Maunder interval). Periodic oscillations between years 1400 and 1600 seem to correspond to periodic changes in the height of oceanic tides (9 yr (PNAS 94 (1997) 8321; PNAS 97 (2000) 3814)) rather than to the solar activity cycles (periodicity of 11 yr). © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Global climate changes over time intervals of 20–100 ky were caused by changes in the insolation due to variation of orbital parameters [8,9]. However, the orbital (Milankovitch) theory does not explain the abrupt climate changes in the time scale of 1–6 ky revealed by the high-resolution profiles of $^{18}O/^{16}O$ in cores of Greenland ice (Dansgaard/Oeschger events [3]), and by more recent oceanic sedimentary records (e.g., [4,5]). During the last few years, elemental analysis of lacustrine sediments from Siberia is being employed for 01the purpose of paleoclimate reconstructions [1,2,10–12]. It was shown by means of SRXRF and NAA [1,2] that some elements found in the sediments of Lake Baikal are proxies of warm and cold global climates on the Milankovitch time scale. For example, the strong "warm" proxies are Sr/Rb(Ba,Cs,Ti) ratios. However, the temporal resolution of the earlier analyses was insufficient to reveal abrupt changes on the millennial time scale.

One of the major purposes of the present studies was the elaboration of a scanning SRXRF procedure, which would allow to measure the distribution of elements in lacustrine sediments at a high temporal resolution. The scanning SRXRF procedure was applied to search climate variability on the millennial time scale in the sediments of Lake Baikal. Secondly, SRXRF was applied to the sediments of Lake Teletskoye to estimate climate variability on the decadal time scale.

2. Methods and samples

2.1. Methods

SRXFA was performed at a station for elemental analysis with synchrotron radiation produced by the VEPP-3 storage ring in the Budker Institute of Nuclear Physics. Two types of samples were used. The first was 6 mm, 35 mg cylindrical tablets of a density of 0.13 g/cm^{-2}. The second was $170 \times 30 \times 5\,\mathrm{mm}^3$ slabs of sediments cut out along the axis of a core; slabs were dried in vacuum, embedded into epoxy resin, and ground on both sides. The procedure of SRXRF with tablets has been described earlier [14]. Scanning SRXRF was performed using a high-precision positioning system with a stepper motor at 0.1 mm intervals (± 0.01 mm). Collimating of the SR beam was performed by the exit slit of the monochromator. Spectra were measured in an automated mode as described in Ref. [13]. The samples were irradiated with a monochromatized and polarized SRXR beam. Two incident beam energies were used. The 22–26 keV band was used for the determination of elements with atomic mass less than that of Mo. The 45 keV band was used to determine light lantanoids, Sb,Sn,I,Ba. The method is described more in detail in [14,15]. We determined the concentrations of the following elements: K,Ca,Ti,V,Cr,Mn,Fe,Cu,Zn,Mo,Pb,Rb, Ba,Sr,La,Ce,Y,Nd,Sn,Sb,Br,I,As,Se,Nb. Data on the concentrations of biogenic silica (BiSi), water content (WC), diatom algae frustulles (DiFr) have been published elsewhere [10,16].

2.2. Sediments

We studied cores taken on top of the underwater Akademichesky Ridge of the Lake Baikal. Stratigraphy of the sediments of Station 15 (53°33′19″N, 108°00′43″E, depth 430 m) obtained in 1994 is described in Ref. [10]. The sediments of Station 2 GC (53°33′04″N, 107°54′53″E, depth 400 m) were obtained by a gravity core in 1998. The core from Lake Teletskoye (Altai Mountains) was taken by a gravity tube at the underwater Sofia Kovalevskaya high in 1998; the description is given in Ref. [17].

