ISSN 0145-8752, Moscow University Geology Bulletin, 2024, Vol. 79, Suppl. 1, pp. S25–S35. © Allerton Press, Inc., 2024.
Russian Text © The Author(s), 2023, published in Vestnik Moskovskogo Universiteta, Seriya 5: Geografiya, 2023, Vol. 78, No. 2, pp. 89–102.

In memory of the pioneer of Khibiny glaciers research
V.F. Perov (1931–2017)

The Structure and Dynamics of Very Small Glaciers in the Khibiny Mountains in the 21st Century

M. A. Vikulina[a, *], F. A. Romanenko[a, **], M. V. Zimin[a, *], L. E. Efimova[a, ****], and B. G. Pokrovskiy[b, *****]**

[a] *Moscow State University, Moscow, 119991 Russia*
[b] *Geological Institute, Russian Academy of Sciences, Moscow, 119017 Russia*
**e-mail: masanna2003@mail.ru*
***e-mail: faromanenko@mail.ru*
****e-mail: ziminmv@mail.ru*
*****ef_river@mail.ru*
******e-mail: pokrov@ginras.ru*

Received July 21, 2024; revised August 30, 2024; accepted October 10, 2024

Abstract—Veniamin Fedorovich Perov, who was a researcher at the Khibiny Station of the Faculty of Geography of Moscow State University, discovered very small glaciers in Khibiny Mountains in 1958. He described four glaciers. They were not studied until 2005, when our research began. We used field observations, drilling, GIS, and remote sensing methods to ascertain the glacier structure and estimate the change in their geometry for 60 years. Snow-ice formations were drilled through, ice cores were collected, and geochemical and isotope-oxygen analyses were performed for the first time. The thickness of the ice cores varied from 0.2 to 1.6 m. Our research has shown that the glaciers remain relatively stable in area despite a weak trend toward shrinkage. According to the analysis of climate changes in the Khibiny Mountains, the snowfall decreased there in the early 2000s; the maximum snow thickness at the meteorological site of the Khibiny station was 55 cm in the winter of 2002/2003. This may be the cause of the shrinkage of the glaciers by more than two times during these years. However, the snowfall increased after 2007. A snow thickness maximum of 180 cm was recorded in 2020, which was the maximum value over the observation period (1984–2020). According to the literature data, the annual average temperature on the plains of the Kola Peninsula has attained 2.3 ± 1°C over the past 50 years; however, the warm-period average temperature has not increased. We believe that this fact, along with the increase in the snowfall amount in recent years, determine the quite stable state of snow-ice formations in the Khibiny, which are more resistant to global warming than mountain glaciers.

Keywords: very small glaciers, glacier shrinkage, Kola Peninsula, Khibiny Mountains, satellite imagery

DOI: 10.3103/S0145875225700048

INTRODUCTION

The dynamics of different glaciation forms during the global warming is currently one of the most urgent issues in mountain glaciology. The degradation of glaciers in different regions, including the Arctic, due to the climate warming has been the subject of many studies (Sarana, 2012; Ananicheva, 2014; Ananicheva et al., 2020; Nosenko et al., 2020). Reductions in the area and volume of glaciers have been measured on Spitsbergen, Novaya Zemlya, Franz Josef Land, islands of the Kara Sea, and in Greenland and amount to tens of meters and thousands of cubic meters per year. However, there are many so-called small glaciation forms, including perennial snowfields and snow-firn-ice formations (SFIFs) in the Arctic and Subarctic mountains. Despite their recent small size (up to hundreds of meters in diameter), they play or could play an important paleogeographic role (Bolshiyanov, 2006). Studies of such objects at the Abramov Glacier station in the Alai Range, as well as in Japan, Canada, and Europe have shown their age to be of many decades and perhaps hundreds of years, which confirms their weak or absent response to climate change (Glazyrin et al., 1993, 2004; Kuhn, 1995; Debeer and Sharp, 2009). Unlike for large glaciers, it is impossible to distinguish the accumulation and ablation zones in them; they do not move but contain ice cores and are preserved for a long time, while sometimes increasing or decreasing in size.

The distinction between perennial snowfields and glaciers remains debatable. There is no common opinion on what a perennial snowfield is and what a small glacier is. The latter is often understood as an object smaller than 0.1 km^2, without any other explanation (*Glyatsiologicheskii*..., 1984).

Half a century ago, M.V. Tronov (1966) classified slope glaciers that do not descend into main valleys and "stable snow-firn accumulations" which at least minimally maintain the appearance and properties of glacial formations as small glaciation forms. At the same time, he distinguished small and very small glaciers as a universal significantly stabile glaciation form on the Earth.

G.E. Glazyrin (Glazyrin et al., 2003) suggested using the notion of "a small glacier" for a glacier (or perennial snowfield) with weak redistribution of its mass due to its movement compared to other mass exchange processes. According to his observations, some perennial snowfields withstand significant climate change almost without consequences, unlike large glaciers. The adaptation to relief conditions enables small perennial snowfields lying 1 km or more below the regional average snow line to survive.

V.A. Sarana (2012), who studied small glaciers on the Putorana Plateau, gave the following definition: a small glacier is a slowly moving firn-ice body which lies below the snow line, occupies one landform, and exists due to a favorable combination of orographic and climate factors under conditions of strong snowdrift transport and avalanche activity.

Numerous observations in mountains at different latitudes show that snow-firn or firn-ice accumulations arise due to high snow concentrations on small areas on the earth's surface. SFIFs have a great variety of sizes and thicknesses, can be residual and embryonic, can lie above or below the climate snow line, and their ice core can significantly change in morphology. These formations remain numerous under recent climate conditions, which leads to considerable interest in the issues of their existence, structure, and classification. These issues can be resolved only via detailed study.

There are also SFIFs in the Khibiny Mountains in the central part of the Kola Peninsula. More than 60 years ago, during the International Geophysical Year (1957–1959), Veniamin Fedorovich Perov (1931–2017), a researcher of the Khibiny Geographical Station (the Khibiny Educational and Scientific Station now, KhESS) (Vikulina et al., 2021), discovered four small glaciers in the Khibiny Mountains (Perov, 1958, 1968). Their existence was previously assumed by the famous researchers A.F. Middendorf, I.K. Tikhomirov, and G.K. Tyshinsky. The glaciers were included in the Catalog of Glaciers of the USSR (*Katalog*..., 1966) and numbered in the order of their discovery. They were not studied in detail until the beginning of the 21st century. The issue of their current state has become especially relevant in the context of the climate warming.

According to observations at lowland weather stations, the annual average temperature in the Murmansk region has increased by 2.3 ± 1°C over the past 50 years (Marshall et al., 2016). Since the area of glaciers has decreased by 22% in some other regions (Polar Urals) in the past 10 years (Nosenko et al., 2020), the increase in temperature should have led to complete melting of small glaciers in the Khibiny Mountains. In the early 2000s, some researchers predicted complete disappearance of the glaciers in the Khibiny Mountains in a short time (Zyuzin, 2006).

