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# Glaciers of the Koryak Highlands: assessment of the state using satellite images and field studies

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**Abstract.** The Koryak Highlands are a poorly explored area in terms of glaciation and its connection to climate. The purpose of this work is, using Sentinel-2 images (2019), to assess the state of glaciers at present against the background of climatic trends. Spatial patterns of trends of mean summer and annual temperatures, total precipitation and precipitation for the cold period from 1966 to 2019 were compiled: the temperature trends increase towards the Kamchatka Peninsula, and the mean summer temperature trends increase from 2 to 3°C. Precipitation trends increase from the continent to the coastal zone, with cold season trends changing from 0 to minus 50 mm. As a result, 212 glaciers and 279 rock glaciers were discovered in the Highlands, whereas 112 objects that had previously been recognised were not identified: either there is no glacier, or its area is less than 0.001 km$^2$. The reduction in glacier areas compared to the USSR Glacier Inventory (1960s) varies widely by river basin, from 35 to 74%. The mean present glacier area varies from basin to basin from 0.4 to 0.11 km$^2$. The glaciers are mainly corrie type of the N, NE and NW aspects. The change of average glacier firn line is from several tens of metres to 400–500 m.

**Key words:**
Koryak Highlands,
glacier,
satellite images,
temperature precipitation trends,
rock glacier

## Introduction

The glaciers of the Koryak Highlands, which are located in the north-east of the Asian part of Russia, on the Bering Sea coast between Anadyr Bay and the Kamchatka Peninsula, are now preserved in the bottoms of circuses and troughs. In recent decades, in the north of Siberia and the Far East, due to climate change, mountain glaciers, both small and medium-sized (Takahashi et al. 2011) are intensively melting; small forms of glaciation are especially susceptible to change (Ananicheva et al. 2019; Ananicheva and Kononov 2020). The term “Small Forms of Glaciation (SFG)” includes small glaciers themselves, perennial snow patches with an ice core, and snow patches that persist throughout the year. This term can denote a set of properties, such as: small size, the presence of ice and firn, weak separation of accumulation and ablation areas, etc. Such glaciers are characteristic of neighbouring Chukotka and Kolyma (Ananicheva et al. 2020). SGFs are also spread across the South Island of Novaya Zemlya, the Subpolar and Polar Urals (Kononov et al. 2005) and the Putorana Plateau. Such glaciers are quite sensitive to changes in local/regional climate.

In this work, the emphasis is on glaciers with open ice found on the Sentinel-2 images of 2019.

The areas of most of the Koryak glaciers are from 0.3 to 0.5 km$^2$. If we assume that small glaciers are those of 0.1 km$^2$ or less, then there are 84 small glaciers among those found in the 2019 images (see the Results section). The location of glaciers in the Koryak Highlands is characterised by two types: there are glaciers concentrated in large groups on the slopes of the highest mountain ranges, and small corrie and hanging glaciers lying in isolated groups far from each other (Catalogue 1982).

The Koryak Highlands are not a well studied area; therefore, the estimation of changes in the size of glaciers using satellite images and verification of these data in situ seems to be extremely relevant.

The USSR glacier inventory for the Koryak Highlands was compiled at the Institute of Geography of the USSR Academy of Sciences according to maps of the 1952 edition. Aerial photographs were deciphered and glacier contours and surface features were transferred onto a topographic map by N.M. Svatkov. In the summer of 1961, he carried out detailed surveys of the glaciers around Mount Ledyanaya, the highest point of the Koryak Highlands, and in 1963 presented a description of the glaciers of the Malinovsky Range (now the Pylginsky Ridge) (Catalogue…1982).

The Koryak Highlands ranges were studied in the 1950s by A.P. Vaskovsky, a researcher of the north-east of Russia, who provided data on 461 glaciers with a total area of 185 km$^2$ (including snow patches) from aerial photographs and maps (Catalogue 1982; Vaskovsky 1955). A few years later, M.I. Malykh, after a thorough analysis of maps and aerial photographs, determined the size of the glaciers of the Koryak Highlands between 60 and 63° N and 166.5 and 176.5° E. He indicated the existence of 282 glaciers here with an area of 180 km$^2$ (Catalogue 1982).

After the study related to the compiling of the Inventory, researchers came to the Koryak Highlands only in the 1990s. They studied various geomorphological objects, among which were rock glaciers (Galanin 2005, 2009). The author of this paper provided the map of rock glacier extent in this region. Ananicheva (2012), for the first time since the 1960s, determined the areas and number of existing glaciers of the Koryak Highlands using satellite images from 2003 (data from the Landsat and Terra satellites were used in the study: images of TM and ETM + and ASTER). At that time, 237 glaciers were found in the Koryak Highlands, and these had a much smaller area in comparison with the Inventory data. Glacier area according to the 2003 images is 54.4 km$^2$.

The large difference between the number of glaciers in the Inventory and those found on the photographs could be explained by the fact that N.M. Svatkov was able to attribute rock glaciers to glaciers, since he worked with topographic maps compiled by other researchers during the surveys of 1950s.

In September 2020, an expedition was carried out to the southern part of the Koryak Highlands, to the glaciers of the Pylginsky Range (Goven Peninsula) to assess the state of glaciers, compare the obtained data with satellite images and earlier studies, and take samples for dating by cosmogenic elements and OSL method (Optically Stimulated Luminescent dating). This study aims to determine the number, area and specific elevations of the glaciers of the Koryak Highlands. We used sufficiently high-resolution Sentinel-2 images (Sentinel-2 is an Earth observation mission from the Copernicus Programme that systematically acquires optical imagery at high spatial resolution (10 m to 60 m) over land and coastal waters) to compare with previously obtained estimates and validate the results by the fieldwork. Another task was to assess the trends in climate change against which the glaciers of the Highlands have been developed in recent decades. Also in this paper, some preliminary results of the expedition in the Koryak Highlands are presented.

In the USSR Glacier Inventory, the glacier groups were identified by their attribution to river

Table 1. Data of the Koryak Highlands glaciers from the USSR Glacier Inventory, (Catalogue…1982)

| Authors | Number of glaciers >0.1 km$^2$; their area | Number of glaciers <0.1 km$^2$; their area | Accuracy of glacier area | ELA (firn) line assessment, m a.s.l. |
|---|---|---|---|---|
| Nikolay M. Svatkov | 715<br>233.1 | 620<br>~27 | 0.1 km$^2$ | By Kurovsky method (500–1600) |

basins and were named after rivers or watershed areas between the ridges (Fig. 1).

