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GEOLOGICAL CRYOGENIC PROCESSES AND FORMATIONS

MAPPING OF GIANT AUFEIS FIELDS IN THE NORTHEAST OF RUSSIA

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Aufeis fields are widespread in the northeast of Russia and exert a substantial impact on many components of landscapes. The public availability of Landsat and Sentinel-2 satellite data has opened up new opportunities for aufeis mapping. Based on satellite images, we have compiled an up-to-date GIS dataset of aufeis fields and analyzed the long-term and seasonal variability of the largest aufeis in the northeast of Russia. The synthesis of historical (aerial photography obtained in the middle of the 20th century) and modern satellite data on aufeis has been used to prepare a new cartographic product, the Atlas of Giant Aufeis (Taryns) of the Northeast of Russia. In this paper, we consider the approaches to aufeis mapping applied in the Atlas, the main characteristics of aufeis fields based on historical and satellite data. According to Landsat images obtained in 2013–2020, we have delineated 9306 aufeis fields with a total area of 4854.5 km^2. Among them, there are 1146 giant aufeis fields of more than 1 km^2 in area. For these aufeis fields, we have analyzed long-term and seasonal dynamics of their area based on satellite images obtained for the period from the 1970s to the present. On this basis, a series of image-based maps have been created and included in the Atlas. For most of the giant aufeis fields, no substantial reduction in their area since the 1970s has been found. The largest aufeis in the northeast of Russia is located in the Syuryuktyakh River basin; its area immediately after the snowmelt season is, on average, 14.4 km^2 larger than the area of the Bol'shaya Moma aufeis, which was previously considered as the largest aufeis in Russia.

Keywords: *aufeis fields, mapping, atlas, Landsat and Sentinel-2 satellite data, aufeis cadaster, GIS database, northeast of Russia.*

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INTRODUCTION

Aufeis is a form of terrestrial glaciation typical for mountainous areas in the permafrost zone. Aufeis fields are formed every year in the cold season as a result of layer-by-layer freezing of groundwater discharged to the surface. Aufeis forming near permanently active springs are called taryn (the term came from Yakut language). Aufeis-taryn may occupy considerable areas (up to 3–5% of the territory in some mountainous regions) and serve as a powerful regulator of groundwater flows and surface runoff [*Yoshikawa et al., 2007; Alexeev et al., 2011; Alexeev, 2016*]. The water reserves in aufeis of Russia amount to at least 50 km^3, which is almost equal to the annual runoff of the Indigirka River [*Sokolov, 1975*].

The most favorable conditions for the formation of aufeis-taryn, including giant ones, occupying the area of more than 1 km^2 [*Petrov, 1930*], are typical of the northeast of Russia (NER). The NER includes the basins of the Yana, Indigirka, Kolyma, Penzhina, rivers of the Okhotsk Sea basin running from the Suntar-Khayat Ridge, as well as the Anadyr River and other rivers of the Chukchi Peninsula.

The NER is characterized by predominantly mountainous relief, up to 3147 a.s.l., with the exception of the Yana-Indigirka and Kolyma lowlands. A larger part of the NER is located in the zone of subarctic continental climate with very cold winter (mean January air temperature is –36°C and below) and short warm summer [*National Atlas..., 2004*]. The entire territory, except for the coast of the Sea of Okhotsk, is located in the zone of continuous permafrost [*Geocryology of the USSR, 1989*]. The thickness of permafrost in the upper reaches of the Yana and Indigirka rivers is up to 350–500 m and more on the top mountain slopes; the depths of seasonal thawing are 0.9–1.3 m [*Geocryology of the USSR, 1989*].

A relevance of the study of aufeis is determined by their fundamental importance and by practical reasons. The history of their research in Russia has more than 100 years.

The first scientific paper in Russian language on the nature of aufeis phenomena was published in 1903 on the basis of the year-round permafrost and hydrogeological observations in South Yakutia [*Podyakonov, 1903*]. Studies of aufeis dramatically intensified at the turn of the 1920s and 1930s which was related to the organization of the Yakut Expedition of the Academy of Sciences of the Soviet Union and the study of water resources and transportation routes in eastern regions of the country. Thus, V.G. Petrov developed methods on dealing with groundwater aufeis located near road structures [*Petrov, 1930, 1934*]. N.I. Tolstikhin classified groundwater feeding aufeis in relation to the permafrost, clarified the definition of aufeis, and distinguished between suprapermafrost, permafrost, and subpermafrost water aufeis [*Tolstikhin, 1931*]. The works of V.P. Sedov and P.F. Shvetsov, in particular, the work [*Shvetsov, Sedov, 1941*], were crucial for the study of the NER aufeis. For the first time in the history of aufeis research, they created situational maps of aufeis fields with indication of the ice thickness distribution and sources of the aufeis formation. It was found that the main part of aufeis fields is formed by deep groundwater sources that discharge freely to the surface.

In the 1940s, attention to the study of aufeis-taryn in the NER increased due to the discovery and development of the richest mineral deposits (gold, tin, tungsten, uranium, etc.).

The works of [*Chekotillo, 1941; Zonov, 1944*] were most important. In the article [*Zonov, 1944*], the author considers aufeis in the entire Yana-Kolyma mountainous area and for the first time identifies and describes aufeis fields that do not melt away completely in summer. In the 1940s, the staff of the Dal'stroy expeditions made a great contribution to the study of permafrost and groundwater. The results of their long-term research were summarized by [*Simakov, 1949*]. The first map of aufeis in the Indigirka River basin was published [*Shvetsov, 1951*].

Regular observations of aufeis fields continued during a quarter of the century, generally, because of the effort of the staff of the Melnikov Permafrost Institute, SB RAS. For the first time, the maps of aufeis areas [*Sokolov, 1975*] and detailed aufeis zoning [*Tolstikhin, 1974, 1975*] were made for the NER. In the 1960s, special aufeis research sites were arranged on several rivers in the NER. The longest series of observations (from 1962 to 1992) was obtained at the Anmangynda aufeis research site organized by the Kolyma Administration for Hydrometeorological and Environmental Monitoring in 1962. Materials of the Anmangynda long-term observations are summarized in [*Alexeev et al., 2012*].

