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SNOW COVER AND GLACIERS

FEATURES OF GLACIATION IN THE NORTHERN BAIKAL AREA AT THE BEGINNING OF THE 21ST CENTURY

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Glaciation of the northern Baikal region is associated with the mountain ridges surrounding Lake Baikal. The underlying rocks are in the frozen state. The existing glaciers are remnants of the vast Pleistocene glaciation, and their area is subjected to continuous shrinking. The analysis of core samples from trees allowed us to reconstruct the climatic background of the glaciation changes in the recent past. A dendroclimatic curve is divided into two periods: the first period lasted until about 1860–1865, when the summer air temperature was almost always below the average temperature for the entire considered period (~16°C); the second part is characterized by the above-average temperatures. During the field work, the current state of the regional glaciation was described for the areas of the Baikalsky, Barguzinsky, and Verkhneangarsky ridges. The areas of glaciation were determined from the Landsat 7 and Sentinel-2 satellite images for 2000 and 2021 and were controlled by orthophotoplans based on the UAV survey in August 2021. The maximum reduction of the area over 21 years is generally typical for small forms of glaciation and reaches 10–30% for the main glaciers. Data on temperature regimes of air and rock surface along an altitudinal profile in the Verkhneangarsky Ridge were obtained for the first time.

Keywords: *Baikal, glacier, permafrost, satellite image, temperature, precipitation, dendrochronology, paleoreconstruction.*

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INTRODUCTION

The northern Baikal region is characterized by the presence of several glacial groups confined to the Baikalsky, Barguzinsky, and Verkhneangarsky ridges (Fig. 1). Like all small forms, the glaciers are very sensitive to climate fluctuations and are unique in their existence near the southern boundary of the cryolithozone. They are mainly located in deep shaded cirques below the snow line and have mostly the northern, eastern, and southeastern exposures corresponding to directions of snowdrift transport. The studies of glaciation in this area began relatively recently, in the 1980s. The geocryological works were previously carried out only in the Baikal–Amur Mainline (BAM) area. Therefore, the obtained data complement the conceptions about the existence and interaction of different objects of the cryosphere in this zone.

Annual tree rings hold a special place among the natural archives, which are used to study the environmental conditions, including climatic factors. A number of advantages, such as high temporal resolution (year–season), precise dating, lifetime of trees, and wide distribution of woody vegetation gave the possibility to use the annual rings and chronologies, derived from them, in climatology, ecology, glaciology, archaeology, etc. [*Fritts, 1976; Vaganov et al., 1998; Shiyatov et al., 2002; Kononov et al., 2005, 2009; McCarroll et al., 2013; Arzhannikov et al., 2017; Voronin et al., 2020*]. The summer temperature reconstructed by the tree-ring chronology allows us to better understand the cause of climatic changes. Factual data on the air and soil surface temperature regime in the area of mountain glaciation of the Baikal region obtained for the first time allow us to assess its influence on the glacier dynamics.

HISTORY OF GLACIER STUDIES IN THE BAIKAL REGION

Glaciers in the ridges in northern part of the Baikal region were first interpreted and mapped according to the aerial imaginary in the 1960s [*Kitov, Plyusnin, 2015*]. However, their field studies began much later because of the limited availability of these materials. First data on the Barguzin Ridge glaciers were published in the early 1980s, when employees of the Institute of Geography of the Siberian Branch of the USSR Academy of Sciences together with representatives of the State Center Priroda studied mountain areas of the Baikal area to work out the methods of the comprehensive investigation and mapping of natural resources of the region on the basis of satellite information. Snow-ice formations with signs of glaciers were detected during the interpretation of satellite images of the upper reaches of the Svetlaya River on the Barguzinsky Ridge. They involved modern moraines, zones of open ice, cracks, bergschrunds, and ogives. This allowed L.D. Dolgushin and G.B. Osipova [*1989*] to reveal that “on the Barguzin Ridge, there are many cirque snow patches and several small cirque glaciers” [*Kitov et al., 2014*]. Earlier, in 1979–1980, the expedition of the Institute of Geography of the USSR Academy of Sciences started working on the glaciers [*Aleshin, 1982*] and performed the first glaciological survey.

New research began only in 2009. The Sochava Institute of Geography, Siberian Branch of the Russian Academy of Sciences restarted the expeditionary glaciological studies in the Baikal region. Field works in 2011 and 2012 confirmed the existence of nival-glacial formations within the Baikalsky and Barguzinsky ridges [*Kitov et al., 2014*].

The discovered glaciers were included in the database (DB) of glaciers of the Northern Baikal, in the Registry of databases of the Russian Federation, as well as in the catalog of glaciers created by the Institute of Geography of the Russian Academy of Sciences [*Catalogue of Russian Glaciers, 2021*].

