Article

High-Resolution Lacustrine Records of Late Holocene Hydroclimate of the Sikhote-Alin, Russian Far East

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Simple Summary: We studied the sediments of small mountain lakes (elevation 565 and 750 m a.s.l.) on the slopes of an ancient volcano, which were formed after large landslides. The lakes are located on the territory of the Sikhote-Alin Biosphere Reserve with unique ecosystems that combine heat-loving and cold-loving elements; rare animals live in this area, including the Amur tiger. These lakes are natural archives, allowing the reconstruction of the natural environment of this unique area with a temporary resolution of up to 30 years. Nizhnee Lake, which developed since 2640 yr is the most sensitive to climate change. Ten stages of the lake evolution with periods of watering and swamping were identified, that controlled by atmospheric precipitation. Our study demonstrates how the communities of swamp plants and diatom microflora responded to temperature fluctuations associated with solar activity and regional manifestations of global climatic events. One of the regional drivers were the intensity of summer and winter monsoons, the change in the position of the centers of atmosphere action and cyclonic activity. The natural environment was especially unstable during the Little Ice Age (14–19th centuries) which was wet with short-term dry episodes.

Abstract: There is little information about moisture changes in different altitudinal belts in mountainous regions of the Southern Russian Far East. We present ecological-taxonomic composition of the diatom flora, the botanical composition of peat of small mountain lake/mire complexes located in the Central Sikhote-Alin within large landslides on the paleovolcano slopes are identified. Frequent changes in diatom assemblages and peat-forming plants indicate unstable hydroclimatic conditions with varying degrees of watering and dry condition up to complete overgrowth of the lakes. Frequent change of sphagnum mosses with different trophic preferences was established. The chronology is based on 11 radiocarbon dates. Accumulation rates reached up to 1.9 mm/year, the temporal resolution for the reconstructions is up to 30–40 years. The tendencies of lake evolution depended on different-scale hydroclimatic changes for the last 4400 yr. The most detailed data for the last 2600 yr were obtained from the Nizhnee Lake sequence, more sensitive to climatic changes. The main reason for the change in the hydrological regime of the lakes was variations in precipitation during short-term climatic changes. The sediment record moisture fluctuations are relatively well correlated with regional patterns reflecting summer monsoon intensity and cyclogenesis activity.

Keywords: mountain lake/mire complexes; diatoms; botanical composition; inundation and dry periods; monsoon; cyclogenesis doi:10.20944/preprints202305.0092.v1

1. Introduction

The climatic instability of recent decades makes relevant work on paleoclimate, which makes it possible to assess the scale of climate changes and the response of biotic components to warmings and coolings in the past. One of the East Asia climatic features is uneven moisture supply throughout the year, controlled by intensity of the winter and summer monsoons. The specificity of atmospheric circulation here is determined by the interaction of air masses in the ocean-atmosphere-continent system. The climate is greatly influenced by cyclonic activity resulting from the interlatitudinal exchange of air masses. The climatic situation controls the seasonal irregularity of moisture, which is associated with the passage of extreme floods and long droughts. The duration of periods with different humidity varied significantly in the Holocene. Winter monsoon variability features exerted significant impacts on Eurasian and Western Pacific climatic patterns in the Holocene [1]. The dynamics of the summer monsoon in the Holocene is well studied for northeast China; there are data on the Korean Peninsula and the Japanese Islands [2–8]. For these regions, there are chronicles information on hydroclimatic changes for Common Era [5, 9–10].

In the Southern Russian Far East observations began in the second half of the 20th century; therefore, on a scale of several centuries-millennia, climatic trends and the intensity of cyclogenesis can only be estimated on the basis of paleoenvironmental records. There is little information on moisture level variations in different altitudinal belts and the response of biota to the changes. Such studies are especially important for mountain areas with unique ecosystems that combine heat-loving and cold-loving plants, including endemics. The strong microclimatic variability in the mountains contributed to the refugia preservation, which played an important role in changing areals and altitudinal belt boundaries during climate changes [11].

Reconstructions performed for different regions of the Southern Far East showed that the development of landscapes in the Holocene was largely determined by hydroclimatic changes associated with the intensity of the East Asian monsoon and the activity of cyclogenesis [12–14]. Lacustrine sediments are the most informative for high-resolution records study that makes it possible to restore the response of the biota to moisture changes. In Primorye, most of climatic reconstructions were made using coastal lake sediments [15–18], mountain plateau paleolake sediments of East Manchurian Mountains [14] and the Southern Sikhote-Alin [19–20], and a paleolake in the river valley [21]. The study highlight the dynamics of vegetation and lake microflora development, which is closely related to changes in hydroclimatic conditions in late Holocene. For the Central Sikhote-Alin, reconstructions have been made only for the Izyubrinye Solontsi Lake, from the group of Solontsovskie (Shanduyskie) lakes [22]. These lakes are located in the Sikhote-Alin Biosphere Reserve, included in the UNESCO World Heritage Site with the mission to preserve the biological and landscape diversity and to monitor the ecosystems of the Central Sikhote-Alin. The group of Solontsovskie lakes includes water bodies located at different heights above sea level that are unique objects, the data of which make it possible to determine the dynamics of biota in different altitudinal zones.

The aim of our study is to reconstruct the environmental and climatic changes on Central Sikhote-Alin Mts., using multi-proxy records of the Nizhnee Lake sediments, and to compare our data with local and regional paleoclimatic data in order to provide new information on variability of the palaeoclimate in poorly studied mountain areas of the Russian Far East with diverse ecosystems.

2. Regional Setting

The Solontsovskie lakes are located on the eastern macroslope of the Sikhote-Alin near the paleovolcano Solontsovsky, erupted ~61–56 Ma [23]. There are 10 lakes formed within large landslides that blocked the stream channels. The Nizhnee Lake (100 × 50 m) is located at 565 m a.s.l. within the altitudinal zone of Korean pine and Korean-pine-spruce forests (400–700 m); Izyubrinye Solontsi Lake (190 × 100 m) – at 750 m a.s.l. within fir-spruce forests (700–1200 m). Distance to sea coast is 33 km (Figure 1).

