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CLIMATE PROCESSES

Climatic Changes in the Arctic Regions of Eastern Siberia over the Last Millenium according to the Lithological–Geochemical Data on Bottom Sediments of Peyungda Lake (Krasnoyarsk Krai, Evenkia)

A. V. Darin[a,]*, D. Yu. Rogozin[b], V. S. Novikov[a], A. V. Meydus[c], V. V. Babich[a], T. I. Markovich[a], Ya. V. Rakshun[d], F. A. Darin[d], D. S. Sorokoletov[d], and Academician A. G. Degermendzhi[b]

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Abstract—Scanning micro-X-ray fluorescence analysis with synchrotron radiation was applied to obtain the depth-variation profiles of element compositions of banded clays in Peyungda Lake (Krasnoyarsk krai, Evenkia) located 30 km southwest of the epicenter of the Tunguska event (1908). The age model was confirmed by a dated layer of anomalous thickness related to the fall and explosion of the Tunguska Cosmic Body (TCB). The variations in the element content in dated core layers were compared with the instrumental meteorological observation data over the last century. The regional average annual temperature and element compositions of the coeval bottom sediments (transfer function) were found to be interrelated. The approximation of the transfer function to the sampling depth of the sedimentary section made it possible to reconstruct the air temperature in the studied region over the past 1000 years. The average annual temperature reconstructions in the study area compared with the global temperature reconstructions in the Arctic region for the same period made it possible to reveal general trends and extreme values.

Keywords: paleoclimatic reconstructions, geochemistry, bottom sediments, Tunguska Cosmic Body, Peyungda Lake, Krasnoyarsk krai

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The relatively well-studied average annual air temperature trends in the northern hemisphere over the past 2000 years are based on a set of local paleoreconstructions, while the spatial patterns remain poorly defined [1]. Many studies were focused on the Holocene climate changes in Europe, North America, Greenland, and China [2, 3]. Based on the recent reconstructions of Arctic temperature conditions over 2000 years, the average annual temperature over the past thousand years was comparable to or even higher than that in the nineteenth–twentieth centuries [3–8]. Today, the Arctic region is an area with the fastest increase in the average annual surface temperature [6, 8, 9], the rate of which is twice as high as the global average. This phenomenon is also known as "a polar amplification" [8, 10, 11].

The high-temporal resolution reconstructions (year on a thousand-year scale) with quantitative calibration using modern instrumental meteorological observations are the most objective for understanding the regional natural climate trends. This study presents the first high-temporal resolution climate reconstruction for a region located in the subarctic part of Eastern Siberia.

Peyungda Lake (60°37′30″ N, 101°38′47″ E; 259 m above sea level) is located on the border of the Tunguska State Nature Reserve (Evenki district of Krasnoyarsk krai), at a distance of 60 km from the settlement of Vanavara, and approximately 30 km southwest of the supposed epicenter of the 1908 Tunguska Cosmic Body (TCB) explosion. The small Verkhnyaya Lakura River, a tributary of the Podkamennaya Tunguska River, flows through this lake. The lake is freshwater, round in shape, with a diameter of more than 800 m and a maximum depth of 30 m [12]. Its area is about 0.6 km^2 (Fig. 1).

[a] Sobolev Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630058 Russia
[b] Institute of Biophysics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia
[c] Astafiev Krasnoyarsk State Pedagogical University, Krasnoyarsk, 660049 Russia
[d] Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia
*e-mail: rogozin@ibp.ru

