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Contemporary state of glaciers in Chukotka and Kolyma highlands

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Abstract. The purpose of this work is to assess the main parameters of the Chukotka and Kolyma glaciers (small forms of glaciation, SFG): their size and volume, and changes therein over time. The point as to whether these SFG can be considered glaciers or are in transition into, for example, rock glaciers is also presented. SFG areas were defined from the early 1980s (data from the catalogue of the glaciers compiled by R.V. Sedov) to 2005, and up to 2017: these data were retrieved from satellite images. The maximum of the SGF reduction occurred in the Chantalsky Range, Iskaten Range, and in the northern part of Chukotka Peninsula. The smallest retreat by this time relates to the glaciers of the southern part of the peninsula. Glacier volumes are determined by the formula of S.A. Nikitin for corrie glaciers, based on in-situ volume measurements, and by our own method: the average glacier thickness is calculated from isogypsum patterns, constructed using DEMs of individual glaciers based on images taken from a drone during field work, and using ArcticDEM for others.

Key words:
Chukotka Peninsula,
Kolyma Highlands,
satellite image,
climate change,
glacier reduction,
stone glacier

Introduction

Mountain glaciers are one of the most sensitive natural indicators of climate change (Dyurgerov and Meier 2000; Hoelzle et al. 2007; Owen et al. 2009). The north-eastern part of Russia is almost completely occupied by mountains. Present glaciation is represented by a wide variety of glaciers. Despite intensification of glaciological research in north-eastern Siberia in recent decades (Takahashi et al. 2011; Ananicheva and Karpachevsky 2015; Kitov and Plyusnin 2015; Osipov and Osipova 2015; Stepanova et al. 2015; Shirakawa et al. 2016; Zhang et al. 2019), knowledge about the present state of glaciation in this area remains incomplete. Even now, glacial formations not previously described are found (Ananicheva et al. 2019). Those most sensitive to climate change are small glaciers or small forms of glaciation (Haeberli et al. 2004; Solomina et al. 2008), which are widely represented in the Kolyma and Chukotka highlands. The term "small forms of glaciation" (further SFG) was first introduced by M.V. Tronov in 1954 (Tronov 1954). It includes glaciers, perennial snow patches with an ice core and perennial snow patches. Small forms of glaciation are also called "embryonic glaciation" (Shumsky 1955): (the term does not relate to young age). Those are spread in the South Island of Novaya Zemlya, the Subpolar and Polar Urals, the Putorana Plateau, the mountains of Chukotka and Kolyma, and elsewhere. "Embryonic" glaciers do not often have a clearly pronounced firn basin, and are small in size and thickness; they have a morphological type – corrie, corrie-hanging, corrie-valley – and are often covered with moraine cover, which prevents them from melting during adverse climatic conditions.

The purpose of this work is to assess the main parameters of the Chukotka and Kolyma SFGs – their size and volume, and changes therein over time. The article discusses whether these small forms of glaciation can be considered glaciers or are in a stage of transition into, for example, rock glaciers.

Research area: topography and climate

Chukotka Peninsula (Chukchi Peninsula) occupies the north-eastern extremity of the Eurasian continent. Administratively, it is part of the Chukotka Autonomous District (737.7 thousand km^2). Chukotka borders with Yakutia to the west, and Koryak Autonomous District to the south. The orographic basis of Chukotka is a mountain-tundra plateau (Sedov 2005). This watershed area stretches between the Arctic and Pacific oceans in a sub-latitudinal direction from the mouth of the Kolyma River to Dezhnev Cape. The Kolyma Highlands are adjacent to the western part of this region (Fig. 1).

The Chukotka Highlands, where the glaciers are located, extend along the Chukchi Sea and are represented by a system of medium-altitude ranges: Chantalsky (1,887 m a.s.l.), the long Pekulnei (1,400 m a.s.l.) and, to the south-east, the Iskaten Range (1,552 m a.s.l.). The basic relief of Chukotka is not alpine: instead, the mountains are flat-topped. The highest massifs and ridges belong to glacial forms: cars, trough valleys, jagged ridges, and sandur plains, subsequently modified by erosion. The coastline is indented with deep bays and inlets. The "middle-mountain" massifs of the Chukotka Highlands include mountain depressions of considerable areal extent.

A significant portion of the Chukotka Highlands is part of the Okhotsk-Chukchi volcanogenic belt. It consists of almost continuous volcanic covers with intrusions breaking through them. The bedrock is mostly composed of bazalts and andesites.

The topography of the Taigonos Peninsula, a part of the Kolyma region, is represented by the Tyninot

Fig. 1. Location of Chukotka and Kolyma glacier systems. Dotted circles with numbers highlight the distribution of glacier groups, indicated by R.V. Sedov

Range, which stretches 170 km from the south-west to the north-east, from the Impoveem River to the lower reaches of the Kechichma River. On average, it rises up to 1,000 m a.s.l., and the highest point is 1,484 m a.s.l. (Sedov 1997a). The mid-mountain Tyninot Range (north of Chukotka Peninsula) is characterised by steep scree slopes; glacial forms such as sharp rugged ridges, through valleys, glacial lakes in valleys and at watersheds, and moraine complexes. A major part of the Kolyma SFG is set here.

The western part of the Kolyma highlands is composed mainly of siltstones and sandstones, and the eastern part is of effusive deposits. Numerous granite intrusions appeared to be sources of non-ferrous metal ore.

The Arctic and Pacific oceans are basic factors forming the region's climate. Therefore, the climatic conditions of the Chukotka Highlands are quite diverse – from subarctic marine (in the northern part of Chukotka Peninsula) to the subarctic continental (in the Chantalsky Range, see Fig. 1), and Arctic ones (in the far north). Strong winds play an important role in the winter season; they form a powerful snow transfer (storms), providing the small glaciers with their nourishment. The Providensky Mountain Massif (Fig. 1, 2) is located in the subarctic maritime climate, but with a large temperature amplitude: the mean temperature is 7.2 °C in summer (June–August), and 14.3 °C in winter (December–February). The smallest amount of precipitation falls in June and averages 28 mm, and the greatest is 90 mm in November. On average, about 700 mm of precipitation falls annually in Providence Bay, in the southern part of Chukotka Peninsula, which is a feature of the maritime climate.