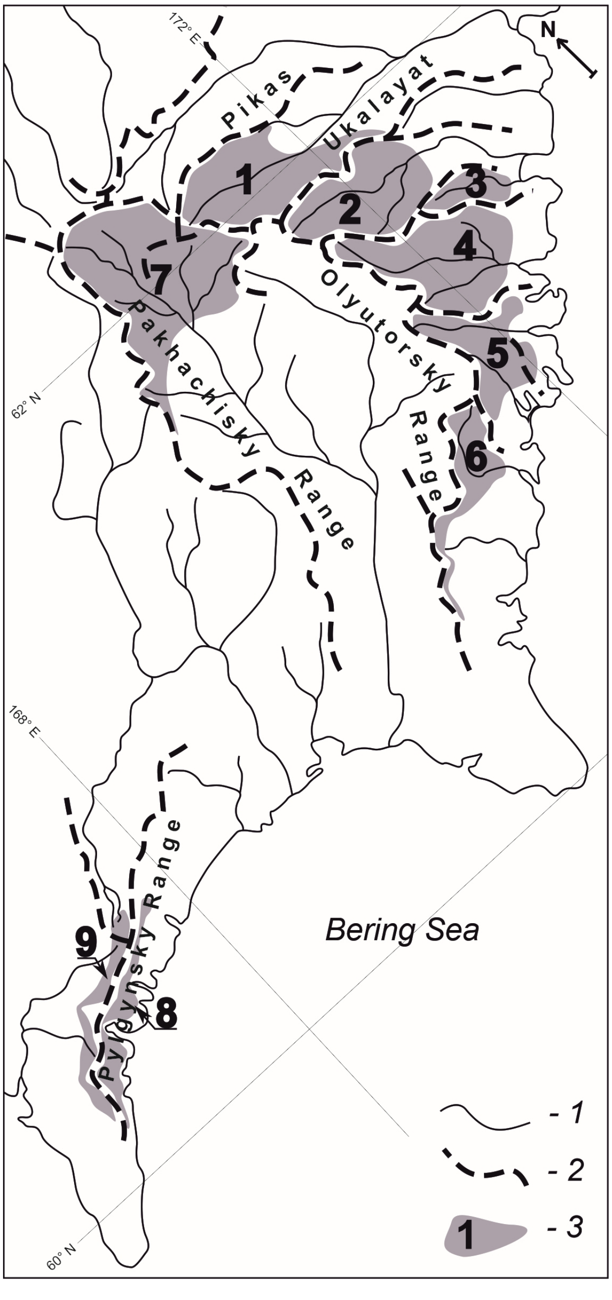


Fig. 1. Schematic map of the Koryak Highlands: 1 - rivers, 2 - watersheds, 3 - glacier areas. The numbers (3) indicate glacier regions within river basins: 1 - between Pikas-Ukalayat ranges, 2 - between Ukalayat-Snegovoy ranges 3 - Ilpi-Imolkanavayam rivers, 4 - Vatyna River, 5 - Anivayam River – Machevna Bay, 6 - Machevna – Apuka River, 7 - Apukavayam River, 8 - Pylgovayam River – Olyutorsky Bay, 9 - Korf Bay

## Characteristics of the orography and climate of the region

The Koryak Highlands extend about 800 km from north-west to south-east; the width is from 80 to 250 km. The elevation of the ridges, as a rule, does not exceed 1500–1800 m, increasing from the outskirts to the centre of the Highlands. Also, the mountain elevations generally decrease from north to south. In the central part, there is Ledyanaya Mountain (2,562 m a.s.l.), the highest point of the Highlands. Several ranges branch off from Mount Ledyanaya – Pikas, Ukalayat, Snegovoy. The main centre of glaciation is located here. The Olyutorsky Range stretches along the coast of the Bering Sea. In the southern part is the Pylginsky Range (the former name is the Malinovsky Range). In the north-eastern part of the Koryak Highlands, there is the Meynypilgyn Range.

Despite their low absolute height, the mountain ranges have a sharply dissected relief of Alpine type. Typical landforms are sharp-pointed ridges, steep slopes covered with moving screes, deep gorges and depressions, as well as trough valleys (Osipova, Electronic resource)

The Koryak Highlands are one of the youngest folded structures in Russia and are entirely part of the Cenozoic folding zone, where folding processes took place in the Neogene and Quaternary. The present relief is formed as a result of the dissection of uneven-aged and uneven-height surfaces of the levelling. Its appearance was significantly modified by the Pleistocene glaciation, which developed steep-slope circuses, depressions with blue lakes and jagged ridges (Gvozdetsky and Mikhailov 1978).

The climate is monsoon, and winter is not very cold, but long-lasting – 7–8 months; mean temperatures for 1966–2020 are from -19.5 to -8.8°C (determined by Markovo, Yamsk-Brokhovo, Kamenskoye, Apuka weather stations).

The glaciers of the Koryak Highlands are fed from the Bering Sea and the Pacific Ocean air masses. The Pacific cyclone brings heavy rainfall in the first half of winter. Annual precipitation is over 700 mm on the south-eastern slope, and 400 mm on the north-western one. Snow does not melt during the year at altitudes above 1,400 m a.s.l. on the northern slopes and 1,980 m a.s.l. on the southern slopes (Catalogue 1982).

The position of the Siberian Anticyclone also influences the solid precipitation rate. Forecasters know the role of orography in the displacement of anticyclones across Central Asia to Siberia: anticyclones are already sharply increasing over Kazakhstan (in winter). It is known that the movement of anticyclones along the "Kara" axis is accompanied by a strong "swelling" of the Siberian Anticyclone over the entire territory of Eurasia (Egorina 2015). Thus, the Koryak Highlands receive more precipitation due to the penetration of cyclones from the south-east of Eurasia.

## Data and methods

Based on Sentinel-2 images from 2018 and 2019, the glaciers of the Koryak Highlands located by a large group of its northern part and a smaller group of the southern part were analysed.