In 2017, a group of glaciers was discovered on the northwestern branch of the central part of the Verkhneangarsky Ridge. According to the results of the 2017–2018 studies, it was revealed that the Verkhneangarsky glacier group is represented by the cirque glaciers and other small forms of glaciation. It was logical to combine the glaciers of the region into the Baikal glacier system [*Ananicheva et al., 2019a*].

PHYSIOGRAPHIC CHARACTERISTICS OF THE AREA

Lake Baikal is surrounded by the mountain ridges on all sides (Fig. 1). The Baikalsky Ridge extends for 300 km along the western shore of Lake Baikal within 54°–56° N. The highest point of the ridge is the Chersky Mountain (2572 m a.s.l.). The slopes of the ridge up to 900–1400 m a.s.l. are occupied by mountainous taiga forests. Larch taiga predominates in the middle and northern parts. Shrub thickets and sparse larch forests predominate above 1400 m a.s.l. [*Tyulina, 1990*].

The Barguzinsky Ridge frames Lake Baikal from the northeast. The low-mountain part of the ridge (600–1000 m a.s.l.) is covered by dark coniferous taiga with dense undergrowth. The middle-mountain (1600–1800 m) and high-mountain (1800–2800 m a.s.l.) parts are mostly devoid of continuous vegetation and are covered by coarse rock fragments [*Kitov et al., 2014*].

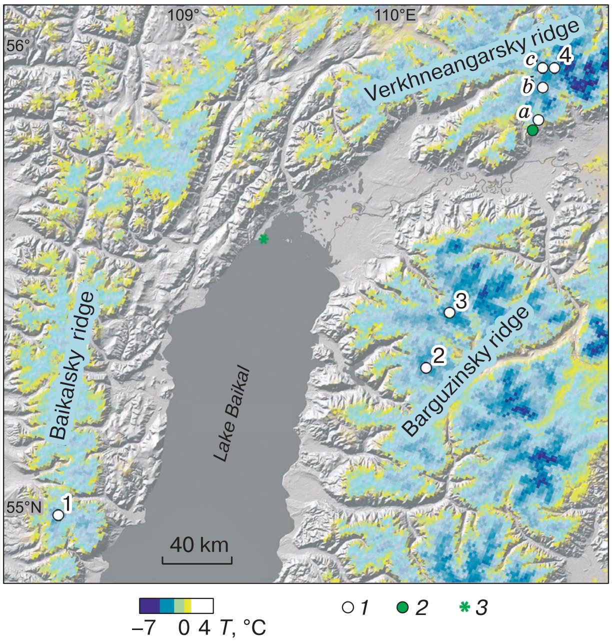

Fig. 1. Studied area.

(*1*) glaciers (1 – Chersky; 2 – Urel–Amutis; 3 – Akuli; 4 – Ogdynda–Maskit), (*2*) wood core sampling site, (*3*) Nizhneangarsk weather station. *T* is the mean annual rock temperature, °C [*Obu et al., 2019*]. Location of loggers to measure air and surface temperatures (*a* – 1280 m, *b* – 2280 m, *c* – 1845 m a.s.l.).

The Verkhneangarsky Ridge is a part of the Stanovoy Highland with the highest point of Bezymyannyi Peak (2641 m a.s.l.). The mountain ridge serves as the southern boundary of the North Baikal Highland and separates it from the Verkhneangarsky Basin. Mixed and larch forests predominate on the lower slopes and are replaced by mountainous tundra at higher altitudes.

The mountain glaciers in this region exist under the conditions of the dry continental climate in the area of continuous permafrost mainly due to precipitation brought from the Atlantic and Arctic Oceans. The redistribution of air flows coming from the Baikal Depression also contributes to the existence of the glaciers regions [*Ananicheva et al., 2019b*].

METHODS

The authors used satellite images for the end of August – the beginning of September, i.e., in the period of maximum melting of the snow cover, to estimate the areas of glaciers in the Northern Baikal region in the 21st century. The archive of images included data from Landsat 7 ETM+ L1 (2000) and Sentinel-2 L1C (for 2021) satellites. Contours were processed and distinguished on the portal [*Sentinel-hub EO-Browser, 2021*]. Delineation of the glaciers on the multispectral images was performed manually.

The error of delineation depended on the boundaries of particular glaciers, as it was not always possible to use the images with the surface completely free of seasonal snow. Taking into consideration pixel size (10 to 30 m) and the characteristic size of glaciers, the error in determining the area of the glaciers could be up to 5%.

The orthofotoplans and digital elevation models were created in the Metashape software on the basis of images from a DJI Mavic 2 Pro drone; the survey altitude was 400–500 meters. The survey was conducted on July 29–30, 2021. The state of glaciation in the middle of the 20th century was assessed using the archived aerial images from 1947–1949 provided by the Department of Remote Sensing Methods of the Institute of Geography, Russian Academy of Sciences. Orthotransformation of stereo pairs was also performed in the Metashape software. The quality of the archived images does not allow us to speak about comparable accuracy with the modern data, but we believe that these data are of interest for the reader.

