Short communication

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# Origin, age and development of mountain lakes of southern Far East during the Holocene monsoon variations

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**ABSTRACT.** A small mountain lakes-mire complex recorded in details Holocene environmental changes controlled by monsoon intensity and cyclogenesis activity. The reconstructions were based on multi-proxy studies (diatom, botanical and pollen analyses). We studied evolution of 8 lakes, located on different altitudes (from 320 to 1600 m). The studied lakes belong to four genetic types (on ancient basalt plateaus, depressions within large landslides on ancient volcano slopes and river valleys, and nival lakes on mountain peaks). Longest records (~9720 yr) of climatic changes was restored for East Manchurian mountains. Period long-term droughts 3050–1075 yr BP was connected with weaking of summer monsoon. Studied lakes of Sikhote-Alin were formed in late Holocene. The data clearly indicated drying events caused by precipitation deficits coincided with climate deterioration. Flood recurrence and cyclogenesis activity were recorded in the lake-mire complex developed on landslides within river valleys.

***Keywords***: climatic changes, droughts, floods, paleolandscapes, cyclogenesis

## 1. Introduction

Mountain lakes represent highly dynamic paleoarchives sensitive to environmental changes, and may be considered among as main objects providing information on rapid short-term climatic shifts in the Holocene. Specific features of the evolution of mountain lakes in the southern Far East are primarily controlled by the monsoon intensity, which accounts for uneven atmosphere precipitation distribution over a year. Distinctive regional features are the prevalence of dry air masses moving from the continent in winter and oppositely directed moisture air flowing from sea to land in summer. An analysis of data obtained from lacustrine sequences of Korea, China, and Japan revealed a considerable changeability in the East Asian monsoon intensity during the Holocene (Li et al. 2011; Park et al., 2019; Yamamoto et al., 2021). Much less abundant data are available on the interrelation between the lake dynamics and monsoon circulation changes in the northern part of the monsoon region. This study was aimed at the analysis of the mountain lake evolution and environmental response to climatic changes, especially to moisture supply.

## 2. Materials and methods

We studied sections of eight lakes located on different elevations: paleolake (elevation 320 m) on the Shufan Plateau (East Manchurian Mts.), lakes and paleolakes on Sikhote-Alin Mts. –on Shkotovskoe (elevation 730 m) and Sergeev Plateaus (900 m), Alexeevskoe Lake on Olkhovaya Mt. (1600 m), paleolake in upper reach of the Milogradovka River (445 m) and Solontsovsky lakes (Nizhnee Lake – on 565 m and Izyubrinye Solontsi Lake – on 750 m). The lacustrine-swamp sequence were drilled using a Russian peat borer and were sampled at 2-5 cm intervals. The biostratigraphic studies included botanical, diatom, and pollen analyses performed according to standard methods. Radiocarbon dating and tephrostratigraphy were used for age-depth models constructed using Bacon 2 (Blaauw and Christen, 2011). Radiocarbon dating was performed at St. Petersburg State University. Tephra B-Tm of caldera-forming eruption of Baitoushan Volcano in 946/947 AD was find in the sections of Southern Primorye and used as age marker. Microprobe analysis of the volcanic glass performed in the Khlopin Radium Institute (St. Petersburg) and Moscow State University. All ages are presented in calibrated years PB.

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## 3. Results and discussion

There are only small shallow lakes in the mountainous regions of the southern Far East. The lakes level fluctuates in different seasons up to complete drying up at the beginning of summer. The lake basins are filled by water in late August-September during the typhoon season. Small lakes, such as Izyubrinye Solonetsi and Nizhnee lakes, are almost completely overgrown. Lake basins are filled with peat and are swales for most of the year. Open water appears here after heavy rains. The development of the lakes proceeded as complex systems – wetlands-lakes, therefore, most of the studied sections are represented by peat.

Several types of lakes can be distinguished according to their genesis. 1) Lakes of mountain plateaus, formed due to fissure eruptions of basalts in the Miocene, occupy depressions in ancient lava flows. Now such lakes are almost completely overgrown and turned into mires. Some lakes existed throughout the Holocene. 2) Lakes formed on large landslides on the slopes of the Paleocene volcano. The age of the studied lakes is late Holocene. 3) Lakes formed by landslides in heavy rainfalls and blocking river valleys. 4) Lakes in the golets belt, which are most likely of nival origin. The development of lakes of various origins are consider below.