Sentinel-2A/2B images were used to decipher the glaciers. The Sentinel-2 data is provided by the European Space Agency (ESA) to users free of charge (https://scihub.copernicus.eu). The images used are listed in Table 2. We used the Arctic DEM v.3.0 mosaic with a spatial resolution of 2 m (https://www.pgc.umn.edu/data/arcticdem, data archive as of 17–24.07.2018; Porter et al. 2018.)

The list of used Arctic DEM scenes is: 65_21_10m_v3.0_reg_dem, 65_22_10m_v3.0_reg_dem, 65_23_10m_v3.0_reg_dem, 66_21_10m_v3.0_reg_dem, 66_22_10m_v3.0_reg_dem, 66_23_10m_v3.0_reg_dem, 67_21_10m_v3.0_reg_dem, 67_22_10m_v3.0_reg_dem, 67_23_10m_v3.0_reg_dem, 68_23_10m_v3.0_reg_dem, 69_23_10m_v3.0_reg_dem.

All glaciers of the Koryak Highlands were deciphered manually at the end of the 2019 ablation period, using infrared RGB synthesis.

The glacier boundaries were drawn in the spectral range 8:4:3 with a spatial resolution of 10 m. The spectral range of channels 11:8:4/3 in which channel 11 has a resolution of 20 m was used for better interpretation and to check the interpretation of the ice-snow-moraine surface. To refine the boundaries of the glaciers, highly detailed satellite images from the ArcGIS base map were used. The contouring was carried out in the ArcGIS program, WGS 1984 UTM Zone 59N projection. Vectorisation was carried out on a scale of 1:10,000.

The deciphering was made more difficult by clouds, seasonal snow cover remaining on the shady slopes, debris of some glaciers, and shadows from the slopes (being inevitable at the end of summer). To clarify the boundaries of the glaciers (especially the upper snow-covered areas), highly detailed images from Esri, Here, Google and Bing, from open sources, were used. Highly detailed images of the coatings were taken, as a rule, before 2019, so the most actively changing tongues of glaciers were deciphered from the Sentinel images of 2019. Sentinel-2 imagery from the end of the 2018 ablation period was used for glaciers in shadow or under seasonal snow cover and the July 2018–2019 imagery. The more data for the same place, the more accurately it is possible to decipher the upper boundary of the glacier, to separate snow patches from glaciers. The elevations of the lower and upper points of the glaciers were determined using the mosaic of the digital elevation model 2016–2018, Arctic DEM 3.0 with a spatial resolution of 2 m.

The Sentinel-2A/2B spacecraft is equipped with an optoelectronic multispectral sensor (MSI) that captures images in 13 spectral channels from the visible and near-infrared (VNIR) to the short-wave infrared range spectrum (SWIR). The spatial resolution of the main channels (three visible and one near-infrared) is 10 m, which makes it possible to decipher the surface of open ice, frozen areas of glaciers, and rock glaciers. The satellites of the Sentinel-2 imaging system have a high spectral resolution, a significant swath (290 km) and – very importantly – a high frequency of filming, that is, the same area is filmed every few days to obtain scenes with minimal cloudiness. Sentinel level 2A data is currently available to users, and it has undergone atmospheric correction, making the terrain clearer.

The optimal time for decoding glaciers for this area is August 10–20, by images of different years. Previously, a large amount of seasonal snow made it impossible to determine the glacier contours correctly. After August 20, excessively large shadows from the mountain ranges can hamper deciphering, and later, on September 5, fresh snow falls. This

Table 2. List of used satellite images of Sentinel 2A/B

| ID | Tile | Date |
|---|---|---|
| L1C_T59VMJ_A016458_20180817T000610 | T59VMJ | 17: 08:2018 |
| L1C_T59VNJ_A016458_20180817T000610 | T59VNJ | 17: 08:2018 |
| L1C_T60VUP_A016458_20180817T000610 | T60VUP | 17: 08:2018 |
| L1C_T59VMH_A016458_20180817T000610 | T59VMH | 17: 08:2018 |
| L1C_T59VNH_A016458_20180817T000610 | T59VNH | 17: 08:2018 |
| L1C_T59VMK_A007764_20180901T000601 | T59VMK | 01:09:2018 |
| L1C_T59VMJ_A007764_20180901T000601 | T59VMJ | 01:09:2018 |
| L1C_T59VNJ_A007764_20180901T000601 | T59VNJ | 01:09:2018 |
| L1C_T59VPJ_A007764_20180901T000601 | T59VPJ | 01:09:2018 |
| L1C_T59VLH_A007764_20180901T000601 | T59VLH | 01:09:2018 |
| L1C_T59VMH_A007764_20180901T000601 | T59VMH | 01:09:2018 |
| L1C_T59VNH_A007764_20180901T000601 | T59VNH | 01:09:2018 |
| L1C_T59VMG_A007764_20180901T000601 | T59VMG | 01:09:2018 |
| L1C_T58VEN_A012569_20190803T002615 | T58VEN | 03:08:2019 |
| L1C_T58VFN_A012569_20190803T002615 | T58VFN | 03:08:2019 |
| L1C_T58VEM_A012569_20190803T002615 | T58VEM | 03:08:2019 |
| L1C_T59VMJ_A012626_20190807T000618 | T59VMJ | 07:08:2019 |
| L1C_T59VNJ_A012626_20190807T000618 | T59VNJ | 07:08:2019 |
| L1C_T59VMH_A012626_20190807T000618 | T59VMH | 07:08:2019 |
| L1C_T59VNH_A012626_20190807T000618 | T59VNH | 07:08:2019 |
| L1C_T58VEN_A012755_20190815T003611 | T58VEN | 15:08:2019 |
| L1C_T58VFN_A012755_20190815T003611 | T58VFN | 15:08:2019 |
| L1C_T58VEM_A012755_20190815T003611 | T58VEM | 15:08:2019 |
| L1C_T58VEM_A012755_20190815T003611 | T58VFM | 15:08:2019 |
| L1C_T59VNJ_A021706_20190818T235618 | T59VNJ | 18:08:2019 |
| L1C_T59VNH_A021706_20190818T235618 | T59VNH | 18:08:2019 |
| L1C_T58VEN_A012812_20190820T001615 | T58VEN | 18:08:2019 |
| L1C_T59VLH_A012812_20190820T001615 | T59VLH | 18:08:2019 |
| L1C_T59VMH_A012812_20190820T001615 | T59VMH | 20:08:2019 |
| L1C_T58VEM_A012812_20190820T001615 | T58VEM | 20:08:2019 |
| L1C_T59VMJ_A021749_20190822T000613 | T59VMJ | 22:08:2019 |
| L1C_T59VNJ_A021749_20190822T000613 | T59VNJ | 22:08:2019 |
| L1C_T59VMH_A021749_20190822T000613 | T59VMH | 22:08:2019 |
| L1C_T59VNH_A021749_20190822T000613 | T59VNH | 22:08:2019 |
| L1C_T59VMG_A021749_20190822T000613 | T59VMG | 22:08:2019 |
| L1C_T58VEN_A021935_20190904T001609 | T58VEN | 04:09:2019 |
| L1C_T58VFN_A021935_20190904T001609 | T58VFN | 04:09:2019 |
| L1C_T59VMJ _A021935_20190904T001609 | T59VMJ | 04:09:2019 |

