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SURFACE AND GROUND WATERS IN TERRESTRIAL PERMAFROST REGION

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CLIMATE-RELATED CHANGES IN THE RUNOFF OF POLAR RIVERS IN WESTERN CHUKOTKA

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The current changes in the runoff of the polar rivers in Western Chukotka (the basin of the East Siberian Sea), associated with the current climate warming in Arctic regions, have been studied. On the basis of the long-term observations of the hydrometeorological regime, an increase in the runoff for most of the rivers has been revealed. The reason of that is climate warming in the Arctic Circle, which, along with the growth of atmospheric precipitation, activates the thawing of the perennial snowfields, high mountain ground ice, and other types of ice of the hydrocryogenic reserve in the rock glaciers and other clastic rocks, where thaw waters are involved in the water exchange. The significance of the geodynamic nature of drained terranes for the river feed has been clarified. The patterns of the accumulation and distribution of the components of the hydrocryogenic reserve in the formation of the river runoff have been considered.

Basin of the East Siberian Sea, climate warming, river runoff, permafrost zone, seasonal thawing layer, hydrocryogenic reserve

INTRODUCTION

The territory of Chukotka Autonomous Okrug was included in the Arctic lands as the Eastern Arctic Sector by decree of President of Russia No. 296 of May 2, 2014 [*State report..., 2018*]. This has resulted in the significant increase in public and private investments in all areas of economic activity. Western Chukotka has become one of the most attractive for the investments. This area is drained by the Anyui River and rivers of the Chaun Bay basin of the East Siberian Sea. The watershed of these rivers is situated to the north of the Arctic Circle and, therefore, referred to polar regions. More than 80 years ago, the tin deposits and, later, the large gold placers were discovered in the valleys of the Malyi and Bolshoi Anyui, Palyavaam rivers; the deposits of ore gold, silver, copper, uranium were explored too [*Volkov et al., 2006*]. The development of mineral resources needs the expansion and improvement of infrastructure networks and calls for solution of the disposal problem for both industrial and radioactive waste [*Tynankergav et al., 2019*]. The effectiveness of these tasks depends on the knowledge of the formation patterns of the river runoff and its changes under current global transformations of the natural environment. These changes were most evident at the end of 20th century, after 1980 [*Ponomarev et al., 2005; Katzov, Porfir'ev, 2012; WMO statement..., 2016; Stochkute, Vasilevskaya, 2016; Ushakov, 2017*]. Many works have been dedicated to the study of the role of climatic transformations in the hydrological characteristics of the northern rivers [*Tananaev et al., 2016; Lamontagne-Hallé et al., 2018; Makarieva et al., 2019*]. However, the features of climatic changes of the polar river runoff have not be studied until now. The authors could not find the publications on this issue both in Russia and abroad. Therefore, this study, most likely, is the pioneering work on this subject.

The purpose of this work is to study changes in the long-term regime of the polar river runoff in the mountain area of Western Chukotka (the basin of the East Siberian Sea) under conditions of current climate warming.

The objects of the study are the polar mountain rivers of Western Chukotka (the basin of the East Siberian Sea). Duration of hydrological observations for these rivers is no less than two 11-year periods of solar activity. This allows us to estimate the river runoff before and after 1980 and to reveal the features of its formation. The subject of the research is the runoff regime of the aforementioned rivers.

MATERIALS AND METHODS

The published materials on the long-term runoff observations on the hydrological posts of the Kolyma, Pevek, and Chukotka meteorological departments on hydrometeorology and environmental monitoring [*Long-term data..., 1985*] and data, derived from the

State Water Cadaster yearbooks, have been used in the work. The data on air temperature and amount of precipitation have been obtained from the electronic database on the site of All-Russian Research Institute of Hydrogeological Information–World Data Center [http://meteo.ru/data]. The data on climatic characteristics, recorded before 1960, have been derived from the reference book [*Klyukin, 1960*]. The changes in the river runoff have been studied by comparison of its average characteristics, row-counted up to and including 1980 and from 1981 to 2010. To calculate relevant norms, climatologists use observations over the last full three calendar decades. Therefore, the authors selected the period from 1981 to 2010. The statistical significance of intra-row homogeneity on average has been estimated on the basis of the Student's criterion with a significance level of 5 %. The data on hydrometeorological, hydrogeological, geocryological, geological conditions, which had been formerly published in some monographs and articles, have been used.

The basic method of the study is the system analysis, when the watershed area of the river at the outlet section is considered as a system including the following elements: water flow in a river channel; permafrost; a seasonal thawing layer; river-channel taliks; a block of the lithosphere, drained by a river; landscape of a river valley. Mountains and highlands in the study area are characterized by the heterogenous distribution of atmospheric precipitation, temperature of air and underlying surface both in the area and altitude belts [*Afanasenko et al., 1989*]. Under these conditions, the climatic parameters, which have been obtained on individual meteorological stations (MS) in the river valleys and on the sea coast, allow us to evaluate only qualitatively the participation of the watershed elements in the formation of the river runoff and their change during climate warming. Therefore, the studied problem can be appropriately referred to weakly structured or even unstructured issue, which can be most efficiently dissolved by means of the expert assessments [*Anokhin, 1996*].

CHARACTERISTICS OF THE OBJECT AND THE SUBJECT OF RESEARCH

The rivers of the considered area have started to be studied in the 1950s, after the discovering the gold-bearing capacity of the river valleys of Chukotka. By now, the statistically significant data on the runoff of the Chukotka rivers, recorded after 1980, have been received for nine hydrological posts in the polar part of the East Siberian Sea basin 320 000 km^2 in area (Table 1, Fig. 1). The hydrological posts are located on stream flows with the watershed area of less than 30 000 km^2. Totally, their area is 64 500 km^2, i.e. about 20 % of the entire considered area.

The studied mountain rivers and creeks are characterized by the uneven distribution of the runoff within the year. The basic volume (94–99 %) of water in the rivers flows in May–September; the period of the open channel lasts 4–4.5 months. Rainfall floods are usually observed at the end of June–the begin-

Table 1. **The data on the hydrological posts**

No. (Fig. 1)	River – post	Watershed area, km^2	Years of runoff observations	
			the beginning	the end
1	Berezovka – Berezovka village	15 400	1965	2010
2	Peimyna – in 1.5 km from the mouth	1480	1968	1994
3	Baimka – Baimka settlement	480	1963	2000
4	Malyi Anyui – Ilirnei settlement	8180	1958	1999
5	Malyi Anyu – Ostrovnoye village	30 000	1960	1997
6	Mukhtuya – Ostrovnoye village	23.7	1960	2006
7	Pogynden – the mouth of the Inkuliveem River	12 000	1960	valid
8	Inkuliveem – in 2.0 km from the mouth	242	1960	valid
9	Palyavaam – in 0.8 km downstream of the mouth of the Kookvyn River	6810	1971	1996

Note. The data were taken for current posts for 2010.