However, our long-term (since 1995) observations contradict this prediction. The main goal of the research we carried out in 2007–2021 was to trace the dynamics of changes in SFIFs in the Khibiny Mountains and the processes of transformation of matter in them and to ascertain the causes of their stability. Following the discoverer of the Khibiny glaciers V.F. Perov and the compilers of the Catalog of Glaciers of the USSR (*Katalog*..., 1966), we call them glaciers, or SFIFs, which is a synonym, in this work.

CONDITIONS FOR THE EXISTENCE OF SMALL GLACIERS IN THE KHIBINY MOUNTAINS

The Khibiny Mountains (1200 m maximum height, Mount Yudychvumchorr) are located beyond the Arctic Circle on the Kola Peninsula and have a plateau-like relief. The four glaciers discovered by V.F. Perov (Figs. 1 and 2) are very small and thin (Tables 1 and 2). They are located at altitudes of 900–1000 m, under conditions favorable for enhanced snow accumulation: at the top of the north-facing slope (glacier no. 1, Fig. 2a); at the foot of the north-facing slope (no. 2, Fig. 2b); and in narrow rock cracks on the east-facing slope (nos. 3 and 4, Figs. 1 and 2c).

They all lie 800–1000 m below the theoretical snow line. According to calculations by G.K. Tushinskii (Tushinskii and Malinovskaya, 1962), the snow line passes here at altitudes of 1600–1900 m rising in the southeastern direction. Due to this low position, the glaciers should be sensitive to climate change. Nevertheless, despite the increase in the annual average temperature they continue to exist, significantly changing in size from year to year and sometimes almost disappearing by the end of an ablation period in early September.

The Kola Peninsula is located in the Atlantic-Arctic region in the temperate belt. Therefore, the climate in the Khibiny Mountains combines features of regional and local mountain climates. The daily average temperature transits through 0°C on summit plateaus (1000–1200 m) on July 6 and August 17 on aver-

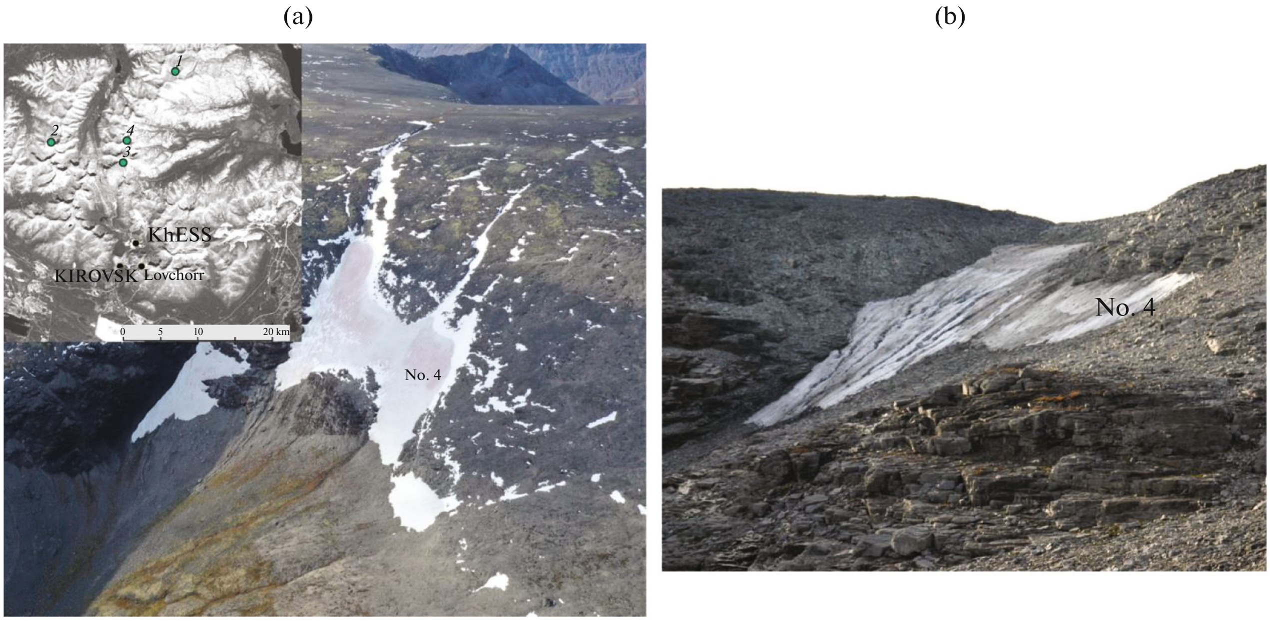

Fig. 1. Glacier no. 4 in different years: (a) September 18, 2006 (dry winter), the glacier shrank to its minimum; (b) September 25, 2020 (cold summer, snowy winter), the length and width of the glacier is about 230–250 m (photo by M.A. Vikulina); the fragment shows the location of glaciers in the Khibiny Mountain.

age, i.e., the frost-free period does not exceed 41 days, and the summer average temperature does not exceed +5.3°C (Mokrov, 2008).

The stable snow cover season on the plateaus lasts from early October to early June. Snowfall can occur in any season. A characteristic feature of the Khibiny Mountains is strong winds; these blow large amounts of snow from the plateaus to the slopes. Wind speed naturally increases with altitude and intensifies in winter when cyclones pass. The monthly average wind speed in winter attains 6.5 m/s on the plateaus, and winds stronger than 15 m/s are observed for about 60 days (Mokrov, 2008).

Solid precipitation accounts for 70% of the total precipitation on the plateaus. According to long-term data, about 700 mm of solid precipitation falls in the Khibiny Mountains per year on average (Zayka et al., 2012), which yields a snow depth of 296 cm after recalculation. However, actual values are significantly lower, since 50–70% of snow is blown off the plateaus. Snowstorms are observed 154 days a year on average on the plateaus (Mokrov, 2008).

For the analysis of the dynamics of temperatures and solid precipitation in the center of the Kola Peninsula, we used data from three weather stations with continuous observation series since 1966 located at different distances from the Khibiny Mountains: Murmansk (142 km to the north), Kandalaksha (86 km to the southwest), and Krasnoshchelye (130 km to the east) (Bulygina et al., 2021). The increase in the annual average temperature is pronounced at these three stations and is confirmed by other studies (Marshall et al., 2016). However, the warm-period average

Table 1. The Khibiny glaciers

Glacier no.	Location	Morphological type	Height range, m
1	Head of the uppermost right tributary of the Kal'yok River, north-eastern edge of the Lyavochor plateau	Drifted cornice glacier	1030–1100
2	Foot of the Chasnachorr plateau, kar in the head of the Chasnayok River	Avalanche glacier at the base of a slope	890–980
3	Eastern edge of the Kukisvumchorr plateau, head of the Tul'yok River	Drifted couloir glacier	940–1070
4	North-eastern edge of the Kukisvumchorr plateau, head of the Yuzhny Kaskasnyunyok River	Drifted couloir glacier	910–1000

