REVIEW

THE LATE HOLOCENE CLIMATIC EVENTS ON THE SOUTHERNMOST RUSSIAN FAR EAST COAST: VARIABILITY DRIVERS

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Received: June 25th 2025 / Accepted: December 21th 2025 / Published: June 30tht 2026
https://doi.org/10.24057/2071-9388-2026-4105

ABSTRACT. Hydroclimatic changes along the southernmost coast of the Russian Far East, as reconstructed over the past 2460 years, were primarily driven by the intensity of monsoon circulation that was strongly influenced by solar activity and processes in the low-latitude Pacific. An analysis of ecological indicators of Lotus Lake environment (diatoms, botanical composition, mineral content) revealed periods of increased and decreased lake level that corresponded to strengthening and weakening of the summer monsoon. Lotus Lake experienced six stages of increasing and decreasing of lake watering. The basin originated as a meso-eutrophic lake connected to the sea. The connection between the lake and the sea was interrupted ~2100 yr BP, which caused a change in the geochemical environment. To understand hydroclimate changes, data on surface temperature anomalies in the western tropical Pacific Ocean were used. These anomalies were strongly influenced by El Niño. Changes in the intensity of the warm Kuroshio Current were one of the factors that influenced precipitation. A comparison of regional data showed spatial heterogeneity in the moisture distribution, which was associated with changes in typhoon tracks during the Late Holocene. The paleoclimatic situation on the southernmost coast of the Russian Far East, which experienced a relatively dry Medieval Climate Anomaly and a wet Little Ice Age, was similar to that of Korea. A sharp decrease in lake depth and swamping of the shores occurred at two periods: at the beginning of global cooling (1650–1600 yr BP), and 1230 yr BP, when there was a slight cooling trend and El Niño activation. The greatest variability in environments occurred during the last millennium. There were frequent and abrupt climatic variations, particularly during the Little Ice Age. Evidence of temperature and hydrological changes was obtained for the solar minima; the swamp wetness around Lotus Lake decreased.

KEYWORDS: coastal lake, hydroclimatic changes, monsoon, typhoon tracks, ENSO, Kuroshio Current

CITATION: Razjigaeva N. G., Ganzey L. A., Grebennikova T. A., Belyanin P. S., Kopoteva T. A., Klimin M. A. (2026). The Late Holocene Climatic Events On The Southernmost Russian Far East Coast: Variability Drivers. Geography, Environment, Sustainability. 177-185
https://DOI-10.24057/2071-9388-2026-4105

ACKNOWLEDGEMENTS: The studies were supported by a grant of the Ministry of Science and Higher Education of the Russian Federation (agreement № 075-15-2024-554 of 24.04.2024). We greatly appreciate anonymous reviewers for taking the time and providing constructive comments.

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

Lakes located on the coast are sensitive archives of short-term climate changes. Shallow lakes are of particular interest for reconstructing hydroclimatic changes because they are sensitive to changes in precipitation associated with the summer monsoon intensity in the southern Far East (Li et al. 2011; Park et al. 2017; 2023). The analysis of the alternation of watering and swamping phases in the development of such lakes (Razjigaeva et al., 2025a) is useful for high-resolution reconstructions of ecosystem dynamics. Due to continuous sedimentation and high sedimentation rates, coastal lake archives can be used to analyze mechanisms of paleoclimatic shifts at the continental margin and reconstruct atmospheric circulation anomalies. These anomalies were determined by changes in the intensity and position of atmospheric centers and the influence of processes that occurred in the low-latitude Pacific (Woodruff et al., 2009; Hu et al., 2016). Studying the long-term dynamics of coastal lakes provides valuable information on their possible future development, which is important in terms of bioresources and land use. In recent years, a series of reconstructions using modern approaches have been performed on coastal lakes in Primorye (Lozhkin et al., 2021; Nazarova et al., 2021; Lyashchevskaya et al., 2023; Razjigaeva et al., 2020, 2023, 2024, 2025a). Logically, this requires obtaining data on the evolution of lakes in southern Primorye, near the boundary of the temperate zone and subtropics. This work aims to reconstruct hydroclimatic changes caused by variations in summer monsoon intensity and cyclogenesis activity based on the analysis of Lotus Lake's development over the last 2500 yr.

REGIONAL SETTING

Lotus Lake (2.9 × 1.8 km) is located 9 km from the seashore on an alluvial-marine plain. It is situated 2.5 km from the Tumannaya (Tumangan) River. The lake had a barrier origin and formed in a shallow depression surrounded by highlands (up to 90 m) in the late Holocene (Mikishin et al., 2008). The lake's depth reaches 2 m, and small streams flow into its northern part. Along the western and northern shores, there is a swamp up to 90 m wide.

The climate is monsoonal. The mean annual temperature is 5.9°C, the January mean is -10.3°C and the August mean is 21°C; the absolute maximum was 36.4°C, and the minimum was -27.2°C. The mean annual precipitation is 704 mm. The most rain falls in August (up to 162 mm), and the least falls in January (8 mm). The prevailing wind direction throughout the year is westerly (38%)[1]. Lotus (*Nelumbo nucifera*) grows abundantly in the lake. The upland areas are covered with stunted oak forests and shrub thickets. Reedgrass (*Phragmites australis*), sedges (*Carex lasiocarpa, C. cryptocarpa, C. pseudocuraica*) and various grass meadows and swamps occupy the accumulative plain.