The climate of the Kolyma region, in particular the mountain ranges of the Taigonos Peninsula where the glaciation is located, is continental with some features of seaside influence (proximity to the Sea of Okhotsk). In winter, temperate maritime and maritime Arctic air masses prevail, and the frequency of continental Arctic ones is high, invading from Yakutia and determining anomalously low temperatures. Despite the harsh winter conditions, the active cyclonic activity characteristic of the region causes sharp temperature fluctuations. The period with mean daily temperature above 10 °C lasts just over a month: from July 10 to August 15. The mean annual temperature is negative, according to Sedov (1997b): at weather stations Gizhiga (-5.4 °C), Taigonos (-2.6 °C), precipitation is 284 and 484 mm, respectively.

We estimated *climate change* by trends of climatic parameters important for the balance of glaciers – temperature (mean annual T_{year} and mean summer T_{sum}) and precipitation (mean annual P_{year} and for the cold period P_{solid}), see Table 1. For the last 46 years (1966–2012). The year 1966 was chosen due to the improvement in precipitation measurement devices in the north of Russia in that year. The T_{year} and T_{sum} trends for the entire Chukotka Peninsula are positive and vary from 1 to 2 °C for the 46 years – from the coast to the peninsula interior. The precipitation trends of P_{year} and P_{solid} are similar: they are both negative in the coastal regions and positive in the continental part between the Cross and Anadyr gulfs. But in absolute terms, they differ somewhat: P_{year} from -100 (most of the Chukotka Peninsula) to +100 mm for the 46 years (on the plateau near the Gulf of Anadyr), P_{solid} from -110 to +100 mm for the 46 years. However, a larger part of Chukotka is characterised by a trend of -50 mm for the 46 years (Fig. 2).

Climatic processes over Chukotka do not promote the development and spread of glaciation. The assessment of the studied glaciers' state dates to the 1980s, since which time climate warming has been characteristic for this region. We estimated the timing of temperature and precipitation changes in the region (and the stations used are listed in Table 1).

The increase in T_{year}, T_{sum} occurs first for the inner region to the west of the Chukotka Peninsula – from the late 1970s to the early 1980s, and later (from the early 1990s) the positive temperature trend began in the region of 66–68° N, in the north of the Chukotka. Since 1994, there has been a steady increase in temperatures in the coastal area on the Chukotka Peninsula.

It is not easy to explain these patterns of positive changes in temperature associated with the regional atmospheric circulation. The most general is: the onset of positive trends earlier on the continent, and later in the coastal zone, from east to west. Dates associated with periods of precipitation changes are distributed more unevenly throughout the region: generally, from the north to 66° N there is an in-

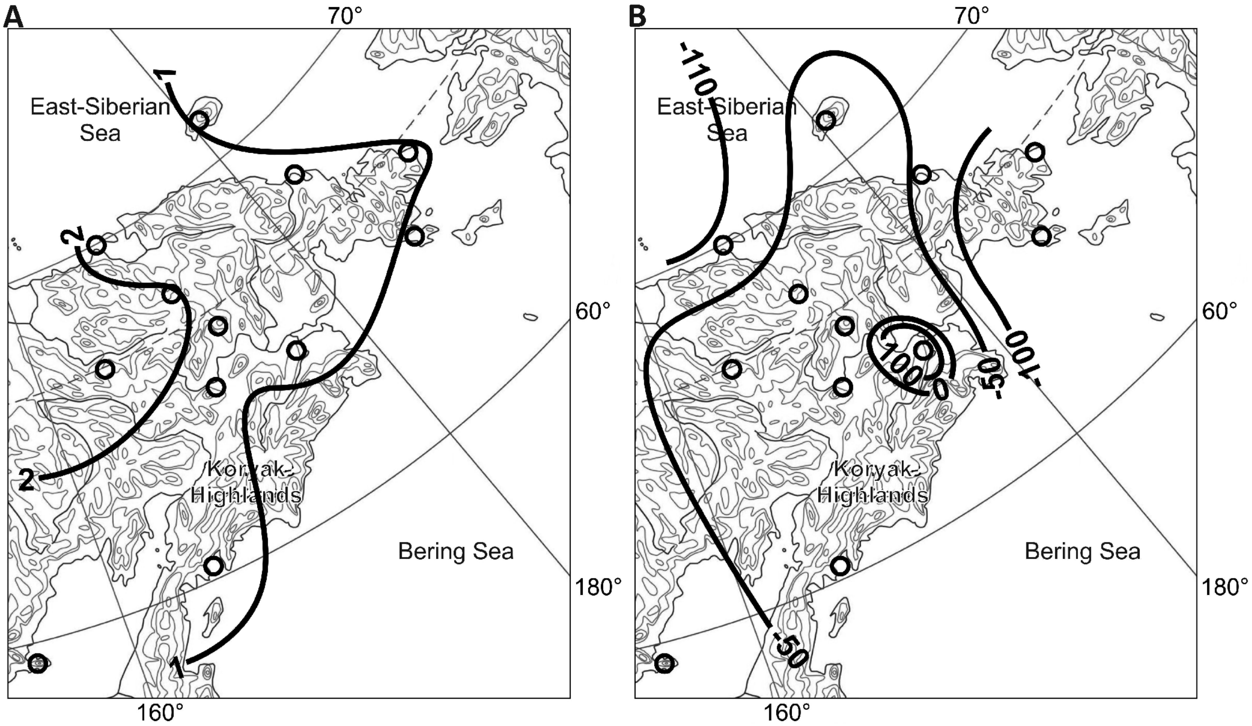

Fig. 2. Trends of the mean summer temperature °C (A), and precipitation of cold period, mm (B), estimated by the data from weather stations over Chukotka Peninsula and adjacent territories for 1966-2012 (weather stations are shown by circles)

crease in precipitation, while to the south of this belt there is mainly a downward trend.