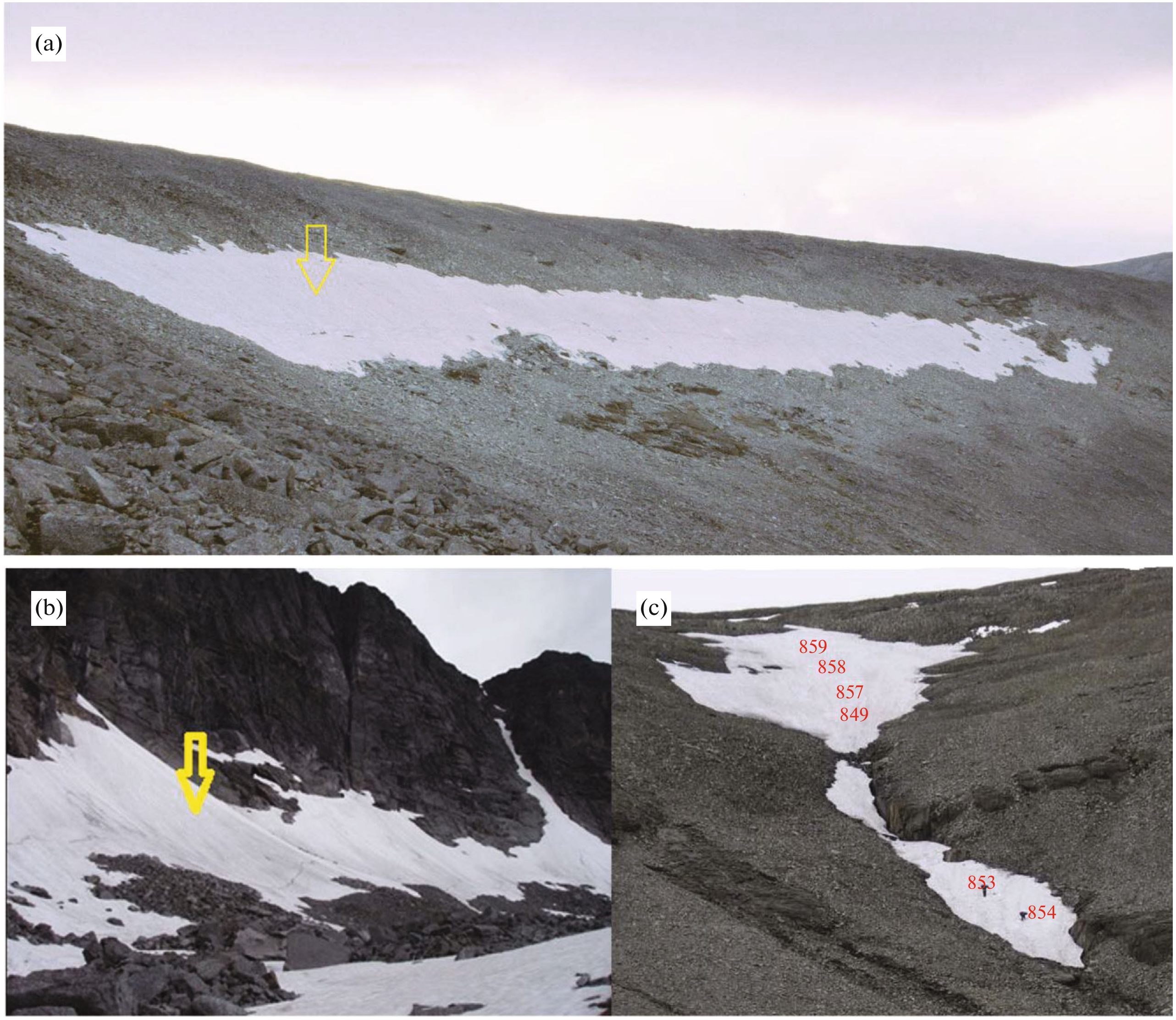

Fig. 2. Khibiny glaciers: (a) glacier no. 1, August 25, 2005 (dry winter, hot summer), ice thickness is 5–10 cm, the arrow shows the position of the pit (photo by M.A. Vikulina); (b) glacier no. 2, July 3, 2006 (dry winter), the arrow shows the position of the pit and borehole (photo by F.A. Romanenko); (c) glacier no. 3, September 28, 2007, ice was found in the uppermost most extensive part of the snow body, separated from the underlying snowfields by a distinct rocky outcropping; numbers are the numbers of pits and boreholes (photo by O.S. Olyunina).

temperatures change insignificantly (Fig. 3a) and warming is mainly observed in winter, spring, and autumn (see Fig. 3b). This is a common pattern in the Arctic and Subarctic: summer remains cool and the cold period warms (Shilovtseva et al., 2011). Comparison between regression coefficients, which reflect the trend in the seasonal average temperatures at the weather stations located in the Khibiny Mountains and on the adjacent plains, has not revealed statistically significant differences (Demin and Volkov, 2017). This allows us to speak about the similar trends and rates of warming in the mountains and on the plains of the Kola Peninsula.

The analysis of the total amount of solid precipitation over 1966–2015 at the three lowland weather stations (there are no data for the last 7 years) shows a certain statistically insignificant decrease. Winters with moderate snowiness predominate, while snowy and dry winters are quite rare (Zaika et al., 2012). However, the calculations do not include data from the last 2 snowy years, 2017 and 2020. Therefore, we used the snow depth measurements at the KhESS site since 1984. No trend toward a decrease or increase in the snow depth was observed at this site before 2010, as well as at the Central weather station on the Lovchorr plateau (Zaika et al., 2012). However, the snow depth has been increasing after 2010, which is confirmed by recent snowy winters (Fig. 4). During the period of observations at KhESS (1984–2021), the stable snow cover season lasts 190 days on average (see Fig. 4) and

Table 2. The sizes of the Khibiny glaciers at the end of an ablation period (late August—September) and the snowfall of a previous winter

		Glacier no. 1			Glacier no. 2			Glacier no. 3			Glacier no. 4		
	Sn	L	W	S	L	W	S	L	W	S	L	W	S
1958*		80	360	0.03	420	50–150	0.03	350	40–90	0.02	240	40–90	0.015
2004**	d							270	50		195		
2005	d	50	350	0.01				300	90	0.02	185	108	0.01
2006	d	22	55	0.0008				60	15	0.0009	90	70	0.003
2007	m							200	30	0.002	100	60	0.004
2009	m							325	133	0.05	194	207	0.18
2012	m	57	411	0.02	126	266	0.015	200	40	0.003	178	50	0.009
2016	m	43	351	0.015	36	157	0.009	191	20	0.005	136	36	0.005
2017	s	56	432	0.02				702	438	0.11	693	277	0.06
2018	m	28	135	0.003	73	55	0.002				93	68	0.004
2019	m	21	232	0.004	115	221	0.014	257	74	0.01	151	104	0.009
S_{av}				0.01			0.01			0.03			0.03

Sn is the winter snowiness (d means dry winter; m means medium snow; s means snowy winter); L is the length (m), W is the width (m), S is the area (km^2); S_{av} is the average area over the period under study (2005–2019); * means according to (Perov, 1968); ** means according to (Zyuzin, 2006).

sometimes attains 228 days (2019–2020). According to data from the KhESS site over the past 20 years, the winters of 2013/2014, 2016/2017, and 201/2020 can be considered snowy (see Fig. 4). The early 2000s had dry winters, with minimal amounts of snow in 2002/2003 and 2005/2006.