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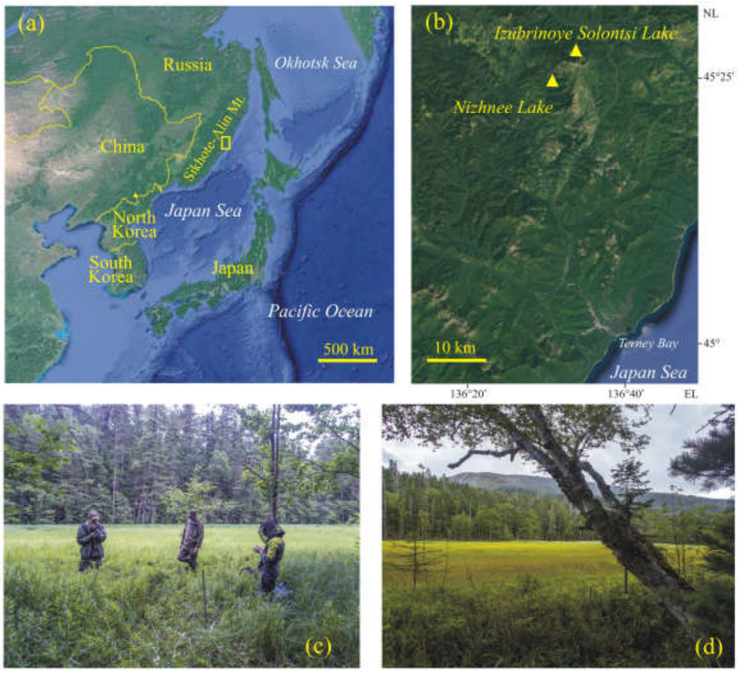

Figure 1. Study area: (a) Position of the study area in NW Pacific region; (b) Solontsovskie Lakes location and position of the studied sections; (c) Nizhnee Lake; (d) Izyubrinye Solontsi Lake.

The average annual temperature in the mountains at an altitude of 500–600 m is +1.5°C, the temperature in January is –18.3°C, and in August +11.8°C [24]. The amount of precipitation is 940 mm/year, with the maximum in August-September. The frost-free period averages 120 days. The height of the snow cover reaches 1 m. Data from the nearby Terney station (WMO 31909) were used.

The features of regional moisture circulation determine the hydrological regime of the Solontsovskie lakes [22]. At the beginning of the summer water often almost disappears due to a high rate of evapotranspiration that leads to filling up by vegetation. During the typhoon season (August-September), the lakes are filled with rainfall, the water level rises promptly, and open water appears here. The lakebeds are composed of permeable deposits, the lake basins are almost completely infilled with peat.

The sod in the marginal part of the Nizhnee Lake basin consists of herb remains of grasses with a predominance of cottongrass (*Eriophorum scheuchzeri, E. vaginatum*) and sedges (*Carex criptocarpa, C. middendorffii*) with *Rynchospora alba*, *Schoenoplectus tabernaemontanii*, fern *Dryopteris thelypteris* and *Iris* sp. Sphagnum mosses (10–35%) include eutrophic *Sphagnum denticulatum* and *S. subsecundum*, as well as hygrophyte *S. divinum*, typical for oligotrophic-mesotrophic heavily watered bogs. Green moss is present singly. The swamp belongs to the mesotrophic type. Larch (*Larix cajanderi*) grows along the edges of the lakes.

3. Materials and Methods

The marginal part of the Nizhnee Lake (45°25′23.56′ N, 136°30′58.54′ E) was drilled using a Russian peat borer. The depth of the sampled section was 3.25 m depth. We took 65 samples of the peat at 5-cm intervals without gaps, stored in sealed plastic bags.

The botanical composition of peat was determined according to Kulikova [25]. The presence of charcoal fragments, green algae, cladocera and testate amoebae also being recorded. Testate amoebae were identified according to Mazei and Tsyganov [26]. Decomposition of plant remains was assessed as the proportion of unidentifiable humic substance [25]. Ash content (non organic content, %) was determined after ignition at 550°C [27].

Diatom samples were prepared using procedures described by Gleser et al. [28] and Battarbee [29]. The samples were heated to 100°C with 30% hydrogen peroxide (H2O2). The diatoms samples were mounted on permanent slides: 0.2 mL of the suspension was pipetted onto a clean coverslip,

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and then the water was evaporated at room temperature. After the coverslips were dry, they were then mounted in a resin with a refractive index of 1.67-1.68. Identification of diatoms was done with a microscope Axioscop (Carl Zeiss, Oberkochen, Germany), at ×1000 magnification. More than 300 valves were counted in each slide. We used atlases of diatoms for species identification and environmental characteristics of individual species [30–35]. The content of diatom valves in 1 gram of air-dry sediment was calculated to determine the productivity of diatom flora depending on the ecological state of the paleo-reservoir at different stages of its development. The main taxa indicative of changes in environments are shown in the diagram. The diatom record was divided into assemblages based on visual inspection and cluster analysis. Principal Component Analysis (PCA) was used as additional proof of zonation. Cluster analysis and PCA was performed using PAST 3.26 software [36]. Shannon diversity index (H) was assessed.

Radiocarbon dating of peat samples was carried out (beta counting) at the Institute of Earth Sciences, St. Petersburg State University (St. Petersburg). Calibration of radiocarbon dates was done using the OxCal 4.4 and "IntCal20" calibration curve [37–38]. The calibrated age was determined by the age-depth model constructed using Bacon 2 [39].

4. Results and interpretation

4.1. Ages, sedimentation rates and resolution

Age-depth model created on the 6 ^{14}C-dates shows that peat accumulation rates in the Nizhnee Lake were fairly uniform (Figure 2, Table 1). According to the age-depth model, the base of the borehole is estimated at 2640 yr BP. At the initial stage, peat accumulation rate was 0.8–1 mm/yr. Rates increased to 1.6–1.7 mm/yr ~1290 yr BP, decreased up to 1.4 mm/yr 980–620 yr BP, increased ~620–320 yr BP (1.6–1.7 mm/year) and decreased in the final stage (to 1.2–1.4 mm/year). The approximate resolution of the paleoenvironmental reconstructions is 50–60 years, and for the last 1290 yr BP – 30-40 years.

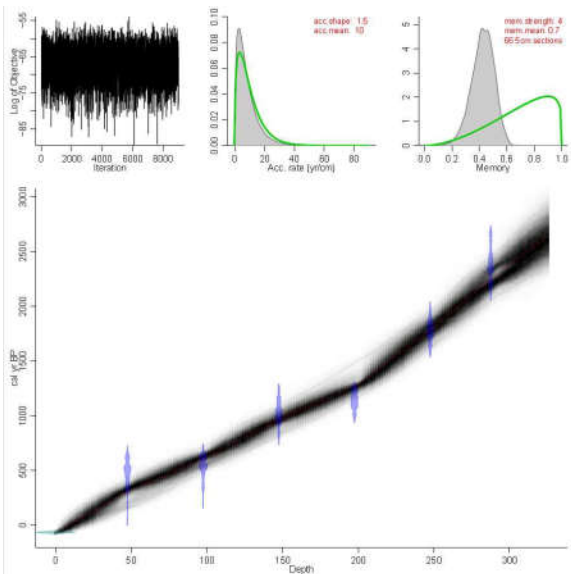

Figure 2. Age–depth model for the studied section 0315 from the Nizhnee Lake sediments, plotted using Bacon [39] with 95% confidence limits shown.

