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GLACIERS AND ICE SHEETS

Ice and Snow Thickness of the IGAN Glacier in the Polar Urals from Ground-Based Radio-Echo Sounding in 2019 and 2021

I. I. Lavrentiev[a], *, G. A. Nosenko[a], A. F. Glazovsky[a], A. N. Shein[b], M. N. Ivanov[c], and Ya. K. Leopold[b]
[a] *Institute of Geography, Russian Academy of Sciences, Moscow, 119017 Russia*
[b] *"Scientific Center for the Study of the Arctic," Salekhard, 629007 Russia*
[c] *Moscow State University, Moscow, 119991 Russia*
**e-mail: lavrentiev@igras.ru*

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Abstract—Small glaciers of the Polar Urals are at the limits of their existence. Their state and changes serve as an important natural indicator of modern climatic changes. In 2019 and 2021, we performed ground-based radar studies of one of these glaciers, the IGAN Glacier, to measure ice thickness and snow cover. We used Picor-Led (1600 MHz), and VIRL-7 (20 MHz) GPRs. According to these data, the glacier has an average thickness of 49 m, maximum 113 m. The glacier has a polythermal structure: a cold ice layer with an average thickness of 12 m (maximum 43 m), overlaps the temperate ice with an average thickness of 37 m (maximum 114 m in the upper part of the glacier). The volume of ice contained in the glacier (in its studied part) is 14.3×10^6 m^3, of which 10.89×10^6 m^3 is temperate ice and 3.44×10^6 m^3 is cold ice. For comparison: according to the radar data of 1968, the total ice thickness then reached 150 m in the central part, and the thickness of the upper layer of cold ice was 40–50 m. Radar snow measurement survey allowed us to plot the distribution of seasonal snow thickness over the glacier surface in 2019 and 2021, where a general spatial pattern of snow thickness increase from 2 m on the glacier terminus to 8 m and more towards the back wall of the cirque which is due to the significant influence of avalanche nourishment and wind transport. Over the last decade, the glacier has lost about 3.2×10^6 m^3 of ice, and if the rate of loss continues, it may disappear in 40–50 years. However, this process may have a non-linear character, as it involves not only climatic factors, but also local terrain features, on the one hand contributing to a high accumulation of snow, on the other hand – to the formation of a glacial lake during glacier retreat, which may intensify ablation.

Keywords: radio-echo sounding, glacier, snow thickness, ice thickness, Polar Urals

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INTRODUCTION

The ongoing climate change and the increasing rate of glacier shrinkage make the issues related to the prospect of their possible disappearance on our planet more and more urgent: from catastrophic consequences to the loss of recreational attractiveness of a number of areas. Glaciers in tropical latitudes – in the Andes and Africa—are in a deplorable state [18, 20]. Glaciers in mid latitudes—in the Caucasus [22] and in the Alps [17]—are in catastrophic decline. The disappearance of glaciers is also recorded above the Arctic Circle—the MGU glacier, which was the second largest glacier in the Polar Urals in the 1950s, had almost disappeared by 2018 [7].

Since regular monitoring is performed mainly on medium and large glaciers, the understanding of the processes occurring with small glaciers on the threshold of their extinction remains incomplete. The number of glaciers in the world provided with instrumental observations over a long-time interval is less than 1% [24]. Studies show that the most vulnerable in this respect are glaciers with sizes less than 0.5 km^2 [10, 16], which account for more than 80% of the total number of glaciers in mountain systems of middle and low latitudes [14, 19]. Depending on regional patterns of climatic conditions, relief, size and morphology of the glaciers themselves, their reduction occurs with different intensity. Quantitative estimates of the changes underway are important for understanding the role of the factors involved in this process and the mechanisms of their interaction.

Studies of the Polar Urals glaciers, started in the middle of the twentieth century, contain the longest series of observations among the glaciers of mountainous regions of the Russian mainland located in polar latitudes. The Polar Urals include the northernmost part of the Ural Ridge, the modern glaciation of which is represented by snow and ice formations with an area of up to 1 km^2. Located below the climatic snow boundary, glaciers exist here due to low air temperatures and high snow concentration in corries and on ledges of leeward slopes as a result of blizzard and avalanche snow transport. Instrumental studies have been continued on the IGAN glacier for almost 70 years. This paper presents the results of recent studies that allow us to assess the current state of the glacier and the changes that have occurred to it.

IGAN GLACIER AND ITS RESEARCH HISTORY

The first information about glaciers in this area was obtained by A.N. Aleshkov during the Second International Polar Year (IPY) (1932–1933), and the most intensive studies were carried out during the International Geophysical Year (IGY) (1958–1959) and the International Hydrological Decade (IHD) (1965–1974) on the basis of two glaciological stations—on Lake Bolshaya Khadata and near the terminus of the Obruchev Glacier. In 1958–1981, the Polar-Ural Glaciological Station was established at Lake Bolshaya Khadata and at the terminus of Obruchev Glacier. The Polar-Ural Glaciological Expedition of the Institute of Geography of the USSR conducted annual mass-balance studies and photogeodetic monitoring of three glaciers of the Polar Urals—Obruchev, IGAN and MGU [2, 8, 9]. The corrie-valley glacier IGAN, located on the eastern slope of Mount Kharnaurdy-Keu (1240 m), according to the data of the first catalog of the Polar Urals glaciers in the 1950s [3], had an area of 1.25 km^2, and by morphology belonged to the corrie-valley type (Fig. 1a).