3. Results and discussion

3.1. Signals of paleoclimates in sediments of Lake Baikal on the Milankovitch time scale

Fig. 1 shows profiles of different climate proxies relative to the profile of BiSi for Core 15 (cf. Refs. [1,10]). Samples were taken at 10 cm intervals. Mean sediment accumulation rate for this core was 4–5 cm/ky, i.e., the temporal resolution is 2–2.5 ky [1,2,10,11]. Peaks of BiSi correspond to warm Oceanic Isotope Stages 1, 5a, 5c, 5e, 7, 9 [11,18–20]. Bold lines in Fig. 1 are the "warm" stack and the "cold correlator". Thin lines are profiles of individual proxies. A stack is a dimensionless profile of paleoclimates obtained by averaging profiles of a few particular elements, or element ratios [1,12]. For Core 15 (Fig. 1), the warm stack is an average of the dimensionless profiles of Sr/Ba(Rb,Cs,Ti,Fe), U/Th, Zn/Nb, U, Mo, Br, heavy REEs (Eu,Yb,Tb). The cold stack is an average of the dimensionless profiles of La/Yb, Ce/Yb, Ba/Zr, La/Zr, Ce/Zr. The cold (warm) correlator is the record of the correlation coefficients of the dimensionless elemental composition of sediment at given depths with the mean dimensionless elemental composition of "typically typically cold (warm)" layers of the same core [1,12]. The correlators were renormalized to vary between 0 and 1. The Oceanic Isotope Stage 3 (OIS3) in Fig. 1 is marked by the oval on the SPECMAP [21] δ^{18}O profile. This stage corresponds to the so-called Karga interstadial of Siberia. Remarkably, the warm stack (the upper part of Fig. 1), unlike BiSi (a proxy of the content of diatom algae frustulles and warm climates in the sediments of Lake Baikal), produces a strong peak during OIS 3, suggesting that the climate of Karga was warm, although somewhat colder than that of Holocene, or of OIS 5e. One more interesting feature is that the peaks of the cold correlator occur immediately after the peaks of BiSi rather than in the middles of the diatom–barren intervals. Detailed discussion of the natures of the warm and cold stacks and correlators is beyond the topic of the present paper. Briefly, we believe that a significant part of the "warm" elements was brought from the catchment basin of Lake Baikal in a dissolved form by waters of its tributaries, whereas the "cold" elements are signatures of suspended solids which were produced in great amounts at times when mountains around the