Wood samples (Scots pine) for the dendroclimatic analysis were taken with a drill at the end of July 2019. At least two samples were taken from each tree at different radiuses. The sampling site was located on the southern macroslope of the Verkhneangarsky Ridge, on the right side of the Vershina Darmikov River valley in the vicinity of the upper forest boundary (Fig. 1). The sampling was performed at five plots spaced apart at about 500 m. At each plot, samples were taken from at least five trees. The sampling site was found at a considerable distance from the weather stations with available records. The nearest Nizhneangarsk weather station is located 90 km away. However, it is located on a flat area in the depression between mountain ridges and in the immediate vicinity of Lake Baikal, so its data cannot be representative of the studied site. Therefore, we used data from nine more stations (Table 1) to obtain a more general picture of climate conditions in the region.

Wood samples were collected and processed, the radial growth rate was measured, and chronologies were determined using standard dendrochronological methods [*Cook, Kairiuksitis, 1990*]. The radial growth rate was measured on the LINTAB 6 device using the TSAP Win computer program (0.01 mm accuracy). The climatic signal influencing on the width of annual rings was judged after the standardization (indexation) procedure. In the standardization of individual chronologies, the age trend is removed. The age trend is considered the main non-climatic factor that manifests itself in variability of the radial growth

Table 1. **Correlation matrix of summer air temperatures recorded at weather stations**

Weather station	Nizhne-angarsk	Bratsk	Kirensk	Ma-makan	Bodaibo	Taksimo	Chara	Orlinga	Kalakan	Zhiga-lovo
Nizhneangarsk (90 km)* 55.5° N, 109.3° E, 477 m a.s.l.		0.67	0.78	0.72	0.65	0.78	0.62	0.82	0.58	0.85
Bratsk (570 km) 56.2° N, 101.5° E, 410 m a.s.l.	0.67** **480*** **		0.70	0.67	0.58	0.70	0.49	0.74	0.54	0.84
Kirensk (250 km) 57.5° N, 108° E, 256 m a.s.l.	0.78 **250**	0.70 **430**		0.89	0.87	0.88	0.77	0.85	0.77	0.85
Mamakan (270 km) 57.5° N, 114.1° E, 244 m a.s.l.	0.72 **370**	0.67 **780**	0.89 **350**		0.99	0.94	0.89	0.81	0.85	0.78
Bodaibo (280 km) 57.5° N, 114.1° E, 278 m a.s.l.	0.65 **390**	0.60 **790**	0.87 **360**	0.99 **10**		0.95	0.91	0.76	0.89	0.75
Taksimo (250 km) 56.2° N, 114.5° E, 513 m a.s.l.	0.78 **350**	0.70 **820**	0.88 **430**	0.94 **170**	0.95 **170**		0.91	0.83	0.89	0.82
Chara (465 km) 56.5° N, 118.2° E, 709 m a.s.l.	0.62 **580**	0.49 **1020**	0.77 **620**	0.89 **270**	0.90 **270**	0.91 **220**		0.69	0.90	0.68
Orlinga (310 km) 56° N, 105.5° E, 338 m a.s.l.	0.82 **220**	0.74 **270**	0.85 **240**	0.81 **530**	0.77 **540**	0.83 **550**	0.69 **770**		0.72	0.95
Kalakan (390 km) 55.1° N, 116.5° E, 612 m a.s.l.	0.58 **470**	0.54 **960**	0.77 **600**	0.85 **340**	0.86 **340**	0.89 **180**	0.90 **220**	0.72 **700**		0.72
Zhigalovo (390 km) 54.5° N, 105.1° E, 416 m a.s.l.	0.85 **280**	0.84 **270**	0.85 **380**	0.78 **650**	0.74 **650**	0.82 **640**	0.68 **850**	0.95 **140**	0.72 **740**	

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* Distance between the weather station and the sampling site, m.

** Pearson correlation coefficients.

*** Distances between stations, m.

rate. As a result, we obtain the chronologies – time series with dimensionless values (indices) allowing us to compare them with one another. Then, the individual indexed curves of the growth rate were combined into the single basic chronology. The standardization procedure was performed using the ARSTAN program [*Cook, Krusic, 2005*].

The temperature regime of air and the rock surface were studied using automatic loggers. The Onset HOBO MX2305 model with an internal electronic temperature sensor was used; the measuring accuracy was ±0.2°C. One logger was placed on a pole or on a tree trunk at a height of 2 m above the surface, and the second logger was placed a depth of 5 cm from the surface. Measurements were taken every 4 hours.

The radiocarbon analysis was performed in the Radiocarbon Laboratory of the Institute of Geography, Russian Academy of Sciences.