Thus, despite an increase in annual average air temperatures on the Kola Peninsula, the warm-period

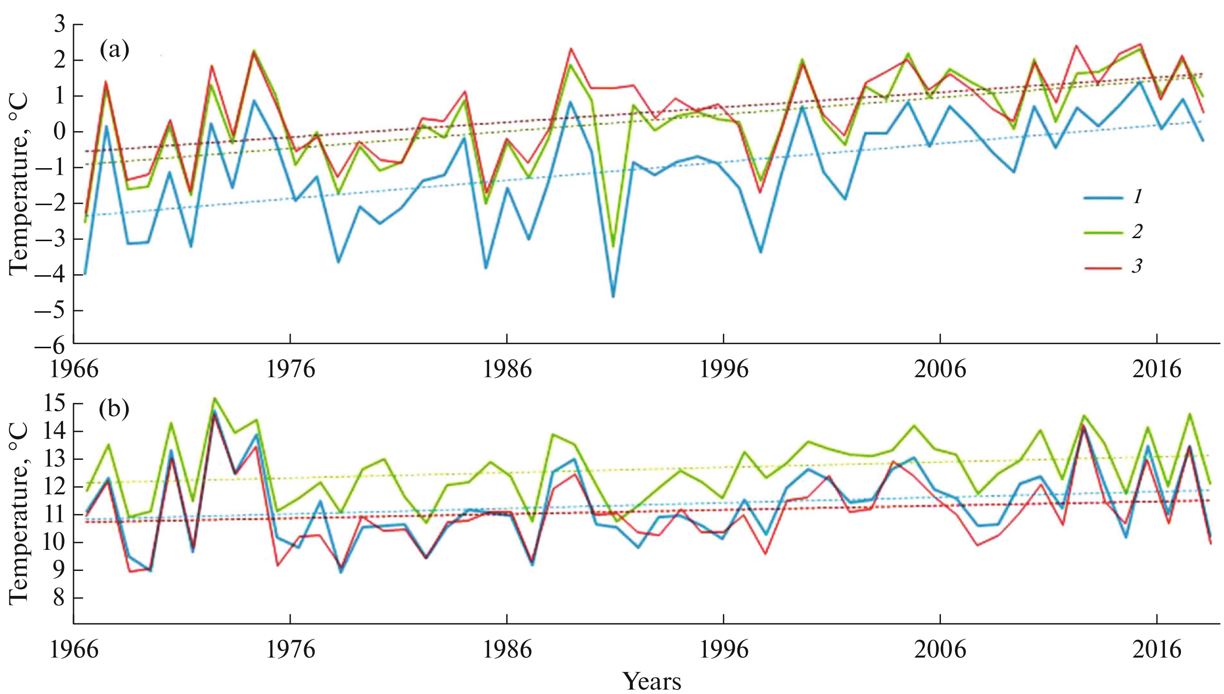

Fig. 3. Long-term variations in the air temperature at weather stations in Murmansk region (Bulygina et al., 2021): (a) annual average and (b) summer average temperatures at Murmansk (*1*), Kandalaksha (*2*), and Krasnoshchelye (*3*) stations. The dotted lines are trends.

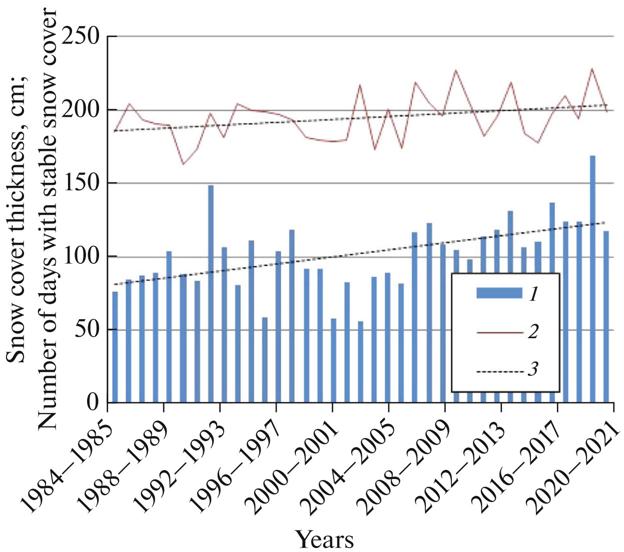

Fig. 4. Variations in the maximum snow cover thickness and the duration of stable snow period at the meteorological site of the Khibiny Educational and Scientific Station: snow cover thickness (*1*), number of days with stable snow cover (*2*), and trend lines (*3*).

average temperature changes little and the amount of solid precipitation is slightly increasing in the Khibiny Mountains.

RESEARCH TECHNIQUE

A comprehensive study of the Khibiny glaciers was carried out in 2005–2009. During the first stage in 2005–2020, we visually observed them throughout the ablation period, measured their sizes during the period of maximum snowmelt in late August–September, dug pits in snow, ice, and firn, and created digital elevation models (Vikulina, 2008). In summer 2006 and the falls of 2007 and 2008, we drilled through two glaciers (nos. 2 and 3) using a Cherepanov ring ice drill (also known as PI-8) and reached the bedrock for the first time. Earlier, the thickness of the glaciers was estimated only from indirect data. Drilling of glacier no. 4 had to be stopped due to thick snow in 2008.

A total of nine boreholes were drilled in three glaciers (Table 3); the bedrock was reached in six of the boreholes. The drilling was usually carried out from the bottom of pits dug in snow to a depth of up to 4.5 m or, less often, from the dense surface of firn snow. The snow-firn layer that covered the ice and the ice were sampled throughout the depth. The core was divided into pieces 10–15-cm long, which were placed in sealed polyethylene bags. Snow and ice melted at an ambient temperature no higher than 10°C. After melting, the water was poured into chemically clean jars and transported to laboratories. Water samples were filtered through a membrane filter (0.45 μm) and preserved for subsequent detection of microelements in them. In 2006, the samples were laboratory analyzed for the contents of the main ions by the standard method (Komarov and Kamenetsev, 2006). Samples collected in 2007–2008 were analyzed in the Laboratory of Geological Phenomena and Processes (Laboratoire des Mécanismes et Transfers en Géologie (LMTG)) of the Midi-Pyrénéés Observatory (Toulouse, France). An Agilent 7700 inductively coupled plasma mass spectrometer was used for estimating the content of cations, and an Agilent 1290 liquid chromatograph (Agilent Technologies, Keysight) was used for anions. The isotope-oxygen analysis was carried out in the Laboratory of Isotope Geochemistry and Geochronology of the Geological Institute, Russian Academy of Sciences, at a Finnigan Delta Advantage measuring complex with a Gas Bench II sample preparation and introduction system.