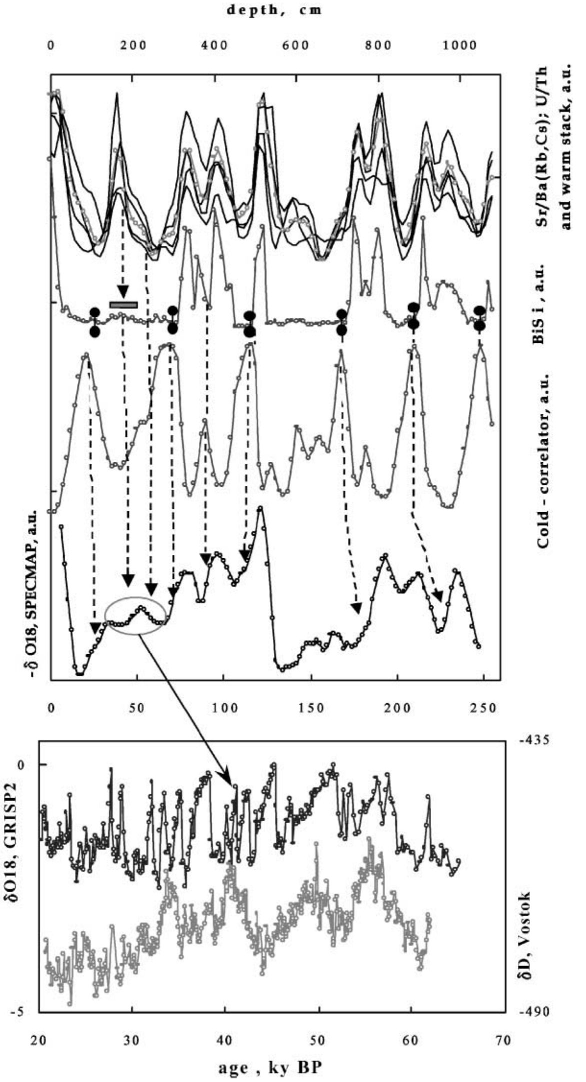

Fig. 1. Profiles of climate proxies in sediments of Lake Baikal (Akademichesky Ridge, Station 15) and isotope profiles in oceanic sediments (δ^{18}O [21]), in the ice of Greenland [31,32], and in the ice of Antarctic [22]. Vertical dumbbells on the profile of BiSi indicate the intervals of the sediments from Lake Baikal which were assumed to be "typically cold" for the purpose of the correlation according to the elemental composition (see the text). The line labeled by cycles in the uppermost profile is the warm stack; the thin lines are individual warm proxy profiles.

Lake Baikal were covered by glaciers [12]. Such kind of model for isotopes of U and Th has been proposed in [11]. The lower panels in Fig. 1 present the high-resolution profiles of δ^{18}O in Greenland ice [31,32] and of δD of ice at Vostok Station in Antarctic [22] for OIS3 (24–58 ky BP) at a temporal resolution of 60–150 yr. These signals are proxies of warmer climates; they reveal high-frequency (millennial-scale) climate fluctuations—Dansgaard/Oeschger (D/O) events. Warm phases of the millennial-scale D/O cycles in the δ^{18}O record in the ice core of Greenland are known as small interstadials (IS) [3]. Evidently, these fluctuations could not be found in the sediments of Lake Baikal sampled at a frequency of 2–2.5 ky (cf. the upper panels of Fig. 1).

3.2. SRXRF scanning of the Karga (OIS 3) interval of Baikal sediments on the millennial time scale

The sediments of Lake Baikal studied in this section belonged to Station 2. Analysis of water content and diatom algae composition of this core at 1 cm intervals revealed that the Bøling warm interval (14.7 ky BP) occurred in 55–60 cm, and OIS 5a (83.5 ky BP) 330 cm below the sediment surface [16]. To find signatures of millennial-scale (D/O) climate oscillations during the OIS 3 interval in these sediments, it was necessary to perform analyses at a frequency of 1 mm. Therefore, we elaborated a scanning SRXRF procedure. This procedure was applied to a slab cut out from Core 2. The slab (1540–2180 mm below the sediment surface) was dried in vacuum, embedded into epoxy resin, and ground on both sides to obtain a block 5 mm thick. Fig. 2 shows the records of warm signals: a stack of Sr/(Rb,Ba, Fe,Ti), sediment humidity (WC) and diatom abundance (DiFr) measured with samples taken at 1 cm intervals compared with the δ^{18}O profile in Greenland ice. The former profile reveals at least six episodes of climate amelioration during the Karga interval. The peaks of the warm geochemical stack partly overlap with the peaks of diatom algae frustulles. The most long-lasting