The positive trend in the area of the Anadyr estuary (Fig. 1b) was observed until 2012, and later the trend turned to negative. By the weather station Egvekinot-Airport, located on the shores of the Cross Bay, Bering Sea, the P_{year} and P_{solid} are still increasing up to now.

How these trends affect the change of small glaciers of the studied regions is discussed below.

Glaciers of Chukotka and Kolyma

The glaciers of the Chukotka Highlands, according to Sedov (1997a), are clustered in several groups (Fig. 1).

The first group of three glaciers is located in the north-east of the Chukotka Peninsula (the groups are given by numbers on Fig. 1). The equilibrium line altitude (*ELA*) is 500 m a.s.l. Our *in-situ* observations indicate that these glaciers are now in the stage of rock glaciers. The second group, consisting of 14 glaciers, is located in the southern part of the peninsula (Provendence Massif), and the *ELA* is from 400 to 550 m a.s.l. The third group, in the Iskaten Range (the Cross Bay, the Gulf of Anadyr), consists of 21 glaciers, with the *ELA* at from 500 to 1,000 m a.s.l.

The fourth group of four glaciers on the Pekulney Range consists of glaciers ~0.3 km^2 in size. The average *ELA* was 740 m a.s.l.

In the fifth group there are five glaciers ranging in size from 0.1 to 0.5 km^2, and they are found on the Chantalsky Range and have an average *ELA* of 1,400 m a.s.l. (Sedov 1992, 1997).

Glaciers of the Kolyma Highlands, according to Sedov (1997b), are spread within two groups (Fig. 1, groups 6 and 7): five are located on the eastern slope of the Kolyma Highlands near the western coast of the Sea of Okhotsk: the *ELA* is 700 to 1,500 m a.s.l., and 14 glaciers are in the northern part of the Taigonos Peninsula, with an *ELA* from 700 to 1,000 m a.s.l., see Table 2. All of them belong to the corrie morphological type.

Forty years characterised by climate warming have passed since the previous assessment of the Chukotka and Kolyma glaciers, and therefore

Table 1. Data of the weather stations used

Title	Latitude, N	Longitude, E	Altitude, m a.s.l
Wrangell Island	70.98	178.48	2
Aion Island	69.90	168.00	13
Cape Schmidt	68.90	-179.40 *	7
Ostrovnoe	68.10	164.20	94
Iyultin	67.90	-178.70	235
Illirney	67.25	168.97	326
Emulveem	66.38	173.33	74
Egvekinot	66.35	-179.12	15
Uelen	66.17	169.83	6
Anguema	67.00	-178.90	138
Anadyr	64.78	177.57	94
Providence	64.40	-173.20	11
Nayakhan	61.90	159.00	23
Taigonos	60.70	160.40	33
Seymchan	62.90	152.40	207
Srednekan	62.50	152.30	266
Nagaev Bay	59.60	150.80	118
Yamsk	59.35	154.08	5
Omsugchan	62.50	155.80	521
Labaznaya	63.30	158.50	709

Minus means that the station is in the Western Hemisphere

a study of these glaciations' current state is now timely.

Methods of calculating glacier areas and volumes

Initially, we had descriptions of the Chukotka and Kolyma glaciers made by R.V. Sedov after his expeditions in the early 1980s. He published them in a series of articles (1988, 1992, 1996, 1997a, b) that contained data on the main glaciological parameters of the glaciers – area, length, equilibrium line altitude, etc. The current state of the glaciers of these remote regions can be estimated from satellite images taken at a specific time – usually at the end of July to August, when these small glaciers have minimal to zero snow cover. The first attempts to measure glacier areas using Landsat-7 images available in 2016 (the beginning of work to assess the glaciers of the Chukotka Highlands) cast doubt on the accuracy of the results.

Therefore it was necessary to check their state *in situ*. In August 2017, we managed to get into one of the regions of the Chukotka Highlands, where, according to R.V. Sedov, there was a group of glaciers in the area of the Lawrence Bay (north of Chukotka Peninsula, group 1 in Fig. 1). The valleys in the area of Vulkannaya Peak (approximate coordinates 65°40' N, 171°31' W) were visited in August 2017. Four cars with SFG were investigated (Ananicheva et al. 2017). Studies at the place made it possible to ascertain the degradation of the smallest glaciers of the Chukotka Highlands.

Later, a number of satellite images were used to analyse the glaciers of Chukotka and Kolyma, such as: CORONA (at a resolution of 5–10 metres), 1975; Landsat (15/30 m), 2005; and Sentinel-2 (resolution 10 m), 2017. The spatial reference accuracy of Sentinel-2 shots is within 11 m, confidence level of 95.5%. Using ArcGIS software, the boundaries of SFG were digitised and their areas were calculated for the respective periods of 1975, 2005, 2017. The

CORONA images were tied to the real surface by landmarks clearly visible in the images. Vectorisation of the boundaries of glaciers carried out manually on orthorectified images synthesised from three channels.

Work with the satellite images was done after processing the materials obtained in a field trip to the area of the Egvikinot basin, the Cross Gulf, Chukotka (Fig. 1, Group 3) in August 2018. The objectives of the field study in 2018 were as follows: a description and instrumental survey of accessible glaciers by GPS and use of unmanned aerial vehicle (UAV) to build 3D models of glaciers. The GPS survey made it possible to assess the error in the estimates of the areas by satellite images: it is 5–11% by six GPS-measured glaciers in this basin.