MATERIALS AND METHODS

A hand-bored hole was drilled using a Russian peat borer Instorfa in the western part of the lake (42°27.470´N; 130°38.203´E), at the contact between the swamp and the floating bog (Fig. 1). Light gray, fine silty sand was uncovered at the base of the section (235–230 cm). Above that (230–115 cm), dark brown gyttja (organic-rich silt) with a sedge peat layer (150–155 cm) was found. The upper part (0–115 cm) consists of dark brown, moderately decomposed sedge-hypnum (85–115 cm) and sedge peat (0–85 cm). We sampled continuously at 5-cm intervals. Diatom and botanical analyses were performed according to standard methods. The concentration of diatom valves in 1 g of air-dry sediment was calculated. For ecological characteristics of individual species, we used (Krammer, Lange-Bertalot, 1991; Kharitonov, 2010; van Dam et al., 1994). We studied the botanical composition of the sediments using the manual of Kulikova (1974) and recorded the presence of macrocharcoal fragments. Quantitative estimates of macrocharcoal content (by volume) were recorded where it constituted >5% of the analyzed material using a microscope. The peat was tested for mineral content (i.e. non-organic content) after ignition at 550 °C. Selected samples were radiocarbon dated in the Institute of Earth Sciences, St. Petersburg State University (Table 1). Radiocarbon dates were calibrated using OxCal v.4.4.1 and the IntCal 20 calibration curve (Reimer et al., 2020). The age-depth model was constructed using the Bacon 2.2 program (Blaauw and Christen, 2011). Scanning electron microscopy and X-ray microanalysis of volcanic glass shards were performed at the V.G. Khlopin Radium Institute, St. Petersburg.

RESULTS

Age model, sedimentation rates, mineral content, tephra

According to the age-depth model (Fig. 2), the accumulation of gyttja began ~2410 yr BP. A thin layer of sedge peat formed 1650–1600 yr BP. Sedge-hypnum peat began to form at 1230 yr BP, and sedge peat – since 860 yr

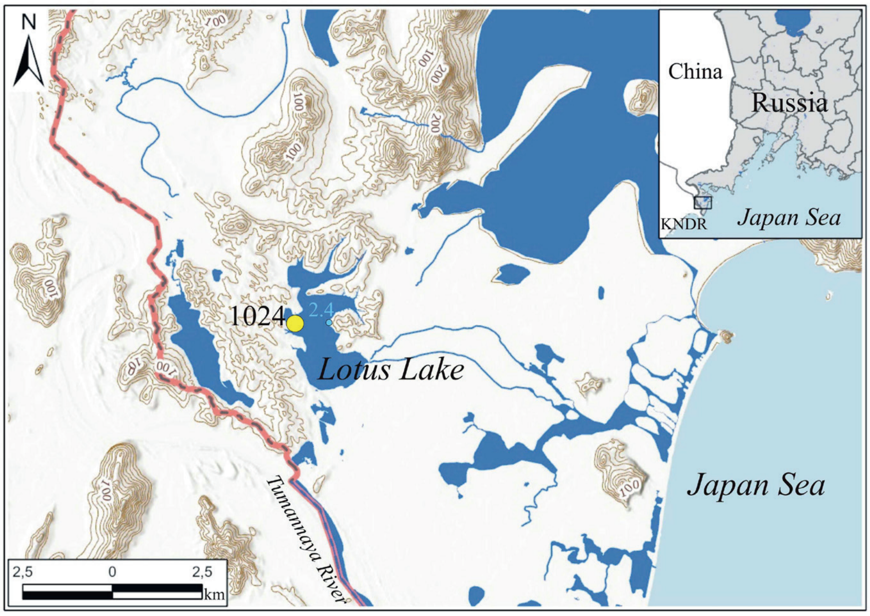

Fig. 1. Study area

Table 1. Radiocarbon and calendar ages of lacustrine-swamp sediments (sections 1024) on the coast of Lotus Lake

Sample N	Depth, m	Material	^{14}C age	Calendar age, cal yr BP (2σ)	Lab. N LU-
9/824	0.40–0.45	peat	382 ± 81	410 ± 82	11671
18/824	0.75–0.80	peat	808 ± 119	760 ± 100	11674
26/824	1.20–1.25	gyttja	1605 ± 178	1530 ± 180	11670
40/824	1.90–1.95	gyttja	2094 ± 157.5	2070 ± 200	11673

[1]https://www.primgidromet.ru

BP. Sedimentation rates were uniform at 0.8–1 mm/yr. The temporal resolution of the reconstructions is 46–60 years.

The sequence includes cryptotephra, represented by high-potassium volcanic glass, the source of which was the Baitoushan volcano. In the lower part of the section, the age of the peat with cryptotephra is 2060–2010 yr BP. An eruption of this age is known from the Erdaobaikhe Museum, China. Cryptotephra B-Tm of the caldera-forming eruption (946/947 CE) with terrigenous material was found too. In the upper part, cryptotephra found at 0.40–0.45 cm has an age of 410–350 yr BP, which is close to the eruption of 1597 CE.

Gyttja from the lower part of the section (2460–2100 yr BP) has the highest mineral content (80–87%). Above that, the mineral content decreases (58–68%). The mineral admixture decreased sharply 1170–860 yr BP. In the overlying peat, the mineral content increased and varied sharply. The maximum was noted in peat formed 690–630 yr BP and 470–410 yr BP; the minimum was noted 240–110 yr BP.

Diatom analysis

In total, 247 taxa of freshwater diatoms were identified in the sediments. Epiphytes dominate (125 species), benthic species – 112 and planktonic and temperate planktonic species – 10. There were also ten marine sublittoral species. The diatom distribution suggests 6 stages in lake evolution (Fig. 3).

The first stage occurs between 2460 and 2100 years BP. The presence of freshwater and marine sublittoral species (up to 1.2%) reflects the development of a meso-eutrophic lake connected to the sea. Among freshwater diatoms, epiphytes dominate: *Staurosira venter, S. construens, Pseudostaurosira elliptica,* and *P. brevistriata* prevail. These species develop in oligotrophic to eutrophic, stagnant waters (van Dam et al., 1994; Krammer and Lange-Bertalot, 1991). Among plankton, *A. granulata* and *A. ambigua*, typical for eutrophic lakes, are the most frequent. High valve concentrations indicate favorable conditions for diatom development. Coastal marine diatoms are represented by the benthic species and planktonic *Paralia sulcata*.