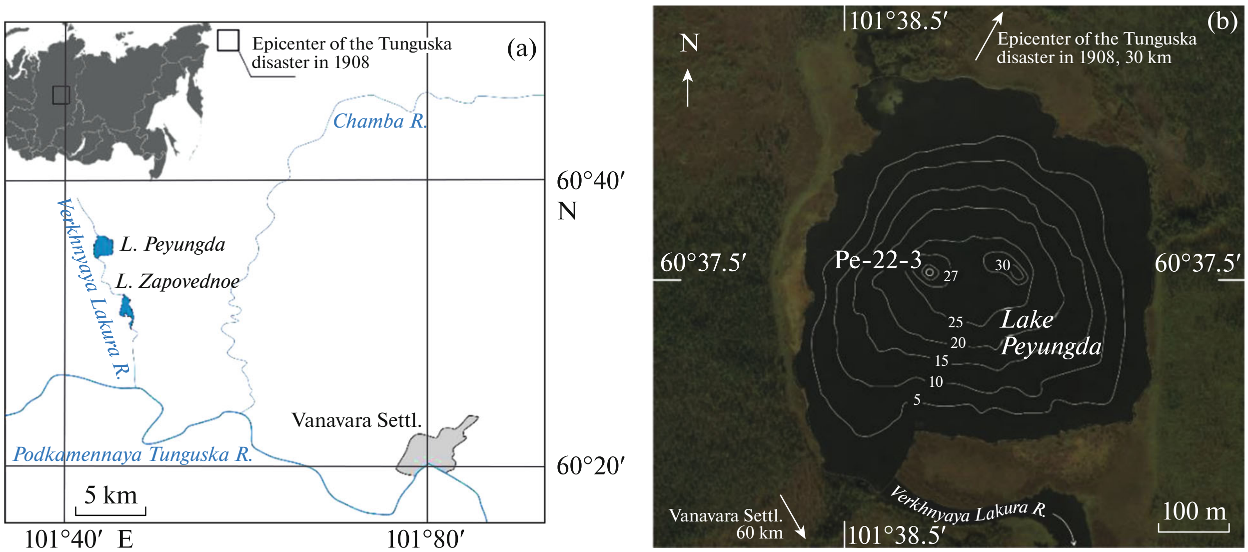

Fig. 1. (a) Geographical location of Peyungda Lake; (b) bathymetry data and core sampling site [12].

In September 2022, a 1187-mm-long core was collected from Peyungda Lake (Fig. 2). Sampling was carried out using a UWITEC gravity sampler (Austria) in the central part of the lake. Special measures were taken to keep safe the top of this core in the course of sampling and subsequent transportation.

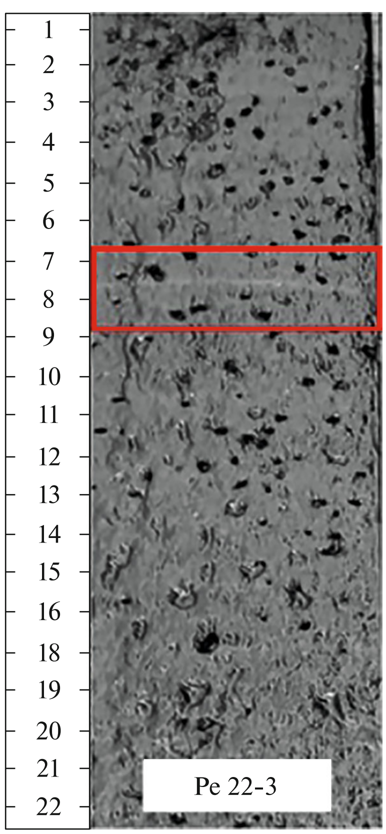

Fig. 2. A core fragment of bottom sediments of Peyungda Lake, depth (cm) from the water–sediment boundary. The layer marking the 1908 TCB explosion is highlighted in red.

The bottom sediments of Peyungda Lake are finely dispersed dark brown and black silts enriched in organic matter and with a poorly defined layered structure; deeper than 1 m, sediments become more compact, with a more pronounced layering. At a depth of 78 mm, there is a clear light layer of up to a few mm thick (Fig. 2).

Solid bottom sediment specimens selected through the core depth were prepared according to the method proposed in [13] and adapted for micro-XRF studies [14]. A solid specimen was used to make thin plates (2 mm thick) for micro-XRF scanning with plane–parallel polished surfaces and optical sections for a visual calculation of the annual layers.

The scanning micro-XRF using synchrotron radiation beams was carried out at the Siberian Center for Synchrotron and Terahertz Radiation, Shared Use Center, according to the method described in [15]. The scanning step was 1 mm, and the measurement time at a point was 30 s. The following rock-forming and trace elements were simultaneously determined at each point: K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Ga, As, Br, Rb, Sr, Y, Zr, Nb, and Mo. The element contents below the detection limits under these conditions were also monitored: V, Cr, Co, Ge, Se, Pb, Th, and U. In addition, the ratio of elastically/inelastically scattered radiation on the sample (Co/Inc) was recorded.