Table 1. Radiocarbon dates and accumulation rates obtained for sediments of the Nizhnee Lake, Sikhote-Alin Mountains.

Lab number, LU-	Sample number	Depth, cm	^{14}C-Age, yr BP	Calendar age (2σ)	Sedimentation rate, mm/yr
8838	10/0317	45–50	470 ± 100	480 ± 100	1.2–1.4
8839	20/0317	95–100	530 ± 90	550 ± 80	1.6–1.7
8840	30/0317	145–150	1100 ± 80	1030 ± 90	1.4–1.5
8841	40/0317	195–200	1220 ± 60	1150 ± 70	1.6–1.7
8842	50/0317	245–250	1850 ± 70	1780 ± 90	1–1.2
8843	58/0317	285–290	2330 ± 70	2380 ± 130	0.8–1

The rates of peat accumulation in the Nizhnee Lake were lower than those in the Izyubrinye Solontsi Lake, where the rate was up to 1.9 mm/year [22], but general trends are well traced. A sharp increase in the rate occurred ~1280 yr BP, at the end of the Medieval Warm Period, and at the beginning of the Little Ice Age the rate decreased, then increased ~500–400 yr BP and has been in decline for the last 400 years.

4.2. Mire vegetation development based on botanical composition of the peat

Waterlogging began in a depression within the landslide, occupied by larch forest. Under humid and cool conditions (2640–2590 yr BP), grass–green moss peat began to accumulate (Figure 3). Remains of 5 species of green mosses were found: *Aulacomnium palustre, Helodium blandovii, Mnium punctatum, Meesia trifaria* and *Drepanocladus* sp. Herbaceous plants are represented by sedges, cottongrass, reeds, and iris. The sphagnum cover included the hygrophytes *Sphagnum jensenii, S. divinum,* and *S. fallax*. A larch forest with birch was developed along the border of the bog up to 2430 yr BP, eutrophic sphagnum-grass and woody-grass peat was formed (305–325 cm). The presence of a large number of burnt twigs and charcoal pieces indicates frequent fires. The cladocera *Chydorus sphaericus*, a species widely distributed in eutrophic freshwater shallow water bodies, appeared. In 2590–2430 yr BP large-scale fires periodically occurred, that caused mire vegetation destruction, as evidenced by the presence of microcharcoals and green moss *Aulacomnium palustre*, an indicator of pyrogenic successions [40].

Lowland grass peat (280–305 cm), mainly cotton grass-sedge, with a significant presence of hydrophytes, including lake cane (*Scirpus lacustris*), horsetail *Equisetum fluviatil*, and water lily *Nymphaéa álba*, began to accumulate ~2430-2160 yr BP. The shrub layer was poorly developed; remains of shrub birch were found. Sphagnum and green mosses practically disappeared (2330–2220 yr BP). The degree of decomposition of the material decreased. Peat formed ~2380–2110 yr BP, has an increased mineral content (up to 43.5%).

The moss cover became more developed ~2160–1290 yr BP – the remains of sphagnum mosses reach up to 50%, green mosses – up to 25% (depth 200–280 cm). Among the herbs, cottongrass and sedge prevailed, the remains of *Comarum*, lobelia, reeds were found, there was a lot of iris. Cranberries (*Oxycoccus palustris*) appeared in abundance. The degree of decomposition became lower. The presence of cladocera indicates waterlogging.

The greatest flowering of sphagnum mosses (*Sphagnum jensenii*) was ~1290–1260 yr BP (depth 195–200 cm). *Baeothryon* sp. appeared among herbs. The outbreak of eutrophic hygrohydrophyte green moss *Limprichtia revolvens* (depth 185–195 cm) indicates a stagnant water regime 1260–1200 yr BP.

Herbaceous-moss peat (depth 155–185 cm) was formed 1200–1010 yr BP. Along with *Sphagnum jensenii* the role of *S. divinum* increased since 1100 yr BP. There are single charcoals, excepted interval 160–165 cm (1080–1040 yr BP). The number of sphagnum and green mosses decreased ~1010–980 yr BP, and herbaceous peat (depth 150–155 cm) with an abundance of cottongrass remains began to

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form, possibly as a result of frequent fires. Herbaceous-sphagnum peat (depth 85–150 cm) of rather homogeneous composition accumulated ~980–560 yr BP. Green mosses are represented by *Limprichtia revolvens, Meesia trifaria*. Cranberries grew in abundance, and many larch needles were found. The abundance of cladocera *Alonopsis elongate* indicates waterlogging.

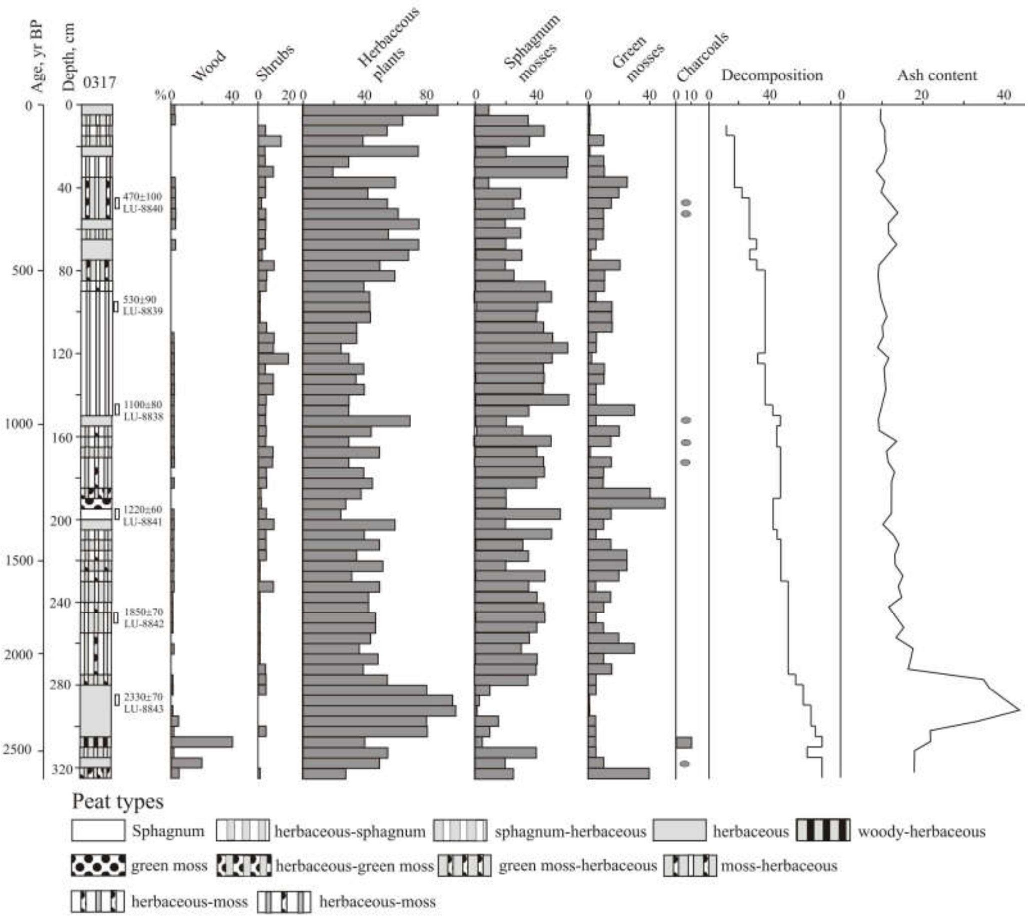

Figure 3. Botanical composition and characteristics, in section 0315, the Nizhnee Lake plus records of charcoal and terrigenous input.