Stage 2 occurs between 2100–1600 yr BP. The role of *Staurosira construens* significant decreases. Perhaps the limiting factor was the increase in nitrogen concentrations caused by the lake's overgrowth. *S. venter*, tolerant of high nitrogen concentrations (van Dam et al., 1994), developed more extensively. A change in the pH may have also played a role due to reduced marine influence for groundwater under a regression (Korotkii et al., 1997). Single valves of the sublittoral *Diploneis pseudovalis* and *D. interrupta* entered the lake during strong storms. The peat layer includes the highest content of the genera *Eunotia* and *Pinnularia*, typical for swamps.

Stage 3, spanning from 1600–1230 yr BP, was observed. The abundance of *Staurosira binodis*, which inhabits meso-eutrophic lakes, increases in the upper part, reflecting more intensive overgrowth of the lake. *Eunotia monodon* var. *tropica*, which inhabits the tropical and subtropical lakes, appeared.

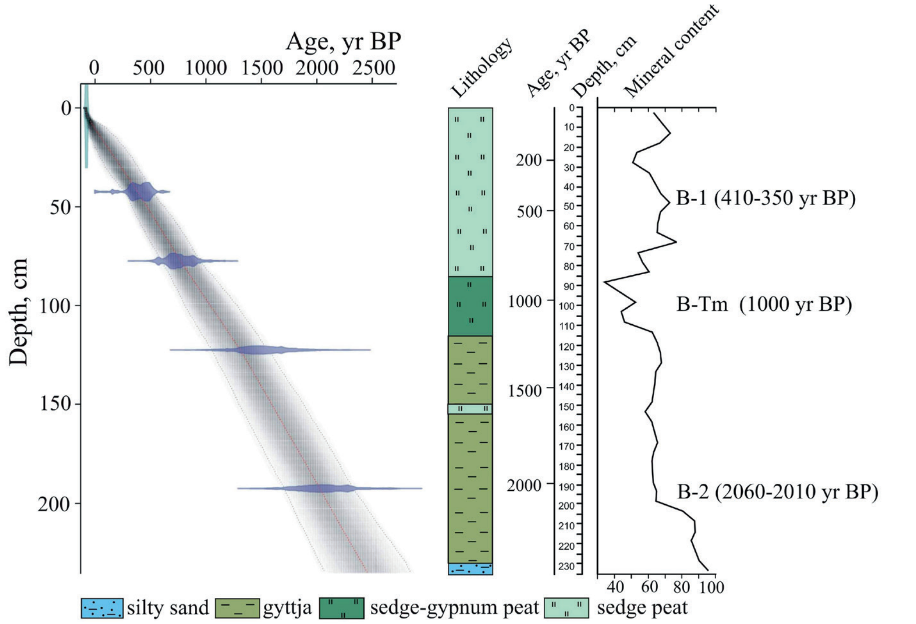

Fig. 2. Age-depth model, lithology, and mineral contents for Lotus Lake sediments; ^{14}C dates with standard deviations are shown in blue; the gray curve shows the 95% confidence interval

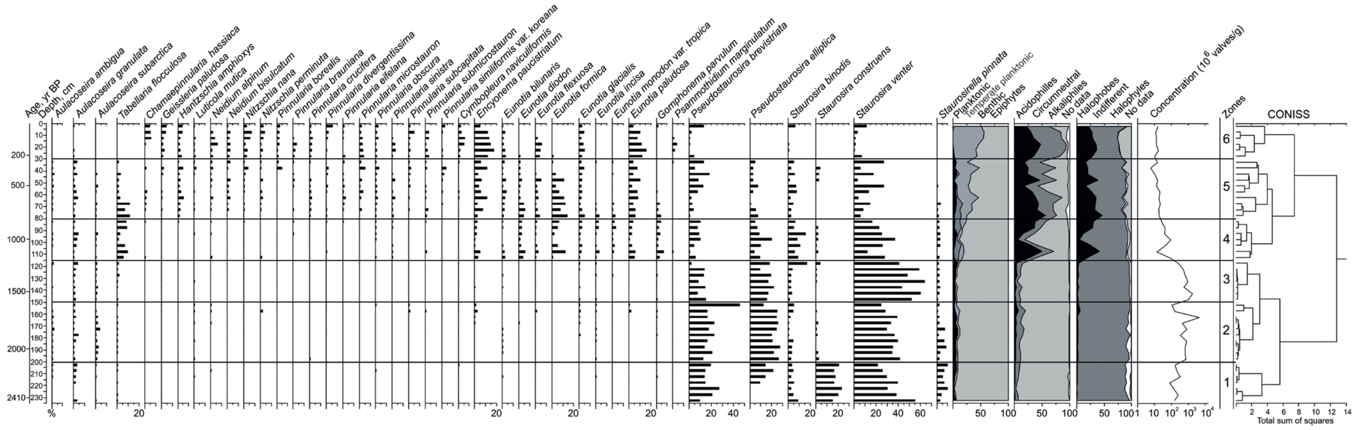

Fig. 3. Diatom percentage diagram for Lotus Lake sediments

Marine species were brought in by strong storms 1500–1400 yr BP.

Stage 4, spanning from 1230 to 800 years BP, has been identified. Diatoms reflect a reduction in lake area. The shores became waterlogged and overgrown. The lake level changed frequently, resulting in unstable ecological conditions. Temporarily planktonic acidophilic *Tabellaria flocculosa*, which preferred shallow lakes and peat bogs (Krammer and Lange-Bertallot, 1991), became dominant. The content of halophobes and acidophiles, represented mainly by the genus *Eunotia*, increases significantly. The content of cold-water cosmopolites increased. *Eunotia monodon* var. *tropica* indicates that the lake is well warmed in summer.