In 1961, the IGAN and Obruchev glaciers became the objects of geophysical studies to determine the ice thickness and the subglacial bed topography [1]. Electrometric and magnetometric methods were used for this purpose. The electrometric works used galvanic resistivity method, probing was performed by symmetric and dipole-axis installations. Magnetometric works consisted in measuring the vertical component of the geomagnetic field using a M-2 type magnetometer. The measurements were carried out in the central part of the glaciers on transverse profiles, as well as along the central axis. Based on the data obtained, it was found that the ice thickness on the IGAN glacier reaches 135–140 m in its middle part, gradually decreasing to 40 m towards the terminus.

In 1968 and 1976, the first ice thickness measurements were made on the IGAN and Obruchev glaciers using a pulse radio altimeter RV-10 (center frequency 440 MHz). Then, for the first time in the practice of geophysical studies of mountain glaciers, measurements were made from a specially equipped all-terrain vehicle GAZ-47 [6]. The antennas (half-wave vibrators with a reflector) were 7.35 m apart and 2.2 m above the snow surface. The reflected signals on the oscilloscope screen were recorded with a camera at 15–30 s intervals. Two closely located profiles along the central axis of the IGAN glacier with a length of about 1110 m were traversed, one of which formed the basis for interpretation of the obtained data (Fig. 1a). Several types of reflected signals from different depths were identified in the obtained records, and the author interpreted them as signals from the glacier bed, internal reflecting horizon (cold and temperate ice separation), and reflections from the bottom moraine in the lower part of the glacier (Fig. 1b). As a result, it was concluded that the IGAN glacier has a three-layer structure: the total ice thickness reaches 150 m in the central part, the upper cold ice layer is 40–50 m thick, and the bottom moraine layer is about 30 m thick [5, 6]. However, by the author's own admission, the explanation of the origin of the reflecting boundaries (between cold and temperate ice, ice and bottom moraine—boundaries IV and V in Fig. 1b) was hypothetical due to the lack of independent confirmation of the results by drilling.

In the 2000s, after a significant gap, studies of the Polar Urals glaciers, in particular the IGAN glacier, were continued. In 2008 and 2018, repeated geodetic measurements of the glacier surface elevation were made using differential GPS receivers. Based on the obtained data, the changes in the area, surface elevation, and mass balance of the glacier over the entire period of instrumental studies were estimated [7, 21]. A high-frequency radar survey of snow cover thickness was conducted on the glacier in 2019 and 2021, and additional radar measurements of ice thickness were made in 2021. The results of these surveys are presented and discussed in this paper.

MEASUREMENT METHODS

In April 2019 and 2021 The Scientific Center for Arctic Research (Salekhard) together with the Institute of Geography of the Russian Academy of Sciences and the Faculty of Geography of the Moscow State University conducted two glaciological expeditions to the IGAN glacier to measure snow accumulation, the data on which are necessary for the subsequent assessment of the glacier mass balance. In addition, one of the tasks was a repeated radar survey of the glacier thickness using modern radar equipment.

Snow Cover

A high-frequency (1600 MHz) Picor-Led radar was used to measure snow accumulation on the glacier. The combined antenna unit of the radar was mounted on plastic sleds. They were moved across the glacier surface by a single operator on skis. Approximately 4 km in 2019 and 5.6 km in 2021 of snow measurement profiles covering the accessible area of the northern, main part of the glacier were acquired. The