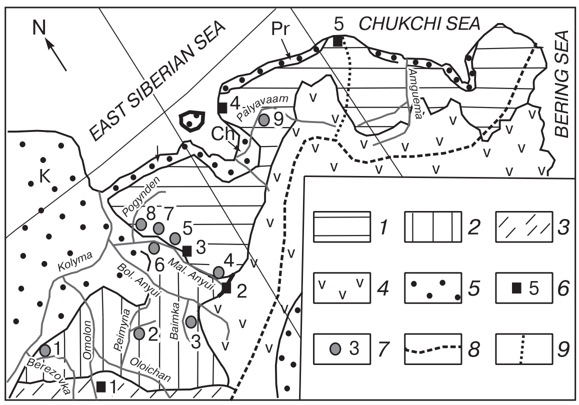

Fig. 1. Geographical-geological scheme of the polar part of Western Chukotka:

1–4: the mountain territories on the basis of tectonic: *1* – the Chukotka terrain of the passive continental margin, *2* – the Anyui-Oloi system of the terrains of the active margin, *3* – the Omolon craton, *4* – the Cretaceous effusive covers; *5* – lowlands: K – Kolymskaya, Ch – Chaunskaya, Pr – Primorskaya; *6* – meteorological stations (numbers are given according to Table 2); *7* – posts (numbers are given according to Table 1); *8* – the main watershed; *9* – the watershed of the rivers of the Arctic seas.

Table 2. **The mean annual air temperatures (*T*, °C) and the amount of precipitation (mm) on Western Chukotka**

No. (Fig. 1)	Meteostations	Coordinates	Abs. elevation, m	Period of observation	Before 1960		1961–1980		1981–2019	
					T	Precipitation	*T*	Precipitation	*T*	Precipitation
1	Omolon settl.	65°14′ N, 160°32′ E	260	1944–2009	–13.2	256	–12.8	261	–11.6	252
2	Ilirnei settl.	67°20′ N, 168°11′ E	426	1945–2009	–13.3	240	–12.4	264	–11.6	266
3	Ostrovnoye vill.	68°06′ N, 164°10′ E	98	1965–2019	–12.0	182	–11.8	227	–10.9	237
4	Pevek	69°43′ N, 170°16′ E	4	1940–2019	–10.1	136	–10.0	187	–9.5	221
5	Cape Schmidt settl.	68°55′ N, 178°29′ W	260	1932–2008	–12.1	no data	–11.9	327	–10.0	262

ning of September; they alternate with the shallowing in drought periods [*Surface Water Resources..., 1969*]. The steady young shore ice or floating ice appear in the rivers in the third ten-day period of September. In the winter months, from October to May, small rivers and creeks are frozen completely. From 1960 to 1980, no runoff has been observed in 14 cases (from February to the end of May) even in the large Malyi Anyui River at the measuring section of Ostrovnoye village (the watershed area is 30 000 km^2) [*Long-term data..., 1985*]. In the following years, the runoff has been ceased only one time during the cold seasons; although, the minimal discharges have been reduced to the first tens of liters per a second. The ice cover starts to break up at the end of May or at the first dates of June.

Landscapes. Arctic tundra and deserts are widely spread in the mountain regions of the studied area. The underlying surface in these landscapes is composed of disintegrated rocks, piled up in the near-watershed zone. Their boundary is at the height of 800 m. Lower, on the valley slopes, tundra is developed on talus covers, composed of gruss-rubble rocks with fine-grained filler. The vegetation cover is represented by lichen spots and bushy willows and alders in the bottoms of watercourses.

The landscapes of the larch forest-tundra sparse forests and the lichen low-bush Siberian dwarf-pine tundras are typical for the valleys of the Berezovka and Peimyna, Bolshoi and Malyi Anyui rivers and their tributaries at the elevations of lower than 400 m [*Belikovich et al., 1997*]. The thin soil cover lies on eluvial-talus rubble-gruss formations in the lower parts of slopes and on gravel-pebble deposits on the bottoms of the river valleys.

Climate of the studied area is determined by its location in the Polar region and the proximity of the Arctic Ocean, the most part of which is covered by ice during all year round. Generally, the duration of the cold period, when the mean daily air temperature is below 0 °C, is from 303 days (Ostrovnoye village) to 316 days (Ilirnei settlement). The mean annual air temperature varies from –9.5 °C (Pevek) to –11.6 °C (Ilirnei settlement). The amount of precipitation is up to 266 mm (Table 2).

The long-term observations on the meteorological stations within the polar part of the basin of the East Siberian Sea (Ostrovnoye, Ilirnei, Pevek) and outside its boundary (Omolon, Cape Schmidt) reveal that, over the last 60 years, the warming has been significantly manifested in the 1980s and following years. The average annual air temperatures over the entire eastern sector of Arctic have changed in a similar way (Fig. 2, *A*) [*State report..., 2018*]. However, the tendency in the increase in precipitation differs from the similar one over the entire Arctic zone of Russia. In the last one, the increase in precipitation (2.6 % of precipitation norm for 10 years) has been recorded from 1976. With regards to the eastern sector of Arctic, the increase in precipitation has been noted only after 1995 (Fig. 2, *B*). The amount of precipitation decreased in the cold season, which has been noted in the intracontinental MS (Table 3) [*State report..., 2018*]. The reasons of the global climatic transformations have not been established. The transformations were likely caused by the planetary changes of ocean currents in 1975, resulted from tectonic movements of the ocean bottom [*Harris, 2002*].

Evaporation, including evapotranspiration, have not been studied in Western Chukotka. The single work on the considered issue is the calculation of the water balance in the watershed of the Tsirkovyi creek in the upper reach of the Malyi Anyui River, which has been carried out by I.M. Papernov [*1965*]. However, the amount of atmospheric precipitation, air temperature, and river runoff have not been measured, but calculated for the 100-m altitudinal belts on the basis of their dependence on the territory elevations, accepted by the author. In the abovementioned work, the evaporation and condensation values have been given on the basis of the working results of the Kolyma Water-Balance Station.