The calculation was carried out using a visually identified pair of layers (spring–summer and winter) making up one annual sedimentation cycle. No breaks in layering were observed, but the annual layers were not clearly distinguished in all cases. The calculation was carried out based on the maximum and minimum

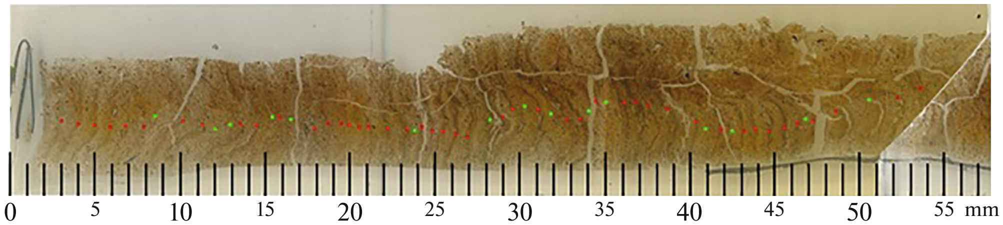

Fig. 3. Thin section Pey-22-3 without magnification, obtained with an optical scanner. Red dots show the minimally (reliably) distinguished annual layers; green dots show additional layers.

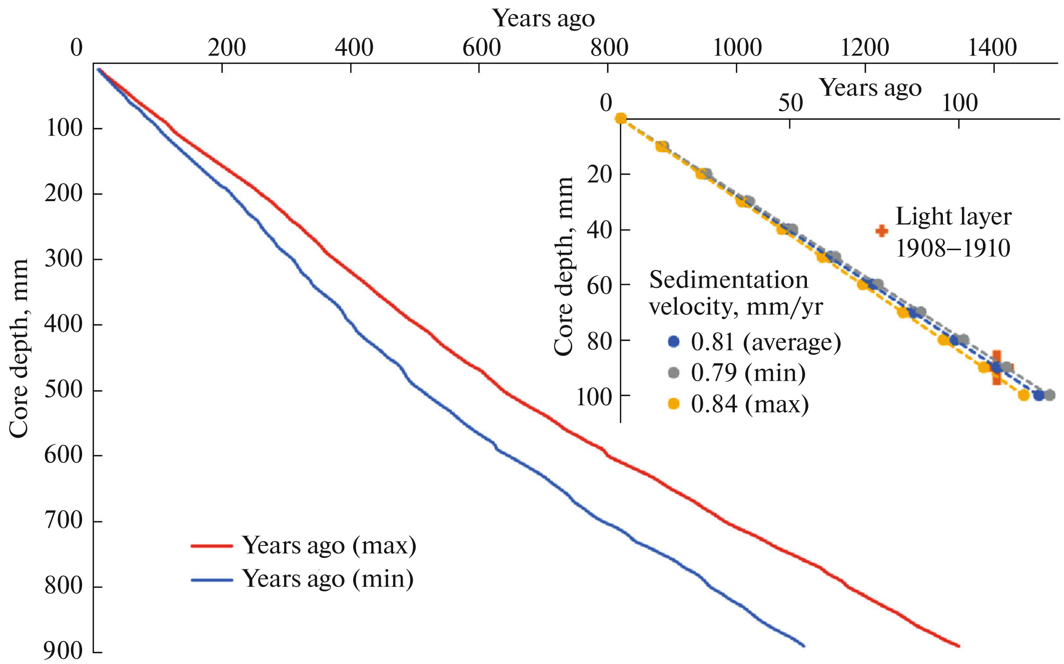

Fig. 4. Age model: (a) for the upper interval of core Pey-22-3 (0–100 mm) according to the varve chronology data and the position of the visually distinguished layer of 1908–1910; (b) through the full sampling depth. (max) Counting only reliably identified layers, (min) reliable and suspected layers.

number of visually identified pairs of layers (Fig. 3). The age model for the upper 0- to 100-mm core interval (Fig. 4) was constructed based on the threefold independent calculation data on the annual layers.