A hydrological role of aufeis and their contribution to the annual runoff distribution was determined. It was established that, in winter, aufeis accumulate up to 70% of subsurface runoff; in summer, the same amount of water enters the river network as a result of aufeis ablation. In most cases, the contribution of aufeis ablation to the annual river discharge is 3–7%, reaching 25–30% in some river basins with the highest aufeis percentage [*Sokolov, 1975; Reedyk et al., 1995*].

Since the early 1990s, the study of aufeis in the NER has ceased. However, at present, the practical importance of their study has increased due to the development of the Arctic regions. For example, aufeis negatively affects the stability of engineering constructions and complicates transport communication, which has been first shown in the works of the classics of geocryology [*Lvov, 1916; Sumgin, 1927; Petrov, 1930*]. Springs, which feed aufeis, may, in some cases, serve as the only source of water supply to settlements [*Simakov, 1949; Simakov, Shilnikovskaya, 1958; Alexeev, 1987*].

Aufeis zones of river valleys and aufeis themselves are well visible on aerial and satellite images. The use of the Earth remote sensing (ERS) data makes it possible to determine the boundaries of the aufeis landscapes and calculate the area of ice fields at a certain point in time during different stages of their development. This provides broad opportunities for the study of the distribution patterns and spatiotemporal variability of aufeis phenomena. The first large-scale studies in this direction were carried out in the NER in the middle of the 20th century. The Map of Aufeis in the NER on a scale of 1:2 M and the Cadaster of Aufeis, which is a supplement to the map, were compiled on the basis of the systematization of aerial photography in the 1940s and 1950s [*Simakov, Shilnikovskaya, 1958*]. They contained data on 7448 aufeis, the area of which ranged from 0.01 to 81.1 km^2 (the area was determined by aufeis glades). The materials were handwritten and kept in the archive of the Geological Administration in Magadan.

For the first time, satellite imaginary data on aufeis were applied in the 1970s [*Topchiev, 1979*]. Satellite images were also actively used during the construction of the Geocryological Map of the USSR, which was created in the early 1970s and completed in 1991 [*Geocryological Map..., 1996*]. This map demonstrates 5109 aufeis. The largest of them were given on a scale, the others were represented off-scale (by points). In 2013, these data were digitized, refined, and verified using the Landsat/ETM+ satellite images [*Prasolova et al., 2013*]. However, these digital data have not been published, which distinguishes aufeis from glaciers, for which there is an updated digital catalog [*GLIMS and NSIDC, 2017*].

In the recent decade, availability of Landsat and Sentinel-2 satellite data has significantly increased the ability to map aufeis. Thus, for the NER, data from Landsat-7, 8 satellites with a spatial resolution of 15 and 30 m have become available since 1999; the Landsat-1 (MSS sensor) data with a spatial resolution of 80 m have been obtained since 1973. This makes it possible not only to assess the current state of the aufeis, but also to analyze their long-term variability.

Like other snow-ice objects, aufeis are identified automatically on the basis of the normalized difference snow index NDSI [*Hall et al., 1995*] or more complex indices [*Morse, Wolfe, 2015*]. Some difficulties in the identification of aufeis on the images are related to their separation from the snow cover [*Pavelsky, Zarnetske, 2017; Makarieva et al., 2019*] and ice-covered water bodies [*Morse, Wolfe, 2015*]. However, these problems are successfully solved by the proper selection of images (the most informative images for the NER are those for the period from late May to mid-June), or through expert verification [*Makarieva et al., 2019*].

Public availability of satellite data and the opportunity to distinguish aufeis according to these data in a semiautomatic mode made it possible to create current cartographic databases of aufeis in river basins of the NER. Based on the synthesis of historical and modern materials on aufeis, the new cartographic product, the Atlas of Aufeis-Taryns in the Northeast of Russia, was prepared [*Alexeev et al., 2021*]. The present paper reports on the characteristics of the used data array and briefly discusses approaches to the mapping of aufeis on the basis of the cartographic and satellite data.

MATERIALS AND METHODS

Cartographic databases [*Makarieva et al., 2021a–d*] created by the authors of this work served as background information for aufeis mapping in the NER. The databases was formed with the use of two sources: the Map and Cadaster of aufeis in the northeast of the USSR [*Cadaster..., 1958; Simakov, Shilnikovskaya, 1958*] and the Landsat-8 satellite images. Specific features of these data and the methods of creating cartographic databases of aufeis were discussed in [*Makarieva et al., 2019*] using the Indigirka River basin as an example. It should be noted that only the actual area of ice, indicated on satellite images, was taken into consideration in this work. As a result, it turns out that the area of aufeis was 1.5–2.2 times smaller than in the Cadaster of 1958. The area of aufeis glades is significantly larger than the actual area of ice, but many of the aufeis glades remain partially or completely free of ice even at the beginning of the period of aufeis ablation.

Data on aufeis contained in the Cadaster (1958) are presented on the new map as point objects (with the area indicated in the Cadaster), while aufeis mapped on the basis of Landsat-8 images are presented as area objects (areas covered with ice at the time of the survey). By now, the database of aufeis has been created on the basis of Landsat images for the entire study territory, except for the Sea of Okhotsk coast.

The Landsat-8 images were downloaded from the USGS web service [*http://earthexplorer.usgs.gov*]. Images for the period of 2013–2020 were used for the aufeis mapping, but more than 50% of all data on aufeis were obtained from the images taken in 2016, when the stable period of low-cloudy weather was observed in early June. More than 130 scenes of Landsat-8 obtained in the first weeks after the loss of the snow cover were processed. The earliest date was May 15 and the latest was June 26. Data processing and interpretation of the aufeis distribution were carried out in the QGIS and ArcGIS packages.

To exclude erroneously selected objects and omissions of aufeis, the results of automated interpretation of aufeis were manually checked. This included determination of aufeis boundaries with the removal of snow-covered areas adjacent to aufeis, the removal of other ice objects, such as ice-covered lakes or riverbeds, and merging together parts of aufeis separated into pieces during ice melting. Such areas were considered as parts of a single aufeis if they were located within the same aufeis glade.

In total, 9306 aufeis with a total area of 4854.5 km^2 were identified within the study territory according to the images (Fig. 1). According to the Cadaster of 1958, there were 6704 on this territory, and their total area reached 9785 km^2. The correspondence of data on aufeis according to these two sources is presented in Table 1 for the five largest river basins of the study region.