Later, until 2020, we analyzed the dynamics of SFIF areas by space imagery made at the end of the

Table 3. The comparative characteristics of the internal structure and composition of ice and snow of glaciers

Glacier no.	Borehole no.	Absolute height of borehole, m	Borehole depth, m	Snow thickness, m	Ice thickness, m	$\delta^{18}O$, ‰, SMOW	Cation content, mg/L
2	2 – 2007	948	1.05	0.95	0.2	–12.0–13.1	Cations 1.0–3.8
	1 – 2006	900	4.46	4–4.5	0.66	–	4–9
3	859	970	3.1	3.1	no	–	–
	858*	955	2.5	>2.5	not accessed	–	–
	857*	953	2.5	2.05	>0.4	–	Cations 0.9–1.5
	849	947	2.3	0.7	1.6	–11.3–14.0	Cations 0.7–4.3
	853	898	1.9	1.9	no	–	
	854	890	1.65	1.65	no	–	
4	256*	950	2.22	>2.5	not accessed	–	–

* Pits and boreholes have not reached glacier bed.

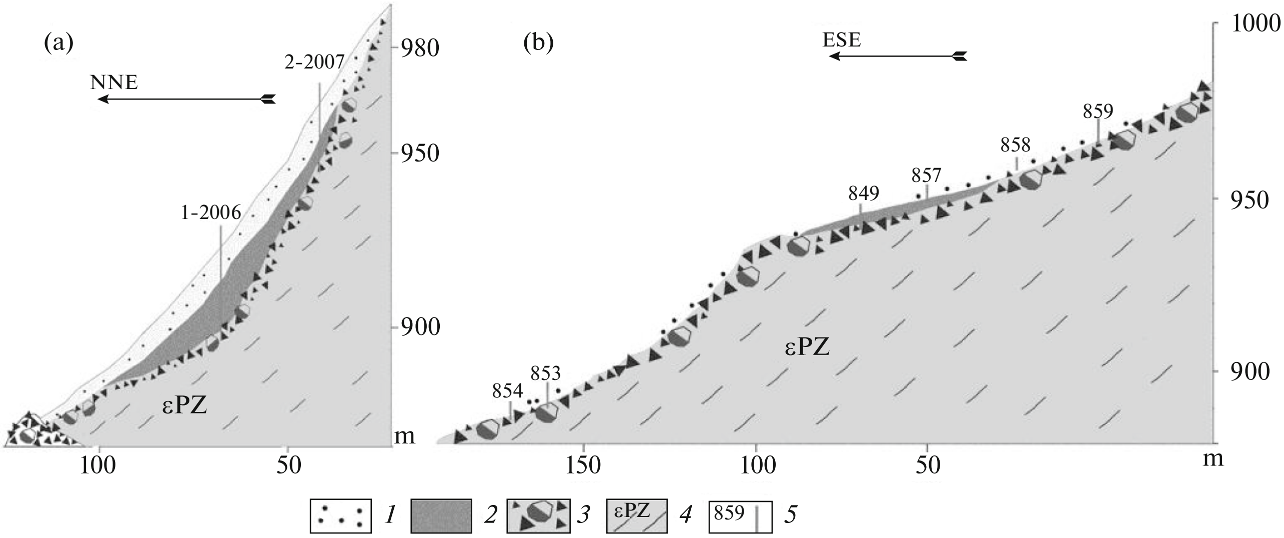

Fig. 5. The internal structure of glacier (a) no. 2 and (b) no. 3 based on the results of pitting and drilling in 2006–2007: ice (*1*), snow (*2*), crushed stone and lumps (*3*), alkaline rocks (*4*), and numbers of boreholes (*5*).

ablation period. We selected cloudless images for the required period in years with different meteorological parameters: GeoEye-1 (2009; 0.5 m), World View-2 (2012; 0.5 m), Spot7 (2016 and 2019; 1.5 m), and Spot6 (2017 and 2018; 1.5 m). For the measurements to be reliable, all remote sensing materials were subjected to photogrammetric processing to eliminate distortions largely associated with the shooting conditions and topography of the objects under study. After the processing, we had multi-temporal orthophotoplans of the territories under study and the boundaries of the glaciers were identified in them using expert interpretation methods of GIS technologies.

Summer 2018 was abnormally hot. Therefore, the sizes of the glaciers were compared with those in the similar hot summer of 2005. Images of 2012, 2017, and 2019, with cold summers, were also analyzed. In 2017, which was snowy, snow remained in the mountains until July. Mean temperatures and amounts of solid precipitation occurred in 2009 and 2016. We had aerial photographs made in August 1958, which made it possible to compare the distribution of SFIFs over 60 years.

RESULTS AND DISCUSSION

The Inner Structure of SFIFs According to Drilling Data for 2006–2008

The first object of drilling was glacier no. 2 at the foot of Chasnachorr Mount, the route to which crossed the Southern Chorgor Pass. In July 2006, a borehole was laid on the glacier surface near its central convex part, where the ice thickness was assumed to be maximum. The depth of the borehole in snow and firn attained 4 m, where the top of the ice body was broken. To penetration into its depth, we used a ring drill with total coring.

In borehole 1-2006 (see Fig. 2b), under a surface snow layer 0.9-m thick, a layer of transparent ice 0.10–0.13-m thick was revealed, which was apparently formed due to active melting and freezing in one of the previous summer seasons. A blind joint moisture-saturated coarse-grained snow layer up to 3–3.3-m thick occurs below (drilling was carried out on July 2 and 3). It was underlain by an ice layer 0.66-m thick lying on the bedrock (Fig. 5a). The upper ice layers were transparent; lower ones were cloudy, with dark gray layers of scattered dust; smooth ice layers almost without air bubbles were in between. A thin (5–8 cm) layer of transparent ice with a small number of bubbles underlay the ice body. Crushed stones and lumps of nepheline syenites were frozen into the ice base, which enriched the lower ice layers with sodium, aluminum, and iron while freezing and melting (Lakes and Glaciers, 2013). Water flowed along the bedrock. The slope of the layers in the core corresponded to the slope of the glacier surface (up to 20°).

In September 2007, when the snow thickness on the glacier surface was minimal, we drilled borehole 2-2007 50-m higher borehole 1-2006. Under a dense coarse-grained firn snow layer ~1-m thick, we found a thin (0.20 m) layer of stratified ice lying on a rock. Transparent layers with a small number of air bubbles alternated with cloudy layers with a large number of air bubbles and sometimes contaminated.