The role of herbaceous plants increased 560–210 yr BP (depth 35–85 cm). Among the sphagnum mosses, the mesotrophic *Sphagnum lindbergii* and the eutrophic hydrohygrophyte *S. subsecundum* appeared. The cladocera practically disappeared ~440 yr BP – conditions became drier. Herbaceous peat formed ~380–350 yr BP. The amount and diversity of green mosses (*Limprichtia revolvens, Scorpidium scorpioides, Calliergonella cuspidata*) increased ~320–210 yr BP. The sphagnum moss layer became more developed 210–130 yr BP (depth 25–35 cm). There was a cottongrass-sedge mire ~130–90 yr BP. The role of sphagnum mosses increased in recent decades, but the surface sod is composed mainly of grasses.

In peat formed 1870–500 yr BP (80–255 cm), testate amoebae are present in large numbers: hydrophiles *Heleopera petricola* and *Archerella flavum* [41], hygrophilic sphagnophiles *Hyalosphenia papilio*, and occasionally *H. elegans*, which are typical of mesotrophic environment [42]. The last two species have an optimum level of swamp waters 20–21 cm and are tolerant to fluctuations 5–15 cm [43]. In peat younger than 2220 yr BP (from a depth of 285 cm), *Centropyxis aculeata, C. constricta*, and *C. laevigata* are found, these species are typical of heavily watered habitats and tending to mesotrophic environments [41].

4.3. Lake development based on diatom data

In the sediments 144 taxa of diatoms were identified: epiphytes (69) and bottom forms (64) predominate, planktonic and temporarily planktonic – 11 species. Most of the identified diatoms are cosmopolitan, 11 boreal and 22 arctoboreal species were found. The attitude to mineralization is known for 128 species, all of them are oligohalobes, With reference to mineralization indifferent species dominate (78), halophobes (39) and halophiles (11) are found. The dominant group is circumneutral species (66) relative to pH, 40 species are acidophiles, 24 are alkaliphiles. The diatom distribution suggests 10 zones, that reflect the lake evolution and changes in the environments (Figure 4).

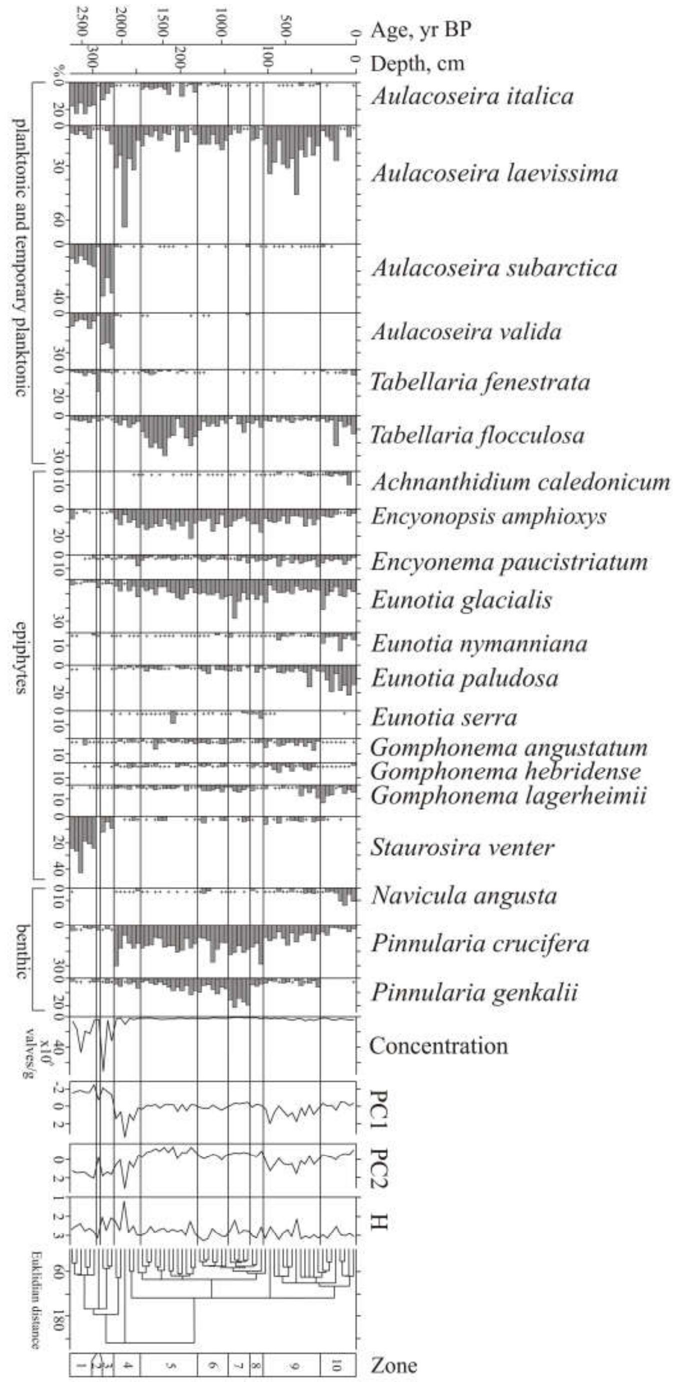

Figure 4. Diatom percentage diagram showing the distribution of the main diatom taxa in sediment core from the Nizhnee Lake (site 0317), PC axes 1 and 2 scores for diatom data, and Shannon H diversity. A 'plus' sign indicates content of frustules less than 1%.

At the initial stage (2640–2330 yr BP, depth 295–325 cm), the lake had littoral zone with aquatic plants. Planktonic species prevailed (zone 1) (Figure 5). Planktonic *Aulacoseira italica*, typical for mesotrophic-eutrophic waters, and *Aulacoseira subarctica* dominated, and among epiphytes *Staurosira venter*, typical for oligotrophic-mesotrophic conditions [34], dominated. With respect to mineralization, indifferent species predominate; with respect to pH, circumneutral species and alkaliphiles predominate. The concentration of diatom valves varies and reaches 46.9x10^6 valves/g.