In Nosenko et al. (2019) the error in determining the area was estimated by the ratio of the area of the buffer zone 10 m wide along the perimeter of the glaciers (on the Polar Urals glaciers) to its area inside the border and, depending on the size of the glacier, was almost the same as ours – from 3 to 11%.

The task of ground and aerial stereo photography with the UAV was to create a series of photo images of each surveyed object to build a digital elevation model (DEM) based on them (using the image metadata, including the coordinates of survey points from the internal satellite positioning system of the UAV) with an accuracy of 0.1 metres. The control of the UAV was carried out manually without prior programming of the shooting programme, due to the lack of information about the shooting area. The flight altitude was from 100 to 250 m. These types of work were carried out in relation to the glaciers reachable for us – Zakrytyi Glacier (66°33'22.3"N, 179°11'34.3"W, at km 29 of the main road Egvikinot-Iultin) 08/04/2018, Shleif Glacier (66°32'14.4"N, 179°09'19.5"W, at km 27 of the road) 08/06/2018, Glacier No. 8 (66°29'06.2"N, 179°06'24"W, at km 22 of the main road Egvikinot-Iultin) and Propuschenny Glacier (66°29'58"N, 179°05'59.9"W, at km 22 of the road) 08/05/2018, and Unknown Glacier (66°31'24.7"N, 179°15'30.3"W, at km 22 of the road) 08/09/2018 (Fig. 3).

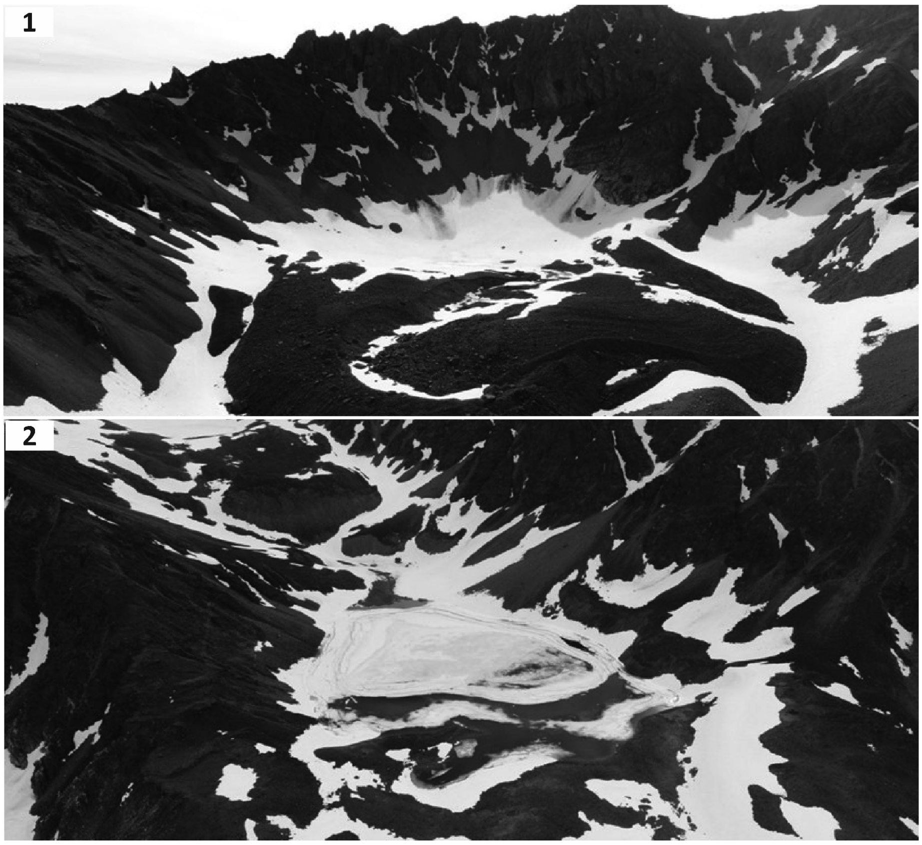

Fig. 3. Photo from drone: 1– Zakrytyi Glacier; 2 – Propushchenny Glacier, Egvekinot basin, the Cross Gulf

The 3D models were built for them in Agisoft and Sputnik software. The dimension is in cm, with a noise ratio of 5%. These models were the basis for calculation of the glacier volume. The problem was how to estimate the underground part of the glaciers. To solve this, a special DEM – an ArcticDEM – was used; it served for constructing the topography of the valleys (by isohypsum) in which there are no small glacial relief forms. We made the assumption that in general the shape of the bottom of the neighbouring valleys is the same as that of those with glaciers. The distribution of relief heights and slopes was calculated for these valleys' obtained topography shapes. For the upper zones, large slope gradients (from 1.25 to 2.0 or 12.5 to 20) are attributed, while valley slope gradients in the areas below are from 0.2 to 0.4. So, we used, by analogy, these isohypsum forms of subglacial topography under the studied glaciers. Combining the edge points of elevations and taking into account the shape of the bottom, we constructed the bed isohypses of glaciers by ArcGIS. These calculations were carried out for each glacier of the region studied (Fig. 4).

As mentioned above, DEMs for six glaciers were obtained by the UAV survey *in situ*. Also, recently the latest version of ArcticDEM (used for other glaciers) became available, the accuracy of which is 2–8 metres. As a result, by subtracting from the image of the glacier topography the values of the bed topography under the glacier, we obtain the final image with thickness over the entire the glacier. The pixel size depends on the accuracy of the DEM, that is, 0.01 m^2 (UAV survey) and 25 m^2 (ArcticDEM). To get values of volume we multiplied the mean thickness of a glacier by its area. In order to verify the calculation we computed volumes as a function of the glacier area V = f (S), where S is glacier area using the empirical formulas of Nikitin (2009).