SPATIAL AND TEMPORAL FEATURES OF THE SUMMER TEMPERATURE REGIME ACCORDING TO DATA FROM WEATHER STATIONS

According to numerous studies, the climatic signal in tree-ring chronologies obtained near the upper (high-altitude) forest boundary is most clearly manifested in data on air temperature of the warm season. To assess the potential of the resulting tree-ring chronology for the climate reconstruction, a comprehensive statistical analysis of the air temperature dynamics recorded at the weather stations was carried out. In spite of significant distances between weather stations and differences in the absolute heights, a significant ($p < 0.001$) statistical relationship between all stations for more than a 50-year-long period was revealed (Table 1).

The Bodaibo and Mamakan weather stations are located at a distance of only about 10 km from one another, which explains the high ($r = 0.99$) correlation between them. However, both stations have a significant disadvantage related to the length of the observation period. For the Bodaibo station, a longer series of measurements is available (1934–2005). For the Mamakan station, data are available for a period from 1958 to 2019. For further analysis, the series of weather records from the Bodaibo station was used. These data were supplemented with data from the Mamakan station for the last 14 years, which made it possible to obtain the generalized series for the period of 86 years.

All weather stations demonstrate a distinct regime of summer temperatures throughout the 20th and early 21st centuries. Up to the end of the 1970s, the summer temperature in the region tended to slightly decrease. Since the early 1980s, all weather

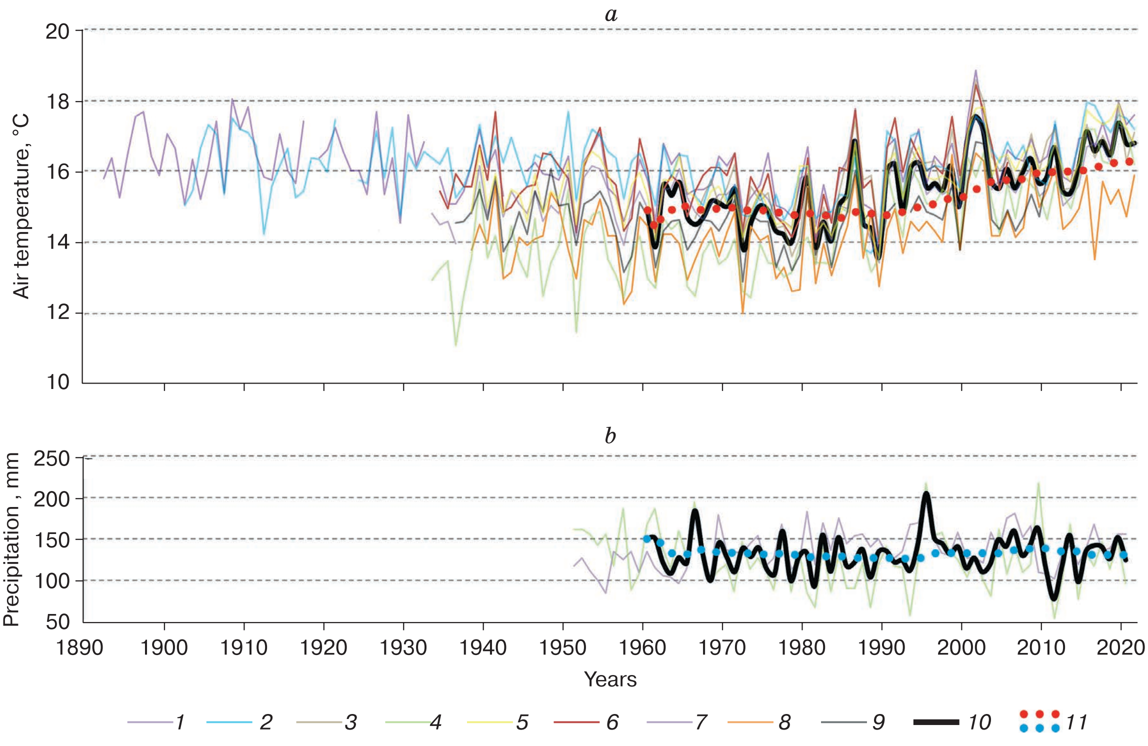

Fig. 2. Mean summer air temperature controlling ablation (*a*) and precipitation of the cold period affecting snow accumulation (*b*) according to records of weather stations:

1 – Kirensk; *2* – Bratsk; *3* – Taksimo; *4* – Nizhneangarsk; *5* – Zhigalovo; *6* – Bodaibo; *7* – Orlinga; *8* – Chara; *9* – Kalakan; *10* – average values for all stations for the period of 1980–2021; *11* – moving average.