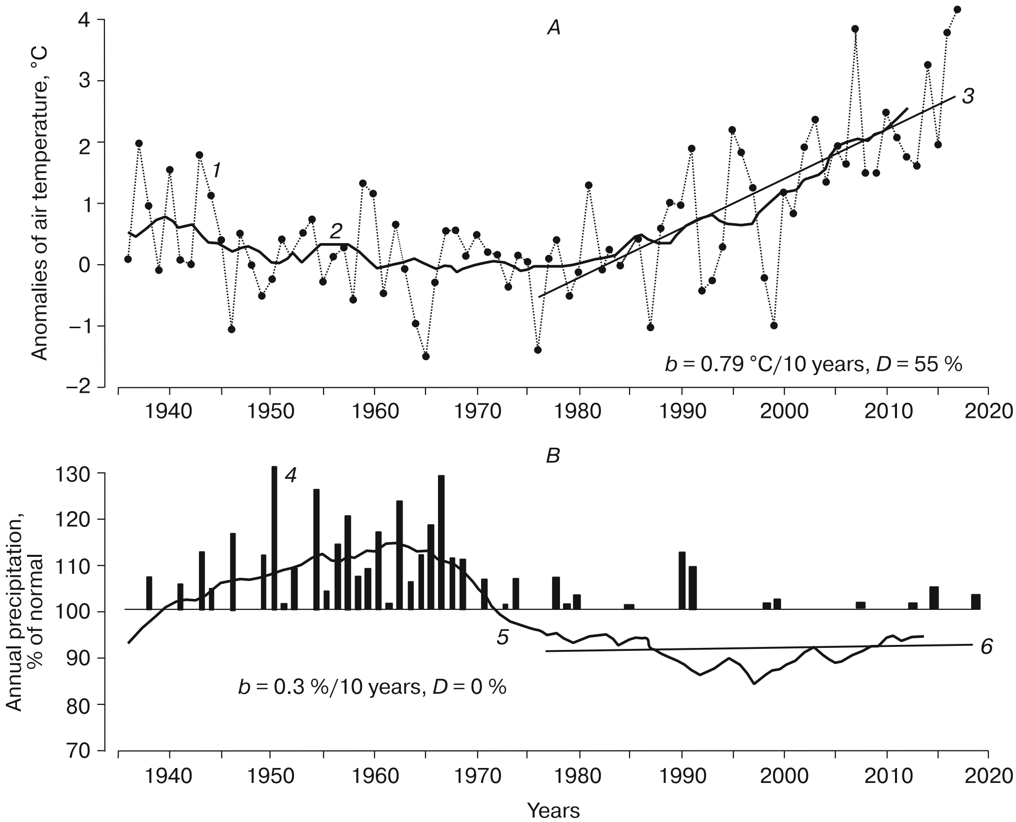

Fig. 2. Dynamic of the basic annual climatic characteristics of the Eastern sector of the Arctic zone of Russia according to the data of Rosgidrometeo for 1936–2018 [*State report..., 2018*]:

A – deviations of the air temperature from the average values (line *1*); *2* – an 11-year summer moving average; *3* – the linear trend for 1976–2018; *b* – a trend coefficient (°C/10 years), *D* – contribution to the total dispersion (%); *B* – annual sums of precipitation (*4*) (% of normal for 1961–1991); *5* – an 11-year summer moving average; *6* – the linear trend for 1976–2018; *b* – a trend coefficient (%/10 years), *D* – contribution to the total dispersion (%).

Therefore, to estimate roughly the amount of evaporation, the authors have been forced to use the materials of this station too [*Boyarintsev et al., 1991; Sushchansky et al., 2002*]. According to these materials, evaporation from the surface of the snow cover does not exceed 12 mm or 10–12 % of the sum of solid precipitation in the Polar Chukotka. In the Arctic tundra and the rock desert, precipitation on coarse clastic taluses penetrates to the ground water level; as a result, probably no more than 5 % of precipitation is spent on evaporation. The value of evaporation on the slopes increases approximately up to 30–32 % of falling liquid precipitation due to decrease in debris sizes and the formation of fine- and thin-grained filler. Evaporation, including evapotranspiration, reaches the maximum values (about 50 % of liquid precipitation) in the watercourse valleys of the basin of the runoff of the Bolshoi and Malyi Anyui rivers in the larch sparse forest. Taking into consideration the predomination of different types of tundra, the authors estimate the evaporation on the studied area in the warm season at about 25 % of falling precipitation.

Table 3. **Amount of precipitation (mm) for the cold period of the year (from October to May) according to materials of the Kolyma department of the hydrometeorological service**

Meteorological stations	Before 1980	1981–2010
Omolon	127	100
Ostrovnoye	105	104
Cape Schmidt	195	154

The geological structure. The studied area involves the Chukotka terrain of the passive continental margin and terrains of the active margin of the Anyui-Oloi system (the Paleozoic-Mesozoic island arcs and subduction zones) [*Byalobzheskiy et al., 2006; Sokolov et al., 2015*]. The composition of the rocks, composing the terrains, is homogenous enough. The rocks are represented by the Precambrian, Paleozoic, and Mesozoic magmatic and tuffaceous terrigenous formations, catagenetically altered and metamorphized in varying degrees. The Triassic terrigenous deposits predominate. The covers of the Low Cretaceous effusive rocks and intrusions of the Late Cretaceous granite are developed.

The Quaternary poorly consolidated deposits of the different origin (eluvial, talus, alluvial, glacial, and fluvioglacial) occur on the slopes and valley bottoms. Their thickness in the floodplains is 5–7 m; sometimes it increases up to 40–60 m. These deposits overlap the Neogene conglomerates, sandstones, and siltstones in the intermountain basins and grabens of river valleys. The particle-size composition of the deposits is associated with their origin, location in relief, composition of weathered bed rocks, and geodynamic nature of the terrains, which are composed of these rocks. Alluvial deposits are represented by pebble stones with gravel. The content of finer fractions increases with depth forming a loamy cement at their base. Talus deposits enrich in fine-grained soil from the upper zones of the valley slopes down to the foots. The minimum content of fine-grained and clayey fractions, under all other things being equal, is observed in the area of the distribution of terrigenous rocks, which compose the terrains of the passive continental margin, and magmatic rocks of different age. The fine-grained and clayey filler in the rubble rocks are typical for the regions, where the terrains of the active margin occur. The above-noted features determine the filtration properties of rocks.