A short-term decrease in the lake level occurred during the cooling 2330–2280 yr BP (depth 290–295 cm). Diatom zone 2 is characterized by a high content of bottom flora. Dominant are temporarily planktonic cosmopolitan *Tabellaria fenestrata*, the arctoboreal *Fragilariforma nitzschioides*, that prefers oligotrophic-dystrophic waters, and the benthic *Hantzschia amphioxys* (13.2%), that can also inhabit soil. The subdominants are the benthic *Pinnularia crucifera*, typical for oligotrophic lakes of the northern regions, and the swamp *Eunotia glacialis.* Diversity of diatom flora increased. The content of halophobes (up to 41.3%), acidophiles (up to 36%), and arctoboreal species (up to 15.5%) increased. The lake became closer to oligotrophic, the temperature conditions, apparently, became colder. The concentration of valves decreased to 2.9x10^6 valves/g. The depression began to overgrow, and in some places, dry areas probably formed.

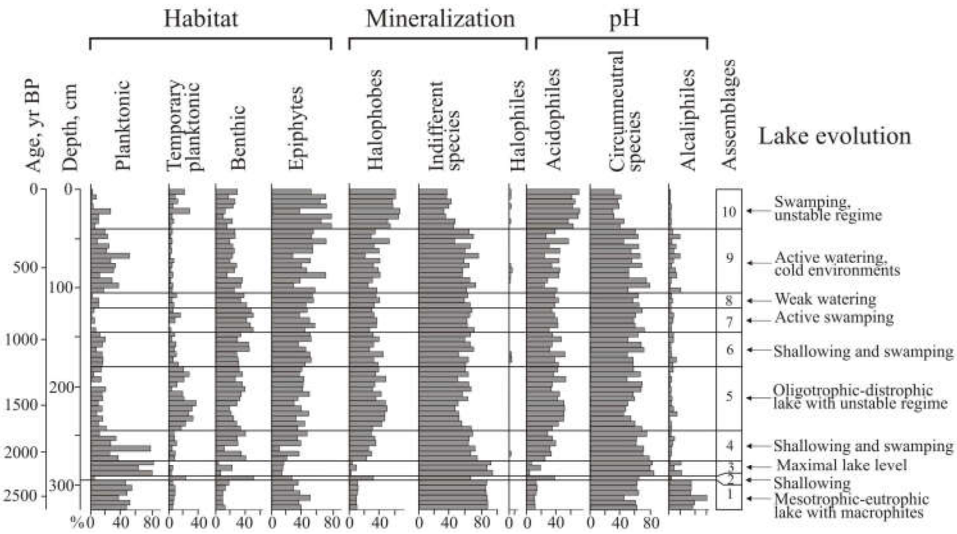

Figure 5. Distribution of ecological groups of diatoms in sediment core from the Nizhnee Lake (site 0317) with regard to habitat type, salinity, pH, and geographical distribution.

The subsequent watering of the lake basin (2280–2110 yr BP, depth 275–290 cm) led to the predominance of planktonic species (up to 79.6%) (zone 3). *Aulacoseira subarctica* and *A. valida*, common in oligotrophic-mesotrophic water bodies of northern and mountainous regions, dominated. The peak in these species coincides with the rapid increase in diatom concentration indicating the rise in diatom productivity. *A. subarctica* prefers heavy snowfalls and thick ice, and the development of this species depends on the amount of winter precipitation and the length of the ice cover [44]. In Kamchatka this species grew when water temperature was ≤4°C, it may develop in low light conditions [45]. The subdominant is *Staurosira venter*. The proportions of acidophyles and halophobes decreased. Content of arctoboreal species is ≤ 8.1%. The concentration of valves is 31–70 million/g. The composition of diatoms indicates the existence of an oligotrophic-mesotrophic lake with thickets of macrophytes.

Zone 4 (depth 245–275 cm) reflects a significant decrease in the level and swamping of the lake 2110–1760 yr BP. *Aulacoseira laevissima*, typical for oligotrophic water bodies, became dominant. This species occurs in shallow glacial lakes (~1 m deep) in the subalpine and alpine belts [34, 46]. *A. laevissima* produces an outbreak ~1990–1930 yr BP, resulting in a severe decrease in diatom diversity. The content of benthic species increased, especially *Pinnularia crucifera*. The subdominants are the epiphytes of oligotrophic and oligotrophic-dystrophic lakes: the arctoboreal *Encyonopsis amphioxys*, the cosmopolitans *Eunotia glacialis* and *Tabellaria flocculosa*, and the arctoboreal *Eunotia lapponica* and *Eunotia serra* that often inhabit wet sphagnum mosses appear. There was an increae of acidophiles (up to 25.2%) and halophobes (up to 26.4%), typical for bog environments, and arctoboreal diatoms (12–25.5%). The concentration of valves decreased (1.4–9.3x10^6 valves/g). Significant fluctuations in the diatom proportions are reflected in the variations of the PC1 and PC2 axes of indicator species (Figure 4).

Zone 5 (1760–1130 yr BP, depth 180–245 cm) indicates that the hydrological regime of the oligotrophic-dystrophic reservoir was unstable. The content of planktonic species varied greatly; *Aulacoseira laevissima, A. italica, A. crenulata,* and *A. subarctica* were found. The content of *Tabellaria flocculosa*, which is typical for peat bogs, increased significantly. Halophobes and acidophiles *Eunotia serra* and *E. lapponica*, which develop optimally at pH 4.9, became permanent components of the flora [30]. The maximum content (up to 10.8%) of these species was ~1500–1440 yr BP. At the time proportion of planktonic species is sharply reduced (up to 1%). Perhaps for a short period the lake was heavily overgrown. The proportion of arctoboreal diatoms rose to 33%, while their content in the underlying and overlying sediments is 15–26.7%. The abundance of valves does not exceed 2.5x10^6 valves/g.

Zone 6 (depth 145–180 cm) reflects a short-term fall in the lake water level ~1130–940 yr BP. The role of *Pinnularia crucifera* increased among the dominants. The benthic *Pinnularia genkalii* appeared among the subdominants. The content of bog species of the genus *Eunotia* increases (up to 27%), including *E. paludosa*, which is typical of sphagnum bogs and tolerant to temporary dry environment [47]. The concentration of valves varies within 0.7–1.8x10^6 valves/g.