Stage 5 occurs between 800–240 yr BP. Diatoms reflect an unstable regime. The proportion of benthic species, mainly from the *Pinnularia* genus, increases up to 44%. Aerophytic *Chamaepinnularia hassiaca*, typical to peatlands, appeared. The participation of *Eunotia paludosa* is also more pronounced. Lower concentrations could be related to a decrease in moisture 350–300 yr BP. This observation is confirmed by the high content of soil diatoms.

Stage 6 covers the last 240 years. The presence of *Geissleria paludosa*, tolerant to temporary drying, *Pinnularia borealis*, and *Hantzschia amphioxys*, typical for soils, indicates soil processes development during dry seasons. Abundant species tolerant of temporary drying, such as *Encyonema paucistriatum* and *Eunotia paludosa*, increased. Significant quantities of *Staurosira venter, Pseudostaurosira brevistriata*, and *S. binodis* in the turf indicate flooding of the swamp during strong typhoons in recent years.

Botanical composition

Eight zones have been identified, demonstrating the development of vegetation from shallow lake to fen (Fig. 4).

Zone 1 dates back to 2460–1960 yr BP. Remains of aquatic plants, including *Potamogeton gramineus*, which grows at depths up to 1 m, prevail. The amount of plant remains increased in the gyttja formed after 2200 yr BP. The upper part contains *Brasenia schreberi* and seeds of *Najas* and *Nelumbo nucifera*. Terrestrial plant remains include burnet *(Sanguisorba)*, green mosses, sedges, and reeds. Green algae, cladocera, and charcoal are present.

Zone 2 was established between 1960–1800 yr BP. The lake shores began to overgrow with club rush (*Schoenoplectus tabernaemontani*) and sedges. Cotton grass and Potentilla pentandra appeared on the swampy shores. The hydrophyte *Myriophyllum spicatum*, which inhabits standing and slow-flowing waters, appeared. Colonies of bryozoans (*Plumatella*) became widespread on the lake bottom.

Zone 3 occurred between 1800–1230 yr BP. Overgrowth of the shores increased. The decrease in pondweed and the increase in sedge proportions reflect a trend of decreasing lake depth 1800–1650 yr BP. The presence of *Sphagnum* indicates cooling 1700–1650 yr BP. Fires occurred in 1750–1710 yr BP and continuously 1450–1230 yr BP.

Zone 4 occurred between 1230 and 860 years BP. A watered hypnum-sedge fen was formed. *Drepanocladus aduncus* was common. Moss *(Climacium dendroides)* grew in the initial stage. Herbaceous plants included sedges, *Rhynchospora*, typical for floating bog, *Phragmites, Lobelia sessilifolia, Equisetum, Iris, Calamagrostis,* and the fern *Thelypteris*. Water plants remains *(Brasenia schreberi, Nelumbo nucifera)* were found. Reed mace *(Typha)* and club rush *(Schoenoplectus tabernaemontani)* grew near the shore. The soil testate amoeba *(Cyclopyxis kahli)* may have been transported from the slopes.

Zone 5 occurred between 860–410 yr BP. A sedge swamp developed. The role of *Calamagrostis langsdorffii* decreased sharply after 690 yr BP under wetter conditions. Remains of aquatic *Nuphar pumilum* are present. Finds of *Glomus* show that there was disturbed land nearby. Conifer wood may have been brought by flooding. The presence of blueberry *(Vaccinium)* and a peak of *Calamagrostis* indicate a decrease in wet conditions between 520 and 470 yr BP. Intense fires occurred 740–690 yr BP.

Zone 6 occurred between 410–240 yr BP. There was still a floating bog with overgrown sedges. The abundance of *Carex appendiculata* that formed large bumps indicates significant fluctuations in the lake level. Green mosses developed only up to 350 yr BP under wetter conditions. Birch bark appeared. *Glomus* was also found. Fires occurred regularly.

Zone 7 spans from 240 yr BP to the mid-20th century. The reed-sedge bog became less wet. Intense fires occurred at the beginning and end of this phase.

Zone 8. In the last few decades, liverworts were found sporadically; favorable conditions for their development probably occurred after floods or during frequent visits by people to the shore, where an observation tower was built.

DISCUSSION

Lake Evolution at the Late Holocene

According to the age-depth model, Lotus Lake formed approximately 2460 yr ago, which confirms the data obtained earlier (Mikishin et al., 2008). The lake was formed within a catchment area separated by a barrier. During the middle Holocene, this area was part of a marine bay (Mikishin et al., 2024). The further development of the shallow lake was closely related to hydroclimatic changes. The development of an accumulative plain at the mouth of the Tumangan River also influenced the lake's evolution. The river's stream migrated southward due to active accumulation of loose material supplied by the river and transported southward.

In the initial stage, fine sand was deposited in the marginal part of the lake, and sedimentation of gyttja began at 2407 yr BP. The high-resolution record obtained makes it possible to