Chemical and Isotopic Analyses

The chemical analyses of ice from glacier no. 2 (hole 2-2007) showed its extremely low mineralization

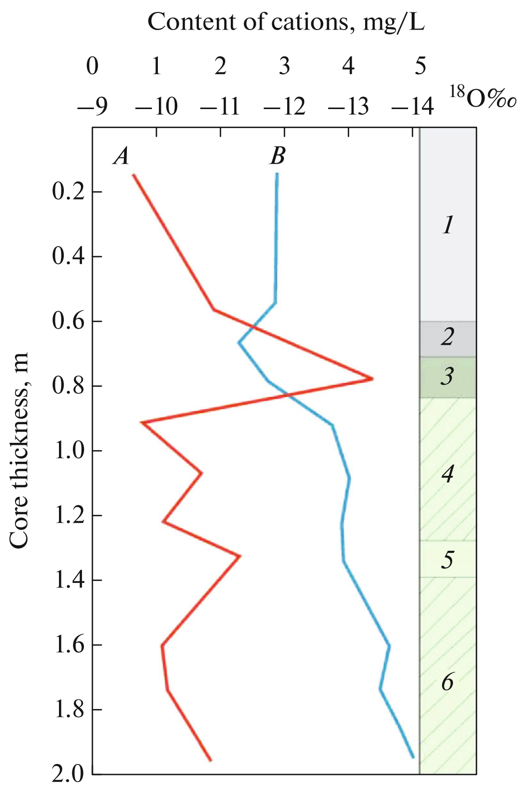

Fig. 6. (*A*) The contents of cations and (*B*) isotope abundance of oxygen in snow and ice of glacier no. 3: snow with ice layers and lenses (*1*), dusty snow (*2*), gray cloudy ice (*3*), ice with alternating transparent and cloudy interlayers (*4*), transparent ice (*5*), and ice with alternating transparent and cloudy interlayers (*6*). Sampling on September 28, 2007.

(4–9 mg/L) and chloride-sodium-calcium composition. Mineralization of overlying snow varied from 2 to 3.5 mg/L. Snow in the upper part has a chloride-calcium-sodium composition. The percentage of sodium increases to 20% or more below a transparent ice layer at a depth of 0.9 m. In the snow depth from 0.21 to 0.38 m, the content of hydrocarbonates increases by 2–3 times down the profile (see Table 3).

Glacier no. 3 has a similar structure. In July 2007, the snow field hiding the glacier occupied almost the entire eastern slope of Kukisvumchorr Mount. During the period of maximum ablation in late September 2007, the glacier consisted of three isolated parts separated by rocky outcrops (see Fig. 2c). The two lower parts of the glacier were formed by firn snow up to 1.9-m thick, and only the upper part contains an ice body 1.6-m thick. This morphology is primarily determined by the bedrock structure. The ice covers a gentler part of the slope, above and below which the slopes increase, the water flows down, and ice does not form. Thus, the glacier lies in a gentle nival niche, which is a characteristic landform in the Khibiny Mountains.

Two snow layers are distinguished in the vertical profile. The surface snow layer is enriched with heavy metals (Zn, Cu, and Ni), and the underlying layer is heavily dusty and contains the profile maximum amount of dissolved and suspended substances (turbidity is more than 3 g/L). In the dusty snow layer, mineralization (13.7 mg/L) and concentration of hydrocarbonate ions are high (more than 5 times higher than the values characteristic of the entire glacier). The gradients in the concentrations of most chemical components between the dusty snow and underlying ice layers are significant (Fig. 6). There are no hydrocarbonate ions in the ice layer; the pH is low (5.3 against 6.4), and the total mineralization is 7.2 times lower. The snow–ice layer of the glacier has high content of zinc; it is comparable to the content of magnesium (0.04–0.06 mg/L) in snow and is 0.02 mg/L on average in ice.

The generalized drilling data show the following features of the structure of glaciers nos. 2–4. Under the surface snow layer with ice interlayers and lenses 2—5-mm thick, there is a stratified thick layer of wet coarse-grained snow. Contact with underlying ice is different: sometimes there is a thin (up to 0.2–0.3 m) firn layer, sometimes snow lies directly on the ice (see Fig. 5b). In glacier no. 3, the upper ice layers are heavily contaminated with dust, while in glacier no. 2 they are transparent. Lower ice is mainly banded, it consists of alternating lighter transparent and darker (cloudy) layers, with inclined dark gray interlayers of scattered dust and transparent ice almost without air bubbles (Fig. 6).

We performed an oxygen-isotope analysis with the aim of identifying interannual difference in the temperature conditions for ice formation. We ascertained that the isotope abundance of oxygen in snow and ice naturally becomes lower down the profile. This indicates that deeper ice layers formed under lower temperatures than the overlying ones. The value of $\delta^{18}O$ changes from −11.3 to −14‰, which indicates the noticeable differences in the temperature conditions for ice formation. According to Fricke and O'Neil (1999), $\delta^{18}O$ values decrease by an average of ~0.5‰ in Arctic latitudes as the annual average Earth surface temperature decreases by 1°C. This enabled us to conclude that the glacier foot formed at a temperature ~4°C lower than today. The isotope abundance of oxygen is at its maximum in the upper heavily contaminated ice layer, where the content of cations is at its maximum, especially of potassium, magnesium, and sodium, and is at its minimum in the bottom ice, which lies directly on the glacier bed covered with rubble and boulders. The value of $\delta^{18}O$ in fresh snow (-14.3‰) is much lower than in compacted snow which has undergone numerous transformations during the ablation period (see Fig. 6 and Table 3).

The snow depth of both glaciers is saturated with water, which is gradually filtering downwards, i.e., water permanently migrates in the snow depth in summer. The ice core melts near the foot and grows on the top due to freezing of water filtering from above. This exchange process is very rapid, judging by the melting rate, and the entire depth is probably renewed in a few years. However, the ice core is preserved in a kind of water "ring" during the warm season: water from melting snow and firn flows down from above, from the sides along the edges of the ice core, and along the bedrock. As soon as the temperature drops below zero, the depth starts freezing, thus turning an SFIF into a single massif. It becomes a source of snow accumulation in winter, which supports the life cycle of such objects, which we saw in direct observations.

V.F. Perov (1968) suggested that the Khibiny glaciers arose during the Fernau stage of cooling (13th–19th centuries) and repeatedly disappeared and reappeared in subsequent periods. They remained small, and their geomorphological activity was very weak. This is evidenced by the near absence of signs of movement of these objects. Ramparts, accumulations of unsorted unrounded material 2–4-m high were discovered only at the foot of glacier no. 2; V.F. Perov considered them to be a consequence of movement of a snow-firn-ice mass. We assume them to be formed not by the movement of the glacier, but by accumulation of debris falling in abundance from a tectonic ditch with heavily fractured sides, which cuts the overlying slope, and rolling down the glacier. We observed debris permanently falling onto the upper part of the glacier and being moved by meltwater and gravity.

Remote Methods

The analysis of satellite and aerial imagery made in August 1958–2020 shows that the most favorable conditions for the formation and preservation of snowfields in the Khibiny Mountains are on the northern, northeastern, and eastern slopes of rock massifs in negative landforms, that is, ditches, niches, bases of ledges, etc. About 60% of the all snowfields are in cirques and kars, most often on slopes with exposure to the east (leeward). About one-quarter of the snowfields are in stream valleys and hollows, the rest are in pass gorges and saddles.