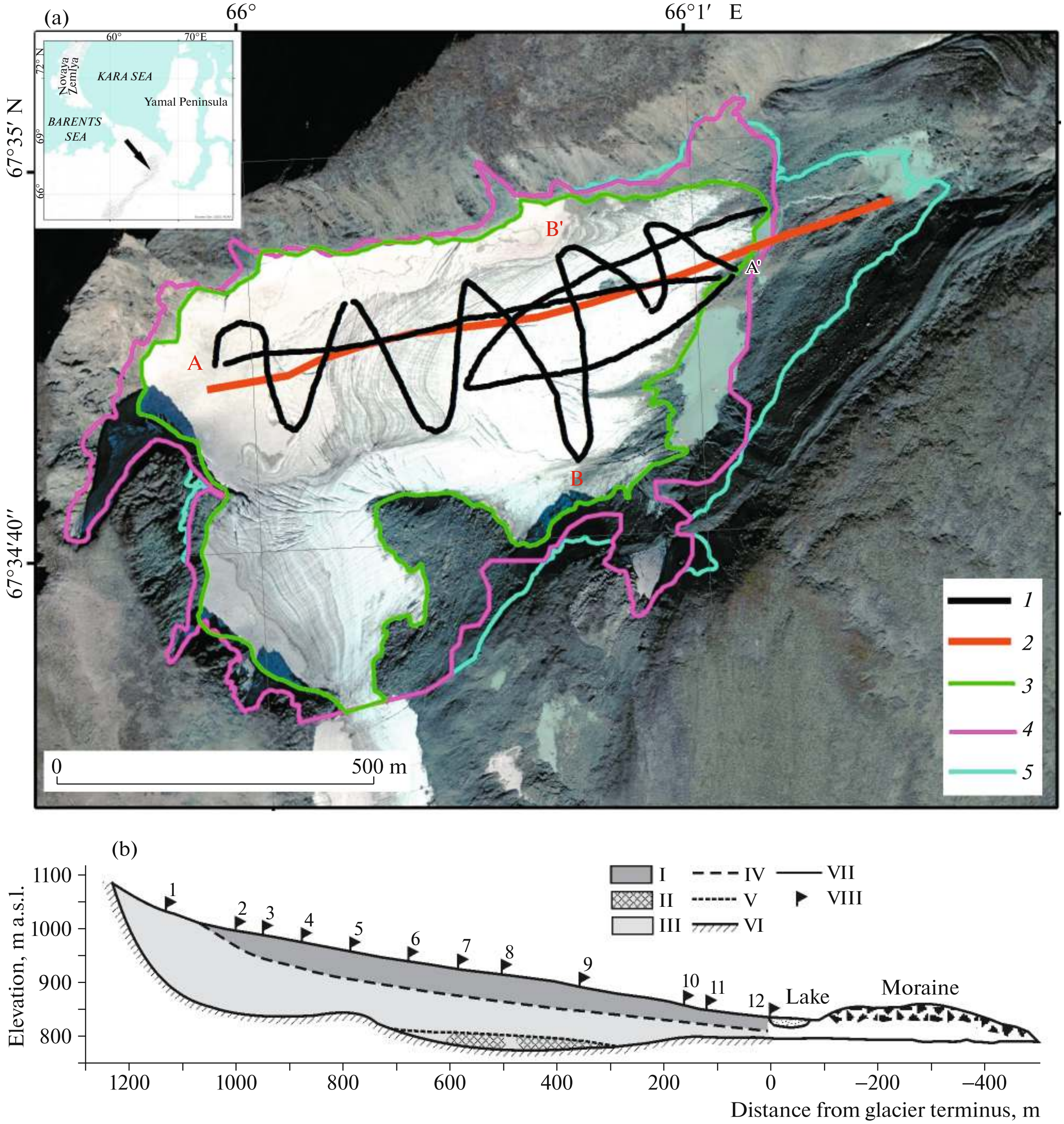

Fig. 1. IGAN Glacier. (a) Radar profiles (*1*, 20 MHz (2021), *2*, 440 MHz (1968) and the glacier outlines in different years (*3*, 2020, *4*, 2008, *5*, 1963); Letters A–A1 and B–B1 show the profiles along which radargrams are shown in Fig. 3. World-View-2 image from Google Earth database, August 2021, was used as a background. (b) Interpretation of the 1968 radar profile: I, cold ice; II, temperate ice; III, basal moraine; IV, boundary between cold and temperate ice; V, boundary between temperate ice and basal moraine; VI, glacier bedrock; VII, glacier surface; VIII – profile pickets [6].

survey dates of April 24, 2019 and April 23, 2021 correspond to the end of the accumulation period. According to HMS "Salekhard" data, the maximum snow accumulation for the winter of 2020/21 was reached by the end of the first decade of April (April 4, 2021) and amounted to 224 mm. If compared with the reanalysis data [11], this value practically coincides with the climatic precipitation record (1991–2020) for this territory for the winter months (the last point on the graph (Fig. 2a)).