We decided to use his formula for the corrie glaciers since no variant of this relationship presented by Bahr et al. (2015) fits the glaciers of Chukotka and Kolyma morphological type. The criteria to use S.A. Nikitin's data is the fact that they are based on direct measurements of volume (echo-sounding) in the Altai Mountains and V = f (S) (V is the volume of the glacier, km^3; S is the area, km^2) formulas were

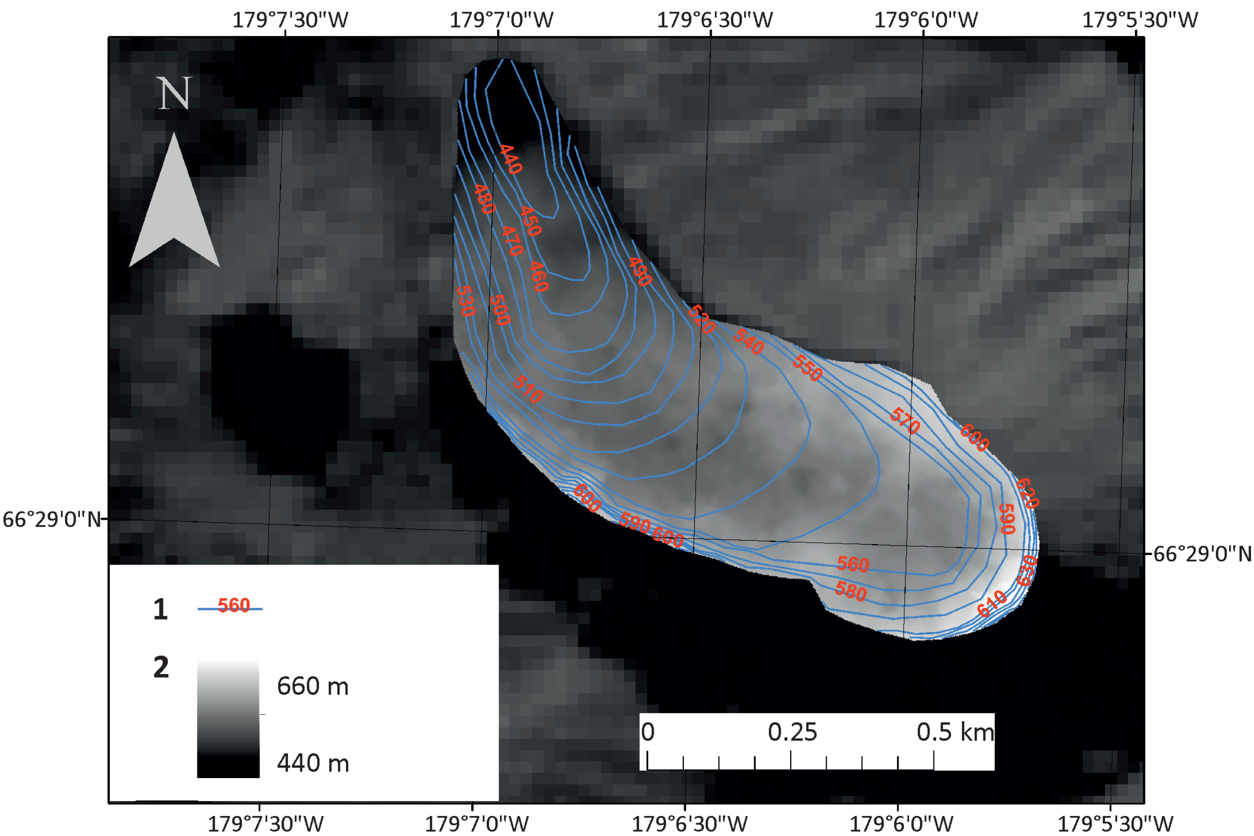

Fig. 4. Propushchenny Glacier, the Gross Gulf (Fig.1, Group 3), Sentinel-2: 1 – isohypses of the glacier bed; 2 – surface topography

obtained for various morphological types, including corrie glaciers.

Therefore, we calculated the volumes of the studied glaciers by the power-law formula of Nikitin (2009) for corrie and corrie-hanging types:

$$V = 0.0487 \times S^{1.244}, (R = 0.91) \quad (1)$$

where R is the correlation coefficient, see more details in the section *Glacier volumes of studied areas*.

We also measured the areas of some glaciers based on archive satellite images of the CORONA mission dating back to the late 1970s, i.e. at almost the same time as when R.V. Sedov was studying the Chukotka glaciers. The CORONA data is a source of historical mid- and high-resolution satellite information that was once declassified by the US Department of Defense and is publicly available. We used images with a resolution of up to 3 metres. They covered areas of four groups of Chukotka and Kolyma glaciers. The results are shown in Table 3.

The results of the calculation of glacier areas and volumes

The recently released quite high-resolution (10 m) Sentinel-2 space images made it possible to measure accurately the areas of the Chukotka and Kolyma glaciers dated to 2017 (Table 2), and the accuracy of the area determination is as much as 5–11%.

Table 2 shows that by 2005 the small glaciers of the Amguema River and the Cross Gulf basins (see Fig. 1 for locations) had undergone the largest retreat. The biggest number of glacial objects among the Chukotka glaciers belongs to the Cross Gulf basin. The smallest glacial formations in the Lawrence Bay group also decreased significantly. This fact is consistent with the earlier onset of positive temperatures trends. The smallest retreat by this time relates to the glaciers of the Providence Bay group (Fig. 1, group 2), and the Kolyma Highlands (Taigonos Peninsular, group 7). These processes are also consistent with trends in temperature and precipitation in these areas (see the “Climate” section above).

Using Sentinel-2 images from 2017, we determined the further reduction extent of the Chukotka and Kolyma glacier area (see Table 2). The retreat values in km^2 are already smaller than in the previous period, but significant (relatively) for the glacial formations of the Group 3 (Cross Gulf basin) and for the part of the Kolyma highlands. In percentage it is shown on Figure 5. The reduction in this period slowed down in the range from 2 to 5 times as compared with the previous evaluation period.