The geocryological settings are determined by the widespread occurrence of the perennial frozen rocks, which have been considered by S.M. Fotiev as a cryogenic aquiclude [*Fotiev, 2013*]. During exploration of tin and gold deposits, it has been established, that the thickness of the cryogenic aquiclude on the watersheds is up to 450 m; under watercourse bottoms of the 3rd and more orders, the thickness reduced up to 70–80 m [*Akimenko, Akimenko, 2000; Malysheva et al., 2012*]. The subpermafrost zone, which is encroached by water and characterized by hypergene fracturing, occurs only under the river channels. The contours of this zone coincide with the river network pattern. The water recharge taliks predominate among the revealed open taliks; therefore, it may be assumed that the very limited volume of subpermafrost waters participate in the runoff, and only in the zones, attributed to current active faults in the low reaches of the rivers. The seasonal thawing layer and river-channel taliks, which are the basic elements of the zone of free (or active) water exchange, play an important role in all river basins at the continuous distribution of the cryogenic aquiclude.

The seasonal thawing starts in June, a base of the seasonal thawing layer reaches its maximum depth in the first 10-day period of September. The depth of the seasonal thawing varies from 0.5–1.5 m on the slopes to 2.5 m in coarse-grained formations at the slope foots, and under the creek channels of the 1st–2nd orders the depth of the seasonal thawing is 3–5 m. Otherwise conditions being equal, the depth of the thawing in thin-grained deposits, coarse-grained deposits, and fissured bed rocks with the fine-grained and clayey filler is less than in coarse-grained and clastic rocks. At the end of September, the seasonal thawing layer on the mountain slopes is drained almost completely or freezes [*Ponomarev, 1960*].

The seasonal freezing occurs not only from above, but also from below; it significantly exceeds a rate of the seasonal thawing [*Afanasenko et al., 1989*]. As it has turned out in the recent decades, the suprapermafrost taliks are developed under the channels of most of the watercourses of the 3rd and more orders. The basic and necessary condition for their development and existence is the presence of water-permeable formations (gravel-pebble, rubble deposits, fissured rocks) with the thickness of more than the depth of the seasonal freezing, i.e. more than 3–5 m [*Tolstikhin, 1974; Mikhaylov, 2013*]. To preserve taliks, it is important to accumulate the snow cover on the bottom of a river valley. The thickness of snow cover has to be 0.7–1.0 m and more to prevent underlying rocks against deep freezing [*Mikhaylov, 2010*].

The aquifer taliks, developed under river channels, are characterized by the maximum thickness (60–80 m) within the current valley grabens. These grabens have been established in the valley of Malyi Anyui River, in vicinity of settlement Ilirnei, in the low reach of the Bolshoi Keperveem River, in the valley of the Bolshoi Anyui River near the mouth of the left tributary (the Baimka River) [*Malysheva et al., 2012*]. In the winter, when the underflow freezes, the similar over-deepened zones are transformed into the cryogenic basins, ground waters of which feed the river-channel icings [*Tolstikhin, 1972; Alekseev et al., 2011b*].

The hydrogeological conditions are related to the features of the geological history of the drained territories [*Glotov, Glotova, 2011, 2013, 2015; Glotov et al., 2018*]. Therefore, within the polar part of the runoff basin of the East Siberian Sea, the authors distinguish the following areas (Fig. 1):

– hydrogeological massifs and admassifs, formed within the Chukotka terrain (a fragment of the passive continental margin) stretching along the coast of the East Siberian Sea;

– hydrogeological massifs and admassifs on the basis of the Anyui-Oloi system of the island arc terrains of the active margin on the watersheds of the Bolshoi and Malyi Anyui, Berezovka, Pegtymel rivers.

In all these regions, the seasonal aquifer layer, the thickness of which is controlled by the depth of the seasonal freezing, is widely formed in the third quarter of the year.

In the winter season, the suprapermafrost aquifer taliks occur in pebble rocks under the river channels and in the close proximity of the channel at the depth of 1.5–2.0 m. The ground water levels are continuously lowered since the beginning of freezing. The icings are formed in the river channels in the zones, where alluvial deposits are pinching out. According to O.N. Tolstikhin [*1974*], the icings are the indicators of the water-bearing capacity of the underflow taliks. Based on O.N. Tolstikhin's materials, the relative percentage of the icing distribution (the ratio of the total area of the icings to the area of the region of their distribution) is 0.69 % on the territory of the Chukotka terrain of the passive continental margin and it is 0.04 % for the area of the Anyui-Oloi system of terrains of the active margin. Thereby, the icings are registered only in two zones in the upper reaches of the Bolshoi and Malyi Anyui Rivers [*Tilstikhin, 1972*]. In terms of geology, these zones are distinguished by the presence of the Paleozoic carbonate formations.

The stated geological, geocryological, and hydrogeological features have been taken into our consideration on the basis of the analysis of the long-term observations of the river runoff.

RESULTS OF THE STUDY OF THE LONG-TERM REGIME OF THE RIVER RUNOFF

Table 4 demonstrates the runoff for two periods of observations (before 1980 and from 1981 to 2010). As it follows from the table's data, there is a tendency of increase in the average annual runoff in most of the rivers. In the main river (the Malyi Anyui) the increase has been no more than 6 %. In the tributaries the increase has grown up to 13.3 % (Pogynden creek) and up to 37.6 % (Mukhtuya creek). There is the inverse relationship between the increase in the runoff and the watershed area. During the period from the beginning of the observations to 1980, a group of the rivers with the runoff depth of 200 mm and more is clearly distinguished. These are Malyi Anyui River (at the measuring section of Ilirnei village), Mukhtuya creek, Baimka River, and Palyavaam River. The same watercourses are characterized by the increased runoff depth during the period after 1981 too. The runoff decreased in the Peimyna and Palyavaam rivers, where the observations were ceased in 1994 and 1996, respectively. The decrease in the total runoff is possibly related to the reduction in the amount of falling precipitation (Fig. 2), the technogenic impacts (fires, open-pit mining) cannot be excluded too. Currently, the unrecultivated valleys of these rivers are actively overgrown by grasses.