In 2015, a core was taken from Zapovednoe Lake, at a distance of 15 km from Peyungda Lake. It contains a light layer of up to 8 mm thick distinguished by high Ti, Rb, and Zr and a number of other elements. The distribution of the ^{137}Cs and ^{210}Pb activity was measured to estimate the sedimentation velocity. The resulting age model dates this layer to 1908–1910 and relates its formation to the TCB explosion [16]. A light layer in the bottom sediment section of Peyungda Lake also has similar geochemical anomalies and probably marks the TCB explosion. For this reason, it was used to verify the age model (Fig. 4).

Under the age model (core depth–sediment age), the element compositions of bottom sediments were recalculated from a linear scale (core depth from the water–sediment boundary) into an integer time series and averaged in steps of three years. When searching for the relationship between geochemical and meteorological parameters, the 1895–2000 data from the nearest weather station in the Vanavara Settlement were used (https://climexp.knmi.nl; http://meteo.ru/data/156-temperature). The multiple regression method [17] was applied to construct the transfer function connecting the regional average annual temperature with the lithological and geochemical data:

$$T = 5.389 \cdot \mathrm{Co/Inc} + 3.887 \cdot \mathrm{Br} + 1.443 \cdot \mathrm{Rb} - 5.657.$$

Br and Rb are the bromine and rubidium concentrations (ppm), while Co/Inc is the ratio of elastically/inelastically scattered excitation radiation in the sample.

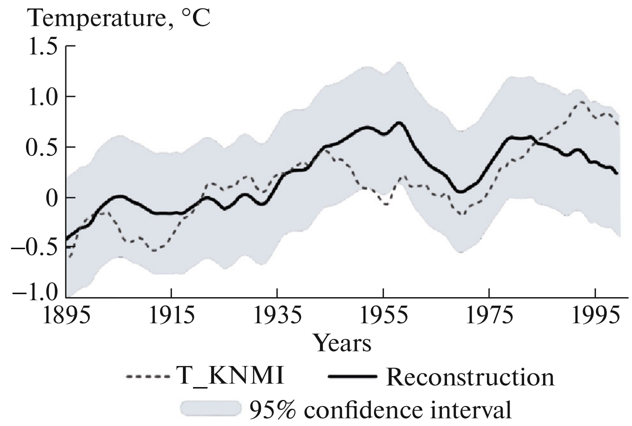

Fig. 5. Smoothed ten-year temperatures in the interval of 1895–2003 (https://climexp.knmi.nl) and reconstruction from the geochemical data; 95% reconstruction error interval.

Without detailing the relationship between the temperature and the lithological–geochemical parameters of dated layers included in the equation presented and with consideration of the entire mathematical processing procedure as a "black box," we should only note that the Br content can be regarded as a measure of the organic component of both allochthonous and autochthonous sediments, while the Rb content can be regarded as a measure of terrigenous material. Co/Inc is based on the X-ray density of the material at the measurement point and occasionally correlates with the climatic parameters [18].

The correlation coefficient between the initial meteorological data used for training (1895–2000) and the calculated values was + 0.58 (n = 105, p = 0.01) in the resulting function. Figure 5 shows a smoothed ten-year temperature series on the training interval, a reconstruction using the transfer function, and an error range. The obtained transfer function was used to reconstruct the temperature for the entire interval studied (up to a depth of 900 mm) corresponding to the period of 2003–967 AD (Fig. 6).

The medieval warming (tenth–thirteenth centuries) is observed, and, despite considerable differences, all reconstructions demonstrate a well-defined Little Ice Age (fourteenth–nineteenth centuries) and the recent warming from the beginning of the twentieth century. The reconstructed temperature trends of the presented reconstructions coincide within the 95% error interval and, thus, are indicative of the fact that the method used and the results obtained are correct.