The comparison of SFIF areas over the past 15 years shows that they constantly change in size, which correlates with the snowfall in a previous winter and the summer average temperatures (see Table 2). The dry early 2000s and hot summer of 2005 led to a strong decrease in SFIF areas, while the increase in the amount of solid precipitation in subsequent years and the repetition of cold years, such as 2008 and 2017, caused their new increase (see Table 2).

Glaciers nos. 3 and 4 are currently stable and are larger on average than in 1958. Thus, the area of glacier no. 4 in September 2020, at the end of the snowmelt period, was twice its size in 1958 (see Fig. 1). Glaciers nos. 1 and 2 are smaller on average compared to 1958. In 2005, glacier no. 1 disintegrated into several snow-firn-ice patches of tens of square meters in area due to the low snowfall in winters of the early 2000s; however, it continued to exist in the same place as a single formation even after the abnormally hot summer of 2018. This confirms the conclusion that the amount of solid precipitation affects the Khibiny SFIFs more than an increase in air temperature.

Thus, formation of SFIFs (small glaciers) in the Khibiny Mountains (existence of similar formations can be assumed in the Lovozero tundra (altitude of 1116 m) and in the Monche and Chuna tundra massifs (1072 m)) is due to a significant amount of precipitation and extremely favorable conditions for snow accumulation on leeward slopes and in depressions, where snow is blown by winds during snowstorms, during a long (7–9 months) winter. Thus, in July 2007, after melting began, the thickness of the snow layer at the foot of glacier no. 3 exceeded 6 m, i.e., it could reach 10 m in April–May. On the Lyavochor plateau, in the region of glacier no. 1, the thickness of the snowdrifts exceeded 1.2 m after the first snowfall on September 24, 2007, and the snow completely covered the glacier. Such snow accumulations due to snowstorms (nos. 1, 3, and 4) and avalanches (no. 2) have no time to melt during a cool summer and turn into small glaciers, or SFIFs.

Similar objects have been found in other mountain systems (Glazyrin et al., 1993, 2004; Kuhn, 1995; Debeer and Sharp, 2009; Sarana, 2012). Is it right to call them small glaciers? These are snow-firn-ice formations which remain for a long time and are highly dynamic. They have an ice core, which distinguishes them from ordinary snowfields, but do not move like glaciers. The special term "passive glacier" has long existed (Bolshiyanov, 2006) for such objects on Arctic plains; the term SFIF is its synonym in essence.

The long-term existence of such objects in the Khibiny Mountains confirms the hypothesis of their stable state under changes in natural conditions. Being small (less than 0.05 km^2 in area), they cannot be considered indicators of the climate change, because they are more stable than large glaciers. They maintain stability, occasionally shrinking when all snow and firn and partly ice accumulated over previous years melt and regaining their size the following year or the year after. The trend in their development depends on the combination of the amount of solid precipitation and temperatures of a particular summer. Snow accumulation is significantly affected by wind transport, i.e., local changes in the wind direction and speed, which are difficult to "catch" and directly measure near a glacier, can significantly increase the amount of snow in negative landforms.

The leading role in ice core formation is played by the amount of water that enters during the melting period and filters through the snow layer and autumn temperatures. The warmer the summer is (the more water enters) and the faster and "sharper" the autumn onset is, the thicker the ice layer is. That is, the size and thickness of the Khibiny glaciers strongly fluctuate; they increase under favorable conditions and shrink considerably under unfavorable ones.

CONCLUSIONS

More than 60 years have passed since the discovery of small glacier forms in the Khibiny Mountains. Perov V.F. considered them glaciers and they were included in the Catalogue of Glaciers of the USSR (*Katalog*..., 1966) under that name. In the early 21st century, direct data on the structure of the snow-firn layer and the thickness of the ice core of these formations were received for the first time. The ice thickness in 2006–2007 was insignificant and ranged from 0.1 m (glacier no. 1) to 1.6 m (glacier no. 3).

Snow, firn, and ice of the Khibiny glaciers have low chloride-sodium-calcium mineralization (4–9 mg/L). Heavily dusty layers with much higher mineralization periodically repeat in the depth. Their formation can be associated with dry warm summer periods, when aeolian dust transfer is most active. This does not occur every year; therefore, the age of the snow-ice depth cannot be assessed by the number of these layers. The isotope composition of oxygen in snow and ice indicated that deeper ice layers were formed at lower temperatures than overlying ones: deep layers freeze in the winter later than surface layers, which freeze in the autumn.

Monitoring of the area of the Khibiny glaciers in satellite images showed that glaciers nos. 3 and 4 remain in a stable state (the average area of each is about 0.03 km^2) occasionally exceeding their areas in 1958. Glaciers nos. 1 and 2 are gradually decreasing: their mean area has decreased by three-times compared to 1958 and does not exceed 0.01 km^2.

Despite the fact that the annual average temperatures have decreased by $2.3 \pm 1°C$ over the past 50 years, the average temperatures of the warm period have not significantly increased, while the amount of snow noticeably fluctuates. Dry winters of the early 2000s, when the maximum thickness of the snow cover did not exceed 55 cm, were replaced by snowy winters (2013/2014, 2016/2017, and 2019/2020). Especially large snowfalls occurred in winter 2019/2020, when the maximum thickness of the snow cover attained 180 cm at the KhESS meteorological site.

These fluctuations in winter snowfall caused changes in the size of the glaciers. Their shrinkage before 2007 and very small ice thickness discovered by drilling were due to previous years with little snow and the hot summer of 2005. The subsequent increase in the amount of solid precipitation led to the recovery of the sizes of some glaciers.

V.F. Perov suggested that the Khibiny glaciers (or SFIFs) arose in the Little Ice Age (the Fernau stage, 13th–19th centuries). However, one can assume that they could have survived since the end of the Valdai Ice Age, periodically nearly disappearing and reappearing according to the mechanism we discovered. That is, the presence of such objects in mountains cannot serve an indicator of climate changes due to their almost "instantaneous" (2–3 years) response to local changes in precipitation, air temperature, and even wind conditions.

ACKNOWLEDGMENTS

The authors are grateful to the staff of the Faculty of Geography of Moscow State University who took part in drilling glaciers in 2006–2008 O.V. Kokin, E.V. Garankina, O.S. Shilova, and D.A. Sokolov, researchers of the Institute of Geography, Russian Academy of Sciences, E.A. Konstantinov and of the Geological Institute, Russian Academy of Sciences, E.A. Moroz and A.A. Chesnokova.

Satellite imagery was received due to the support of the GEOPORTAL Collective Use Center of Moscow State University.