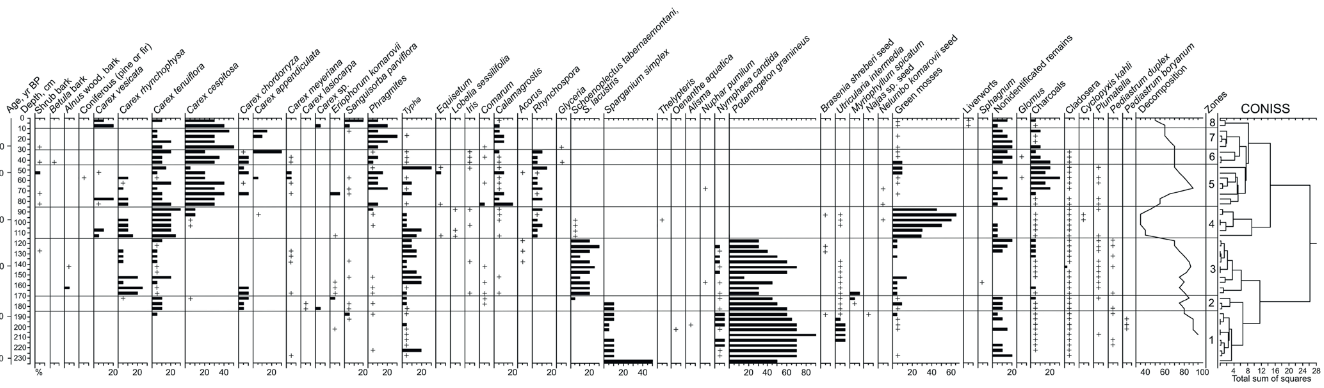

Fig. 4. Botanical composition of Lotus Lake sediments plus records of some microfauna, charcoal, terrigenous input, and tephra

reconstruct the lake's evolution in detail.

The sequence records the transition from global cooling to warmer conditions comparable to the Roman warming period (Fig. 5k). This warming was insignificant and caused no major ecological changes to the ecosystem. The initial stage of lake development occurred during a period of slight increases in precipitation. Flooding 2430–1770 yr BP was also recorded in the development of peat bogs on the Boisman Bay coast (Razjigaeva et al., 2025a). The progradation of the seashore and subsequent disconnection of the lake from the sea during minor regression (Korotkii et al., 1997) led to a change in geochemical environments and a shift in the dominant diatoms ~2100 yr BP. These changes created more favorable conditions for diatom development, and valve concentrations in sediments increased significantly (up to 4698x10^6 valves/g). During this period, the terrigenous influx into the lake decreased. Since the main source of mineral admixture was hollow waters, we conclude that precipitation likely decreased as well, resulting in drier conditions. Shallowing of Gniloye Lake on the Nakhodka Bay coast (Lyashchevsky et al., 2023) and the paleolake at the top of the Amur Bay (Razjigaeva et al., 2023) were noted ~2010–2000 yr BP too. The periphery of Lotus Lake was actively overgrown with *Potamogeton gramineus*, one of the main sources of organic material. During the warming period (2060–1960 yr BP) *Brasenia schreberi* and *Nelumbo nucifera* appeared among the aquatic plants. The appearance of *Myriophyllum* indicated a stagnant regime 1800–1750 yr BP.

During the cooler and drier climate of 1750–1710 yr BP, the swampy shore became overgrown with alder, and fires became more active. These fires were likely associated with human development of the coast (Kuzmin et al., 2005). The beginning of cooling ~1740 yr BP was recorded on the Amur Bay coast (Razjigaeva et al., 2023). Along the southern coast of Primorye, this period was characterized by decreased precipitation (Mikishin et al., 2008).

At the beginning of the cooling period (1700–1650 yr BP), Lotus Lake became slightly shallower. Sedges appeared along the shoreline, and a brief sedge swamp developed (1650–1600 yr BP). Diatom concentrations dropped sharply (Fig. 5a). The dry period associated with the cooling at 1650 yr BP was also evident on the Nakhodka Bay coast (Lyashchevskaya et al., 2023).