Table 3 shows the comparison of the areas between Sedov’s catalogue and the CORONA data.

Taking into account that 1) CORONA images were made at about the same time as the studies

Table 2. The mean area of the Chukotka and Kolyma glacial systems for different periods

The number on Fig.1, name of the glacial system	Data of R.V. Sedov, early 1980s	Data of LandSat, 2005 1980-2005		Data of Sentinel-2, 2017 2005-2017	
	Mean area, km^2 (number of glaciers)	Mean area by 2005, km^2 (number of glaciers)	Retreat, km^2	Mean area by 2017, km^2 (number of glaciers)	Retreat, km^2
1. Lawrence Bay	0.10 (3)	0.06 (3)	0.04	0.05 (3)	0.01
2. Providence Bay	0.16 (14)	0.17 (14)	0.01	0.15 (14)	0.02
3. Cross Gulf	0.41 (21)	0.27 (21)	0.14	0.23 (21)	0.05
4. Peculney Range	0.30 (4)	0.21 (4)	0.09	0.17 (4)	0.04
5. Chantalsky Range	0.22 (5)	0.13 (5)	0.11	0.09 (4)	0.02
6. Kolyma Highlands	0.34 (5)	0.25 (5)	0.09	0.19 (5)	0.06
7. Kolyma - Taigonos	0.14 (14)	0.10 (14)	0.04	0.08 (14)	0.01
Number of glaciers	**66**	**66**		**65**	

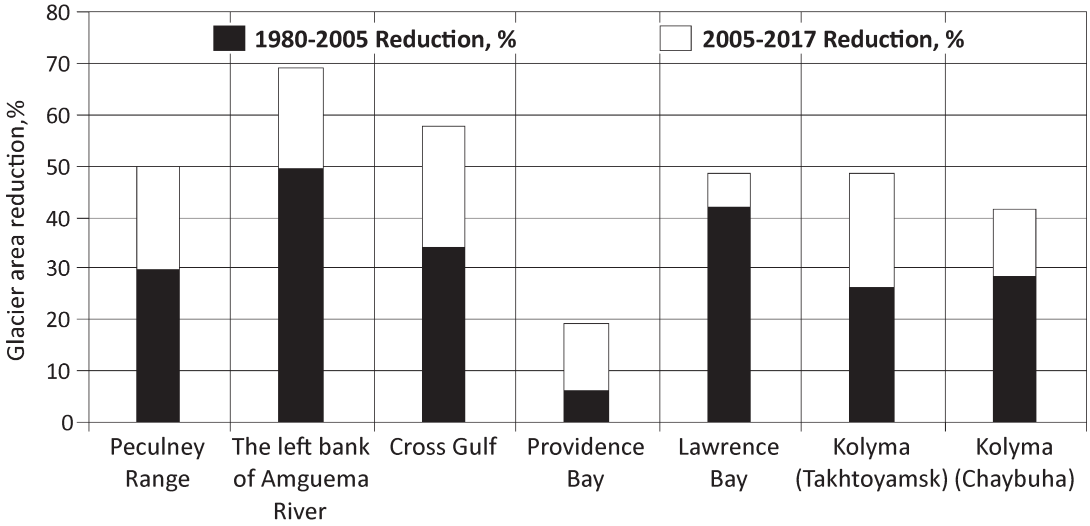

Fig. 5. Reduction in the area of the Chukotka and Kolyma glaciers for different periods

Table 3. Glacier areas averaged over the groups by CORONA images for the onset of 1980s

Chukotka and Kolyma highlands groups	Mean area by the end of the 1980s (CORONA), km^2	Number of glaciers	Difference between CORONA and R.V. Sedov catalog, 1980s
1. Lawrence Bay	0.09	3	0.01
2. Providence Bay	0.20	14	-0.03*
5. Chantalsky Range	0.19	3	0.07

* – minus near the value is for a group, which the area of glaciers in the images was larger than in the catalog.

of R.V. Sedov, and 2) the period was not marked by pronounced warming, and therefore the glaciers were stable, we can consider this data as a verification of the areas from Sedov's catalogue. Since the difference between the values is small, we can say that the catalogue (Sedov 1997a, b) is right, as well as the CORONA images.

Glacier volumes of studied areas

Due to the absence of measured thickness values for estimating the volumes of the objects under study we had to use empirical formulas of volume/area relationship – in particular those given by Nikitin (2009). Present areas of the glaciers were obtained from interpretation of the satellite images.

Next, we estimated the changes of these values for different time periods, on average for each glacial group; the results are shown in Table 4 and Figure 6.

The patterns of area and volume changes are similar for the area change within the studied groups. The relative values of changes by 2017 follow the same logic. Considering that Nikitin (2009) derived formula 1 for a warmer region than Chukotka and Kolyma and for corrie glaciers larger in size than those studied in this work, we tried to estimate the volumes by another method, which is described in the "Methods" section above.

Employing the DEM obtained from the UAV and the Arctic DEM, we constructed the bed topography (using isohypses) for the 57 Chukotka and Kolyma glaciers, calculated the mean thickness of each glacier and, having calculated glacier areas, obtained the volumes of studied glaciers by 2017.

Table 5 shows the results of a comparison of the results obtained using the methods described.

In terms of percentage, the differences for individual glaciers and groups appeared to be in the range of 8.1–12.6%.