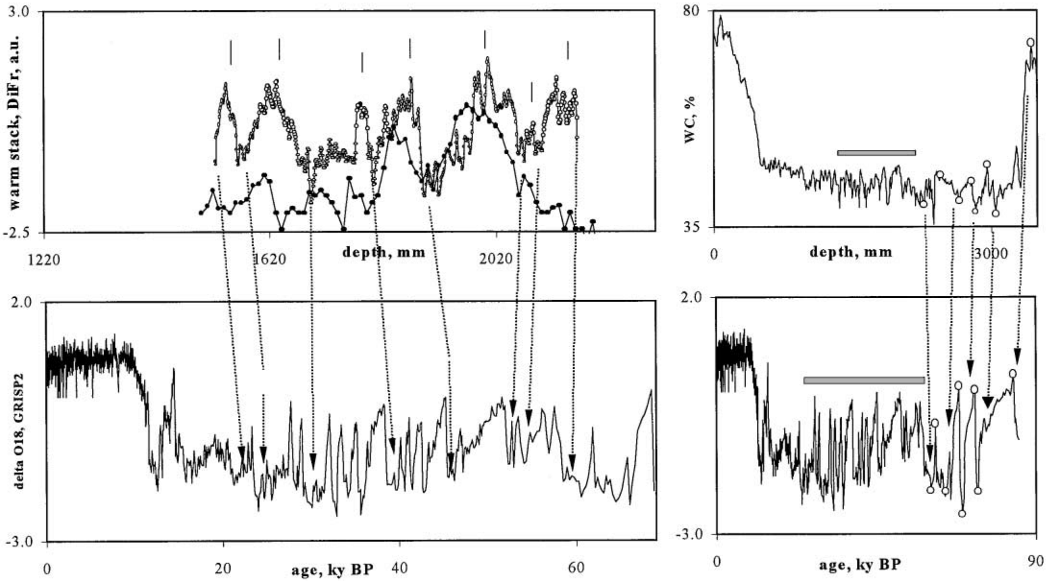

Fig. 2. A high-resolution record of climate proxies in the sediments of Lake Baikal (Station 2, Akademichesky Ridge) belonging to OIS 3 as compared to the δ^{18}O profile in Greenland ice [32]. The warm stack is the averaged dimensionless profile of Sr/Rb(Ba,Ti,Fe) determined by scanning SRXFA. DiFr is the dimensionless profile of the total concentration of diatom algae frustulles measured at 1 cm intervals.

and significant warm events, corresponding to IS 19 (68.4 ky BP), IS 20 (72.7 ky BP) and OIS 5a (83.5 ky BP) are well pronounced on the profile of water content (WC), cf. Refs. [10,20]. These events are marked by circles on the right panel of Fig. 2. The mechanism which causes pervasive abrupt climate oscillations on the millennial (1–2 ky) time scale is not yet known. It is evident that these oscillations are not due to the changing insolation, because insolation changed on a much longer, Milankovitch (20–100 ky) time scale. It is known that millennial-scale climate oscillations involve changes in the temperature of surface waters of the ocean, and occur globally [3–5]. One might speculate that the continent responded to abrupt oscillations instantly. The arrows in Fig. 2 indicate cooling events, which seem to have been simultaneous in Greenland and in the middle of the Asian continent.

Fig. 3 presents the profile of the warm correlator for the sediments of Core 15 and depth-age model of Karga interval for Station2. A depth-age model of Core 15 is based on the correlation of BiSi and WC profiles for this core [10] with the isotope ocean curve δ^{18}Î (SPECMAP) according to Refs. [11,18–20]. The depth-age model of Karga interval for Core 2 is based on the correlation of simultaneous events in Greenland and in Lake Baikal according to Fig. 2. It is remarkable that the sediment accumulation rate during OIS 3 at station 2 is ca. 1.7 cm/ky, almost three times smaller than the mean sediment accumulation rate, 4.3 cm/ky. Cold intervals OIS 2 and 4 are marked clearly by the minimums of the warm correlator and sediment accumulation rate during OIS 2 and 4 is much greater than this mean value, presumably, due to an increase of the flux of suspended matter produced by mountain glaciers (cf. Fig. 3 with Fig. 2 of Ref. [23]). Consequently, the warm and cold correlators may be used not only as proxies for labeling the time history of sources of terrigenous input, but as proxies of a sediment accumulation rate (cf. Ref. [23]).