Discrepancy between the total area of aufeis given in the Cadaster of 1958 and estimated from recent Landsat images is caused by the different accounting methods. In the Cadaster, the area of aufeis glades was estimated, while the Landsat images demonstrated the area covered with ice at the time of survey. The Landsat images were taken during the period of active melting of aufeis, so it was necessary to reconstruct their maximum area (before melting). This was done on the basis of data on the size category of aufeis and the number of days of the aufeis melting before the image was taken [*Sokolov, 1975*]. On average, the calculated maximum area of aufeis in the river basins was 15–30% larger than the area directly estimated from the images (Table 1).

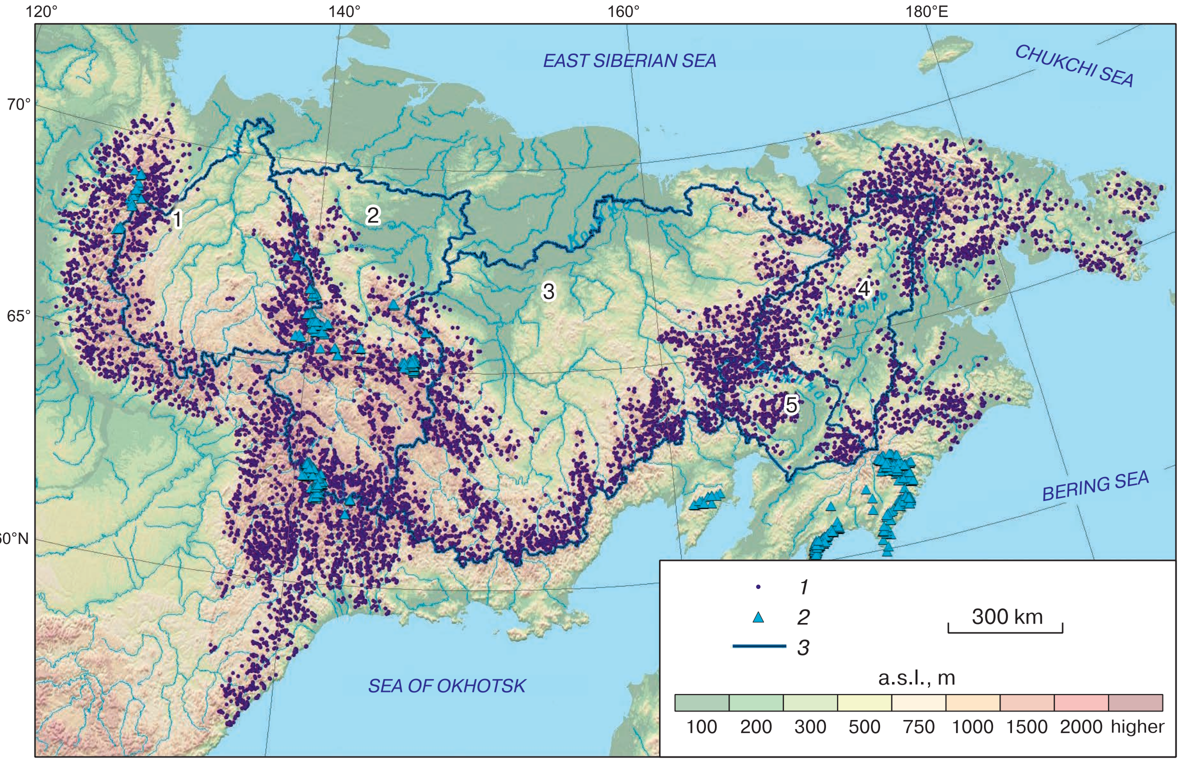

Fig. 1. Spatial distribution of aufeis in the northeast of Russia (excluding the northern coast of the Sea of Okhotsk) identified by the Landsat-8 satellite data.

(*1*) Aufeis (according to Landsat data), (*2*) glaciers (according to GLIMS data), (*3*) boundaries of river basins. Basins of large rivers: 1 – Yana, 2 – Indigirka, 3 – Kolyma, 4 – Anadyr, 5 – Penzhina.

Selective comparison of the reconstructed aufeis area with the area of aufeis glades gives ambiguous results. In most cases, the reconstructed area is close to the area of aufeis glades. However, there are numerous aufeis glades, for which the reconstructed area is several times smaller than the area of aufeis glade. In such cases, the aufeis in the images usually look like several ice massifs within one vast glade, and the total area of ice is many times smaller than the area specified in the Cadaster. Such aufeis presumably belong to the areas with extinction of aufeis processes according to the classification [*Zonov, 1944*]. However, to estimate real temporal changes in their area, additional studies of the images obtained in different years are required. The largest aufeis which demonstrate the signs of extinction are located in the Chukchi Peninsula.

Therefore, according to the modern data, the number of aufeis is greater than that indicated in the Cadaster of 1958, but their total area is significantly smaller. A similar result was obtained earlier for the Indigirka River basin [*Makarieva et al., 2019*]. How-

Table 1. **Comparison of Cadaster [*1958*] and Landsat image data on the number of aufeis areas within the five largest river basins in the NER**

River basin–outlet	Number and area (km^2) of aufeis according to the Cadaster of 1958		Number and area (km^2) of aufeis according to Landsat images		
	aufeis confirmed by Landsat images (by the presence of ice)	aufeis unconfirmed by Landsat images	aufeis confirmed by the Cadaster	aufeis absent in the Cadaster	maximum calculated aufeis area
Yana–Yubileiny	268 (616.4)	117 (122.2)	262 (309.8)	320 (102.4)	513.8
Indigirka–Vorontsovo	605 (1845.8)	243 (140.1)	582 (974.9)	572 (238.6)	1627.4
Kolyma–Chersky	1100 (1605.3)	662 (332.6)	1072 (714.2)	1138 (164.4)	1163.5
Anadyr–3 km upstream the Utesiki River	357 (661.2)	147 (101.7)	351 (280.6)	399 (71.4)	396.5
Penzhina–mouth	302 (410.9)	122 (125.5)	288 (106.5)	250 (48.7)	189.5

ever, this difference may well be related to the aforementioned differences in the approaches to the assessment of aufeis area rather than to a real decrease in the area of aufeis.