Source: own elaboration

window can change by several days from year to year depending on summer air temperatures, the solid precipitation amount accumulated during the previous cold season, cloudiness and other factors. In our study, we used Sentinel-2 images from August 3, 7, 15, 18, 20, 22 and September 4, 2019, as well as August 17 and September 1, 2018 (See Table 2). This number of images allowed us to exclude cloud and shadow effects. On the Sentinel-2 images, which show open ice and moraines, the degree of debris coverage is not significant; glaciers with an area of more than 0.1 km$^2$ are easily deciphered.

At the beginning of the work, the Sentinel-2 images of 2018, the latest images available at that time, were deciphered in order to determine the glaciological and other characteristics of the Koryak

Highland glaciers, such as their area, firn line altitude, elevations and changes thereof. Not all of them were ideal for delineating glaciers, due to the weather conditions that year.

In 2019, the situation happened to be better for image survey of this region due to the weather conditions and the absence of early autumn snowfall. The presence of a highly detailed substrate became a key factor in determining the size of small glaciers of less than 0.1 $km^2$.

In 2020, an expedition was conducted to the glaciers of the southern part of the Koryak Highlands, in order, among other things, to check the area estimates obtained from satellite images on the ground and obtain the altitude positions of glaciers by DEM.

When analysing space images of Sentinel-2 in 2018, three groups of objects were identified: glaciers with open ice (type 3), glaciers covered with a debris cover (type 2), and objects possibly related to rock glaciers (type 1). Due to the large extent of the glaciers' coverage by debris cover, there was uncertainty regarding the accuracy of interpreting their sizes; therefore, the glacier area (Sled, Table 3) and their confidence interval were determined.

The temperature and precipitation trends (linear) were determined by the regression equations for the series of these parameters with the accepted error intervals of ±0.1 °C for temperature and ±5 mm for precipitation. The meteorological parameters were taken from the VNIGMI-MCD database (Bulygina et al. Two electronic recourses, no specific year)

The equilibrium line altitude (ELA) was calculated using the simplified Kurowsky method for all glaciers (Kalesnik 1963). The estimates for this parameter are determined with an error of 5 to 15% (Ananicheva et al. 2010). Applying the method of Kurowsky (Braithwaite 2015), we obtain the long-term average ELA for the period of its reduction. During the advance of the glacier, errors due to the assumption of stationarity and linearity of ablation have the same sign (i.e., they add up), and during periods of glacier reduction they have the opposite sign (i.e., they compensate each other) (Zverkova et al. 1982). However, the glacier ELA should be considered as firn line under the modern climate conditions of the Koryak Highlands.

Orthophotomaps and DEM were compiled in the Metashape software, images from the DJIMavic 2 Pro UAV were used, and the survey height was 400–500 metres.

The snow boundary values from aerial photographs of glaciers taken from the UAV during the expedition showed a small difference between the snow boundary and the firn line: calculated by the Kurowsky method, it does not exceed 3%. The average relative difference between these values was also minimal, at 2.0±0.2%. We then averaged firn line altitude over groups of glaciers within the identified basins. The images can also decipher the snow boundary at the end of the ablation period. Therefore, to check the applicability of this method, we also measured the snow boundary altitude for the 50 largest glaciers (areas from 0.29 to 3.36 $km^2$) using the Kurowsky method.

During field works on the Pylginsky Range glaciers in the southern part of the Koryak Highlands (the glaciers of this part were studied earlier [Svatkov 1965]), four glaciers were surveyed by UAV, with spatial data processed as mentioned above. We also made a field identification of glacier contours in the valley of the Ev'vayam River (over 30 km) and the watershed part of the range.

## Results and discussion

### Trends in air temperature and precipitation

The glaciers' current state is influenced by a high degree of climate change. Therefore, an assessment of the general tendencies of variations in climatic parameters important for glaciers was made. For that, trend maps of annual ($T_{year}$) and mean summer temperatures ($T_{sum}$) as well as total precipitation ($P_{year}$), precipitation of the cold period ($P_{cold\ season}$, when temperatures were steadily lower zero throughout the month), and precipitation of the warm period ($P_{warm\ season}$, during the rest of the months) were compiled. They are based on available data of weather stations. The period used was from 1966 (when the indicators of precipitation gauges at the northern stations of the Russian Federation were corrected) to 2019. The trends are significant, based on the Student criterion. In modern statistical software packages, the significance of the trend is determined directly by evaluating the *p* – level regression coefficient *α*.

Fragments of the schematic maps previously published in Ananicheva and Kononov (2020) show that $T_{year}$ trends grow from 2.5 to 3.0 °C towards the Kamchatka Peninsula, and $T_{sum}$ changes from 1.5 to 3.0°C for 1966–2019 (Fig. 2a and b). $P_{year}$ trends increase from zero in coastal areas to +100 mm inland, and the same direction is observed in $P_{warm\ season}$, whereas negative trends are typical for $P_{cold\ season}$ – from zero to -50 mm (Fig. 2c–e).

The mean annual and mean summer temperature trends over the last ten years (2010–2020) change as follows: the $T_{year}$ trend is higher than the $T_{sum}$ trend. The closer to the Arctic latitudes, the more significant the trend, which might be due to more intensive Arctic warming (Arctic amplification). The variations over the years $T_{sum}$ and $P_{cold\ season}$ (critical parameters associated with ablation and accumulation, respectively) were analysed by weather stations' records to assess the climate effect on glacier changes.