FUNDING

The works by M.A. Vikulina, F.A. Romanenko, and L.E. Efimova were supported by the Ministry of Science of Higher Education of the Russian Federation (state assignment Evolution of the cryosphere under climate change and anthropogenic impact, no. 121051100164-0; state assignment Evolution of the natural environment in the Cenozoic, relief dynamics, geomorphological hazards, and risks of nature management (no. 121040100323-5), and state assignment Analysis, modeling and forecasting changes in hydrological systems, water resources, and quality of land waters, no. 121051400038-1), respectively). Work by M.V. Zimin was supported by the Russian Foundation for Basic Research (project no. 18-05-60221).

CONFLICT OF INTEREST

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

REFERENCES

Ananicheva, M.D., Estimation of the areas, volumes and heights of the recharge boundary of the glacial systems of the North-East of Russia based on satellite images of the beginning of the XXI century, *Led Sneg*, 2014, no. 1 (125), pp. 35–47.

Ananicheva, M.D., Kononov, Y.M., and Belozerov, E.V., Contemporary state of glaciers in Chukotka and Kolyma highlands, *Bull. Geogr. Ser. Phys., Geogr.*, 2020, vol. 19, pp. 5–18. https://doi.org/10.2478/bgeo-2020-0006

Bolshiyanov, D.Yu., *Passivnoe oledenenie Arktiki i Antarktidy* (Passive Glaciation of the Arctic and Antarctica), St. Petersburg: Arctic Antarctic Res. Inst. Publ., 2006.

Bulygina, O.N., Razuvaev, V.N., Korshunova, N.N., and Shvets, N.V., *Description of the Dataset of Monthly Total Precipitation at Russian Stations*, Database State Registration Certificate No. 2015620394 (2014). http://meteo.ru/data/158-total-precipitation#описание-массива-данных (Accessed February 1, 2021–March 31, 2021).

Debeer, C.M. and Sharp, M.J., Topographic influences on recent changes of very small glaciers in the Monashee Mountains, British Columbia, Canada, *J. Glaciol.*, 2009, no. 192, pp. 691–700. https://doi.org/10.3189/002214309789470851

Demin, V.I. and Volkov, A.V., Comparison of changes in air temperature in the Khibiny and on the surrounding foothill plain, *Fundamental. Prikladn. Klimatol.*, 2017, no. 3, pp. 16–27. https://doi.org/10.21513/2410-8758-2017-3-16-27

Fricke H.C., O'Neil J.R. The correlation between $^{18}O/^{16}O$ ratios of meteoric water and surface temperature: its use in inves-tigating terrestrial climate change over geologic time, *Earth Planet. Sci. Lett.*, 1999, vol. 170, pp. 181–196.

Glyatsiologicheskii slovar' (Glaciological Dictionary), Kotlyakov, V.M., Ed., Leningrad: GIMIZ, 1984.

Glazyrin, G.E., Kamnyanskii, G.M., and Pertsiger, F.I., *Rezhim lednika Abramova* (Abramov Glacier Regime), Leningrad: Gidrometeoizdat, 1993.

Glazirin, G., Kodama, Y., and Ohata, T., Stability of drifting snow-type perennial snow patches, *Bull. Glaciol. Res.*, 2004, no. 21, pp. 1–8.

Katalog lednikov SSSR. T. 1, Ch. 1 (Catalog of Glaciers of the USSR. Vol. 1, Iss. 1), Leningrad: Gidrometeoizdat, 1966, pp. 45–51.

Komarov, N.V. and Kamentsev, Ya.S., *Prakticheskoe rukovodstvo po ispol'zovaniyu sistem kapillyarnogo elektroforeza "Kapel'"* (A Practical Guide to Using Capillary Electrophoresis Systems "Kapel"), St. Petersburg: Veda Publ., 2006.

Kuhn, M., The mass balance of very small glaciers, *Z. Cletscher. Glazialgeol.*, 1995, no. 31, pp. 171–179.

Marshall, G.J., Vignols, R.M., and Rees, W.G., Climate change in the Kola Peninsula, Arctic Russia, during the last 50 years from meteorological observations, *Am. Meteorol. Soc.*, 2016, no. 29, pp. 6823–6840. https://doi.org/10.1175/JCLI-D-16-0179.1

Mokrov, E.G., *Seismicheskie faktory lavinoobrazovaniya* (Seismic Factors of Avalanche Formation), Moscow: Nauchn. mir, 2008.

Nosenko, G.A., Murav'ev, A.Ya., Ivanov, M.N., Sinitskii, A.I., Kobelev, V.O., and Nikitin, S.A., The response of the glaciers of the Polar Urals to modern climate changes, *Led Sneg*, 2020, vol. 60, no. 1, pp. 42–57.

Ozera i ledniki. Vliyanie izmenenii klimata i opasnykh prirodnykh yavlenii na prirodopol'zovanie Evropeiskogo Severa (Lake and Glaciers. Impact of Climate Change and Natural Hazards on the Use of Natural Resources in the European North), St. Petersburg: Russ. State Hydrometeorol. Univ., 2013, pp. 80–81.

Perov, V.F., The first glacier in the Khibiny mountains, *Priroda*, 1958, no. 7, p. 88.

Perov, V.F., *Snezhniki, ledniki i merzlotnyi rel'ef khibinskikh gor* (Snowfields, Glaciers and Permafrost Relief of the Khibiny Mountains), Moscow: Nauka, 1968.

Sarana, V.A., Very small glaciers of the Russian sector of the Arctic and Subarctic, *Vestn. Mosk. Univ., Ser. 5: Geogr.*, 2012, no. 2, pp. 82–87.

Shilovtseva, O.A., Kononova, N.K., and Romanenko, F.A., Climate change in the Arctic regions of Russia, in *Climate Change Adaptation: Ecology, Mitigation and Management*, New York: Nova Sci. Publ., 2011, pp. 35–63.

Tronov, M.V., More about small forms of glaciation, *Mater. Glyaciol. Issled.*, 1966, no. 12, pp. 250–253.

Tushinsky, G.K. and Malinovskaya, N.V., The position of the "365" level over the territory of the USSR and the connection of this level with glaciation, *Inform. Sb. Rabotakh Mosk. Univ.*, 1962, no. 9, pp. 5–9.

Vikulina, M.A., The use of geographic information systems for the study of snow-nival phenomena, *Mater. Glyaciol. Issled.*, 2008, no. 105, pp. 120–124.

Vikulina, M.A., Vashchalova, T.V., Tutubalina, O.V., Rees, W.G., and Zaika, Y.V., Moscow University's field station in the Khibiny Mountains, in *Russian Arctic: A 70-Year History to the Present Day, Polar Record*, Cambridge Univ. Press, 2021, vol. 57, pp. 1–12. https://doi.org/10.1017/S0032247421000012

Zaika, Yu.V., Vikulina, M.A., and Chernous, P.A., Long-term dynamics of nival processes in the Khibiny Mountains, *Led Sneg*, 2012, no. 1, pp. 69–74.

Zyuzin, Yu.L., *Surovyi lik Khibin* (The Severe Face of Khibiny Mountains), Murmansk: Reklam. Poligr., 2006.

Translated by O. Ponomareva

Publisher's Note. Allerton Press remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
AI tools may have been used in the translation or editing of this article.