To study the relation between the runoff and the runoff-forming factors, the authors have compared the plots of the long-term fluctuations of average air temperatures, precipitation, and average annual runoff on the basis of the materials of the Pogynden River's gauge and the nearby meteorological station of Ostrovnoye village (Fig. 3). It is well illustrated that, over the last 55 years, the trend of climate warming is characterized by a steady increase in air temperature, which is approved by the Student's criterion with a significance level of 5 %. The average long-term amount of precipitation has tended to decrease until

Table 4. **The average annual runoff of the polar rivers of Western Chukotka**

River	Post	Watershed area, km^2	Period of observations	Long-term average runoff depth over a year, mm	Increase (+), decrease (–)	
					mm	% to the period before 1980
Berezovka	Berezovka village	15 400	1965–1980	117	+23	+20
			1981–2010	140		
Peimyna	In 1.5 km from the mouth	1480	1968–1980	153	–12	–10
			1981–1994	141		
Baimka	Baimka settl.	400	1963–1980	203	+21	+10
			1981–2000	224		
Malyi Anyui	Ilirnei village	8180	1958–1980	236	+3	+1
			1981–1999	239		
Malyi Anyui	Ostrovnoye village	30 000	1960–1980	187	+11	+6
			1981–1997	198		
Mukhtuya	Ostrovnoye village	23.7	1960–1980	213	+80	+38
			1981–2006	293		
Pogynden	Mouth of the Inkuliveem River	12 000	1960–1980	143	+19	+13
			1981–2010	162		
Inkuliveem	In 2 km from the mouth	242	1960–1980	87	+25	+29
			1981–2010	112		
Palyavaam	In 0.8 km downstream the Kookvyn River	6810	1971–1980	201	–7	–3
			1981–1996	194		

the middle of the 1990s of 20th century, however, it is statistically insignificant. This decrease was clearly manifested in the summer months. Thereby, in June 1982, only 18 mm of precipitation fell, in August of the same year – 3 mm. However, the tendency of the increase in the annual runoff of the Pogynden River is as steady as the air temperatures (Fig. 3).

The increase in the river runoff points to the fact that with climate warming, the water sources, additional to the atmospheric precipitation, are involved in the water exchange. The authors consider that these sources in the mountains are the waters, preserved in a solid form in perennial snowfields, rock glaciers, high mountain ground ice, perennial icings, and, possibly, in buried wedge ice and other types of ground ice, i.e. the cryogenic resource of the planet according to V.R. Alekseev [*2012*]. The authors believe that the "hydrocryogenic reserve" is the most appropriate term in this case. Possibly, the rock glaciers may occur to be one of the most significant water sources. A.A. Galanin has revealed, for the first time, the wide distribution of the rock glaciers at the foots of mountain slopes in Chukotka and their possible involvement in the formation of the water runoff [*Galanin, 2009*]. The immensity of the hydrocryogenic reserves in the Upper Pleistocene glacial and fluvio-glacial deposits should be noted. These deposits are accumulated in the watercourse valleys, graben-valleys, and intermountain basins. They are characterized by the high ice content (up to 72.0–80.7 %) at the average porosity coefficient of 1.42, i.e. the deposits are swelled by ice [*Sinitskaya et al., 1977*]. The authors assume that the maximum increase in the runoff depth during climate warming, which has been noted for the lateral tributaries of the Malyi Anyui River, is caused by the fact that the hydrocryogenic reserves play a major role in the watercourse feeding precisely in the valleys of the first order.

The runoff-forming significance of thawing of high mountain ground ice, which is one of the hydrocryogenic reserves, has been revealed, for the first time, by V.R. Alekseev and E.A. Boyarintsev on the area of the Kolyma water-balance station. These researchers payed attention to the possible replenishment of the high mountain ground ice resources during the temporal climate cooling [*Alekseev et al.,*

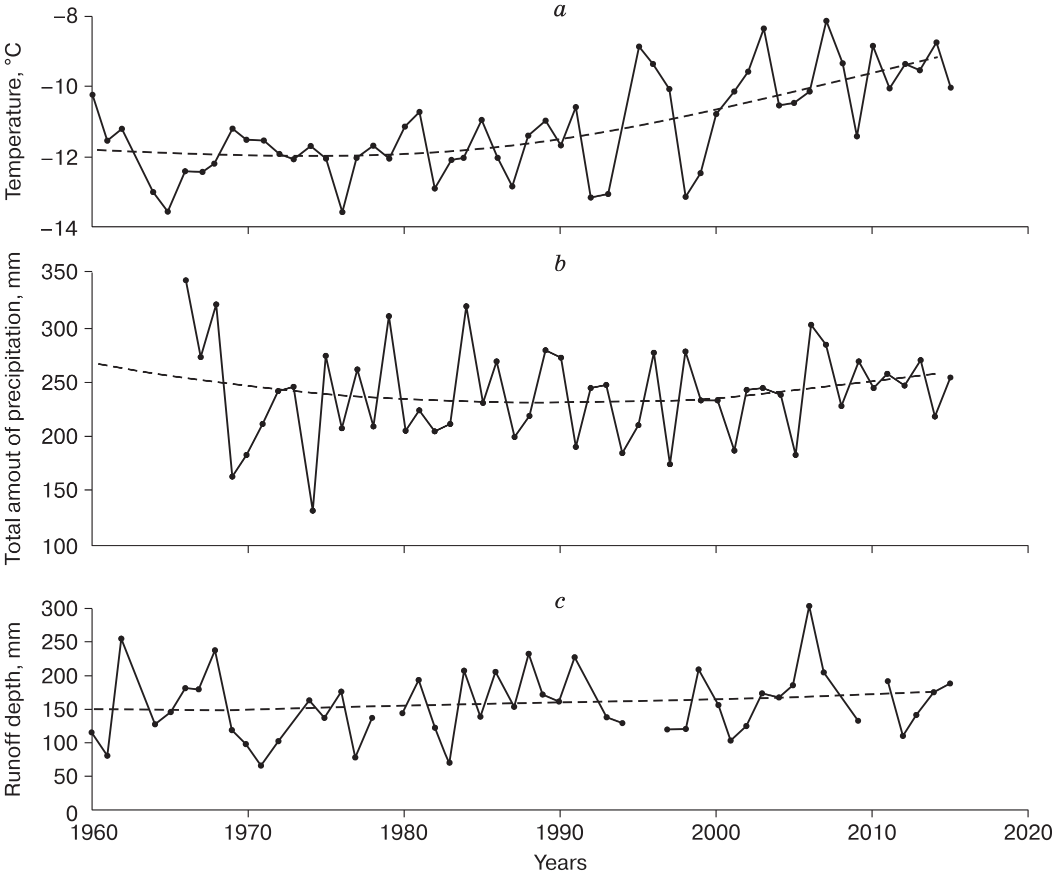

Fig. 3. The time variations of the mean annual air temperature (*a*), the total amount of atmospheric precipitation during a year (*b*) on the Ostrovnoye meteorological station and mean annual water discharges on the Pogynden River (*c*).