So, according to the Apuka weather station, (coastal: 60.4° N, 169.6° E, see Fig. 2), warming in summer in this area has been going on since the beginning of the 1970s, with an increase in $T_{sum}$ of 2.5 °C since then, while $P_{cold\ season}$ decreased with a trend of 70 mm per 49 years. Precipitation decreases on average over the year and in the cold season: 1950–70 $P_{year}$, $P_{cold\ season}$, $P_{warm}$ season being 539, 346 and 193 mm, respectively, and in 1971–2020 being 480, 278, and 203 mm, respectively.

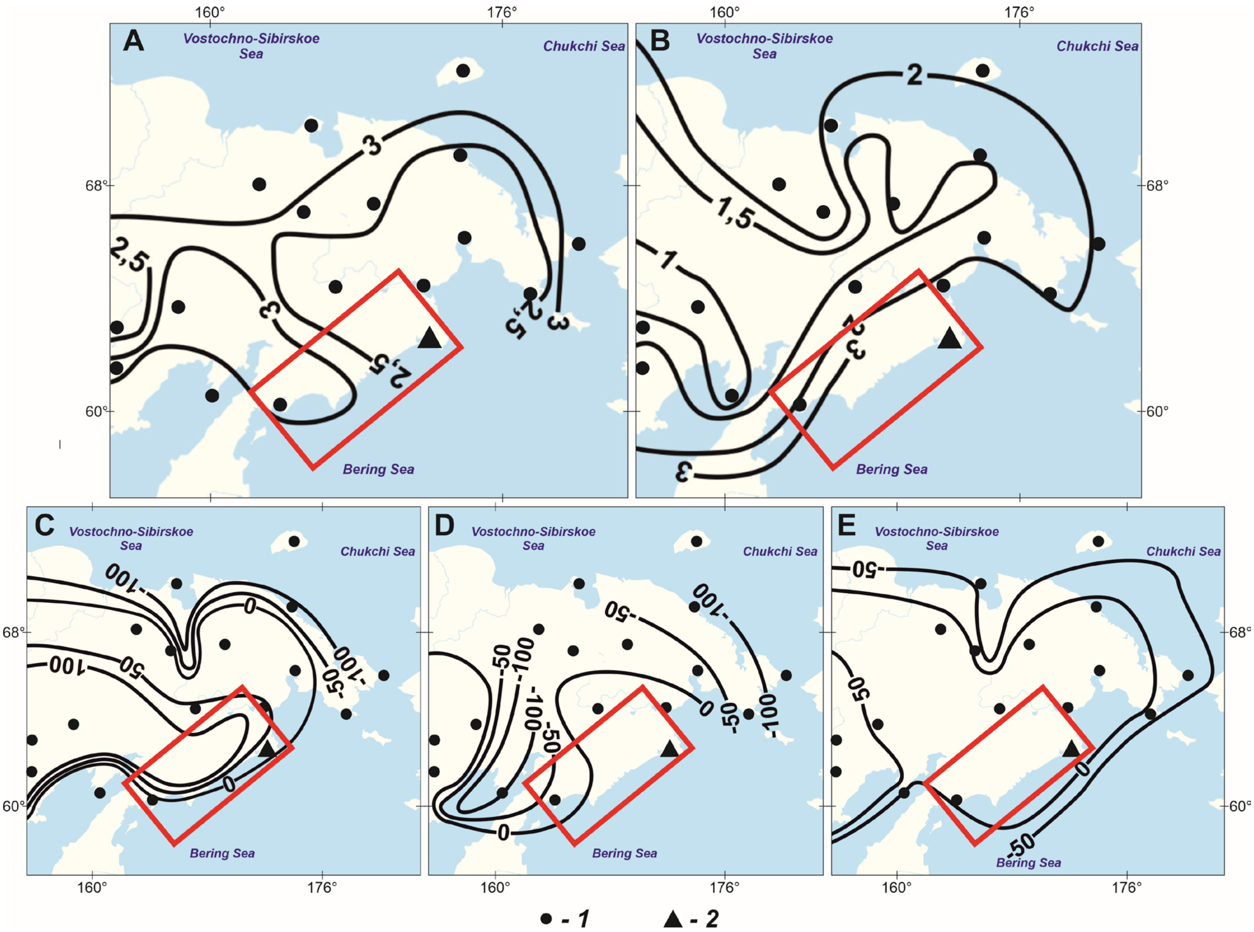


Fig. 2. Koryak Highlands. Trends for the period 1966–2019: (A) of mean annual temperature [°C]; (B) mean summer temperature [°C]; (C) of annual precipitation sum [mm]; (D) cold-period precipitation [mm]; (E) warm-period precipitation [mm]. 1 - locations of weather stations, fragments taken from maps in (Ananicheva and Kononov 2020), 2 - Apuka weather station, given in this paper

## Change in glacier geometry by Sentinel-2, 2018

The mean area decrease of glaciers with open ice (type 3) since the time indicated in the USSR Glacier Inventory for the northern part was 0.42–0.35 km$^2$, for the southern part 0.42–0.40 km$^2$, for glaciers of the second type – 0.18–0.13 km$^2$ and 0.15–0.13 km$^2$, and type 1 (rock glaciers) – 0.9– 0.7 and 0.5–0.4 km$^2$, respectively. The latter is possibly related to overestimating the area of objects covered with debris, which the Inventory's author mistook for glaciers (they were covered with snow). The confidence interval for determining the glacier area is 0.10±0.05 km$^2$.

Glacier reduction was analysed with respect to aspect: most are characterised by N, NE or NW aspects. Glaciers facing north decreased by 0.43–0.33 km$^2$, while glaciers of other aspects (noticeably fewer) decreased by 0.35–0.30 km$^2$. These trends are consistent with climatic conditions – a trend towards greater increases in summer temperatures and a decrease in solid precipitation from north to south at these latitudes (Fig. 2 a–d). The firn line altitudes in the northern part of the Koryak Highlands are on average 1,020 m a.s.l., while for the southern part they are on average 985 m a.s.l., and objects of other aspects are above 995 m. Compared to the Inventory data, they had risen by 2018 from 100 to 300 m.