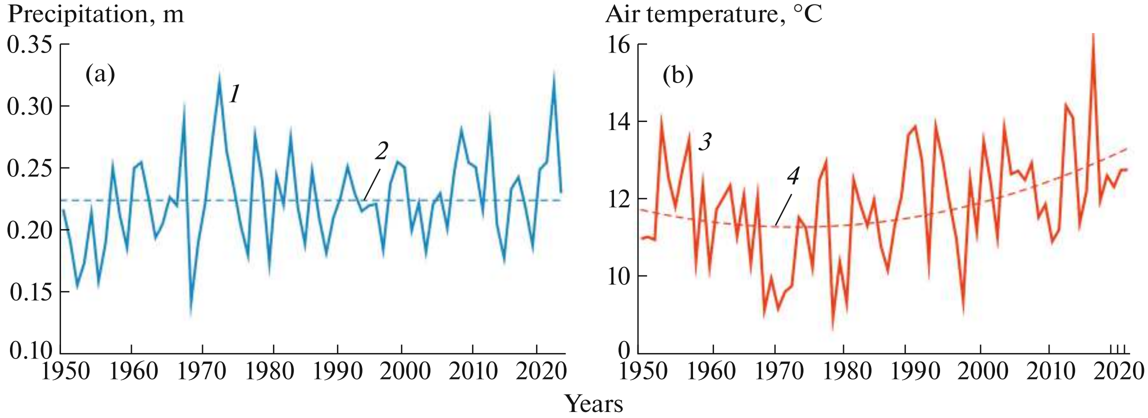

Fig. 2. Changes in the main climatic indicators of the study area in the period 1950–2021. (a) *1*, winter precipitation (m), *2*, the climate normal line of winter precipitation in 1981–2010; (b*) 3,* summer air temperatures (°C) "Salekhard" HMS, *4*, the polynomial trend line of the 2nd order.

The air temperature at the glacier altitude (840–1000 m a.s.l.) remained negative during the days of work, snow melting had not yet started and therefore the conditions for radar survey of the snow strata were favorable. Two pits were dug in the central and lower parts of the glacier down to the ice surface, where the snow structure was described, and its density was measured. The depth of the pit in the central part was 515 cm, the snow density gradually increased with depth from 0.27 to 0.57 g cm^{-3}. On the glacier terminus snow thickness in the pits was less and amounted to 180 cm, and the density varied from 0.28 to 0.46 g cm^{-3} with depth. These data were further used to determine the radio wave propagation velocity in the snow strata (229 m/ns) and to convert travel time of radar signals into snow thickness.

Ice Thickness

For ice thickness measurements we used the 20-MHz VIRL-7 radar [23], previously successfully used for glacier thickness measurements in the archipelagos of the Russian Arctic, the Caucasus, Altai and other mountain systems. Radar components—receiver, transmitter, control unit, GPS, and power supplies—were mounted on two sleds. A Garmin GPS Map64x receiver was used for navigation, and the receiver and transmitter were synchronized via fiber optic cable. The entire construction was moved across the available area of the glacier by the operator on skis: in total, about 4 km of profiles were traversed both along the central axis and across the glacier (Fig. 1a).

Visualization and processing of radar data was performed in the program RadexPro Plus 2011.1 [4]. The processing graph consisted of standard procedures: delay removal, antenna ringing removal (mean subtraction), bandpass filtering, and amplitude correction for spherical divergence. In addition, Stolt-FK migration was also applied to the low-frequency sounding data processing to correct the radar records using Fourier analysis to improve the ice thickness and bedrock geometry by correcting the depth and position of the side reflections. To convert the travel time of electromagnetic signals into thickness, an average velocity equal to 168 m μs^{-1} was taken into account [6]. In Fig. 3 shows typical radargrams obtained on the glacier with a 20 MHz radar.

RESULTS AND DISCUSSION

Snow Cover

Based on the results of radar snow measurements data processing (Figs. 4a, 4b) using ArcGIS software, schemes of snow cover thickness distribution over the glacier surface in 2019 and 2021 were constructed (Figs. 4c, 4d). Interpolation of snow cover thickness data was performed using the Topo to Raster method in ArcGIS 3D Analyst Tools. The glacier accumulation area is limited by steep rock faces, even in winter free of snow, so the snow cover thickness at the line of contact with them was assumed to be zero. In the terminus area, where there is no such framing and snow thickness is low, the data of direct measurements with a probe along the glacier boundary were used. Measurements in the control pits at the intersection of the longitudinal and transverse profiles (Fig. 4a) confirmed the results of the radar survey with an accuracy of 0.1 m. These maps show a general pattern of gradual increase of snow thickness from the glacier terminus to the rear wall of the corrie from 2 to 8 m and more. Such snow distribution for this glacier is due to the significant influence of avalanche nourishment from steep sides in the accumulation area and the predominant north-western transport of precipitation. It can be seen on the maps that despite the similarity and similar range of values, the pattern of accumulation fields in different years may differ depending on the combination of meteorological factors and their inter-