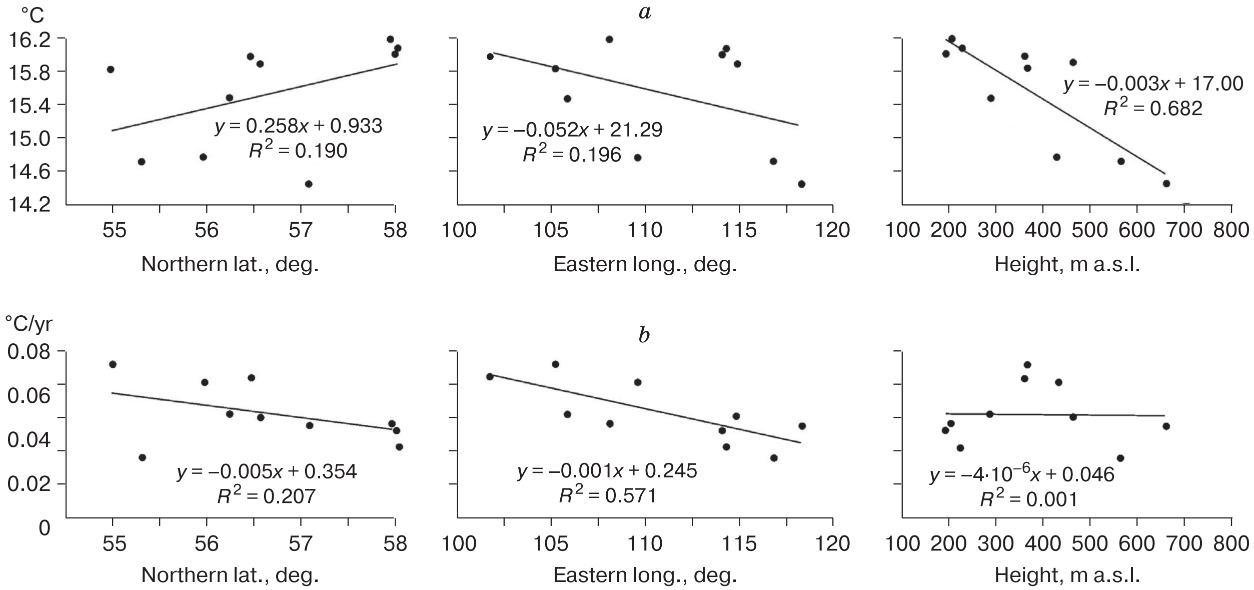

Fig. 3. Dependence of the (*a*) value and (*b*) increase rate of the mean summer temperatures on the location of weather station.

For (*a*), the period of 1960–2019 was used; for (*b*), the period of temperature rise manifested at all the stations from 1980 to 2019 was taken into account.

stations have indicated an opposite trend towards the rise in summer air temperatures. Precipitation is quite stable; the trend is weakly expressed: a slight increase until 2012 and a decrease in recent years have been recorded (Fig. 2). It is obvious that the value of the summer air temperature primarily depends on the altitude of the station (Fig. 3*a*). At the same time, the rate of warming in the late 20th–early 21st centuries tends to slow down from west to east, as evidenced by the approximation coefficient $R^2 = 0.57$ (Fig. 3*b*). It should be noted that the latitudinal pattern in warming during recent decades also takes place. Only one weather station – Kalakan – substantially lowers the statistical significance of this pattern (Fig. 3*b*).

In general, fluctuations of the summer air temperature display a definite trend typical of the entire study area.

RECONSTRUCTION OF THE SUMMER AIR TEMPERATURE

The dendroclimatic reconstruction for the last 230 years was obtained on the basis of the significant relationships between the width of annual rings and the summer air temperature (Fig. 4). Visual analysis subdivides the entire reconstructed period into two parts. In the first part (until about 1860–1865), the summer air temperature was almost always below the mean summer air temperature (~16°C) for the entire considered period. During the second part, the summer air temperature was generally higher than the mean summer air temperature, except for interval at the end of the 20th century (Fig. 4).

According to available data, the Little Ice Age (LIA) preceded the 20th century and was characterized by cooling and the development of mountain glaciation [*Lamb, 1977*]. Most likely, the first part of the presented reconstruction reflects the final stage of the LIA. During this time, summer temperatures dropped to 14.2–14.5°C (1794, 1804, 1847, and 1860), which was 1.8–1.5°C lower than the mean summer temperature for the entire considered period by. These years were the coldest in the last 230 years. Then, climate warming began, which passed through several stages to reach its maximum in the 1940s. Then, temperatures began to fall; from about 1965 to 1995, the summer temperatures were below the long-term average. The cooling in these 30 years was comparable to the cold interval at the beginning of the reconstruction (Fig. 4) in the mean summer temperatures. Since the 1980s, the summer temperatures have been steadily increasing. This coincides with the dynamics of the summer temperature fluctuations at the nearest weather station of Nizhneangarsk (Fig. 2*a*), where the mean summer temperature from the beginning of the observation to 2021 increased by 3°C.

The current climatic conditions of the study area for the glacier zone in winter are characterized by strong western winds leading to the redistribution and compaction of the snow cover and to the formation of thick snow patches and cornices [*Aleshin, 1982*].