## Change of glacier geometry by Sentinel-2, 2019

Further, we were able to obtain more accurate estimates (thanks to the Sentinel-2, 2019 images and the highly detailed substrate), which differ from the results of the 2018 survey. When decoding the Sentinel-2, 2019 images, we had already determined the disappeared glacial formations (112 glaciers and rock glaciers) and they were not taken into account. For basins, such as the area between the Ukalayat and Snegovoy ranges and the basins of the Ilpi and Vatyna rivers and the Apukawayam River, the glacier area reductions between the Inventory and the data for the 2018 Sentinel-2 images differ significantly from those between the Inventory and the 2019 images (Fig. 3, columns 2 and 3). These

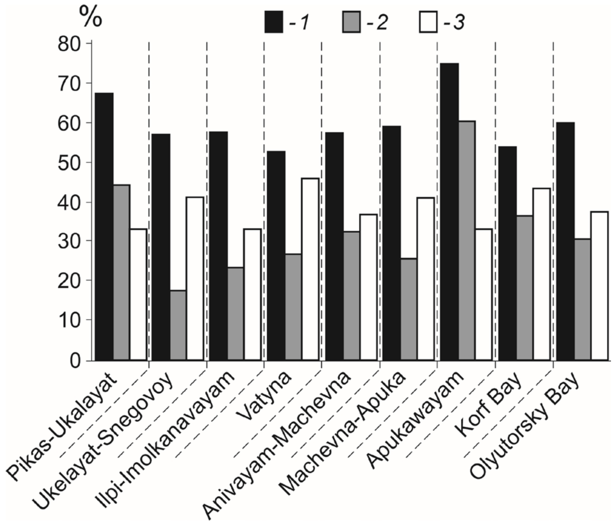


Fig. 3. Reduction in glacier areas in the Koryak Highlands [%]: (1) from the Inventory (the 1960s) to 2019; (2) reduction [in %] in total area of glacial objects (glaciers and supposed rock glaciers) between Sentinel-2 (2018) and the 1960s; and (3) the same objects, (by Sentinel-2, 2019) [%]

basins are characterised by the largest number of glacial objects covered with detrital material with hard-to-define contours, and small glaciers (<0.1 km$^2$) are more widespread in these areas.

Next, we will focus on the analysis of 2019 images. When analysing them, 212 glaciers were found. Their contours are well deciphered: open ice and various types of moraines are visible in the images, and the degree of coverage of debris material is not large.

Compared with the Inventory estimates, the area of these glaciers $D_{led}$ (%) was reduced for different basins from 35 to 74% (Fig. 3, column 1). The Inventory of glaciers on the Koryak Highlands was compiled according to topographic maps and aerial photography. The number of glaciers is almost 2.5 times more than that found by the satellite images. Many rock glaciers were mistaken for "living" glaciers.

We tried to reassess possible overestimating of glacier areas in the USSR Glacier Inventory for this region, based on the fact that its author, N.M. Svatkov, studied several glaciers around Ledyanaya Mountain during his field works (Svatkov and Tsvetkov 1965). Among the glaciers he observed to have a relatively large area (1.5–2.0 km$^2$), the reduction by 2019 amounted to between 45 and

55%. These values can be considered more realistic for glaciers of this size.

We have compared orthophotomaps of glaciers made from aerial photographs from UAVs during the expedition with satellite images for four glaciers: Nos. 678, 679, 680 and 685 (the numbers are given according to the USSR Glacier Inventory). The difference in area is from 2 to 12%.

The total glacier area of the studied region is 49.59 km$^2$. The glaciation area by basin is given in Table 3 and the mean glacier area in Table 4. It does not exceed 0.4 km$^2$ for all groups. The largest mean glacier area belongs to basins 1, 2, and 4 (see Fig. 1), while the mean glacier area for the entire glaciation of the Koryak Highlands is 0.24 km$^2$, which coincided with the mean glacier area of the Olyutorsky Bay basin.

In absolute values, the reduction in area in 2019 since the compilation of the USSR Glacier Inventory (the 1960s) for this region by basins is as follows: glaciers of the Pikas-Ukalayat basin decreased by 23.8 km$^2$, Ukelayat-Snegovoy by 13.5 km$^2$, Ilpi-Imolkanavayam by 1.4 km$^2$, Vatyna by 7.4 km$^2$, Anivayam-Machevna by 6.35 km$^2$, Machevna-Apuka by 2.5 km$^2$, Apukawayam by 11.0 km$^2$, Korf Bay by 7.3 km$^2$, and Olyutorsky Bay by 4.8 km$^2$. In relative units, the glacier reduction is shown in Figure 3.

The range of glaciers area and their number for 2019 are shown in Figure 4. Some glaciers of the Koryak Highlands disintegrated – as a rule, into two fragments; there are 43 such cases.

We also determined 279 rock glaciers (the presence of ice in the images is not visible), with a total area of 19 km$^2$. In 112 cases, the glacier indicated in the Inventory was not found, or its area was <0.001 km$^2$. In total, we deciphered 603 glacial objects, of which, 212 are glaciers with open ice. Thus, at this stage, current estimates (2019) of the areas of all glaciers of the Koryak Highlands have been obtained; a comparison with the USSR Inventory of Glaciers is not completely rateable and requires verification on independent materials from other surveys (historical images of CORONA).

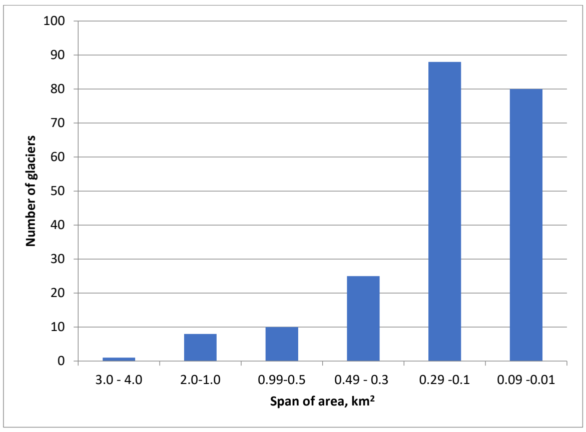


Fig. 4. Range of glacier areas (km$^2$) and number of glaciers for 2019

## Comparison of the glacier change results with other sources

Comparison of the results obtained with our previous work (Ananicheva 2012) shows that the number of glaciers has decreased by 25. The total area of all objects (including glaciers) has decreased 14.3 km$^2$ more than according to estimates in (Ananicheva 2012). In the same work, an analysis of the reduction in the area of retreating glaciers by groups (of the same morphological type and aspect) showed that the sizes of glaciers of eastern, northern and north-eastern aspects decreased as much as possible. At present, a decrease in the area is more typical for glaciers of northern aspects.