A significant drop in the lake level as a result of further overgrowth was about 940–760 yr BP (zone 7, depth 120–145 cm). The content of planktonic diatoms decreases, benthic species and epiphytes predominate. The proportion of species of the genera *Eunotia* (up to 35.5%) and *Pinnularia* (up to 45.8%) increases, among which species characteristic of near-neutral or slightly acidic waters of oligotrophic reservoirs dominate (*Eunotia glacialis, Pinnularia crucifera, P. genkalii*). Subdominants are *Encyonopsis amphioxys* and *Tabbelaria flocculosa*. In some periods 910–870 and 840–800 yr BP (depths 135–140 and 125–130 cm), complete overgrowth of the lake is recorded. The concentration of valves decreases to 0.2x10^6 valves/g. At the beginning of this stage, when the lake was completely overgrown, diatom diversity decreased sharply.

Zone 8 (depth 105–120 cm) reflects a slight inundation of the lake ~760–660 yr BP. The content of *Aulacoseira laevissima* increased and the proportion of bottom species decreased. Climatic conditions were cold: the content of arctoboreal species, including *Eunotia serra,* reaches 29.5%. The concentration of valves increases to 2.1x10^6 valves/g.

Stronger watering was recorded ~660–250 yr BP (zone 9, depth 40–105 cm). The proportion of planktonic species increased to 49.7%. *Aulacoseira laevissima* became dominant, indicating the watering of the catchment. Climatic conditions remained cold, the content of arctoboreal species reached up to 29%. The concentration of valves varied from 1 to 4.7x10^6 valves/g, diatom productivity was unstable. Short-term shallowing of the lake was recorded ~380–350 yr BP (depth 55–60 cm). Here, the content of planktonic species decreased to 8.1%, and the participation of *Eunotia paludosa* and *E. nymanniana*, which are able to live with insignificant moisture [47], increased. Diversity of diatoms possibly increased due to formation of various biotopes during seasons with contrast moisture. The variations of the PC1 and PC2 axes show instability of environments and lake ecosystem (Figure 4).

The subsequent development of the lake took place under conditions of progressive shallowing. Zone 10 (depth 0–40 cm) with domination of epiphytes (up to 77%), such as *Eunotia paludosa* and *E. glacialis*; and subdominants *Eunotia nymanniana* and *Encyonema paucistriatum* indicates weak moisture. In the top layer, the content of benthic *Navicula angusta*, which is distributed mainly in oligotrophic waters and mosses in mountainous regions, increases [33]. Increase the content of planktonic species (*Aulacoseira laevissima, A. italica, A. subarctica, A. crenulata*) up to 25.4% shows significant watering of the lake in the first half of the 19th century. The content of *Tabellaria flocculosa* also increases significantly. Less severe inundation of the lake manifested in the first half of the 20th century – the proportion of planktonic diatoms in depth 0.10–0.15 m reaches 6.3%. Decrease of planktonic species in the top (1.2%) indicates complete overgrowth of the lake. In peat formed in the phases of watering, the concentration of valves reaches 3.5x10^6 valves/g, in other layers it is less than 2x10^6 valves/g. In general, acidophiles and halophobes dominated. The content of arctoboreal species decreased from 32.7 to 10% in the top.

4. Discussion

The study of two sections of organogenic deposits in lake basins showed that large landslides on the slopes of the Solontsovsky paleovolcano took place repeatedly; and caused different time of small lakes formation. Izyubrinye Solontsi Lake (4400 yr BP) is older than Nizhnee Lake (2600 yr BP), the course of their development was metachronous, most likely due to different altitudinal positions, but the trends were similar and reflect the climatic changes in the late Holocene in the Central Sikhote-Alin. Figure 6 demonstrate comparison of our results for paleoclimate proxies with sun activity [7] and palaeotemperatures [48, 49]. The main factor determining the development of the lakes and features of sedimentation was the change in moisture, which was controlled by the precipitation. Mire vegetation and diatom microflora in the lakes were highly depended on changes in watering, as evidenced by the frequent change of peat-forming plants with different trophic preferences and diatom assemblages with species that prefer different habitats and geochemical environments. The cover of vascular plants in the mires very weakly reacted to climatic changes: 2–3 species of sedges and cottongrasses with some hydrophytes dominated throughout the entire period.

Due to very significant seasonal fluctuations in the level of swamp waters inherent in this region, waterlogging periodically changed from stagnant, accompanied by an outbreak of green mosses development, to weakly flowing, as indicated by periodically appearing terrigenous material. Significant seasonal fluctuations in the level of swamp waters were typical for the entire period.

Formation of the Nizhnee Lake and the beginning of peat accumulation occurred during a cooling that had a global scale (2800–2600 yr BP) and was accompanied by a decrease in moisture in Asia [50]. Intensity of summer monsoon weakened at that time (3600-2100 yr BP) in Northeast China [2–3, 51]. In the Lower Amur region, the environments were especially dry~2570 yr BP [12]. Mountain lakes and mires in the southern Sikhote-Alin developed differently during the cooling. A moisture decrease was recorded 2735–2040 yr BP in the Muta peat bog (570 m a.s.l.), located on the main watershed [52]. A progressive decrease in depth of the paleolake was noted at 3010–2630 yr BP for the Larchenkovo swamp and Shkotovskoe Plateau (730 m a.s.l.) [19].

At the initial stage the Nizhnee Lake was a mesotrophic-eutrophic reservoir, more watered than Izyubrinye Solontsi Lake. The flooding of the basins depended on local geomorphological features. The water in the Nizhnee Lake was weakly alkaline, apparently, due to parent substrate. Prolonged dry seasons were the cause of large-scale fires that occurred 2590–2430 yr BP. Activation of fires at that time was also recorded for the Bikin River basin, and the Southern Sikhote-Alin [53–54].

The drop of the Nizhnee Lake level was recorded during a short-term cooling of 2330–2280 yr. BP. Overgrowing of the lake led to a decrease of pH value. Productivity of diatoms became lower. A sharp rise in halophobes content indicates an increase in atmospheric nutrition. The level fall and the overgrowing of Izyubrinye Solontsi Lake began ~ 2270 yr BP, woody peat with *Larix* accumulated around the lake [22]. At that time, species capable of living with weak moisture were widely developed in the diatom flora: the benthic *Pinnularia borealis*, and the acidophilus *Eunotia praerupta* dominated among epiphytes in the Izyubrinye Solontsi Lake; *Hantzschia amphioxys* – in the Nizhnee Lake. According to estimates made for the sea coast (Langou I Bay), temperatures reached a minimum (about 1 °C below the present) at ~2280 yr BP [18]. Severe frosts and snowfalls in the 4th–3rd centuries BC are noted in the annals of China [49].