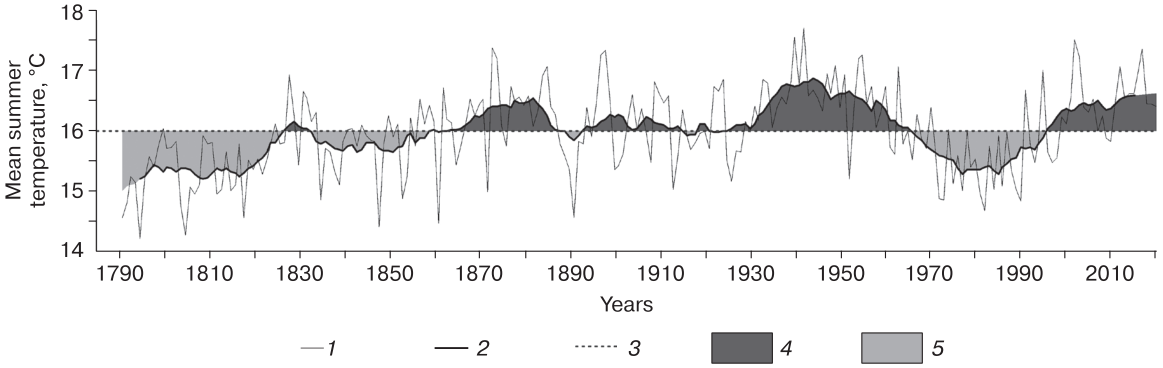

Fig. 4. The dendroclimatic reconstruction of summer air temperatures in the Verkhneangarsky Ridge area for the last 230 years.

1 – annual values; *2* – smoothed by 11-yr average; *3* – average for the entire observation period; *4* – periods with temperatures above the average; and *5* – periods with temperatures below the average.

At the stations relatively close to glaciers (Nizhneangarsk, Kirensk), the mean annual air temperature ranges from –2.3 to –3.7°C (14 to 16°C in summer), annual precipitation is 390 mm, including 120–140 mm in the cold season (for 1966–2020). The maximum precipitation falls in July–August, the minimum, usually in March.

As seen from Fig. 2*a*, the trend of the mean summer temperature has been positive since the 1980s; it averages 2°C over 40 years. This contributes to the increased intensity of the glacier ablation and to prolongation of the ablation period. Warming takes place due to the summer and autumn temperatures resulting in a longer period of ablation.

Thus, climate changes in the past several decades have not contributed to the development of glaciation.

DYNAMICS OF THE GLACIATION AREAS

According to the archival aerial imaginary of the late September in 1947–1949, the areas of the main glaciers were 0.19 km^2 (Ogdynda–Maskit), 0.24 km^2 (Urel–Amutis), and 0.53 km^2 (Chersky). In the 1960s, the areas of the Chersky and Urel–Amutis glaciers were 0.47 and 0.24 km^2, respectively [*Kitov, Plyusnin, 2015*].

Using the Landsat and Sentinel-2 images and orthophotoplans from UAV imagery, the areas of the glaciers were determined for the period 2000–2021. Table 2 demonstrates the results, including data on changes in the area of the glaciers in the 21st century according to various calculations. In terms of morphology, the studied glaciers belong to the cirque type of glaciers; some of them can be considered as small forms of glaciation.

Comparison of the areas occupied by glaciers in 2000 and 2021 attests to their reduction from about 2.0 to 0.9 km^2. Figure 5 demonstrates changes in the boundaries of the main glaciers for that period. The

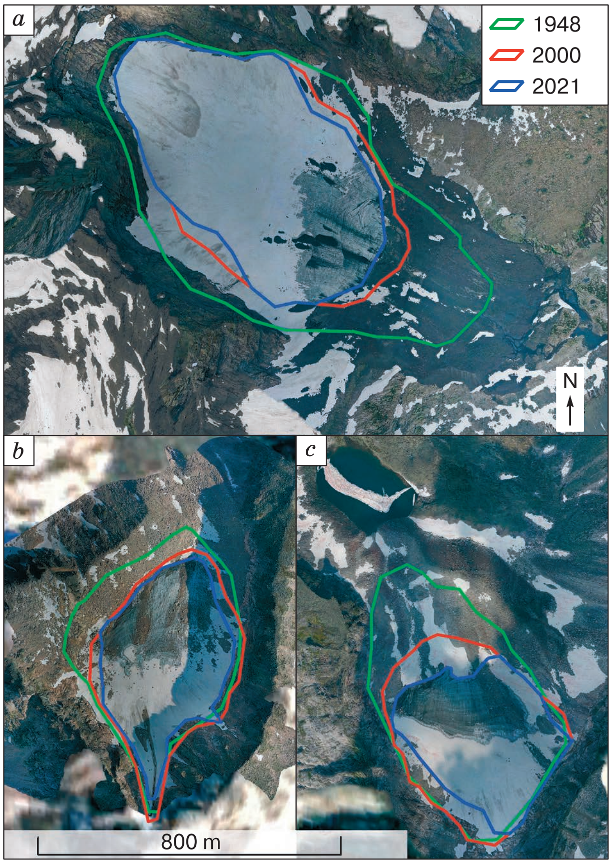

Fig. 5. Contours of the Chersky (*a*), Urel–Amutis (*b*), and Ogdynda–Maskit (*c*) glaciers in 1948 (from aerial images) and in 2000, 2021 (from Landsat/Sentinel-2 imagery).