Creation of the maps of the spatial distribution of aufeis

An important indicator of the spatial distribution of aufeis and their significance for the hydrological regime of the territory is the aufeis percentage (aufeis area, % of the total area of the territory). It was calculated by two methods: in cells of a regular grid of 50 × 50 km and as an average for local catchments. In the first method, for each cell, the areas of all aufeis fields were summarized, and then the obtained values of the aufeis percentage were interpolated from a center of each cell. The tension spline method was used for interpolation.

The second method assumed the preliminary construction of a scheme of catchments. For this purpose, a thalweg network was created on the basis of the GMTED-2010 global digital elevation model (DEM) with a cell size of 230 m [*Danielson, Gesch, 2011*]. In further calculations, only those thalwegs, for which the catchment area exceeded 1000 DEM cells (approximately 50 km^2), were taken into consideration. All objects of the third and higher orders were selected from these thalwegs according to the Horton–Strahler scheme [*Strahler, 1952*], and then their catchment boundaries were plotted in automatic mode. Considering the low spatial resolution of the initial DEM, the manual editing of the selected catchment areas was necessary in many cases. Verification was performed by matching the selected catchment boundaries and the hydrographic network with the digital cartographic base of VSEGEI on a scale 1:2.5 M [*http://vsegei.com/ru/info/topo/*]. The percent of aufeis area of the total local catchment area was calculated at the next stage. The calculation was made both on the basis of historical data [*Cadaster..., 1958*] and recent satellite images.

ANALYSIS OF CARTOGRAPHIC MATERIALS PRESENTED IN THE ATLAS

The Atlas of Aufeis-Taryns in the Northeast of Russia presents the maps of the aufeis distribution compiled according to the Cadaster (1958) data and on the basis of Landsat images (for the latter, the minimum area is 1 ha). Aufeis in the basins of the main rivers of the NER (Indigirka, Yana, Kolyma, Anadyr), Chukotka rivers (Amguema, Lyulyuveem, Palyavaam), and the largest rivers of the Sea of Okhotsk basin (Penzhina, Ulbeya, Nyadbaki) have been mapped. The Atlas includes the maps of aufeis-taryn distribution in the basins of the largest rivers (Fig. 1) and their local catchments, the maps of the aufeis percentage in the large river basins (Fig. 2), the maps of

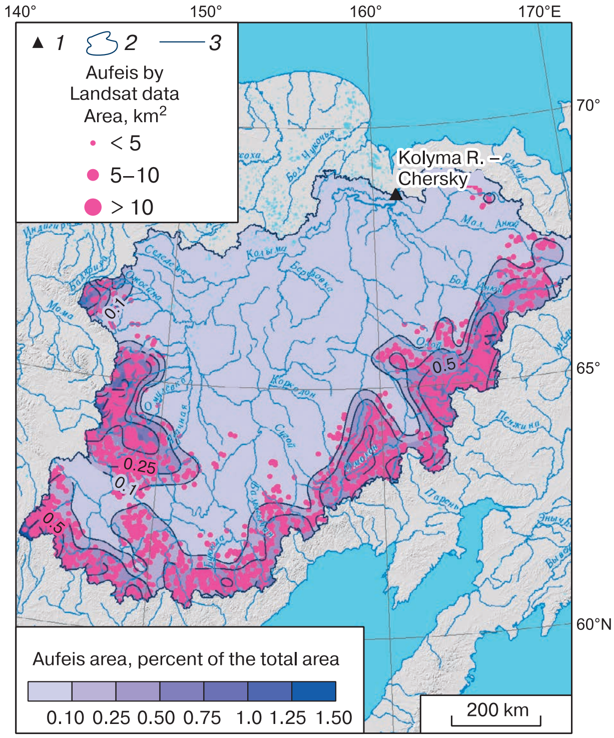

Fig. 2. Aufeis percentage in the Kolyma River basin according to Landsat-based data.

1 – Gauging stations, *2* – the Kolyma River basin, *3* – isolines of the aufeis percentage.

the aufeis percentage as a function of the river length for the main river basins, and a series of maps created on the basis of satellite imagery and characterizing the current state and dynamics of giant aufeis.

In addition, during expeditions of 2020–2021, we surveyed some aufeis glades in the basins of the Indigirka and Kolyma rivers from an unmanned aerial vehicle (UAV). The orthophoto maps of the Anmangynda aufeis and aufeis in the Kyubyume River basin [*Makarieva et al., 2021e*] and other objects were prepared on the basis of these data. They are also presented in the Atlas.

The map of aufeis resources (Fig. 3) gives the general characteristics of the water reserves that can be accumulated in the NER aufeis. Such a map was first published in the Atlas of Snow and Ice Resources of the World [*1997*] on the basis of data obtained by B.L. Sokolov. Aufeis resources (measured in millions of cubic meters per 1000 km^2) were calculated for the largest river basins of the NER.

The maximum aufeis percentage within the study area is typical of the Indigirka River basin and especially of some of its tributaries flowing down from the Chersky Ridge. The Syuryuktyakh River basin is characterized by the highest aufeis percentage (over 3%) in the NER.