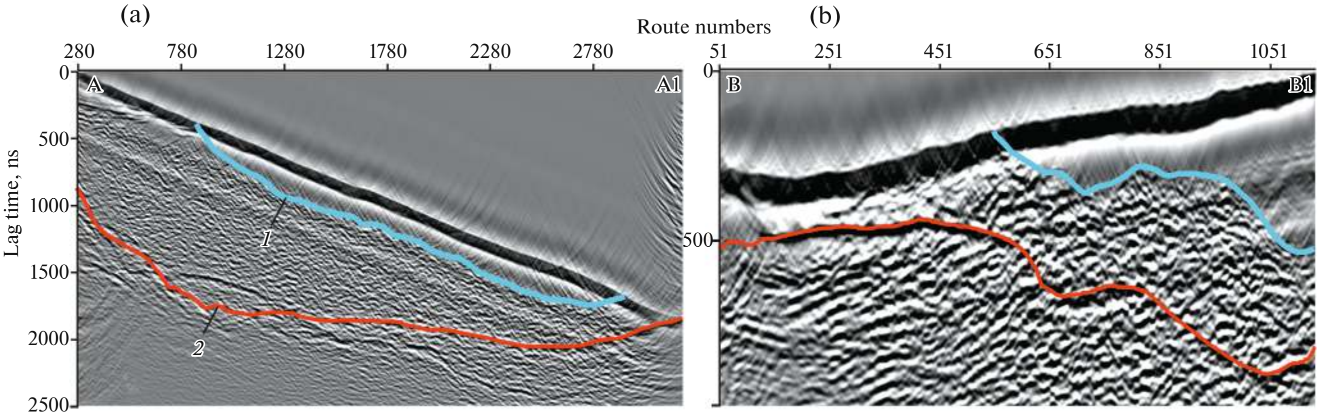

Fig. 3. Radargrams: (a–b) obtained at a frequency of 20 MHz on profiles A–A1 and B–B1 (Fig. 1a); *1*, reflection from the interface between cold and temperate ice; *2*, from the glacier bed.

action with the topography. For example, the depression in the mountainous frame of the rear part of the corrie creates conditions for a powerful jet of air masses formation, which provides increased concentration of snow along the glacier axis and its projection to the surface (Fig. 4d). The trace of this jet, preserved until the end of the 2021 ablation period, is also visible on a photograph taken during the summer expedition in August 2021 (Fig. 4e). This trace is absent on the 2019 map. This is probably due to some deviations from the usual paths of cyclones over the territory of the Polar Urals in the winter period of a given year and, consequently, a different combination of factors affecting the distribution of precipitation in space and time.

Annual observations of the mass balance and photogeodetic monitoring of the glacier boundaries and surface elevation were carried out on the IGAN glacier in the period from 1958 to 1981. According to the observations in these years, the snow thickness in the glacier accumulation area reached 9 m in spring [8]. The results of radar measurements from 2019 to 2021 showed a close value—more than 8.5 m.

After the end of work on the glacier (April 25, 2019), during the return to Labytnangi, measurements of snow thickness and density were made along the 70 km route from the glacier along the valleys of the Syadotayakha and Longot'yogan rivers to the intersection with the route to Bovanenkovo. The results showed that snow thickness and density decrease rapidly with distance from the main watershed. While snow thickness was 1.5–2 m at the head of river valleys, in the piedmont tundra zone it decreased to 0.4 m, and in some places there was no snow at all (0–0.1 m) in flat tundra areas. On the one hand, this confirms the regular distribution of snow cover thickness in the plain, piedmont and mountainous areas of the eastern slope of the Polar Urals, which was determined during the studies of 1957–1963 Polar-Ural glaciological expedition of the Institute of Geography of the Russian Academy of Sciences [8]. On the other hand, the performed measurements showed a good agreement of the obtained values with the results of observations of those years. Thus, the snow cover thickness in the average winter of 1960/61 along a similar route by the neighboring Khadata River valley varied from 164 cm (station at the lake) to 16 cm (at the exit from the piedmont to the tundra).

All this suggests that despite high interannual variability, the general pattern of snow cover distribution for the Polar Urals has changed little since the 1950s. Therefore, the amount of snow accumulation on glaciers (one of the main components of the mass balance) should not have changed significantly during this period either.

However, glaciers continue to shrink. According to the data of HMS "Salekhard" [15], a steady increase in summer air temperatures affecting the intensity of ablation processes has been observed since the middle of the last century (Fig. 2b). They have increased for the last two decades by almost 2°C, and in the last 6 years (2015–2021) annually exceed the climatic norm of 1961–1990, which was 11.2°C. In 1958–1981, during the operation period of HMS "Bolshaya Khadata," a close relationship between air temperatures in the glacial zone of the Polar Urals and the air temperature at HMS "Salekhard" was established (the correlation coefficient between daily temperatures was 0.89) [8]. The data obtained by the automatic weather station "Campbell" working over the IGAN glacier at the top of Mount Kharnaurdy-Keu (1240 m) in 2008–2009 showed that such a relationship persists at present [21]. It follows that for the last two decades the glaciers of the Polar Urals have been in an unfavorable temperature regime, where ablation has become a determining factor in the formation of their mass balance. Estimates made by geodetic method during the period 2008–2018 showed an average annual specific