It is not easy to compare the data on the Koryak glaciers included in the Randolph Glacier Inventory (RGI). One of the reasons for the discrepancies with the RGI is that they were obtained by automatic deciphering. In this Inventory, images were used whose ID, shooting date and number of decoded glaciers are as follows:

Landsat-7 ETM+ LE07_L1TP_095016_20000714_20200918_02_T1
LE07_L1TP_095017_20000714_20170210_01_T1
14/07/2000 101
Landsat-5 TM LT05_L1TP_095018_20090816_20200827_02_T1 16/08/2009 29
Landsat-5 TM LT05_L1TP_093017_20090919_20200825_02_T1 19/09/2009 184
Landsat-8 OLI LC08_L1TP_097018_20130810_20200912_02_T1 10/08/2013 166

1. July 14, 2000 – too early for the interpretation of glacier contours. At this time, there are contours and still a lot of snow patches, which hinder the correct determination of contours: many snow patches were

Table 2. Aspect of the glaciers of the Koryak Highlands for 2019, % of total number of glaciers in the group

| Basins | Area of glaciers, km² | Number of glaciers | Glacier aspect | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | N | NW | W | NE | E | S | SW |
| Between Pikas-Ukalayat ranges | 11.40 | 34 | 29.4 | 23.6 | 2.9 | 29.4 | 11.8 | 2.9 | 0 |
| Between Ukalayat-Snegovoy ranges | 10.30 | 36 | 30.6 | 22.2 | 11.0 | 30.6 | 5.6 | 0 | 0 |
| Ilpi-Imolkanavayam rivers | 1.10 | 8 | 25.0 | 75.0 | 0 | 0 | 0 | 0 | 0 |
| Vatyna River | 6.76 | 17 | 17.6 | 41.2 | 17.6 | 0 | 0 | 11.8 | 11.8 |
| Anivayam River – Machevna Bay | 4.74 | 34 | 20.6 | 41.2 | 20.6 | 5.9 | 2.9 | 2.9 | 5.9 |
| Machevna – Apuka River | 1.85 | 17 | 29.4 | 47.1 | 17.6 | 5.9 | 0 | 0 | 0 |
| Apukavayam River | 3.76 | 25 | 20.0 | 12.0 | 32.0 | 8.0 | 0 | 8.0 | 20.0 |
| Korf Bay | 6.32 | 27 | 33.3 | 22.3 | 25.9 | 7.4 | 0 | 0 | 11.1 |
| Pylgovayam River – Olyutorsky Bay | 3.36 | 14 | 14.3 | 35.7 | 21.4 | 0 | 0 | 0 | 28.6 |
| Total | 49.59 | 212 | | | | | | | |

*Source: own elaboration*

Table 3. Morphological type of glaciers in the Koryak Highlands for 2019, % of total number of glaciers in the group

| Basins | Number of glaciers | Mean glacier area, km² | Corrie | Corrie-valley | Valley | Twinned | Hanging |
|---|---|---|---|---|---|---|---|
| Between Pikas-Ukalayat ranges | 34 | 0.33 | 26.5 | 20.6 | **52.9*** | 0 | 0 |
| Between Ukalayat-Snegovoy ranges | 36 | 0.29 | 36.2 | **52.8** | 8.3 | 0 | 0 |
| Ilpi-Imolkanavayam rivers | 8 | 0.14 | **75.0** | 25.0 | 0 | 0 | 0 |
| Vatyna River | 17 | 0.4 | **70.6** | 5.9 | 17.6 | 0 | 5.9 |
| Anivayam River – Machevna Bay | 34 | 0.14 | **91.2** | 8.8 | 0 | 0 | 0 |
| Machevna – Apuka River | 17 | 0.11 | **94.1** | 5.9 | 0 | 0 | 0 |
| Apukavayam River | 25 | 0.15 | **72.0** | 20.0 | 4.0 | 4.0 | 0 |
| Korf Bay | 27 | 0.23 | **48.2** | 33.3 | 0 | 0 | 18.5 |
| Pylgovayam River – Olyutorsky Bay | 14 | 0.24 | **64.3** | 7.1 | 7.1 | 14.4 | 7.1 |
| Total | 212 | 0.24 | | | | | |

* prevailing morphological types of glaciers in the group are marked in bold
Source: own elaboration

designated as glaciers, but the glacier area turned out to be overestimated.

2. August 16, 2009 – the ideal time and imaging, the glaciers were decoded correctly, while glacier N 521 was missed.
3. September 19, 2009 – the time when there is usually a lot of snow, which is not suitable for deciphering glaciers. By this date, the snow cover had not yet formed, but, due to the low sun, many glaciers (including large ones) fell into shadows and were not shown.
4. 2013 was snowy; as of August 10, 2013, there was much snow on the slopes of the Koryak Highlands, which made it difficult to decipher the glaciers. As in the first case,

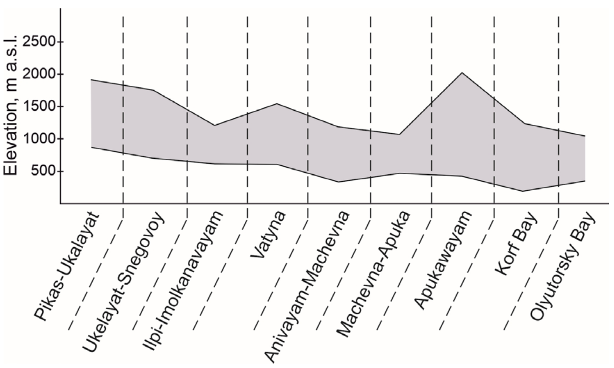

Fig. 5. Elevation range of glacial group's location in the Koryak Highlands (m a.s.l.)

the glacier areas are overestimated due to the snow cover.

## Koryak glaciers: aspect and morphological type

Koryak Highland glaciers by 2019 satellite images analysis are distributed by aspect and morphological type, in % of the total number in groups, as shown in Tables 3 and 4.