*Lakes on mountain plateaus.* The most ancient lake was found on the Shufan plateau. This is one of the first and longest records (~9720 yr) of palaeogeographic events in the mountains of southern Far East. The sediments record short-term fluctuations of climate, notably moisture, which is relatively well correlated with regional patterns reflecting summer monsoon intensity. Not only temperature background changed, but the moisture supply varied over wide limits. Four stages of higher humidity (9720-7490 yr BP; 6930-3740 yr BP; 1075-360 yr BP; the last 200 years) and 3 stages of drier climate (7490-6930 yr BP; 3740-1075 yr BP; 360-200 years BP) have been recorded. There were pronounced seasonal contrasts in early Holocene, the water being well heated in summer. The hydrological regime in the depression changed drastically about 7630 yr BP. Since then prolonged dry seasons alternated with occasional rainfalls, and the groundwater feed gained in importance in the water supply to the lake. A hypnum bog appeared around the lake, on the drained areas. Herb-dominated communities developed there since the Holocene optimum. In the late Holocene the reduced moisture supply led to the shrub layer development over the swamp. An increase in aridity was recorded at ~3740 yr BP, beginning from the cooling ~3050 yr BP the driest environments set in and persisted to 1075 yr BP, that well correlated with regional patterns reflecting summer monsoon intensity (Li et al., 2011; Park et al., 2019). At the Medieval Holocene Optimum the water influx into the depression increased sharply, the more so since 940 yr BP. The Little Ice Age was also humid. The maximum water input into the depression has been recorded in the last 200 years.

On Sikhote Alin plateaus shallow lakes with swampy coasts existed during late Holocene. There are several stages recognizable in the lake evolution. The maximum depth of Skotovskoe Plateau paleolake was about 4480–3490 yr BP, under conditions of heat and moisture supply greater than at present. A short period of waterlogging is dated to ~ 3490–3380 yr BP. At its final stage there were alternating phases of flooding and shallowing, with a general tendency toward waterlogging. Between 3010 and 2630 yr BP the lake area was notably reduced and the herbaceous–dwarf-shrub–sphagnum swamp took its place; within the swamp a few small shallow lakes could persist until the last 240 years, when the water supply was essentially lessened. At present, there is a landscape facies of reed-sphagnum swamp facies in the place of the paleolake, with isolated low-stemmed larch trees. In the marginal part of the swamp the peat accumulation started ~ 4480 yr BP. Since then the swamp passed several episodes of flooding and drying. Unstable climatic conditions 4900 yr BP determined most of the features of the hydrological regime of the paleolakes of Sergeevskoe Plateau. Reduced groundwater level and a greater role of atmospheric precipitation were usually related to cold events.

*Lakes on landslides on ancient volcano.* Development of Izyubrinye Solontsi Lake that formed 4400 yr BP and Nizhnee Lake (2600 yr BP) were metachronous due to different altitudinal positions. Organogenic deposits accumulated at high rates (up to 1.9 mm/yr). Nizhnee Lake response more sensitively to climatic changes. Frequent changes in diatom assemblages and peat-forming plants indicate unstable hydroclimatic conditions. A lake with a mesotrophic-eutrophic regime became oligotrophic-mesotrophic ~2330 cal. BP, had maximum depth and productivity ~2280–2110 yr BP; became oligotrophic ~2110 yr, and from 1760 yr BP - oligotrophic-dystrophic. A significant decrease in the lake level has been observed in the last millennium. Coolings were accompanied by a decrease in moisture, but the Little Ice Age was wet.

*Lakes on landslides within river valleys.* Lake-mire system in the Milogradovka River valley existed last 3400 yrs. Long dry events coincided with global coolings and the weakening of the East Asian monsoon. Compared to the swamps of the main Sikhote-Alin watershed and plateaus, cyclogenesis activity was recorded in the peat bog section more detail. Separate large floods also occurred during dry periods, probably in the summer-autumn season and were caused by the passage of typhoons and deep cyclones. Under conditions of more frequent floods and regular flooding, the swamp in the valley became more humid.

*Nival lakes.* Alekseevskoe Lake is located on the flattened peak of Olkhovaya Mt. within the permafrost-nival depression (width up to 100 m). We assume that the lake was formed during the Little Ice Age ($^{14}$C-date 370 ± 70 yr BP, 410 ± 70 cal yr BP, LU-7709), which was wet. The lake level was not constant. The maximum level was in the second half of the Little Ice Age (XVI-XVIII centuries), which may correspond to humid cold conditions in the upper mountain belt.

## 4. Conclusions

Small mountain lakes in the southern Far East are sensitive paleoarchives of moisture changes, mainly controlled by summer monsoon intensity and cyclogenesis activity. The longest periods of long-term droughts were identified in the southernmost Primorye. In Sikhote-Alin at higher altitudes, the dry phases were shorter and coincided with cold events. The Little Ice Age was a wet with frequent fluctuations in temperature and moisture.

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## Conflict of interest

The authors declare no conflict of interest.

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