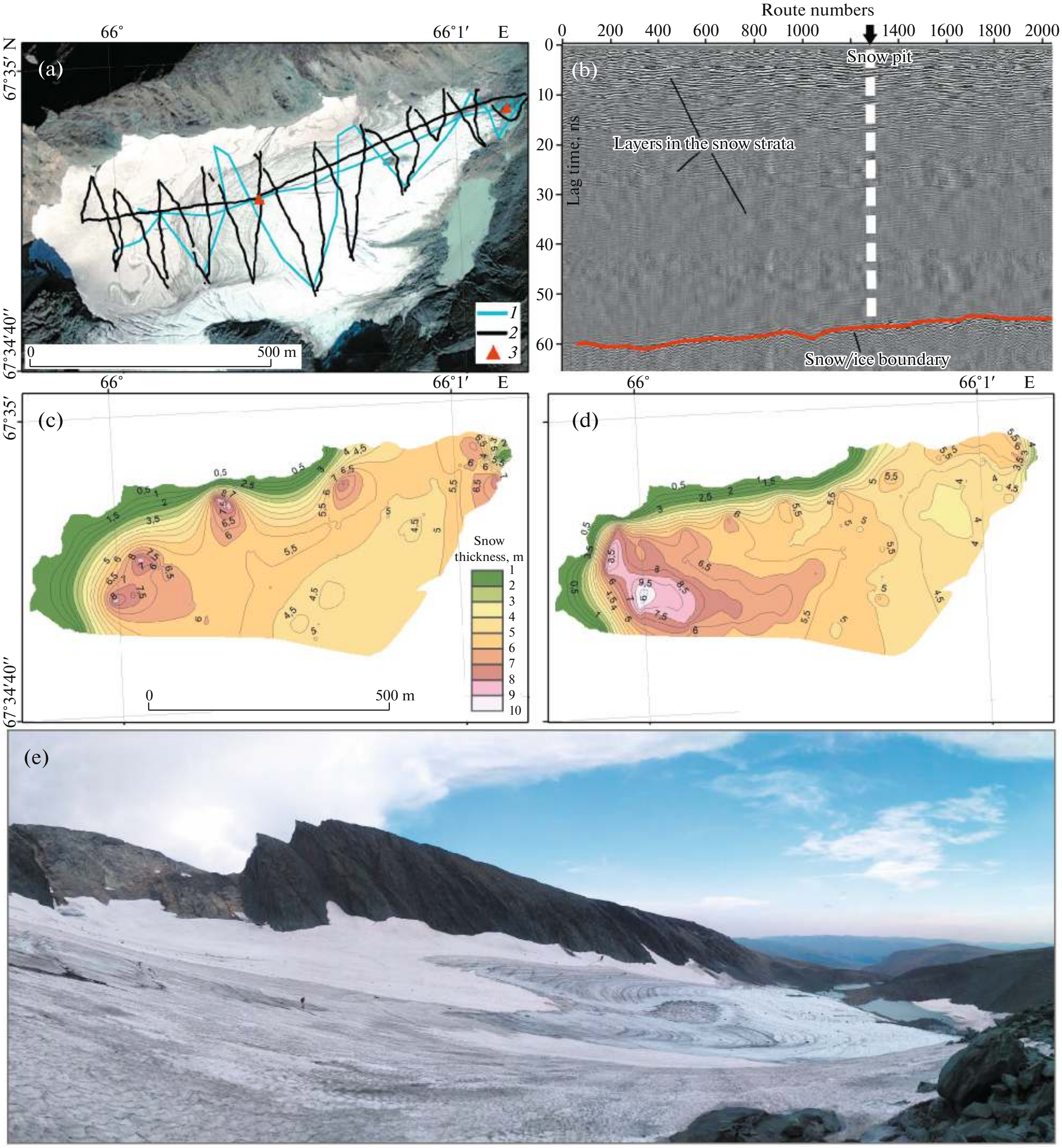

Fig. 4. Results of the snow radar survey on IGAN Glacier: (a) high-frequency (1600 MHz) radar profiles in 2019 (*1*) and 2021 (*2*) and location of snow pits (*3*); (b) typical radar section of the snowpack on the glacier; (c) schemes of snow thickness distribution (accumulation) on the IGAN Glacier in 2019; (d) schemes of snow thickness distribution (accumulation) on the IGAN Glacier in 2021; (e) the IGAN Glacier at the end of the ablation period in 2021 (Photo by A.N. Shein).

mass balance of –336 ± 61 mm w.e. [7]. Compared to 2019, the summer temperatures in 2021 were almost 1°C higher. It can be assumed that the mass balance of the IGAN glacier in 2020–2021 was even more negative. Thus, the main cause of the Polar Urals glacier shrinkage is considered to be a steady increase in summer air temperatures in recent decades.

Ice Thickness and Internal Structure of the Glacier

During the period of instrumental studies from 1963 to 2021, the glacier has undergone significant changes. By 2005, its southern part, located on a gentle section of the Kharnaurdy-Keu mountain slope, had almost disappeared, and therefore modern studies are focused mainly on its northern, corrie-valley part.