It was recently proposed [6,7] that pervasive high-frequency climate oscillations were caused by almost periodic change of the height of oceanic tides due to the resonances of the Moon orbit. Higher tides induce stronger mixing and cooling of the surface of the ocean. The signal is transferred to the continents by atmospheric circulation. The authors of Ref. [6,7] revealed a series of typical periods of higher tides: ~6, 9, 18, 180, 360, 1820 and ~4800 yr. They apply the tidal hypothesis to explain the pervasive millennial-scale (1500 ± 500 yr [4]) global climate oscillations during the last 30 ky. The model does not explain all the pervasive millennial-scale oscillations recorded

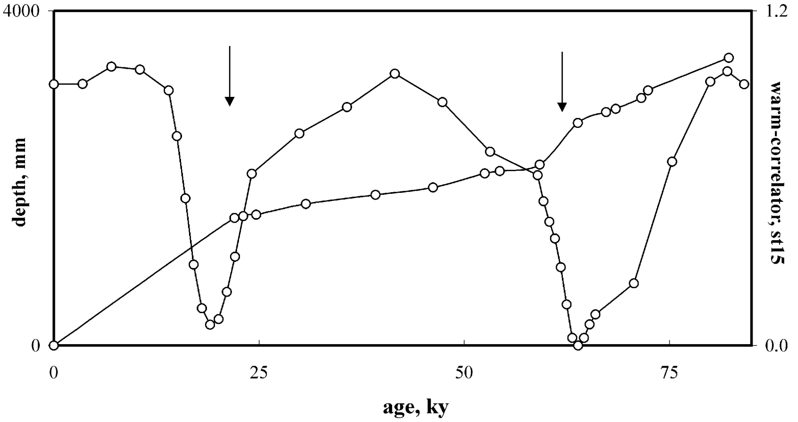

Fig. 3. Profile of the warm correlator for Station 15 and the assumed depth-age model of Karga interval (OIS3) for Station 2.

in oceanic sediments and the fact that the distribution of distances between D/O events in Greenland ice exhibits a maximum at ca. 3500 yr [4]. In spite of this, tidal forcing as the driving force of changing climates deserves serious consideration. Firstly, tides provide about 40% of the energy needed for the ventlation of the deep waters of the ocean [7]. Another argument is the finding of decadal mean global temperature oscillations during the time of instrumental observations, and synchronous oscillations in concentrations of atmospheric CO_2 since 1958 [24], which seem to be governed by the tidal (9 y) cycle. The experimental finding of 6–9, 18, 93 and 180 yr cycles in lacustrine sediments, where a sediment accumulation rate is much higher than that in the Lake Baikal, might serve as an indirect argument for a support of the tidal hypothesis.

3.3. High-resolution SRXRF of sediments of Lake Teletskoye

The sediment accumulation rate in the Lake Teletskoye (Altai Mountains) is 40–50 times greater than that in Lake Baikal [17]. Fig. 4 shows data of SRXRF for Fe, K, Ca, Ti, and V for a sediment core taken in Lake Teletskoye on the underwater Sofia Kovalevskaya high. The age-depth model is based on ^{137}Cs [25] and radiocarbon dating and on the assumption of constancy of the mean value of the sediment accumulation rate. It is seen that highly periodic oscillations of the elemental composition of the sediment