Dashed lines – trend lines.

2011a]. Generally, the participation of the hydrocryogenic reserves in the formation of the runoff during the current climate warming has been poorly studied, but its important role in the formation of the current runoff is quite noticeable. On the basis of materials of the long-term works of the Kolyma water-balance station, the abovementioned researchers have established that, when the sum of air temperatures in the warm period of the year is more than 700 °C, the runoff increases by 20–50 mm due to thawing of high mountain ground ice. When this sum is less than the boundary value, the cryogenic accumulation of water occurs. This process is likely proper for other elements of the hydrocryigenic reserves up to the boundary temperature, under which the depth of the seasonal thawing exceeds the depth of the seasonal freezing. Crossing this boundary will mean the irretrievable loss of the hydrocryogenic reserves. Currently, for the expert estimation of a share of the hydrocryogenic reserves in the river runoff, this share can be taken equal to the feed share of the mountain watercourses by high mountain ground ice, i.e. 20–50 mm.

The polar rivers are characterized by the runoff mostly in the period of an open channel, therefore, the long-term changes in the runoff in the 3rd quarter (July–September) are of interest (Table 5). In the 3rd quarter of a year, when almost all elements of the active water exchange zone participate in the river runoff, the last one has increased on six measuring sections for the period of observations after 1981.

Meanwhile, in some watercourses, the long-term decrease in the runoff has occurred. This was revealed in the measuring sections of the mentioned rivers, where the reduction in the total annual runoff was noted (Peimyna and Palyavaam). However, the runoff also decreased in the warm period in the Malyi Anyui River at the measuring section of settlement Ostrovnoye. The cease of observations in the middle of the 1990s for the first two rivers, allows us to associate the decrease in water discharges in the warm season with the decrease in the amount of precipitation without their compensation by thaw waters of the hydrocryogenic reserves. It might happen, however, that the water discharge had been lowered in the considered rivers, because the water losses for evapotranspiration increased due to the intensification of the grasses' and moss's growth on the slopes and valley bottoms of the watercourses under the climate warming.

The maximum values of the runoff depth (more than 100 mm) for the July–September over all the years of observations have been recorded in the measuring sections of the Mukhtuya creek, Malyi Anyui River (in vicinity of settlement Ilirnei and village Ostrovnoye), and Baimka River. In the Palyavaam River, this parameter decreased over the period of 1981–1996 in relation to the preceding runoff depth from 115 mm to 111 mm, but remained the most significant in comparison with other rivers. It should be noted that, in this quarter, the minimum 30-day period of an open channel on the polar rivers falls on the second half of August–September [*Long-term data..., 1985*]. During this time, the thawing of ices of the hydrocryogenic reserves reduces or ceases. The rivers are generally fed by ground waters of suprapermafrost

Table 5. **The data on the river runoff in the 3rd quarter (July–September)**

River	Post	Watershed area, km^2	Period of observations	Runoff depth, mm	The minimum runoff over 30 days in the summer low-water period, mm
Berezovka	Berezovka village	15 400	1965–1980	35	3
			1981–2010	46	4
Peimyna	In 1.5 km from the mouth	1480	1968–1980	64	6
			1981–1994	51	8
Baimka	Baimka settl.	400	1963–1980	96	12
			1981–2000	108	12
Malyi Anyui	Ilirnei village	8180	1958–1980	100	20
			1981–1999	102	19
Malyi Anyui	Ostrovnoye village	30 000	1960–1980	83	14
			1981–1997	81	14
Mukhtuya	Ostrovnoye village	23.7	1960–1980	111	14
			1981–2006	168	22
Pogynden	Mouth of the Inkuliveem River	12 000	1960–1980	50	8
			1981–2010	70	11
Inkuliveem	In 2 km from от the mouth	242	1960–1980	10	1
			1981–2010	21	2
Palyavaam	In 0.8 km downstream the Kookvyn River	6810	1971–1980	115	28
			1981–1996	111	23

taliks, so the increase in the runoff in the most part of watercources point to the growth of their volume. The decrease in the minimal runoff in the 30-day low-water period in the Palyavaam, Malyi Anyui (near settlement Ilirnei), and Baimka rivers, when water losses occur only in the narrow floodplains due to evaporation, may be caused by the runoff loss due to bypass filtration through the newformed taliks. The formation of the last ones is possible not only during climate warming, but also during the open mining in the river valleys, which is accompanied by the formation of numerous artificial water bodies. On the watershed of the Palyavaam River, the placer gold mining had continued no less than 40 years, it is still has being ongone in the valley of the Baimka River, upstream the measuring section. To operate of the gold-copper ore deposit "Peschanka", copper reserves of which are the largest in the world, the wide-ranging preparatory works have started here since10 years ago. We assume that the geological-geomorphological consequences of all these works are affected the cryogenic-hydrogeological situation.

DISCUSSION

The increase in the air temperature in the eastern sector of the Arctic zone of Russia was accompanied by the decrease in the amount of the atmospheric precipitation [*State report..., 2018*]. This was consistent with data of the Ostrovnoye meteorological station in the middle reach of the Malyu Anyui River. However, the tendency of the increase in the average annual runoff in the 3rd quarter of a year, was also registered on the rivers, where the hydrometeorological observations had been carried out until the end of the 1990s–the beginning of the 2000s. Therefore, the authors conclude that during climate warming, manifested in the increase in the average annual air temperature until the middle of the 1990s, the thawing of perennial snowfields and ices of the hydrocryological reserves was activated owing to deepening of the base of the seasonal thawing layer [*Konstantinov et al., 2006*]. Thaw waters from this reserve were involved in the formation of the water runoff. As a result, after 1980, the annual runoff depth has grown for most of the watercourses, apart from the Palyavaam and Peimyna rivers, on the watersheds of which the volume of the gydrocryological reserves is probably insufficient to compensate deficit of precipitation. The reduction in the volume of the ground ices and perennial snowfields was possibly caused by the 40–50-year human activity on the alluvial gold mining or by any other reasons. The patterns of the area distribution of the ground ices and perennial snowfields in the mountain regions of the Polar Chukotka should be studied.