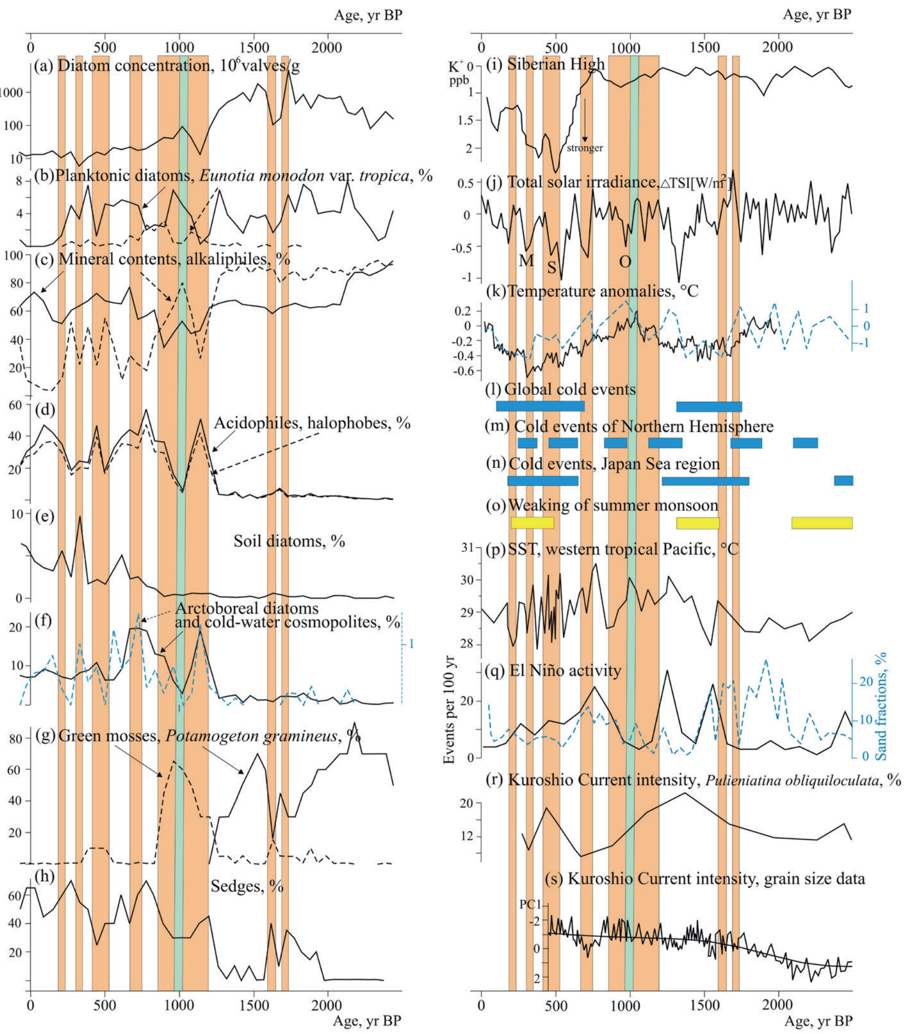

Fig. 5. Synthesis of data on the biotic component reconstruction compared to paleoclimatic proxy. (a–h) biotic components of Lotus Lake; (i) K+ concentration in the Greenland GISP2 ice core, a proxy for the intensity of the Siberian High (Mayewski et al., 2004); (j) TSI variability based on ^{10}Be measurements in polar ice (Steinhilber et al., 2009), Grand Solar Minima: M – Maunder, S – Spörer, O – Oort; (k) black line – Decadal mean air temperature variations (°C) relative 1961–1990 CE, Northern Hemisphere (90–30°N) (Ljungqvist, 2010); blue line – deviation of annual temperatures for Amur River Region from modern average temperature (Klimenko et al., 2000); (l) global cold events (Wanner et al., 2011); (m) cold events, Northern Hemisphere, (Gorbarenko et al., 2024); (n) cold events, Japan (Sakaguchi, 1983); (o) weaking of summer monsoon (Chen et al., 2015; Li et al., 2011); (p) SST variations, western tropical Pacific (Stott et al., 2004); (q) black line – El Niño events per 100 years (Moy et al., 2002), blue line – content of sand in the sediments of Junko Lake, Galapagos (Conroy et al., 2008); (r, s) abundance of the warm water species *Pulleniatina obliquiloculata* (Jian et al., 2000) and grain-size data (Ding et al., 2022), as proxy of Kuroshio Current intensity: vertical bars show yellow – dry periods, and blue – wet periods

Slight flooding of Lotus Lake occurred due to an increase in river inflow 1600–1230 yr BP. The shores began to overgrow with *Scirpus* and *Typha*, while pondweed continued to dominate among aquatic plants near the shore. The presence of the *Eunotia monodon* var. *tropica* in the lake indicates that the water warmed up considerably in the summer. Conditions in the southernmost Primorye were much warmer than those in Peter the Great Bay, where cooling persisted until 1300 yr BP (Lyashchevskaya et al., 2023). The increase in fire frequency and intensity 1450–1230 yr BP can probably be attributed to human development along the coast (appearance of Mohe settlements). Storm activity, as indicated by the presence of marine diatoms, increased 1500–1400 yr BP, which is consistent with the Boisman Bay data, where strong storms were recorded 1650–1440 yr BP.

The most contrasting changes in Lotus Lake's development occurred at 1230 yr BP, when the shores began to swamp due to decreased atmospheric precipitation. The concentration of planktonic diatoms decreased significantly (Fig. 5b). Hypnum-sedge peat began to accumulate. At the same time (1240 yr BP), the paleolake on Shkot Island began to be actively swamped (Razjigaeva et al., 2020).

A slight cooling in the sediments of Lotus Lake was recorded 1170–1100 yr BP by an increase in the content of cold-water cosmopolites and arctoboreal diatoms (Fig. 5f). Diatom concentrations fell sharply. During the Medieval Climate Anomaly, sedge-hypnum peat began to accumulate near the lake shores (from 1100 yr BP). The sharp decrease in mineral content (Fig. 5c) indicates that at this time the terrigenous input with river runoff and slope wash was decreasing. The amount of precipitation in the southernmost Primorye decreased. Increased effective evaporation under warmer conditions than the present day apparently also played a role in the development of the bog. A small cold signal – an increase in the content of arctoboreal diatoms and a decline in *Eunotia monodon* var. *tropica* (Fig. 5b, f) – is juxtaposed with the Oort solar minima (Fig. 5j). The minimum mineral content was observed at ~920–860 yr BP, the number of planktonic diatoms decreased (Fig. 5b), and the participation of *Drepanocladus aduncus* sharply increased on the peatland.

Dry phases of close age were also recorded in other peatlands. On the Amur Bay coast, a sharp decrease in the paleolake level was recorded at ~1190–970 yr BP (Razjigaeva et al., 2023). A decrease in peatland flooding at the paleolake site was also recorded in the Boisman Bay. To the north on the Primorye coast, the situation was different. On the Nakhodka Bay coast, the second half of the Medieval Climate Anomaly (1060–840 yr BP) was humid (Lyashchevskaya et al., 2023), while in Eastern Primorye, an increase in humidification was observed since 1300 yr BP (Razjigaeva et al., 2025b).

The swamp along Lotus Lake became a sedge swamp 860 yr BP. As the development of clump-forming sedges progressed, the amount of reed grass *(Calamagrostis langsdorffii)* increased. The moisture regime changed from constant to variable, contrasting by seasons. A sharp increase in mineral content in peat (Fig. 5c) indicates strong floods caused by strong typhoons. The degree of peat decomposition increased which was also affected by regular fires.