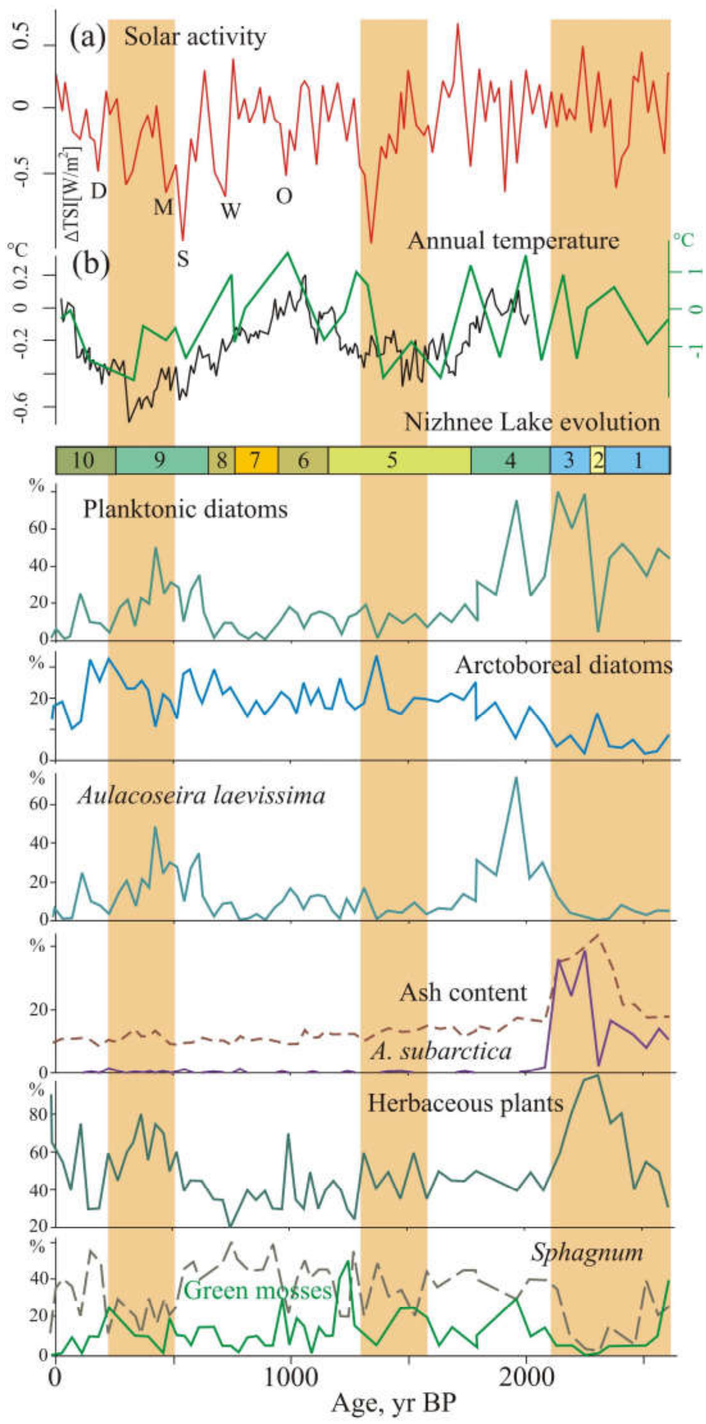

Figure 5. Compilation of selected proxy records from sediments of the Nizhnee Lake with sun activity and palaeotemperatures. (a) Solar activity fluctuations reconstructed based on 10Be measurements in polar ice [7], periods of the Grand Solar Minima: O – Oort, W – Wolf, S – Spörer, M – Maunder, D – Dalton; b) black line –Decadal mean temperature variations (°C) relative AD 1961–1990, estimations of extra-tropical Northern Hemisphere (90–30°N) [48]; green line – reconstruction of annual temperatures for the Amur River Region from modern average temperature [49]. The vertical orange bars show the abrupt summer monsoon declines [2–3].

The maximum watering of the Nizhnee Lake was ~2280–2110 yr BP, which coincides with a slight warming connected with increased solar activity [7, 55]. There was an outbreak of diatoms in the lake, especially plankton. The pH values were close to neutral. Ash content of peat increased due to slope wash during frequent heavy rains, associated with the passage of typhoons. It is possible that at that time the vegetation on the landslide surface was sparse and did not prevent active erosion. It is possible that a new landslide formed in the upper part of the catchment above the Nizhnee Lake. Abundance of *Aulacoseira subarctica* possibly indicates strong snowfalls and thick ice cover [44]. The activation of winter cyclogenesis occurred under the conditions of weakening of the Siberian High [56]. The weakening of the Siberian anticyclone contributed to the activation of winter cyclogenesis. Exactly the conditions of activation of slope wash during snowmelt or typhoons, this species, capable of developing under low light conditions, became dominant. Sphagnum and green mosses disappeared from the swamp, herbaceaus peat accumulated. Possibly, active slope wash and increased terrigenous supply was one of the reasons for the reduction of the moss cover. The watering ~2370–2150 yr BP was recorded on the mires of the western macroslope of the Central Sikhote-Alin (Bikin River basin) and to the south, on the Sergeev Plateau mires (2380–2130 yr BP) [20, 54]. On the eastern macroslope of the Sikhote-Alin, the maximum flooding of the swamp in the valley of the Milogradovka River was 2310-2250 years ago [21].

A gradual fall of the lake level with some fluctuations took place in cooler conditions~2110–1760 yr BP. The drop of annual temperature was ~1°C lower than the present [18]. Cladocera appeared in abundance in the Nizhnee Lake. At that time, the green mosses *Limprichtia revolvens* and *Scorpidium scorpioides,* typical for waterlogged swamp areas [57], developed widely on the mire. The peak of planktonic diatoms indicates a short-term watering ~1990–1930 yr BP. The peak of *Aulacoseira laevissima*, usually living in shallow glacial lakes, indicates a cold event, correlated with short-time solar minima [7] (Figure 6). Testate amoebae, typical of heavily watered environments, including sphagnophiles, developed in abundance ~1870 yr BP. A sharp change in diatom diversity indicates significant transformations in the reservoir ecosystem.

Unlike Izyubrinye Solontsi Lake, which was relatively stable 2270–1230 yr BP with a tendency of shallowing and desiccation, the Nizhnee Lake had an unstable regime 1761–1133 yr BP (Figure 6). The geochemical environment changed ~1710 yr BP: the pH value decreased (to 4.9). Cold conditions are indicated by the development of a stable sphagnum cover (1870–1550, 1390–1340 yr BP). The peak of cooling in the Central Sikhote-Alin was accompanied by a significant reduction of atmospheric precipitation and caused a short period of strong overgrowth of the lake ~1500–1440 yr BP. It is correlated with the end of the global cold event (1650–1450 yr BP), which was accompanied by drying in Asia [49–50, 55]. At this time (1600–1300 yr BP), a weakening of the summer monsoon was recorded [2]. Some authors consider the boundaries of this cooling in a wider range – 1750–1350 yr BP [48]. The cooling manifested in Primorye [58] and Sakhalin [13], cold Kofun stage (1760–1220 yr BP) was identified in the Japanese Islands [9]. A short-term cooling and strong mountain lake shallowing were recorded between 1800 and 1500 yr BP on Kamchatka [59].