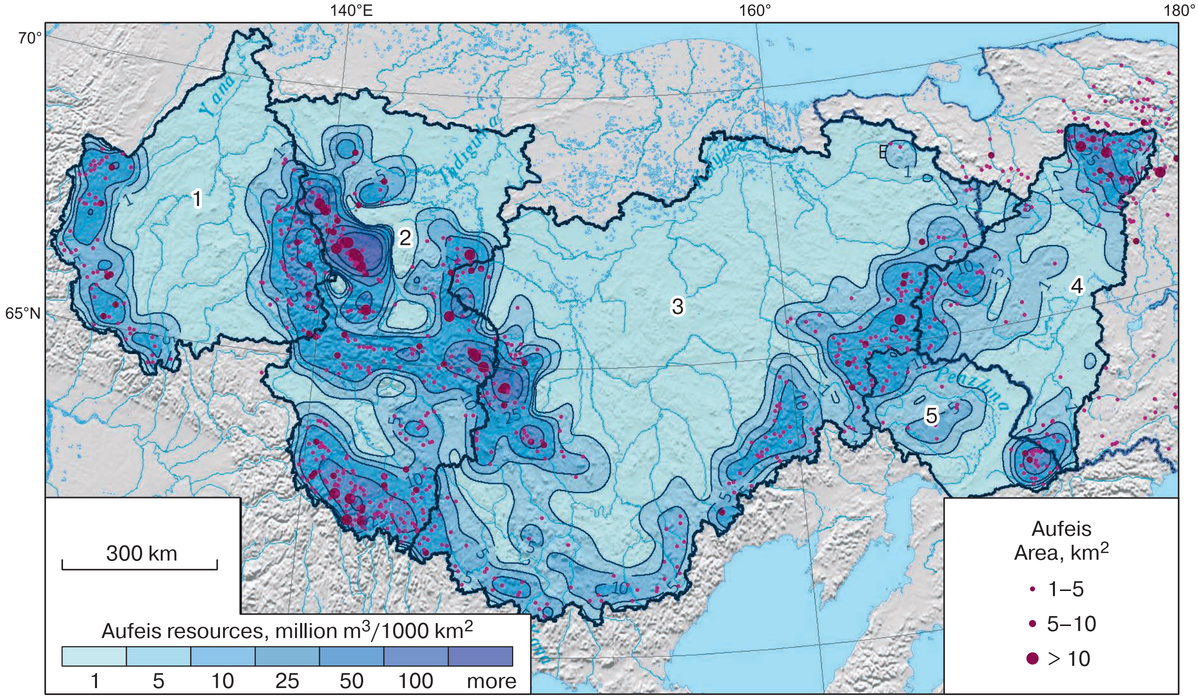

Fig. 3. Aufeis resources in the basins of the Yana (1), Indigirka (2), Kolyma (3), Anadyr (4), and Penzhina (5) rivers calculated on the basis of the Landsat-8 data.

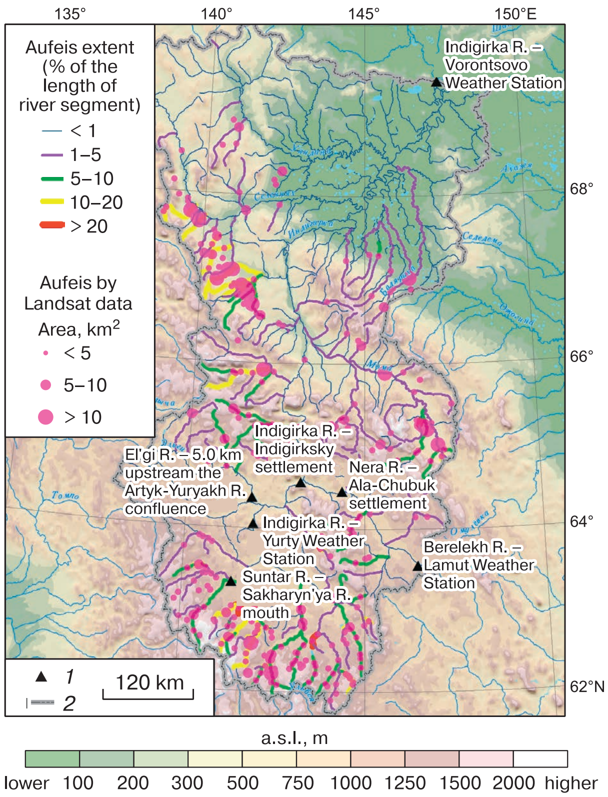

Fig. 4. Relative percentage of aufeis length along the river length in the Indigirka River basin.

1 – Gauging stations, *2* – catchment boundaries.

Taking into account aufeis fields obtained from satellite data and the VSEGEI cartographic base [*http://vsegei.com/ru/info/topo/*], the aufeis percentage along the length of the rivers was calculated (Fig. 4). This parameter characterizes the spatial distribution of aufeis along streams in general and has a high correlation with the aufeis percentage in the river basins.

Taking into consideration a low accuracy of the cartographic base, the aufeis percentage was assessed not for the streams themselves but for the 500-m-wide buffer zone around them. The width of the chosen buffer zone corresponds to the possible displacement of a stream according to the cartographic data relative to its true position.

According to V.G. Petrov's classification, giant aufeis are defined as aufeis having an area of more than 1 km^2 [*Sokolov, 1975*]. Overall, 1146 such aufeis have been detected in the NER. For 42 of them, the maximum calculated aufeis area exceeds 10 km^2. This estimate is significantly lower than that previously obtained on the basis of the area of aufeis glades. Therefore, in [*Ivanova, Pavlova, 2018*], 36 aufeis were identified in the Indigirka River basin and 14 aufeis in the Yana River basin with the area of more than 10 km^2. The most significant group of seven aufeis with the area of more than 10 km^2 is located in the Syuryuktyakh River basin, where the aufeis percentage exceeds 2%, according to satellite data.