During the Little Ice Age (LIA), Lotus Lake had an unstable hydrological regime, which was also typical for other coastal lake development in Southern Primorye (Razjigaeva et al., 2024, 2025a). On the one hand, there was an increase in watering of the swamp along the lake, and on the other hand, there were drier periods, as evidenced by the decrease in mineral content 800–690 yr BP and the development of soil diatoms (Fig. 5c, e). Their peaks, along with arctoboreal species, record a cold and dry event 350–300 yr BP, which was close to the Maunder minima (Wanner et al., 2022). The signals to the Spörer minima were recorded by an increase in cold-water cosmopolitans, acidophiles, and halophobes (Fig. 5d, j), indicating active swamp waterlogging. At 690–350 yr BP the development of swamp vegetation was strongly influenced by the pyrogenic factor; fires were most likely of anthropogenic nature. Finds of the *Glomus* complex indicate the proximity of disturbed lands. In general, the first half of the LIA (up to 520 yr BP) was colder. Lotus Lake framing swamp became less wet 240 yr BP, which was well observed in the development of other peatlands (Razjigaeva et al., 2024; 2025a). The mineral content decrease of peat corresponds to a decrease in mineral input to the lake 240–110 yr BP. Higher content of cold-water cosmopolites was observed in peat that accumulated in the late 18th-early 19th centuries (Dalton minimum). Since the middle of the XIX century, the swamp developed in unstable conditions – with high watering and increased frequency of floods in recent decades, there are signs of anthropogenic influence (Busse, 1898).

Short-time climatic events, correlation and main drivers

A detailed record of changes in biotic components recorded in Lotus Lake sediments allows us to characterize hydroclimatic events on the multi-decadal scale (see Fig. 5). Changes in moisture in the region were primarily related to variations in the summer monsoon, which controlled the main mass of atmospheric precipitation. The investigations for central and northeastern China and the Korean Peninsula show that summer monsoon intensity and precipitation anomalies on decadal to centennial scales were strongly dependent on variations in solar irradiance, which determined the contrast between the tropical Pacific and the Asian continent (He et al., 2013; Chen et al., 2015; Park et al., 2017).

The investigations on modern climate variability show that processes within ocean-atmosphere zone interaction at low latitudes in the western Pacific Ocean, including variations in the SST and El Niño, play an important role in altering the monsoon circulation (Byshev et al., 2014; Kwon et al., 2010; Hu et al., 2015; Xu et al., 2016). An important component of the climate system is the warm Kuroshio Current, the low-frequency variability of which plays a major role in the distribution and meridional exchange of heat and moisture and the anchoring of major storm tracks in the area of its influence (Kwon et al., 2010). The influence of these factors has been shown in studies of modern climate shifts (Byshev et al., 2024) and has been manifested at the paleoscale (Park et al., 2017; 2023; Ding et al., 2022). These processes were important in the monsoon dynamics of the Late Holocene. Typically, during Holocene cooling and during El Niño activation, SST in the tropical Pacific declined, leading to the summer monsoon weakening and a significant decrease in the intensity of cyclogenesis (Park et al., 2023).

The obtained record indicates more complex situations on the coast in the last two millennia than in the inland parts of the southernmost Primorye (Razjigaeva et al., 2021). The high-resolution record of paleoclimatic events shows a combination of trends in background temperature and humidification, sometimes synchronous, sometimes multidirectional, which was not always reflected in the records obtained for nearby areas of Primorye and northeastern China. The paleoclimatic data for Lotus Lake of the response of biotic components are closer to the reconstructions made for the coast of the Korean Peninsula and Jeju Island, where the Medieval Climate Anomaly was drier and the LIA was wetter (Park et al., 2017).

The summer monsoon intensity is increasing ~2100 cal yr BP affected Jingpo Lake area, northeastern China (Chen et al., 2015), did not manifest in the southernmost Primorye; moreover, precipitation decreased, and conditions became drier: terrigenous supply into the lake and the number of planktonic diatoms decreased. There were no sharp increases in SST (Stott et al., 2004), and Kuroshio Current intensity decreased (Ding et al., 2022). During this time, El Niño intensity increased (Conroy et al., 2008), which, based on modern observations, can influence the precipitation decreasing. In years of strong El Niño, the intensity of the summer monsoon decreased and the activity of the winter monsoon increased (Byshev et al., 2014).

The moistening decrease is traced to the transition period (1800–1700 yr BP) and the beginning of cooling (1700–1600 yr BP), comparable to the Kofun period in Japan (1710–1220 yr BP) (Sakaguchi, 1983) and the global cold event (1650–1450 yr BP) (Wanner et al., 2011). Total solar irradiance (TSI) decreased (Steinhilber et al., 2009), the land temperatures (Klimenko et al., 2000; Ljungqvist, 2010) and SST of the western tropical Pacific were lower (Stott et al., 2004), a weakening of the Kuroshio Current was observed (Ding et al., 2022), and El Niño was activated (Conroy et al., 2008) (Fig. 5q, s).

The subsequent watering of Lotus Lake and increase in precipitation could be due to the activation of the Kuroshio Current (Ding et al., 2022), which promoted the penetration of warm humid air masses to the coast of the southernmost Primorye. This influence did not extend inland – a decreasing of the summer monsoon intensity was noted in northeastern China at this time (Chen et al., 2015).

A slight watering of Lotus Lake with more active river inflow occurred 1600–1230 yr BP. An increase in the proportion of planktonic species indicates the activation of typhoons 1300–1230 yr BP. The increase in wetting in Eastern Primorye was recorded approximately at this time (~1310 yr BP) (Razjigaeva et al., 2025b).

On the coast of Peter the Great Bay, the hydrological conditions in the development of lakes were unstable; both periods of watering and drier phases were distinguished (Lyashchevskaya et al., 2023; Razjigaeva et al., 2025a). Small islands in the southernmost part of Japan (Kamikoshiki Island) were wet ~1700–1480 yr BP, then wetness decreased (van Soelen et al., 2016), the larger islands experienced frequent flooding during the Kofun Period (Sakaguchi, 1983). Apparently, the main tracks of typhoons and deep cyclones passed here.