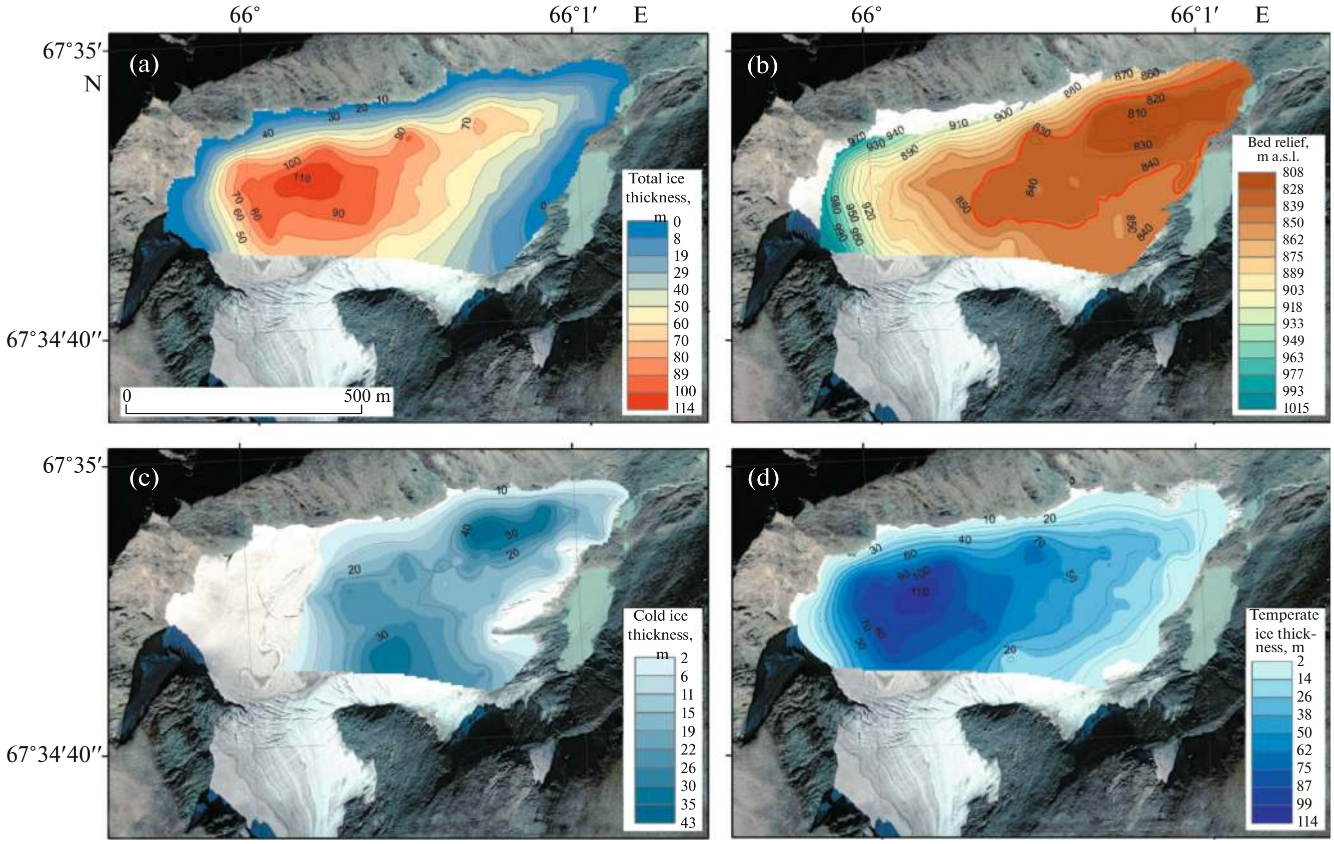

Fig. 5. (a) Total ice thickness, (b) bed topography, (c) cold ice and temperate ice thickness of the IGAN glacier in 2021. The red line on (b) highlights the 840-m contour line (explanation in the text).

The volume of the entire glacier has decreased by 19.7 million m^3 from 1963 to 2018, of which the last decade accounted for 3.2 × 10^6 m^3. Taking into account the area changes that occurred, the cumulative mass balance of the whole glacier for 1963–2018 was –19.06 ± 2.67 mm w.e. The northern part of the glacier lost 22.0 ± 2.51 mm w.e. during this entire period. [7]. Measurements with a low-frequency radar in 2021 showed that the ice thickness reaches 114 m here and averages 49 m. The root-mean-square deviation in the difference of ice thickness at 16 profile intersections amounted to 0.5 m. The average ice thickness at these intersections of 63.2 m gives a standard error of measurements of about 1%. Analysis of the obtained radargrams (Fig. 3) showed that the IGAN glacier has a polythermal structure of the Scandinavian type. The upper cold ice layer with an average thickness of 12 m (maximum values reach 43 m) overlaps the temperate ice with an average thickness of 37 m, reaching a maximum value of 114 m in the upper part of the glacier (Fig. 5). The volume of ice contained in the studied part of the glacier is 14.3 × 10^6 m^3, of which 10.89 × 10^6 m^3 is temperate ice and 3.44 × 10^6 m^3 is cold ice.