Attention should be drawn to the fact that the runoff parameters in the 3rd quarter of a year are controlled by the physical-geographical and geological conditions. When the seasonal thawing layer thaws to the depth of 15–20 cm, i.e. in the first 10-day period of July, the surface slope runoff is completely transformed into the groundwater runoff even when heavy and persistent rains fall [*Kuznetsov, Nasybulin, 1970*]. Actually, in the 3rd quarter, the rivers in the cryolithozone are fed by ground waters of the seasonal thawing layer. For this layer as well as for the river-channel taliks, the water source is both falling rains and thaw waters of the gydrocryological reserves. During the 30-day period of the minimal runoff, the basic source of feeding is aquifer taliks. Volumetric and filtration parameters of the seasonal thawing layer and taliks are in turn depended on the geodynamic nature of the drained terrains. The most appropriate conditions for the accumulation and filtration of water are formed under weathering of the rocks, which compose craton terrains and terrains of the passive margins, and the carbonate rocks on terrains of the active margins. This explains why, among the polar rivers of Western Chukotka, the average runoff depth of more than 190 mm is characteristic of the watercourses, which drain the Chukotka terrain of the passive continental margin (the Palyavaam River) and the island arc terrains of the active margin, at the bases of which the carbonate formations occur (the upper reach of the Malyi Anyui River, Baimka River, Mukhtuya creek). These watercourses are characterized by the highest rates of the river runoff and the icing percentage in the 3rd quarter and in the 30-day period of the minimal runoff.

CONCLUSIONS

The study of the long-term changes in the runoff of the polar rivers of Western Chukotka (the basin of the East Siberian Sea) has allowed to reveal the following hydrological features.

1. The current climate warming is accompanied by the increase in the river runoff for most of the rivers. This is due to the increase in the amount of the atmospheric precipitation as well as to the increase in the mean annual air temperatures. The last-mentioned is resulted in the melting of the previously accumulated perennial snowfields, ground ices in deposits of glacial complexes and rock glaciers, and high mountain ground ice at the top of frozen formations as well as other components of the hydrocryogenic reserve in the mountain regions of Arctic.

However, there are the rivers, the runoff of which has generally decreased over the year and during the individual phases of the regime. This is presumably due to the destruction of the part of the hydrocryogenic reserve during the alluvial gold mining, and, probably, to the activization of water evaporation under the long-term increase in air temperature.

2. The relationship between the runoff characteristics and the geodynamic nature of the draining terrains as well as with the presence of carbonate rocks in their composition has been marked out.

3. The necessity of studying regularities of the distribution patterns of the perennial snowfields, rock glaciers and other elements of the hydrocryogenic reserve of water and its possible association with the geodynamic nature of terrains has been proved.

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References

Afanasenko, V.E., Zamolotchikova, S.A., Tishin, M.I., Zuev, I.A., 1989. North Chukotka region. In: Geocryology of the USSR. Eastern Siberia and the Far East. Nedra, Moscow, pp. 280–292 (in Russian).

Akimenko, G.M., Akimenko, A.V., 2000. State geological map of the Russian Federation, scale 1:200 000, sheet R-58-XXXV-XXXVI. 2nd ed. Explanatory note. VSEGEI, St. Petersburg, 198 pp. (in Russian).

Alekseev, V.R., 2012. Meltwater – the cryogenic resource of the planet. Geografiya i prirodnye resursy (Geography and Natural Resources), No. 1, 24–31.

Alekseev, V.R., Gorin, V.V., Kotov, S.V., 2011a. Naled – taryns of Northern Chukotka. Led i sneg (Ice and Snow), No. 4, 85–83.

Alekseev, V.R., Boyarintsev, E.A., Gopchenko, E.D., Serbov, N.G., Zavalij, N.V., 2011b. Mechanisms of cryogenic flow regulation in the formation of the water balance of small mountain rivers in the permafrost zone. Ukrainskiy gidrometeorologicheskiy zhurnal (Ukraine Hydrometeorological Journal), No. 8, 182–194.

Anokhin, A.N., 1996. Methods of Expert Judgment. Tutorial. Institute of Atomic Energy, Obninsk, 148 pp. (in Russian).

Belikovich, A.V., Galanin, A.V., Galanin, A.A., et al., 1997. Nature and resources of Chukotka. SVNC DVO RAN (Northeast Scientific Center of the Far Eastern Branch of the Russian Academy of Sciences). Magadan, 236 pp. (in Russian).

Boyarintsev, E.L., Gopchenko, E.D., Serbov, I.G., et al., 1991. Experimental studies of evaporation from the land surface in conditions of slight thawing in the active layer. 10 sec Dep. in the Research Center of the All-Russian Research Institute of GMI-DID 01.16.91. No. 1046 (in Russian).

Byalobzheskiy, S.G., Goryachev, N.A., Shpikerman, V.M., 2006. Kratons and orogenic belts of the East of Russia. In: Geodynamics, magmatism and metallogeny of the East of Russia. Dal'nauka, Vladivostok, Book 1, pp. 144–152 (in Russian).

Fotiev, S.M., 2013. Underground waters of cryogenic area of Russia (classification). Kriosfera Zemli (Earth's Cryosphere), XVII (2), 41–59.

Galanin, A.A., 2009. Rock glaciers of the North-Eastern Asia: mapping and geographical analysis. Kriosfera Zemli (Earth's Cryosphere), XIII (4), 49–61.

Glotov, V.E., Glotova, L.P., 2011. Terrain tectonics in the formation of the groundwater runoff in the active water-exchange zone of Mountainous River Valleys in the Cryolithzone. Russian J. Pacific Geology 5 (5), 458–468.

Glotov, V.E., Glotova, L.P., 2013. The relationship between the foundation of the Okhotsk-Chukotka volcano-plutonic belt and the water resources of the active water exchange zone. Vestnik (Bulletin) NEISRI FEB RAS, No. 4, 67–75.

Glotov, V.E., Glotova, L.P., 2015. Hydrogeology of the zone of active water exchange on the Arctic coast of the North of the Far East. Vestnik (Bulletin) NEISRI FEB RAS, No. 1, 28–36.