Therefore, since our method is independent, we obtained the power-law formulas for the small corrie glaciers of the Chukotka and Kolyma highlands (Fig. 7). The relationships have high correlation coefficients that confirm the possibility of our meth-

Table 4. Changes in the volume of glaciers by groups for different periods of time, calculation by the formula 1

Glacier system, number on Fig. 1	Mean volume up to 1980s, km^3	Onset of 1980s-2005		Mean volume up to 2005, km^3	2005-2017		Mean volume up to 2017, km^3
		total volume reduction, km^3 (%)	volume reduction per year, km^3/year		total volume reduction, km^3	volume reduction per year, km^3/year	
Chukotka:							
1. Lowrence Bay	0.002	0.0023 (46.0)	1.0^{-04}	0.001	0.0013	1.1^{-04}	0.001
2. Providence Bay	0.005	0.0038 (11.3)	1.7^{-04}	0.004	0.0036	3.0^{-04}	0.004
3. Cross Gulf	–	0.020 (75.5)	8.7^{-04}	0.007	0.004	3.3^{-04}	0.006
4. Pekulney Range	–	0.004 (43.9)	1.7^{-04}	0.005	0.004	3.3^{-04}	0.004
5. Chantalsky Range	0.005	0.005 (67.7)	2.2^{-03}	0.003	0.002	1.6^{-04}	0.002
Kolyma (name of the glacier group, a settlement as a orienteer):							
6. Kolyma Highlands (Chaybuha)	–	0.012 (43.5)	4.2^{-04}	0.008	0.007	5.8^{-04}	0.007
7. Taigonos Penisula (Tokhtoyamsk)	0.009	0.003 (38.6)	1.3^{-04}	0.003	0.002	1.6^{-04}	0.002

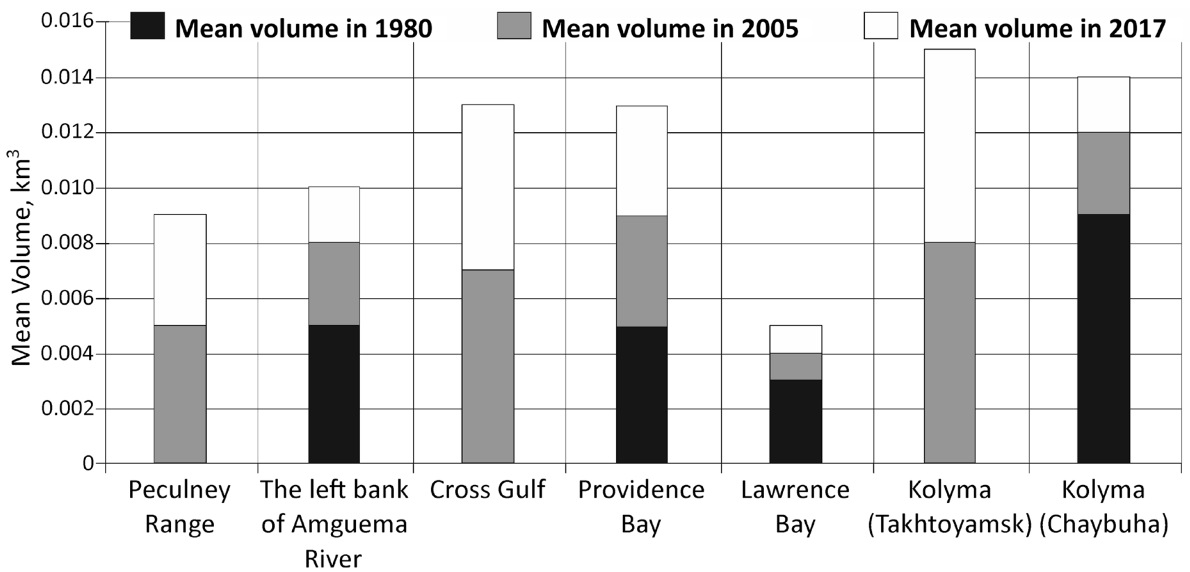

Fig. 6. Mean volume for glacier groups (by S.A. Nikitin's formular) in various periods of time

od being used for estimating volumes of such type of glacier.

The formulas are as follows:

For Chukotka glaciers (corrie type):

$$V = 0.0263 \times S^{1.0785}, (R = 0.981) \quad (2)$$

For Kolyma glaciers (corrie type):

$$V = 0.045 \times S^{1.2465}, (R = 0.986) \quad (3)$$

The relationship of the calculated values of glacier volumes to elevation (height) is weak (correlation coefficients are not higher than 0.45): for glaciers located closer to the sea, this relation is positive, and for small glacial forms in the continental part it is negative. The elevation range of the first group is 600–900 m a.s.l, the second is 800–1,000 m a.s.l; the aspect of all glaciers is northern.

Table 5. Volumes of Chukotka and Kolyma glaciers, estimated by different relationships V = f (S)

Glacier system	Mean volume by the isohypses of the glacier bed, km³	Mean volume by the S.A. Nikitin's formular, km³	Number of glaciers
Chukotka:			
1. Cross Gulf	0.0048	0.0049	20
2. Providence Bay	0.0040	0.0040	10
3. Chantalsky Range	0.0018	0.0020	4
4. Pekulney Range	0.0038	0.0039	4
Kolyma:			
5. Kolyma Highlands	0.0020	0.0020	14
6. Taigonos Peninsula	0.0067	0.0068	5