In the northern part of the Highlands, between the Pikas and Ukealat ranges, valley glaciers of the northern aspects are preserved and prevail. To the south, between the Ukelayat and Snegovoy ranges, most of the glaciers are of the corrie-valley type. Further to the south, the corrie glaciers of NW aspect prevail and, in the valley of the Apukawayam River, there are corrie glaciers confined to slopes of western aspect. In the basin of Korf Bay, the glaciers of W and NE aspects are approximately equally divided, and Olyutorsky Bay is more confined to the NW aspect. The northern aspect of glaciers is currently contributing to the reduction in glacier size due to the Arctic amplification effect. Also, the influence of local/regional factors is related to heat input into glacier valleys, relief host forms, and the height of ridges that decrease from north to south.

Figure 5 shows the range of relief elevations (from the minimum to the maximum elevation point) in each basin: the glacial groups are located within the Highlands and are numbered from north to south. The elevations of the location of glaciers in the Apukovayam River basin, between the Ukelayat and Pikas and Pikas and Snegovaya ranges, reach 2,000 m; the rest are lower, and the glaciers of Korf Bay basin descend to below 500 m a.s.l. The rise of the firn line as compared to the Inventory for various basins is 400–500 m, the heights of the glacier tongues approximately doubled relative to the rise of the firn line.

Permafrost under the bed of glaciers provides the necessary cold reserve for them. Congelation nourishment in the warm season is carried out at the expense of ice cold reserves. These conditions contribute to glacier existence below the snow line on the slopes of ranges (coastal) at altitudes up to 800 m a.s.l. and a pronounced altitudinal vegetation zonation.

## Preliminary expedition results

An important part of the region study was field work in the area of the Pylginsky Range on the Goven Peninsula in 2020, which made it possible to assess the accuracy of the satellite images and estimates of glacier areas, to gain an idea of the Holocene–Pleistocene history of glaciers in this area, and to collect samples for dating of glacial deposits in order to confirm or clarify this understanding.

The preliminary results of the expedition include the following.

In the south of the Koryak Highlands (Pylginsky Range), glaciers of N and NW aspects have been preserved in deep cars of the upper tier of the nodal peaks of ridges exceeding 1,000 m. Among the surviving ones are corrie glaciers in deeply shaded circuses of the upper tier. They completely occupy the bottom of their car, and the upper border of the firn basin extends to half of its walls' height, without reaching the ridge. The tongues of glaciers terminate at the crossbar, often hanging over them in the form of a steep hump. The glacier fronts of NW aspect are more gentle, armoured with a layer of moraine and hidden under a seasonal snow cover (Fig. 6a and b). Complete degradation of corrie glaciers on the slopes of the western and eastern aspects in the area studied was noted.

The structures of moraine complexes of various glaciers have common features. There are three rows of young (possibly Holocene) moraines and at least three rows of older ones (possibly Pleistocene). As


Fig. 6. (A) Glacier No. 679 according to the USSR Glacier Inventory, Western slope of the Pylginsky Ridge, photo from drone, September 2020; (B) photo from Sentinel-2, 2019 rock glacier, No. 167, Southern slope of the Ukalayat Ridge, Koryak Highlands

a result of these stages of glaciation, a trough valley up to 5 km wide was formed. The glaciers appear to have been mostly valley/dendritic and formed valleys adjacent to the main valley of the Yevyayam River.

The formation of the oldest moraines is Late Pleistocene. The peculiarity of the Pylginsky Range glaciers is that these remnants of moraines lie at low altitudes (up to 100 m a.s.l.) and the most distant ones are possibly located at the bottom of Korf Bay. The moraine below Lake Ivtyl-Gytgyn corresponds to MIS-2, judging by the data from Glushkova (2011). When we have available cosmogenic element dating and OSL results, we will be able to clarify these data.

During the research of nival-glacial landforms on the high-mountain slopes of the Koryak Range (Glushkova 2011), rock glaciers were found that formed in the second half of the Holocene. Their age was determined using radiocarbon, lichenometric and other methods. It is assumed that some of them were formed as a result of deglaciation of valley glaciers of the last glaciation, the edges of which experienced oscillations in the Neoglacial epoch of the Holocene about 4.5 K years ago. Then the degradation of glaciers and their transformation into rock glaciers resumed.

## Conclusions

Analysis of temperature trend shows that warming in Koryak Highlands region started in 1970s. Annual temperature trends grow from 2.5 to 3.0 °C towards the Kamchatka Peninsula, and mean summer temperature changes from 1.5 to 3.0 °C for 1966–2019. Precipitation of the cold period mainly decreases. Such conditions do not contribute to the preservation of glaciation here.

The areas of the glaciers of the Koryak Highlands and their characteristic altitude parameters were determined by Sentinel-2 images of 2018 and 2019; data for these years were compared with those indicated in the USSR Glacier Inventory. For the basins identified in the USSR Glacier Inventory for this region, a relative reduction in glacier areas was obtained (they are from 35 to 74%). These data require verification against other data.

In the Koryak Highlands there are now 212 glaciers with a total area of 49.6 $km^2$. These are mainly corrie glaciers of northern aspects. In the basins adjacent to Ledyanaya Mountain, valley glaciers prevail (53% in the group). The rest are dominated by corrie glaciers. Since the assessment of 2012, the area of the glaciers became 14.3 $km^2$ less. The reduction in glacier size is mostly characteristic for glaciers that face north. This relates to more intensive Arctic warming.

When analysing the images, the firn line altitudes were determined and were compared with the data of the USSR Glacier Inventory. Changes in this parameter of individual glaciers varied from several tens of metres to maximum values of 400–500 m. The heights of glacier tongues are approximately double that. The glacier areas and elevations obtained from the images were compared with the values measured in the field for four glaciers in the southern part of the Koryak Highlands. The difference is from 2 to 12%. However, some methodological limitations were noticed such as the need to use higher-resolution satellite images to better delineate the shape of glaciers partially covered by debris, and to classify small glaciers based on this and other remote-sensing materials. The next stage will be an analysis of CORONA images dated to the 1970s to validate the USSR glacier inventory data and receive more precise dynamics of glacier changes.

During an expedition in 2020 to the valley of the Ev'ayam River, the presence of moraines of the Holocene and Pleistocene was fixed. New research is needed to explain the age of moraines and the sequence of glacial events in this area.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

## Author contributions

Study design: MA; data collection AA; statistical analysis: MA; result interpretation: MA; manuscript preparation: MA; literature review: MA.

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