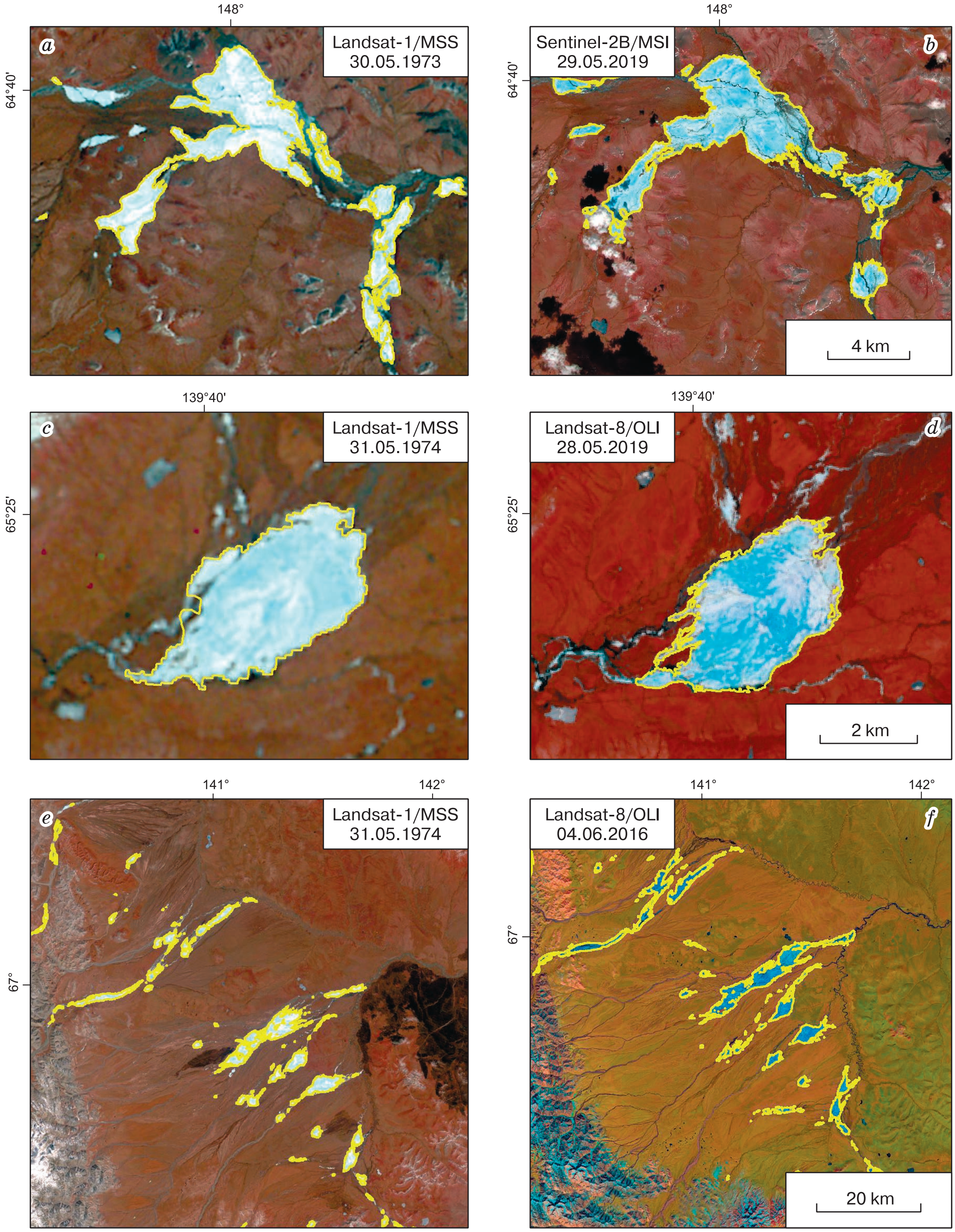

Fig. 5. Changes in the area of individual giant aufeis in the basins of the Kolyma (*a, b*), Yana (*c, d*) and Indigirka (*e, f*) rivers between 1973, 1974 and 2016, 2019 according to the Landsat and Sentinel-2 images.

Ice area (km^2): *a* – 35.7, *b* – 35.3, *c* – 9.2, *d* – 7.9, *e* – 163.3, *f* – 223.0.

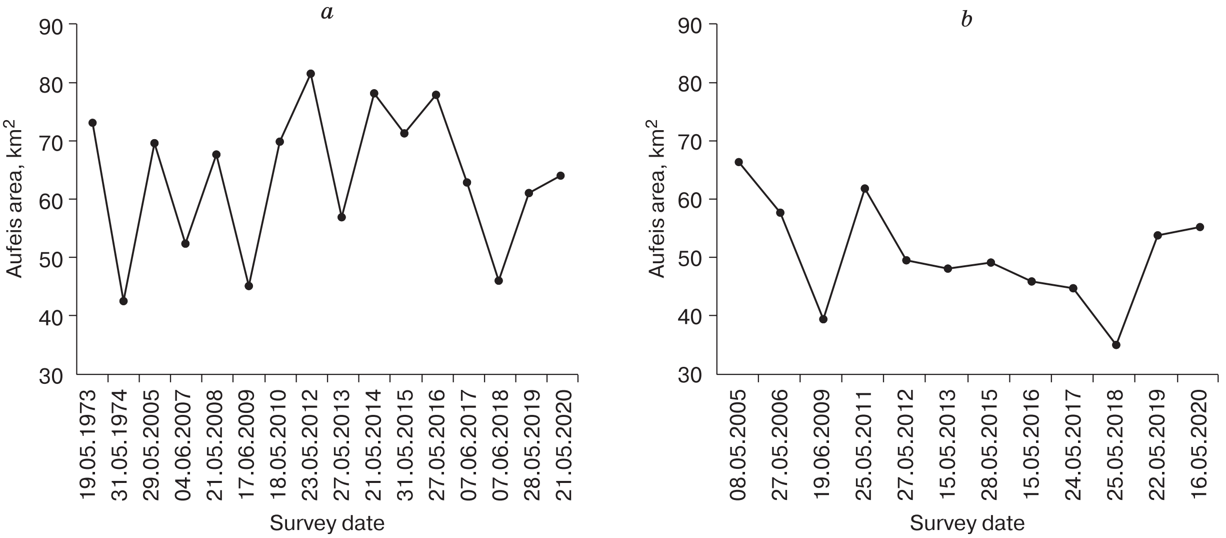

Fig. 6. Interannual variability of the area of the (*a*) largest aufeis in Syuryuktyakh River basin and (*b*) Bolshaya Moma aufeis at the end of spring (2005–2020) according to Landsat-7, 8 and Sentinel-2 images.

The Atlas considers single giant aufeis or their groups. For each giant aufeis in the Atlas, the long-term and interannual variability was analyzed on the basis of Landsat-1–8 and Sentinel-2 images, and series of maps and schemes were plotted. According to the dictionary [*Baranov et al., 1999*], these maps can be referred to as image-based maps.

The general view of an aufeis glade delineation of the aufeis proper during the periods of its maximum development (in the absence of snow cover) and maximum melting was based on the Sentinel-2 images in natural colors with a spatial resolution of 10 m. The maximum and minimum aufeis areas were determined using data for one specific year, not for the entire observation period.

The image-based maps of dynamics of the aufeis area in the initial period of ablation are based on multi-temporal Landsat images for the period from 1974 to 2020 (Fig. 5). They characterize the change in the maximum area of aufeis determined after the loss of the stable snow cover. Based on a series of the Landsat images for the period of 2000–2020, it was established that the average area of the largest aufeis in the Syuryuktyakh River basin during the period of its maximum development (64.9 km^2) is significantly larger than the area of the Big Moma aufeis (50.5 km^2), which was previously considered as the largest aufeis in Russia (Fig. 6).