The beginning of active swamping of Lotus Lake shores (1230–1100 yr BP) coincided with the cooling trend, well expressed on the solar activity curve and paleotemperature curve (Fig. 5j, k). The age is similar to cold event "1b" (1350–1120 yr BP) of the northern hemisphere (Gorbarenko et al., 2024). At this time, El Niño activation occurred in the Pacific (Moy et al., 2002). Decreasing precipitation led to a lesser terrigenous supply into Lotus Lake. The slight watering (1040–980 yr BP) corresponded to a sharp increase in TSI (Steinhilber et al., 2009) and a temperature peak (Klimenko et al., 2000; Ljungqvist, 2010). At this time (1075 yr BP), the dry period on the Shufan Plateau (East Manchurian Mountains) ended (Razjigaeva et al., 2021). Watering of Gniloe Lake on the Nakhodka Bay coast was recorded at ~1060 yr BP (Lyashchevskaya et al., 2023). In southernmost Japan, a short-term increased recurrence of strong typhoons was recorded at this time (Woodruff et al., 2009).

The sharply variable moisture regime with long dry seasons, observed in the southernmost Primorye in the second half of the Medieval Climate Anomaly, was probably also related not only to the increase in evaporation under warmer conditions than the present but also to the influence of El Niño. The spatial pattern of moisture change in the region was not uniform. In the area of Lotus Lake and to the north (the Boisman Bay), the decrease of peatland watering was recorded at 945–830 yr BP. Wet conditions on the Nakhodka Bay coast were 1060–840 yr BP and became drier 840–730 yr BP (Lyashchevskaya et al., 2023). On the coast of Eastern Primorye, the Medieval Climate Anomaly was humid (Nazarova et al., 2021). On the Korean Peninsula, according to annals, the recurrence of droughts increased 950–870 yr BP: it was dry on Jeju Island. This is attributed to the El Niño influence, changes in SST in the Philippine Sea and in the western tropical Pacific, which controlled the direction of tropical cyclone tracks (Park et al., 2017). Significant decreases in rainfall associated with reduced typhoon generation in the western Philippine Sea under the influence of El Niño have also been observed along the coast of eastern China and southern Japan (van Soelen et al., 2016; Park et al., 2017).

The unstable climate during the LIA, recorded in Lotus Lake section by frequent changes of watering and shallowing phases, was related to both abrupt, rapid changes in solar activity and high dynamic processes in the low latitudes of the western Pacific, where significant SST variations were observed (Stott et al., 2004). At the beginning of the period, the change from El Niño to La Niña regime occurred (Moy et al., 2002). The Siberian High became strongly activated ~700 yr BP (Mayewski et al., 2004), leading to the intensification of the winter monsoon, which blocked the penetration of cyclones coming from the sea, which was manifested in the development of "dry" winter seasons. In the first half of the period, the intensity of the Kuroshio Current decreased (Ding et al., 2022), which could reduce the meridional transport of moist air masses.

In the southernmost Primorye, the cooling of 800–630 cal yr BP accompanied by a decrease in precipitation coincided with the Wolf minima (Wanner et al., 2022), well expressed on the solar activity curve. During El Niño activation, tropical SST decreased significantly, and Kuroshio Current activity also decreased (Fig. 5p–s). The drier conditions favored the passage of fires 740–690 yr BP. The chronological framework of this dry period compares well with the long period (770–630 yr BP) of the most severe droughts during the last millennium in Korea, as chronicled in annalistic records (Park et al., 2017).

In general, during the LIA, moisture content increased in the southernmost Primorye. There was a tendency for intensification of the Siberian High intensity (Fig. 5i). The drier conditions of 520–410 and 350–300 yr BP were observed when the intensity of the summer monsoon decreased, as recorded in the lake deposits of Russky Island (Razjigaeva et al., 2024) and pollen records from northeastern China (Li et al., 2011). At this time, solar activity was weakening (Steinhilber et al., 2009), the Siberian High had the greatest intensity (Mayewski et al., 2004), and tropical SST significantly decreased (Stott et al., 2004). The Kuroshio Current weakened ~350–300 yr BP (Jian et al., 2000). The decrease in humidification 240–170 yr BP was of roughly the same nature.

On the Korean Peninsula and in Japan, the LIA was also wet. There is also similarity in the manifestation of dry periods. According to annals, decreasing typhoons and prolonged droughts were observed 530–430 yr BP (Park et al., 2017). In southwestern Japan, wetting decreased ~300 yr BP (van Soelen et al., 2016).

CONCLUSIONS

The development of Lotus Lake over the last 2460 years was largely determined by hydroclimatic changes associated with the monsoon circulation dynamics. Processes in the western part of the tropical Pacific had a great influence. The analysis of the lake record indicates a strong variability in the intensity of the East Asian summer monsoon on a multidecadal scale. The manifestation of El Niño and the change in the activity of the Kuroshio Current were a great factor, which determined the spatial differences in the manifestation of separate events and strongly influenced the cyclogenesis.

The periphery of Lotus Lake represents a classic example of lake overgrowth and peatland formation. The diatom flora reacted to the discontinuance of connection with the sea ~2100 yr BP, which caused a change in the geochemical environment in the lake. Several periods of increasing and decreasing lake watering up to the formation of a sedge swamp 1650–1600 cal yr BP at the beginning of global cooling has been identified. The most dramatic changes in the shore zone with the formation of a green moss swamp occurred 1230 yr BP during the trend to short-term cooling and El Niño activation. There has been considerable variability in environments during the last millennium, and ecological factors changed particularly frequently and sharply during the LIA. Drying tendencies have been noted at solar activity minima. The course of hydroclimatic changes, reconstructed on the response of biotic components of Lotus Lake, was closest to the paleoclimatic situation on the Korean Peninsula coasts and Jeju Island. High-resolution paleoclimatic reconstructions indicate that changes in the regional natural environment were significantly influenced by the complex interaction of such important drivers as variations in solar activity, large-scale atmospheric circulation, and paleoceanological conditions in the low latitudes of the Pacific. ■

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