The subsequent development of the Nizhnee Lake reflects the unstable climatic variability during the transition to the Medieval Warm Period. A short-term cooling ~1290–1260 yr BP led to the development of sphagnum mosses. Perhaps, due to weakly decomposition sphagnum remains, the rates of peat accumulation increased. Development of green moss *Limprichtia revolvens* and *Baeothryon* indicates cold wet environments with stagnant water regime 1260–1200 yr BP. Hypnum peat accumulated at the time. The watering phase of the Izyubrinye Solontsi Lake was also noted ~1230 yr BP [22]. A long period with abundant river flow and severe floods in the Bikin River basin began ~1260 yr BP [54]. This cold event coincided with solar minima 1300-1200 yr BP [55].

The warming correlated with the Medieval Warm Period is distinguished by pollen data of Izyubrinye Solontsi Lake sediments ~1080–810 yr BP. On the sea coast of Eastern Primorye annual temperature was ~1.5°C higher than present [18]. Nizhnee Lake water level decreased, it began to overgrow actively ~1130–940 yr BP. In the mire, the role of herbaceous plants increased. Among the mosses, *Sphagnum divinum*, typical for mesotrophic bogs, developed. Role of green mosses diminished sharply ~1010–980 yr BP. Presence of microcharcoal indicates fires in the surrounding territories (1130–1100, 1070–1040, 1010–980 yr BP). Frequent fires during the Medieval Warm Period also occurred in the South Sikhote-Alin, possibly connected with human activity in the Middle Ages [20].

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The lake level fall and active overgrowth of the Nizhnee Lake ~940–760 yr BP probably occurred during a temperature decrease. The lake may have been completely overgrown 910–870 and 840–800 yr BP. The Izyubrinye Solontsi Lake reduced 960–840 yr BP. Here, a cold episode is recorded ~840–810 yr BP, there was a small fire near the lake.

The Nizhnee Lake watering began with a change in the climatic regime 760–660 yr BP and especially during 660–250 yr BP (the Little Ice Age). This cooling is related to solar forcing – solar activity decreased significantly [7, 60–61]. Annual temperature was 1.5–2°C lower than present [49, 62–63]. The Little Ice Age was likely the coldest period of the last 8000 years, the climate was unstable with high variability of seasonal temperatures [61]. Climatic condition of Southern Far East was controlled by strengthening of the Siberian High and the Aleutian Low [64]. Apparently, at that time there was an increase in cyclonic activity [8, 65]. Summer monsoon became active with short-time period of weakening [2, 65]. Winter monsoon was weak after 1000 yr BP and intensified during the Little Ice Age [8, 66].

The mire vegetation and diatom communities of the Solontsovskie lakes responded to highly variable environmental changes during the Little Ice Age. In the Central Sikhote-Alin, conditions in the first half of this period were colder, as in other continental regions of the Southern Far East [54, 67]. The proportion of arctoboreal diatoms and *Aulacoseira laevissima* increased, especially 610-420 yr BP. The conditions were cold and wet, sphagnum mosses were widespread in the mire. The development of the green moss *Meesia trifaria* on margin of the Nizhnee Lake indicates an increase in mineral nutrition.

The decrease in the proportion of arctoboreal species allows us to identify several short-term warmer episodes 660–620, 530–500, 440–410 yr BP. As a rule, the proportion of phytoplankton increased at this time. The abundance peaks of arctoboreal diatoms (690–660, 590–560, 470–440 yr BP) apparently correspond to minimums of solar activity, including Wolf and Shpörer minima [60–61, 68]. The number of cladocera was sharply reduced from 590 yr BP; they disappeared with further swamping and overgrowing of the lake. On the western macroslope of Sikhote Alin flooding of the valleys and an increase in the frequency of floods were observed 645–550, 490–420 yr BP, the cold dry phase was ~420–220 yr BP [54]. Short-term shallowing of the Nizhnee Lake is recorded 380–350 yr BP, the participation of arctoboreal diatoms increased, the grass layer on the mire became more developed, and the participation of sphagnum mosses decreased sharply. At the time, a cold episode stands out in the global records [48, 60]. A fire near the lake was ~350–290 yr BP. The mineralization of peat increased somewhat. The swamp became drier.

The progressive shallowing of the lake last 250 years was due to endogenous development. The hydrological conditions in the basin were unstable, and the pH decreased. Watering decrease and an abundance of arctoboreal diatoms ~240–210 yr BP record the Maunder minimum (1645–1710 CE). The number and variety of green mosses increased in the mire. After shallowing, a flooding was recorded in the first half of the 19th century and less significant one – at the beginning of the 20th century.

5. Conclusions

The paleoenvironmental records from small lakes detected several short-term late Holocene climatic events in the mountain region in the Russian Southern Far East. The sediments of the Solontsovskie lakes are natural high-resolution archives that allow us to restore a detailed record of the paleoclimatic events. Comparison of small lake data showed that the Nizhnee Lake reacted more sensitively to hydroclimatic changes and showed high environmental variability. Izyubrinye Solontsi Lake was more stable, but the development of both lakes had general trends. Climate instability in the last 2600 yr BP determined the features of the hydrological conditions of the Nizhnee Lake, which were expressed in frequent changes of diatom assemblages and peat-forming plants. The successive change in the lake trophic state was traced. A lake with a mesotrophic-eutrophic regime became oligotrophic-mesotrophic 2330 yr BP, its maximum depth and productivity was 2280–2110 yr BP; became oligotrophic 2110 yr BP, and from 1760 yr BP - oligotrophic-dystrophic. For a long period, the moistening conditions were unstable, the stages of watering and drainage, up to short-term episodes of complete overgrowth, are distinguished. A decrease in the lake level was significant over the last millennium. The lake bogging especially intensified in the last 250 years, pH decreased, a flooded oligotrophic-dystrophic mire developed near the lake. The swamp vegetation was also unstable due to changes in water content, as evidenced by often successions of sphagnum mosses with different trophic preferences. Drying phases, as a rule, corresponded to cooling periods. Climate fluctuations appear to be linked to the intensity of summer monsoon. The Little Ice Age was the exception and was characterized by high moisture and an increase of precipitation that was connected with active cyclogenesis. The signals of solar minima are traced in high-resolution proxy records. High variability of lake ecosystem demonstrated changes of moisture availability within atmosphere-ocean-land system resulted in regional and microclimate response to global climatic events and variability of modes of atmosphere circulation and changes of predominant cyclone tracks.

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