The image-based maps of the aufeis area dynamics during the ablation were prepared using Sentinel-2 images for 2019. For this purpose, the images were selected from the moment of the snow loss in May–early June to the maximum ice melting in August–September. The aufeis were identified according to the method [*Makarieva et al., 2019e*] adopted for the Sentinel-2 images.

CONCLUSIONS

Aufeis-taryn are important element of mountainous landscapes in northeastern Asia and a powerful factor in the transformation of the environment. The development of the cartographic database and the Atlas of aufeis-taryns opens a new stage in the study of this phenomenon. The maps presented in the Atlas, demonstrate the location and size of ice fields 50–70 years after their first identification on aerial photos in the late 1940s.

The obtained characteristics of aufeis, including data on intra-annual and interannual variability of some of them, are the most important sources of information for analysis of current changes in the climatic and geocryological and hydrogeological conditions of the region. Estimates of the maximum aufeis percentage for river basins and the volume of aufeis resources can become the basis for determining the contribution of aufeis to the river discharge in the NER.

The comparison of aufeis characteristics according to data of the Cadaster of 1958 and modern satellite images (despite ambiguity of comparing these data sources) confirms that, over the last 50–70 years, the spatial distribution and the aufeis area has changed in the NER. However, it is difficult to accurately estimate these changes due to the differences in the methods of estimating the aufeis area. The reasons for these changes have not yet been analyzed, and their identification requires a comprehensive interdisciplinary study [*Makarieva et al., 2021e*].

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References

Alexeev V.R., 1987. Aufeis. Novosibirsk, Nauka, 159 p. (in Russian).

Alexeev V.R., 2016. Long-term variability of the spring taryn-aufeise. *Led i Sneg* **56** (1), 73–93 (in Russian).

Alexeev V.R., Boyarintsev E.L., Dovbysh V.N., 2012. Long-term dynamics of the size of the Anmangynda aufeis under climate change. Modern problems of stochastic hydrology and flow regulation. In: *Proc. All-Russia Sci. Conf. Dedicated to the Memory of A.V. Rozhdestvensky (Moscow, April 10–12, 2013)*. Moscow, p. 298–305 (in Russian).

Alexeev V.R., Gorin V.V., Kotov S.V., 2011. Aufeis-taryns of northern Chukotka. *Led i Sneg* **116** (4), 85–93 (in Russian).

Alexeev V.R., Makarieva O.M., Shikhov A.N., Nesterova N.V., Ostashov A.A., Zemlyanskova A.A., 2021. Atlas of Giant Aufeis-Taryns in Northeast of Russia. Novosibirsk, SB RAS, 302 p. (in Russian).

Atlas of Snow and Ice Resources of the World, 1997. Institute of Geography RAS. Moscow, Nauchnyi Mir, 371 p. (in Russian).

Baranov Yu.B., Berlyant A.M., Kapralov E.G., Koshkarev A.V., Serapinas B.B., Filippov Yu.A., 1999. Geoinformatics. Explanatory Dictionary of Basic Terms. Moscow, GIS-Association, 204 p. (in Russian).

Cadaster to the Map of Aufeis in Northeast of the USSR. Scale 1:2 M, 1958. Magadan, Central Thematic Expedition of the Northeastern Geological Department, 398 p. (in Russian).

Chekotillo A.M., 1941. The region of great icing (icing of Eastern Yakutia). *Byull. Akad. Nauk SSSR, Ser. Geol*., No. 1, 94–113 (in Russian).

Danielson J.J., Gesch D.B., 2011. Global Multiresolution Terrain Elevation Data 2010 (GMTED2010). U.S. Geological Survey Open-File Rep. 2011–1073, 26 p.

Geocryological Map of the USSR on a Scale of 1:2.5 M. E.D. Ershov (Ed.), 1996. Vinnitsa (Ukraine), State Cartographic Factory, 16 sheets.

Geocryology of the USSR. Eastern Siberia and the Far East. E.D. Ershov (Ed.), 1989. Moscow, Nedra, 516 p. (in Russian).

GLIMS and NSIDC: Global Land Ice Measurements from Space Glacier Database. NSIDC, Boulder CO, USA. – https://doi.org/10.7265/ N5V98602, 2005 (updated 2017).

Hall D.K., Riggs G.A., Salomonson V.V., 1995. Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer (MODIS) data. *Remote Sens. Environ.* **54**, 127–140.

Ivanova L.D., Pavlova N.A., 2018. Formation and dynamics of aufeis in the Indigirka River basin in the last sixty years. In: *Proc. All-Russia Workshop Groundwater in the East of Russia* (XXII Meeting on Groundwater in Siberia and the Far East with International Participation, Novosibirsk, June 18–22, 2018). Novosibirsk, Izd. Novosib. Gos. Univ., 218–222 (in Russian).

Lvov A.V., 1916. Search and Testing of Water Supply Sources in the Western Part of the Amur Railway under Conditions of Permafrost. Irkutsk, Tip. P.I. Makushina & V.M. Posokhina, 881 p. (in Russian).

Makarieva O.M., Shikhov A.N., Ostashov A.A., Nesterova N.V., 2019. Historical and recent aufeis in the Indigirka River basin (Russia). *Earth Syst. Sci. Data* **11** (1), 409–420.

Makarieva O.M., Shikhov A.N., Ostashov A.A., Nesterova N.V., Zemlyanskova A.A., Semakina A.V., Alexeev V.R., 2021a. *Certificate of State Registration of Database No. 2021620267. Aufeis of the Northeast of Russia: GIS Catalog for the Chukchi Peninsula, Russian Federation*. Publ. February 12, 2021. – https://www1.fips.ru/registers-doc-view/fips_servlet?DB=DB&DocNumber=2021620267&TypeFile=html (in Russian).

Makarieva O.M., Shikhov A.N., Ostashov A.A., Nesterova N.V., Zemlyanskova A.A., Alexeev V.R., 2021b. *Certificate of State Registration of Database No. 2021620317. Aufeis of the Northeast of Russia: GIS Catalog for the Indigirka River Basin, Russian Federation*. Publ. February 24, 2021. – https://www1.fips.ru/registers-doc-view/fips_servlet?DB=DB&DocNumber=2021620317&TypeFile=html (in Russian).