The orthophotos by the end of July 2021 were used as the base layer.

Table 2. **Areas of glaciers of the Baikal region**

No.	Ridge (total area of glaciers)	Glacier ID	Coordinates	Exposure	Area, km^2			Reduction over, % (2000–2021)
					2000*	2012**	2021***	
1	Baikalsky (0.58 km^2)	Ru10-19.0001	108.70° E 55.0° N	SE	0.03	0.04	0.01	67
2		Ru10-19.0002	108.70° E 55.01° N	SE	0.10	0.06	0.08	20
3		Ru10-19.0003	108.70° E 55.01° N	E	0.10	0.06	0.08	20
3		Ru10-19.0004	108.69° E 55.03° N	SE	0.02	0.01	0.001	95
5		Ru10-19.0005 Razirvanny	108.70° E 55.04° N	E	0.10	0.03	0.05	50
6		Ru10-19.0006 Chersky	108.70° E 55.06° N	E	0.35	0.38	0.31	11
7		Ru10-19.0007	108.73° E 55.47° N	E	0.01	0.01	0.01	0
8		Ru10-19.0008	108.65° E 55.83° N	SE	0.09	0.03	0.04	56
9	Barguzinsky (0.13 km^2)	Ru10-20.0001 Urel–Amutis	110.36° E 55.46° N	NE	0.15	0.09	0.13	13
10	Verkhneangarsky (0.12 km^2)	Ogdynda–Maskit	110.53° E 56.13° N	N	0.17	–	0.12	29
11	TOTAL				1.12	–	0.83	25.8

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* According to [*Kitov, Plyusnin, 2015*].

** According to [*Catalogue of Russian Glaciers, 2021*].

*** According to [*Sentinel-hub EO-Browser, 2021*].

greatest reduction in area is typical for the small forms. In general, the dynamics of glaciers in the region reflect the trend of climate changes.

Table 2 demonstrates that the glaciers of the Northern Baikal region are currently at the stage of degradation of varying degrees of intensity. From 2000 to 2021, the area of all studied glaciers of the region decreased. The total reduction of the area of glaciers over these two decades reached 25.8%. For particular glaciers, it varied from 0 to 95%. This variation is related to the size of glaciers and their location. Position relative to the direction of moisture-carrying air flows, aspect (leeward or windward slope of the glacier location), shading (direct sunlight exposure is minimal), and a host form (the best preservation of small glaciers is in deep cirques) have the strongest influence. Glaciers on the slopes of the southeastern exposure are affected by the most intensive degradation; a little less glacier degradation is manifested on the slopes of the eastern and northern aspects. The key factors of the glacier degradation are the increase in the mean annual air temperature and, more importantly, the increase in the mean summer air temperature during the last decades, as well as the reduction of precipitation during the cold period. Compared to archival aerial images, the areas of major glaciers have decreased by 40% since the mid-20th century. It is interesting that the images of 1948 clearly illustrate the absence of glacier Ru10-19.0001, which confirms the high dynamics of variability of the smallest forms of glaciation in the area.

The maximum development of glaciation in the northern frame of Lake Baikal took place in the Late Pleistocene (35–15 ka ago). Deposits in the bottom of the central part of the valley of the Ogdynda–Maskit Glacier (1820 m a.s.l.) in the Verkhneanagarsky Ridge were dated (IGAN 7747). According to these data, this glacier has not descended lower, at least, for the last 5800 years. A zone of modern rock glaciers is an additional factor of the altitudinal zonation, which helps to reveal the area of glaciation in the past. The lower boundary of the rock glaciers coincides with the paleo-snow line [*Enikeev, Staryzhko, 2009*]. F.I. Enikeev [*2020*] reconstructed an orographic snow boundary of the maximum phase of the Sartan epoch of the Late Pleistocene glaciation. It encompassed the areas with predomination of solid precipitation forming the snow cover. The latter determined the areas of glacier feeding in that time. The largest of them covered the watershed areas of the ridges mentioned in this paper, and the Northern and Southern Muysky and Kodar ridges.

THE AIR AND ROCK SURFACE TEMPERATURES OF THE VERKHNEANGARSKY RIDGE

In the mountainous areas of the studied region, permafrost is widespread at heights above 900–1000 m a.s.l. [*Ershov, 1989; Obu et al., 2019*]. This is confirmed by the presence of the active rock glaciers, the development of polygonal relief, etc. It is known that the subzero mean annual temperatures of rocks contribute to the stability of glacial systems, but data on rock temperatures have not been available so far for the studied region.