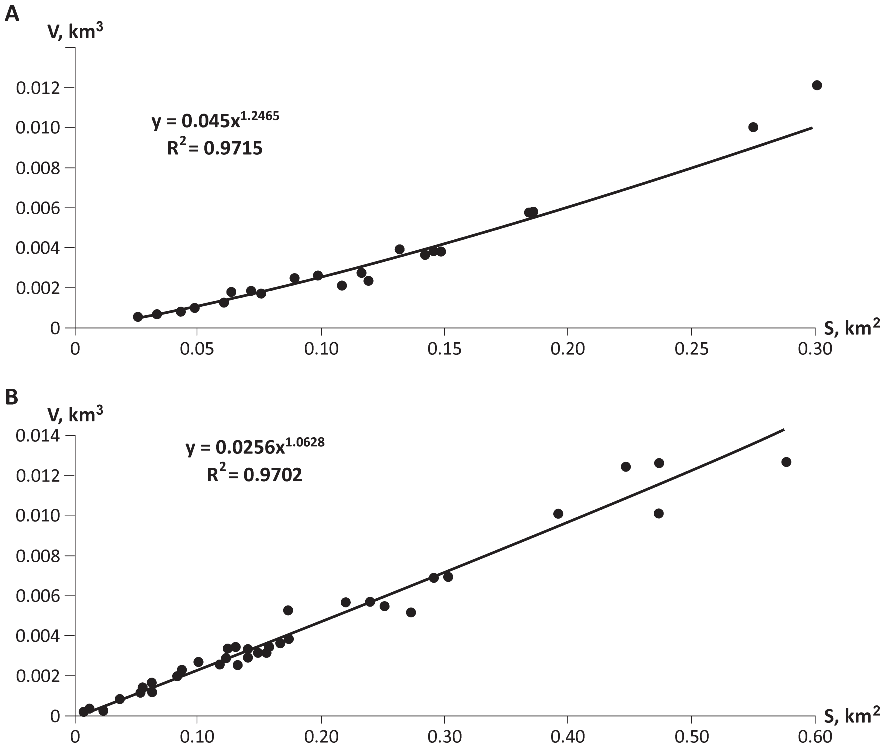

Fig. 7. Dependences of the glacier volume (V) on its area (S): A – Chukotka Highlands, B – Kolyma Highlands and Taigonos Peninsula

Discussion

We defined objects studied both with the use of satellite images and *in situ* (in the area of the Lawrence Bay, north of Chukotka Penisula and the Egvekinot Basin, Cross Gulf), as small forms of glaciation (SFG) – basically, corrie glaciers. These objects have significant supraglacial moraine cover; we saw glacial ice along the sides and in the front of the SFG. However, during field studies we did not have the possibility of drilling and echo-sounding, so we cannot say for sure what the ice content in them is, nor what volume the bodies of ice have.

These objects have signs of movement – crevasses, bergschrunds, uneven relief, moraine on their surface, etc. (Fig. 3).

Sedov personally visited all the glaciers listed in his papers; he identified these small glacier forms as active glaciers. He expressed doubt only with regard to the glaciers of the Lawrence Bay group (Fig. 1). In August 2017, during the survey of these glaciers, we concluded that the glaciers of this group are in the process of transition to rock glaciers. However, the question of how to distinguish a transitional form from an active glacier requires additional research.

A recent paper on this topic is Fischer's doctoral thesis (2018), which aims to: 1) evaluate the sensitivity to climate change of very small glaciers (VSG) of less than 0.5 km^2 in area, 2) measure the geodetic mass balance and the surface lowing by terrestrial laser scanning (TLS), and 3) compile a new glaciers catalogue of the Swiss Alps (update the previous one). In 2010, VSG accounted for 118 km^2 in area (13% of the total area of the glaciers), had an average thickness of 19 m, and accounted for a total ice volume of 2.18 km^3 (3.6% of the total volume of all glaciers). The horizontal surface velocity of VSG ice in Switzerland is usually of the order of several metres per year. Many VSG are currently exhibiting a polythermal temperature regime, and about one third are at least partially covered with detritus. The entire series of VSG in the Swiss Alps showed greater sensitivity to the observed climate changes compared to larger glaciers.

There are some features of the small glaciers of the Alps that are common with those studied in this work.

The question of whether continental SFGs are more sensitive than resistive to climate change is debatable; it can be answered by collecting and analysing new data. Another problem is to differentiate active glaciers covered with stones from rock glaciers, while deciphering the satellite images.

We identified groups of formations including various small glaciers and rock glaciers, and consider them as small forms of glaciation. We can assess their change (reduction) caused by climate change; it is also appropriate to take into account that there is an alternation between these formations within the SFG by transition from one form to another under climate change. As for transition of glaciers into rock glaciers, which are an important geomorphic element of glaciated mountain landscapes, there are problems associated with identifying rock glaciers on a morphological basis alone, which is amplified by the multiple ways in which rock glaciers can form in different glacial, periglacial, and paraglacial settings (Knight et al. 2019). Sometimes it is necessary to use echo-sounding and drilling on these bodies to understand their origin.

Rock glaciers are climatically more resilient than glaciers and contain potentially hydrologically valuable ice volumes. At decadal and longer timescales, under future climate warming, degradation of ice within rock glaciers may represent an increasing hydrological contribution to downstream regions (Jones et al. 2019). This is important for the Chukotka, Kolyma and Koryakia regions, already now and in the future.

Conclusions

This paper includes the results of field studies in the Chukotka Highlands and assessment of satellite images of the Chukotka and Kolyma highlands for various periods of time, as well as the use of DEMs. The aim of the work was to assess the main parameters of the glaciers of Chukotka and Kolyma – their size and volume, and changes therein over time – as well as discussing the state of small forms of glaciation in these regions.

Climate trends in the regions under study do not contribute to the development of glaciation: temperature trends are positive (+1–2 °C for almost 50 years), and the precipitation trend during the cold period is mostly negative (-50 mm). The trends in temperature and precipitation change at the weather stations of Chukotka and Kolyma are estimated.

The areas of glaciers are defined for the beginning of the 1980s to 2005 and up to 2017 by various satellite images and data from the R.V. Sedov catalogue. Glaciers of the Chantalsky Range and the Iskaten Range reduced most. Glaciers of the southern part of Chukotka Peninsula experienced the smallest reduction. Volumes are determined by the formulas of S.A. Nikitin for corrie glaciers, and by our own method: the average thickness of glaciers was calculated from the isohypses of the bed topography of the neighbouring valleys constructed by the ArcticDEM and the visible glaciers – by the DEM of individual glaciers made by UAV during field work and ArcticDEM. Basically, the changes in volumes are similar to those of areas of the glacier systems.

Volume/area formulas were obtained based on volume calculation of the Chukotka and Kolyma small forms of glaciation existing there. These data were sent to the GLIMS programme.

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No potential conflict of interest was reported by the authors.

Author contributions

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

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