Makarieva O.M., Shikhov A.N., Ostashov A.A., Nesterova N.V., Zemlyanskova A.A., Alexeev V.R., 2021c. *Certificate of State Registration of Database No. 2021620317. Aufeis of the Northeast of Russia: GIS Catalog for the Kolyma River Basin, Russian Federation*. Publ. February 26, 2021. – https:// www1.fips.ru/registers-doc-view/fips_servlet?DB=DB&DocNumber=2021620332&TypeFile=html (in Russian).

Makarieva O.M., Shikhov A.N., Ostashov A.A., Nesterova N.V., Zemlyanskova A.A., Alexeev V.R., 2021d. *Certificate of State Registration of Database No. 2021620317. Aufeis of the Northeast of Russia: GIS Catalog for the Kolyma River Basin, Russian Federation*. Publ. February 26, 2021. – https://www1.fips.ru/registers-doc-view/fips_servlet?DB=DB&DocNumber=2021620333&TypeFile=html (in Russian).

Makarieva O.M., Nesterova N.V., Ostashov A.A., Zemlyanskova A.A., Tumskoy V.E., Gagarin L.A., Ekaykin A.A., Shikhov A.N., Olenchenko V.V., Khristoforov I.I., 2021e. Perspectives of the development of complex interdisciplinary hydrological and geocryological research in the northeast of Russia. *Vestn. St. Petersburg Univ., Earth Sciences* **66** (1), 74–90.

Morse P.D., Wolfe S.A., 2015. Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada. *J. Geophys. Res.: Earth Surface* **120** (9), 1670–1686.

National Atlas of Russia. Vol. 2. Nature and Ecology. A.A. Klochko, M.A. Romanovskaya (Eds.), 2004. Moscow, GOSGISTSENTR, 495 p. (in Russian).

Pavelsky T.M., Zarnetske J.P., 2017. Rapid decline in river icings detected in Arctic Alaska: Implications for a changing hydrologic cycle and river ecosystems. *Geophys. Res. Lett.* **44** (7), 3228–3235.

Petrov V.G., 1930. Aufeis on the Amur–Yakutsk Highway. Leningrad, Izd. Akad. Nauk SSSR & Avtodor. Inst. NKPS SSSR, 177 p. (in Russian).

Petrov V.G., 1934. Experience in determining the force of groundwater pressure in ice. In: *Proc. Commission for the Study of Permafrost*. Moscow, Izd. Akad. Nauk SSSR, vol. 2, 59–72 (in Russian).

Podyakonov S.A., 1903. Aufeis in Eastern Siberia and the causes of their occurrence. *Izvest. Ross. Geogr. Obshchestva* **39**, 305–337 (in Russian).

Prasolova A.I., Pizhankova E.I., Yakovenko E.D., 2013. Development of satellite image interpretation technique for updating the layer of aufeis on the digital geocryological map of Russia. In: *Conf. Geocryological Mapping: Problems and Prospects,* Moscow, RUDN, p. 121–124 (in Russian).

Reedyk S., Woo M.K., Prowse T.D., 1995. Contribution of icing ablation to streamflow in a discontinuous permafrost area. *Canad. J. Earth Sci.* **32**, 13–20.

Shvetsov P.F., 1951. Groundwater of the Verkhoyansk–Kolyma Mountainous Fold Area and Features of Its Manifestation Associated with Low-Temperature Permafrost. Moscow, Izd. Akad. Nauk SSSR, 279 p. (in Russian).

Shvetsov P.F., Sedov V.P., 1941. Giant Aufeis and Ground Water of the Tas-Khayata Ridge. Moscow; Leningrad, Izd. Akad. Nauk SSSR, 81 p. (in Russian).

Simakov A.S., 1949. Some data on the aufeis in the Kolyma–Indigirka region. In: *Materials on Geology and Mineral Resources of the Northeast of the USSR*. Magadan, vol. 6, p. 66–80 (in Russian).

Simakov A.S., Shilnikovskaya Z.G., 1958. The Map of Aufeis in the Northeast of the USSR. A Brief Explanatory Note. Magadan, Northeastern Geol. Survey, Dept. Geol. Subsoil Protection, 40 p. (in Russian).

Sokolov B.L., 1975. Aufeis and Streamflow. Leningrad, Gidrometeoizdat, 190 p. (in Russian).

Strahler A.N., 1952. Hypsometric (area-altitude) analysis of erosional topology. *Geol. Soc. Am. Bull.* **63**, 1117–1141.

Sumgin M.I., 1927. Permafrost of Soil within the USSR. Vladivostok, Dal'nevost. Geofizich. Observatoriya, 372 p. (in Russian).

Tolstikhin N.I., 1931. Groundwater in permafrost Regions. In: *Reports at the 1st All-Union Hydrological Congress*. Leningrad, Geolgiz, 5 p. (in Russian).

Tolstikhin O.N., 1974. Aufeis and Groundwater in the Northeast of the USSR. Novosibirsk, Nauka, 164 p. (in Russian).

Tolstikhin O.N., 1975. Aufeis and groundwater in the northeast of the USSR. In: *Study and Protection of Water Resources*. Moscow, Nauka, 18 p. (in Russian).

Topchiev A.G., 1979. Space methods in studying the valleys and aufeis of the Chulman region. In: *Problems of Geography*. Vol. 3. Geomorphology and Construction. Moscow, Mysl, p. 46–54 (in Russian).

URL: http://earthexplorer.usgs.gov (last visited: July 22, 2021).

URL: http://vsegei.com/ru/info/topo/ (last visited: July 22, 2021).

Yoshikawa K., Hinzman L.D., Kane D.L., 2007. Spring and aufeis (icing) hydrology in Brooks Range, Alaska. *J. Geophys. Res. Biogeosci.* **112**, 1–14.

Zonov B.V., 1944. Aufeis and aufeis fields on the rivers of the Yana–Kolyma mountainous country. In: *Proc. V.A. Obruchev Permafrost Institute, USSR Acad. Sci.* Moscow, Izd. Akad. Nauk SSSR, vol. **IV**, p. 33–92 (in Russian).

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