The automatic air and rock surface temperature sensors installed in the area of the Verkhneangarsky Ridge allowed us for the first time to analyze the patterns of changes of the air and rock surface temperatures from 460 to 2200 m a.s.l. for the period from August 2019 to the late July 2021 (Fig. 6) [*Abramov et al., 2021*].

The mean annual air temperature is –0.9°C at the level of Lake Baikal (460 m a.s.l., Nizhneangarsk weather station); it drops to –5.1°C at 1280 m a.s.l. and to –9.6°C at 2280 m a.s.l. The period of the subzero air temperatures in the mountains lasts from the end of September to May; at heights above 2000 m a.s.l., subzero air temperatures may be observed during the whole summer. In winter, temperature inversions may be formed, when a temperature in the lower part of valleys is lower than on tops of ridges.

Altitudinal gradients of the mean annual air temperature are 0.53°C/100 m at 460–1280 m a.s.l. and 0.45°C/100 m at 1280–2280 m a.s.l. These gradients agree with the gradients obtained for other mountain areas of the northern Russia.

The mean annual surface temperature was –6.2°C in the lower part of the Ogdynda–Maskit Glacier (1845 m) and –4.5°C in the upper part of the ridge (2280 m). Freezing of the active layer begins in the late September, and thawing begins in the late May. The higher surface temperature in the top part, as it can be seen from the character of temperature fluctuations, is most likely related to the formation of thick snow cornices, which isolate the rock surface from cooling. These data agree with the results of the temperature simulation at the permafrost table from satellite data [*Obu et al., 2019*].

CONCLUSIONS

The glaciers of the ridges in the Baikal region have been actively decreasing in recent decades. The small glaciers of the Baikal region located on the slopes of the southeastern exposure have been subjected to the greatest degradation. Glaciation of the three ridges has generally decreased by 25.8% over two decades of the 21st century, while relatively large glaciers have lost 10–30% of their area (and about 40% since the mid-20th century).

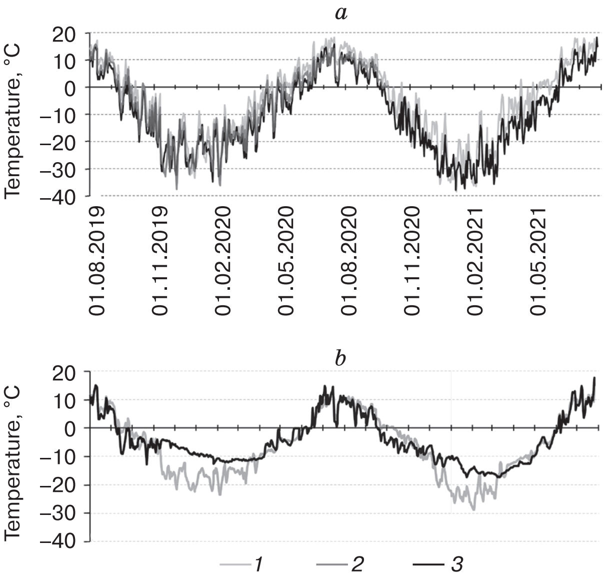

Fig. 6. Dynamics of the (*a*) mean annual air temperature and (*b*) rock surface temperature in the Vershina Darmikov valley (*1, 3*) and at the Ogdynda–Maskit Glacier (*2*).

1 – 1280 m; *2* – 1845 m; *3* – 2280 m.

At present, the degradation rate of glaciers depends on their location on a slope, activity of snowdrift transport, and avalanche snow accumulation.

The temperature regime of the studied area is spatially stable. During most of the 20th century, the summer season temperature varied without a distinct trend. Since ~1980 and up to the present, the steady widespread warming is observed. The warming rate decreases in the eastward direction. The summer temperatures strongly depend on the elevation of weather stations. According to the dendroclimatic reconstructions, the period from the late 18th to the mid-19th centuries is characterized by the lowest summer temperature over the last 230 years.

Location of a glacier bed on permafrost contributes to maintenance of the cold reserve, which is a factor in preservation of these glaciers in cirques. The mean annual temperature of the rock surface (at a depth of up to 10 cm) in the area of glaciers existence (1800–2200 m a.s.l.) ranges from –5 to –7°C. In the crest part of the ridges, the milder temperature conditions on the surface of rocks are observed in winter, which is most likely associated with the formation of thick snow cornices.

The modern climatic conditions and the observed trends of their change cannot be considered favorable for the existence of glaciers in the Northern Baikal region. However, the glaciation is still far from the complete disappearance. Glaciers have decreased in area and thickness. A comprehensive assessment of their present state and forecast for the future is the relevant research task.

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