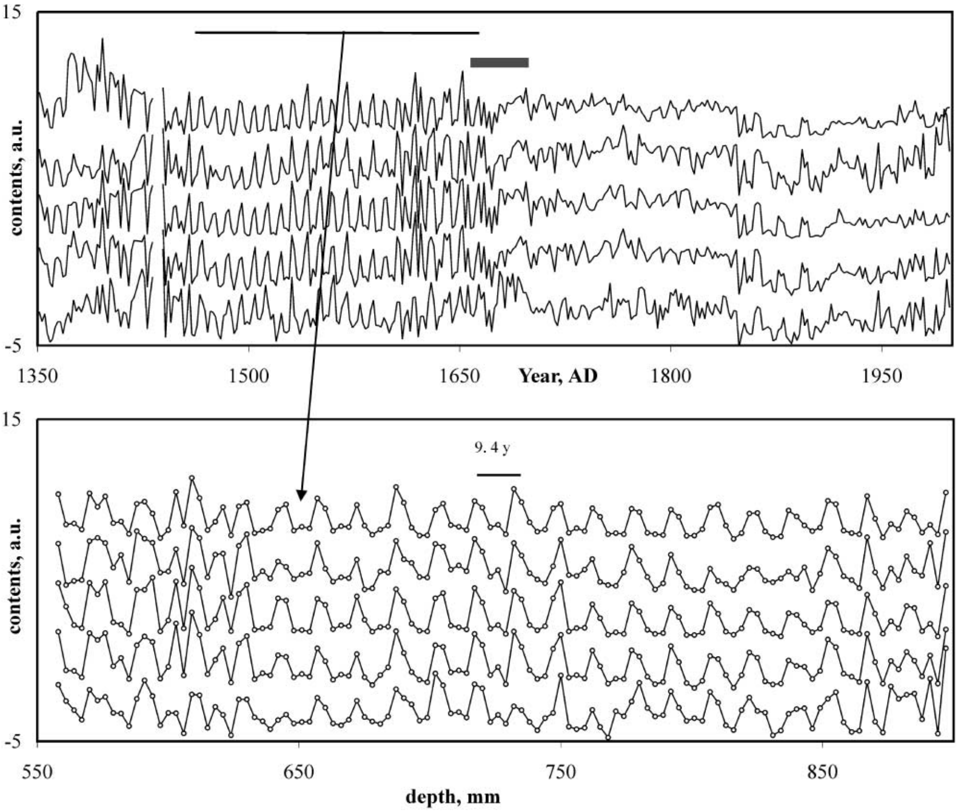

Fig. 4. Profiles of the elements (Ca, Fe, K, Ti, V) from Lake Teletskoye. The bottom panel presents the original data for an interval where behavior of the geochemical indicators is periodic. The linear depth-age model was applied (see the text).

occurred over the time interval between years 1400 and 1650. The period of these oscillations was 9.4 yr. However, the oscillations faded out after 1650. The reason of this fading is not yet known.

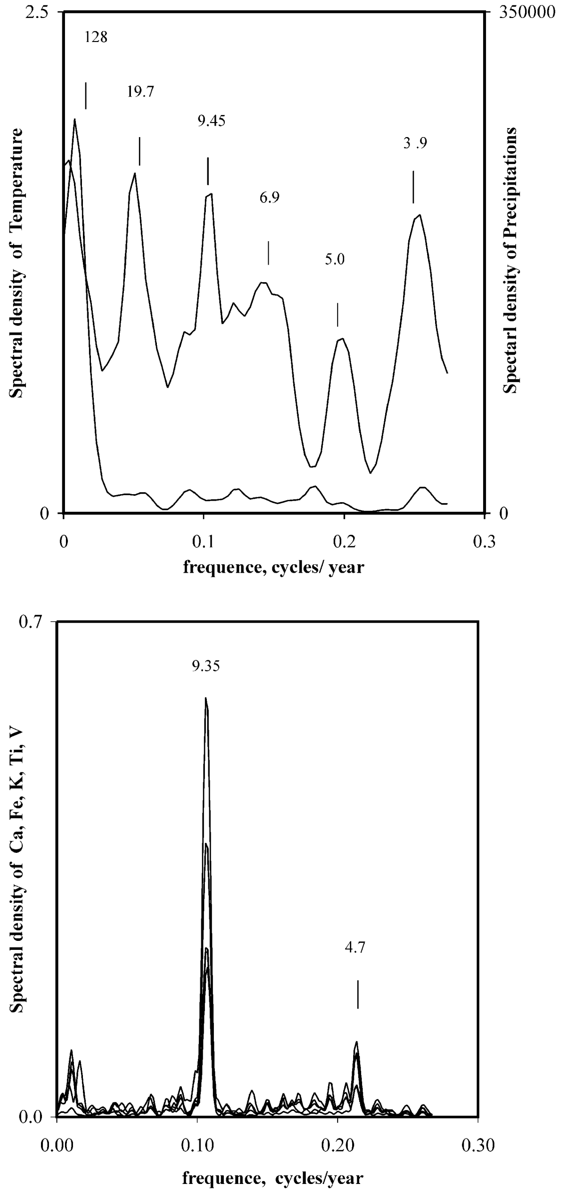

Fig. 5. Spectral analysis data of the paleorecords on the interval of years 1400–1600, and of possible forcings: temperature and precipitation in Barnaul city over of the period of instrumental observations (1860–1998).