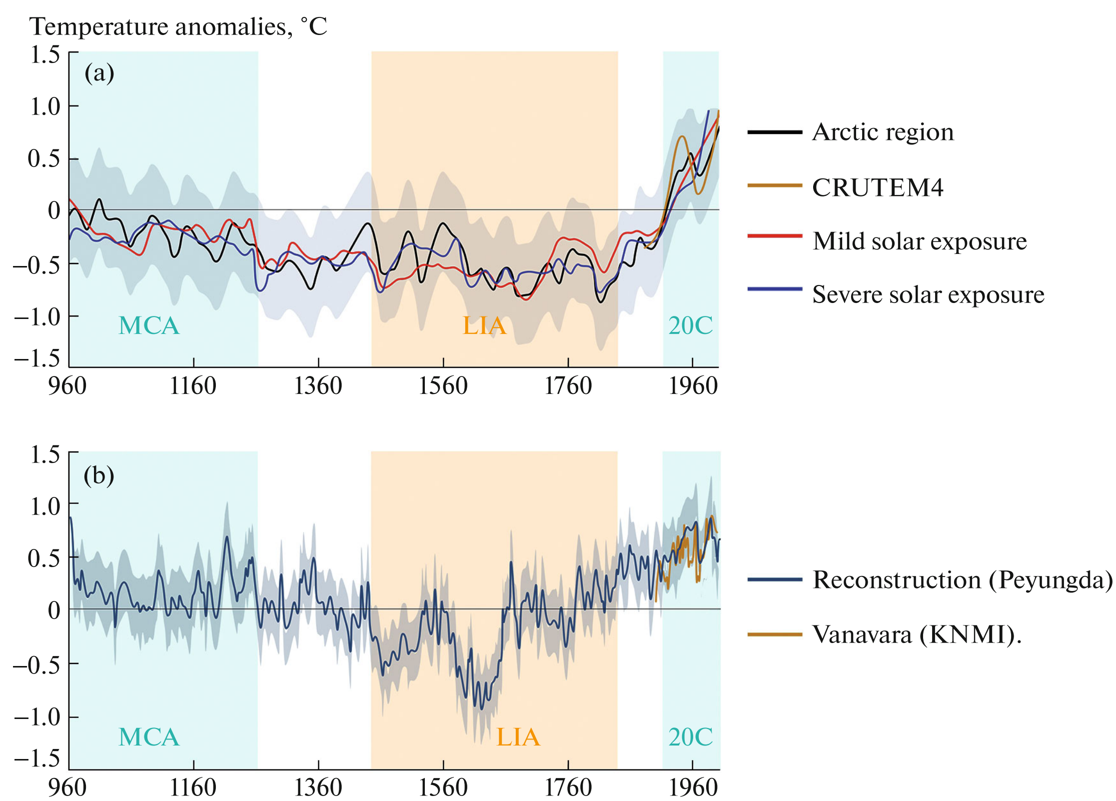

Fig. 6. Regional temperature reconstructions: (a) comparison of the literature meteorological data (CRUTEM4, dataset of global historical air temperature anomalies since 1850) and the reconstructed Arctic temperature variations [9, 19]; (b) comparison of the average ten-year instrumental meteorological data (Vanavara Settlement) and the temperature reconstruction we obtained in Peyungda Lake. The 95% uncertainty interval is shown in gray.

CONCLUSIONS

(1) The bottom sediments of Peyungda Lake are thin-layered sediments containing rhythmically interbedded individual annual layers (banded clays) which make it possible to build a reliable age model of the core depth–age of the sediment layer by counting individual layer pairs.

(2) A layer related to the 1908 TCB explosion is identified visually and based on geochemical anomalies in Peyungda Lake and a number of other lakes in the region. This layer makes it possible to verify age models over the last century.

(3) The advanced analytical micro-XRF using synchrotron radiation beams was used to construct time series of lithological and geochemical data on the compositions of individual layers of bottom sediments with a high temporal resolution (year, season).

(4) A significant correlation between element compositions of dated layers of bottom sediments and the regional instrumental meteorological data makes it possible to construct transfer functions and to obtain climatic paleoreconstructions over the last millennia.

(5) The temperature reconstruction we obtained based on the study of bottom sediments of Peyungda Lake, within the estimated errors, coincides with the literature reconstructions of the average annual temperatures in the Arctic region. Hence, our method can be regarded as reliable and correct.

(6) The presented reconstruction of the regional average annual temperatures is calibrated according to the regional weather observations, has a quantitative error estimate, and can be used to obtain a natural periodicity of climate cycles.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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