Glotov, V.E., Glotova, L.P., Ushakov, M.V., 2018. The relationship of mountain river runoff with the geological history of drained terranes. Geoekologiya. Inzhenernaya geologiya. Gidrogeologiya. Geokriologiya (Geoecology. Engineering Geology. Hydrogeology. Geocryology), No. 4, 4–26.

Harris, S.A., 2002. Global heat budget, plate tectonics and climatic change. Geografiska Annaler 84A, 1–10.

Katzov, V.M., Porfir'ev, B.N., 2012. Climate change in the Arctic: implications for the environment and the economy. Arktika: ekologiya i ekonomika (Arctic: Ecology and Economics), No. 2 (6), 66–79.

Klyukin, N.K. (Ed.), 1960. Applied Climatological Guide of the North-East of the USSR. Magadan, 427 pp. (in Russian).

Konstantinov, P.Ya., Argunov, R.N., Gerasimov, E.Yu., Ugarov, I.S., 2006. On the relationship between seasonal thaw depth and interannual variation of mean annual ground temperature. Kriosfera Zemli (Earth's Cryosphere), X (3), 15–22.

Kuznetsov, A.S., Nasybulin, Sh.S., 1970. Features of runoff formation on the Upper Kolyma rivers. In: Collection of works of the Magadan Hydrometeorological Observatory. Magadan, Iss. 5, pp. 52–65 (in Russian).

Lamontagne-Hallé, P., McKenzie, J.M., Kurylyk, B.L., Zipper, S.C., 2018. Changing groundwater discharge dynamics in permafrost regions. IOP Publishing Ltd, 20. Environmental Research Letters, 13 (8), 1–12.

Long-term data on the regime and resources of land surface water, 1985. Gidrometeoizdat, Leningrad, vol. I, iss. 17, 429 pp. (in Russian).

Makarieva, O., Shikhov, A., Nesterova, N., Ostashov, A., 2019. Historical and recent aufeis in the Indigirka River basin (Russia). Earth Syst. Sci. Data, No. 11, 409–420, DOI: 10.5194/essd-11-409-2019.

Malysheva, G.I., Isaeva, E.P., Tikhomirov, Yu.B., 2012. The State Geological Map of the Russian Federation. Scale 1:1,000,000 (3rd ed.). Sheet Q-59. Explanatory note. VSEGEI, St. Petersburg, 226 pp. (in Russian).

Mikhaylov, V.M., 2010. Diversity and systematization of taliks in river valleys. Kriosfera Zemli (Earth's Cryosphere), XIV (3), 43–51.

Mikhaylov, V.M., 2013. Floodplain taliks of the North-East of Russia. Academ. Publishing House Geo, Novosibirsk, 244 pp. (in Russian).

Papernov, I.M., 1965. Calculation and distribution of precipitation in the basin of Malyi Anyui. In: Collection of works of the Magadan Hydrometeorological Observatory. Gidrometeoizdat, Leningrad, iss. 1, pp. 41–58 (in Russian).

Ponomarev, V.M., 1960. Groundwater of a Territory with a Thick Stratum of Permafrost. Izd. AN SSSR, Moscow, 200 pp. (in Russian).

Ponomarev, V.I., Kaplunenko, D.D., Krohin, V.V., 2005. Climate change trends in the second half of the twentieth century in Northeast Asia, Alaska and the Northwestern Pacific Ocean. Meteorologiya i gidrologiya (Meteorology and Hydrology), No. 2, 15–26.

Sinitskaya, V.M., Sabel'nikov, A.V., Efimova, D.V., 1977. Anyuysko-Chukotskiy region. In: Engineering Geology of USSR. Moscow University Publ., Moscow, vol. 4, pp. 157–178 (in Russian).

Sokolov, S.D., Tuchkov, M.I., Ganelin, A.V., et al., 2015. Tectonics of the South Anyui structure (North-East Asia). Geotektonika (Geotectonics), No. 1, 5–30.

State report on the state and environmental protection of the Russian Federation in 2017. Chapter 12. Arctic zone of the Russian Federation. Min. Nature of Russia, Moscow, 2018, pp. 683–725. – URL: nangs.org/analytikcs/minprirody-rossii-gosudarstvennyj-doklad-o-soswtoyanii-i-ob-okhrane-okruzhyushchej-srede-rossiyskoi-federasii-pdf.

Stochkute, Yu.V., Vasilevskaya, L.N., 2016. Long-term changes in air and soil temperature in the Far North-East of Russia. Geograficheskiy Vestnik (Geographical Bulletin), No. 2 (37), 84–96.

Surface Water Resources of the USSR, 1969. Vol. 19. North-East. Gidrometeoizdat, Leningrad, 282 pp. (in Russian).

Sushchansky, S.I., Glotov, V.E., Glotova, L.P., 2002. Long-term, seasonal and diurnal changes in the drainage factors and the total water flow of the stream Kontaktovyi. In: Factors of formation of the total runoff of small mountain rivers in the Subarctic (based on materials from the Kolyma water-balance station). NECS FEB RAS, Magadan, pp. 35–58 (in Russian).

Tananaev, N.I., Makarieva, O.M., Lebedeva, L.S., 2016. Trends in annual and extreme flows in the Lena River basin, Northern Eurasia. Geophysical Research Letters 43 (20), 10764–10772, DOI: 10.1002/2016GL070796.

Tolstikhin, O.N., 1972. Hydrogeology of the USSR. Vol. 26. Northeast of the USSR. Nedra, Moscow, 297 pp. (in Russian).

Tolstikhin, O.N., 1974. Icings and Groundwater of the North-East of the USSR. Nauka, Novosibirsk, 162 pp. (in Russian).

Tynankergav, G.A., Yampol'skiy, V., Gavrilin, D.A., 2019. Chukotka – Development – New Horizons. Globus. Geologiya i biznes (Globe. Geology and Business), No. 1 (1955), 32–46.

URL: http://meteo.ru/data (last visited: 12.01.2018).

Ushakov, M.V., 2017. Modern changes in the thermal regime of the vegetation and winter periods in Chukotka. Geograficheskiy vestnik (Geographical Bulletin), No. 2 (41), 81–90.

Volkov, A.V., Goncharov, V.I., Sidorov, A.A., 2006. Gold and silver deposits of Chukotka. SVKNII DVO RAN (NEISRI FEB RAS), Magadan, 221 pp. (in Russian).

WMO statement on the status of the global climate in 2015. WMO-No. 1167. Geneva, Publications Board World Meteorological Organization, 2016, 26 pp. (in Russian).

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