Presumably, sedimentation in the Lake Teletskoye since 1650 has changed due to tectonic reasons. However, it is known that the time interval between 1600 and 1720 was characterized by a dramatic cooling in Europe (the Maunder period). It was found recently, that the concentration of CO_2 in the atmosphere also dropped dramatically during 1600–1850 [26]. Presumably, the cooling, which started in year 1600, changed the geomorphological and geochemical setting in the catchment basin of Lake Teletskoye in such a way that the former climate signals became invalid.

We cannot exclude solar activity from the forcing factors as postulated in [27]. Clear 11 yr period of solar activity has been found during the interval of its instrumental observations (1700–1998). Nevertheless, this hypothesis seems less probable [6,28], because the changes in the insolation were small. For example, these changes during the time interval from 1700 to 1998 were less than 0.1% [6,30]. Moreover, the dominating period of oscillations of the power of sun irradiation is 90–100 yr, rather than 11 yr [29,30]. The results of spectral analysis of the instrumental data on the temperature and precipitation in 1860–1998 in Barnaul, a city not far from the Lake Teletskoye, are shown in Fig. 5. The same figure presents data of the spectral analysis of the Lake Teletskoye sedimentary record for 1400–1600. It is seen that, during the instrumental period, 11 yr cycles do not manifest themselves neither in temperature nor in precipitation. On the other hand, maxima of spectral density are observed at 19.7, 9.5 and 6 yr periods. These periods are similar to those of the oceanic tides (6–9 and 18 yr [6]). It seems reasonable to assume that the same tidal 19.7 and 9.5 yr cycles were the driving force of the periodic changes of the temperature in 1860–1998 as well as of the composition of the sediments of Lake Teletskoye in years 1400–1600. However, a verification of the hypothesis on the height of oceanic tides (the reason of changes in sea surface temperature) as the driving force of abrupt climate oscillations on different time scales needs analysis of other records, and, especially, an elaboration of precise and accurate dating methods.

4. Conclusions

SRXRF of the sediments of Lake Baikal and Lake Teletskoye revealed climate oscillations on different time scales. Orbital forcing is the major reason in climate changes on the long-time scale ~20–100 ky. Scanning SRXRF of the interval of the sediments of Lake Baikal belonging to OIS3 (24–58 ky BP, the Karga interstadial in Siberia) at a temporal resolution of 5–50 yr revealed 6–7 periods of abrupt cooling and warming, similar to the pervasive millennial-scale climate oscillations detected in Greenland ice (D/O events) and oceanic sediments (IRD events). It was revealed that warm and cold correlators may be used not only as proxies for labeling a time history of sources of terrigenous input, but as those for a sediment accumulation rate in Lake Baikal. The sediment accumulation rate is low during warmer Karga interval (OIS3, 24–58 ky BP), but it is greatly increased during cold periods (18–24 and 64–72 ky BP) before and after the Karga's interval. SRXRF of sediments of the Lake Teletskoye revealed a strong 9.4 yr periodicity of geochemical signals for the time interval between years 1400 and 1600. Solar activity cycles with the periodicity of 11 yr manifest themselves neither in the local instrumental record of 1860–1998 nor in the Lake Teletskoye sedimentary record. The facts obtained give some support to the hypothesis that abrupt cyclic changes of climate are driven by quasi-periodic changes in the height of oceanic tides forced by resonances of the Moon orbit.

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