It is only possible to speak hypothetically about the presence and thickness of the bottom moraine layer described in [6]. The interference created by the signal re-reflection from the sides on the obtained radargrams (Fig. 3) does not allow us to unambiguously interpret its upper and lower boundaries.

The digital elevation model (DEM) of the glacier bed was used to construct the glacier bed topography scheme, which was created based on the results of DGPS survey conducted by the Scientific Center for Arctic Research of the Yamalo-Nenets Autonomous District in August 2020. The survey was conducted on August 22–24, 2020. At this time of the year, the air temperature in the Polar Urals at the glacier altitude becomes negative. Ice surface velocities of the IGAN glacier are almost zero. Measurements of coordinates and elevations of the glacier surface were carried out using GNSS EFT M2 geodetic equipment (two receivers: one as a base and the other as a rover) in the "Kinematics" mode with reference to historical bases. The distance between 4645 survey points varied from 20 to 60 m, depending on the elevation difference and stability of satellite signal acquisition to obtain a fixed solution. About 80% of the glacier area was surveyed, and the measurement error in elevation did not exceed 12 mm. A DEM of the glacier surface was built using

AutoCAD Civil 3D software based on these data. In the DEM construction process and during interpolation, the accuracy of determining intermediate elevation values decreases and depends on the distance between survey points and surface curvature. On the IGAN glacier, the glacier surface available for survey was relatively flat, without abrupt changes in slope. The distance between survey points ranged from 20 to 60 m, and between profiles 15–20 m. The maximum possible elevation deviation within one interpolation step did not exceed ±1.0 m. Since the ice surface elevation can be considered unchanged during the winter period before the spring radar survey, the bedrock topography within the study area was obtained by subtracting the radar data (ice thickness) from the elevations of this DEM (Fig. 5b).

The bedrock topography scheme shows that approximately 30% of the glacier area (0.09 km^2) is located below the 840 m elevation line. At the same level is the surface of the lake formed in the fold between the right lateral moraine and the glacier in recent years. The first signs of its appearance were discovered by an expedition of the Institute of Geography of the Russian Academy of Sciences in 2005. The surface level and the size of the lake vary throughout the year and depend on both the intensity of glacier melting and the drainage system capacity, which, in turn, is not constant. Direct contact of the lake water with the glacier not only promotes more intensive ice melting along the front line, but also creates preconditions for its spreading along the bedrock under the glacier terminus, which may additionally accelerate the process of its degradation. In the future, if the existing climatic conditions persist, this may lead to the formation of another lake in place of this relatively flat part of the bed and to the retreat of the glacier to higher levels in the rear part of the corrie.

CONCLUSIONS

The results obtained allow us to assess the changes that have occurred with the IGAN glacier from the middle of the last century to the present. Comparison with radar data from 1968 suggests that the glacier's size is shrinking. Measurements in 2021 showed ice thickness reaching 114 m and averaging 49 m. Nevertheless, the glacier still retains a polythermal structure, although the total ice thickness and the thickness of the upper cold layer have also decreased markedly (by about 30%). At present, the volume of the investigated part is 14.3×10^6 m^3 of ice. If we estimate the rate of volume reduction according to the mass balance data—about 3.2×10^6 m^3 has melted over the last decade [7], complete disappearance of the glacier can be expected in 40–50 years if current climate change trends persist. However, this process is nonlinear, as it involves not only climatic factors, but also local terrain features. The steep-walled mountain frame of the glacier accumulation area and the relatively high (among other corrie-valley glaciers of the Polar Urals [8]) altitudinal level of its position should be attributed to such features preventing the glacier from rapid disappearance. Additional avalanche nourishment in combination with blizzard transport provide increased snow concentration on the glacier surface. At the same time, the presence of negative landforms on the bedrock can lead to the formation of glacial lakes and, at some stage, accelerate the process of its shrinkage. A similar situation led to the rapid disappearance of the MGU glacier located 23 km to the north in the area of Maly Shchuchie Lake [7]. For many years this glacier was among the three largest glaciers in the Polar Urals, but over the last two decades its size has been decreasing at a catastrophic rate. One of the main reasons was the formation of a lake on the gentle bottom of the cirque, which contributed to the rapid breakup of the glacier terminus. For the IGAN glacier, based on the gradual increase in the bedrock topography elevation (Fig. 5b), such a scenario is less likely, although the process of its reduction may be non-uniform.

As the terminus retreats to higher levels and the ablation area shrinks, its contribution to the glacier mass balance will decrease, and it is possible that at some point the balance will become close to zero. Accordingly, the rate of change of the glacier size will slow down significantly and it will be able to remain in such a state for an indefinitely long time. Further development of the situation will depend on which of the possible scenarios of climate change will be realized in the future. In any case, the results obtained in this study will contribute to the understanding of the glacier's reaction to the ongoing changes.

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CONFLICT OF INTEREST

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

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