EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth`s Cryosphere, 2018, vol. XXII, No. 5, pp. 35–41 http://earthcryosphere.ru/

CRYOGENIC PROCESSES AT ARCTIC SEAS' SHELFS AND ON SHORE

DOI: 10.21782/EC2541-9994-2018-5(35-41)

PERMAFROST AGGRADATION ON TIDAL FLATS OF THE KARA SEA

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The low accumulative laidas (tidal flats) are the areas of the permafrost aggradation. Long-term observations of the thermal regime of upper permafrost have been carried out at two sites: Marre-Sale (western coast of the Yamal Peninsula), and Sopochnaya Karga (western coast of the Taymyr Peninsula). The mean annual ground temperature is –3.5...–4.5 °C at Marre-Sale, and –4.8...–7.7 °C at Sopochnaya Karga. Heat flux from the atmosphere to the upper permafrost can reach 3.4 W/m^2. A high correlation between the heat fluxes and the mean annual air temperature anomalies has been established.

Laidas (tidal flats), permafrost, mean annual temperature, temperatures gradient, heat flow

INTRODUCTION

The estimation of trends and rate of the permafrost strata evolution in the context of rapidly changing climate in recent decades has become one of the key priorities for scientific research in the Arctic. Of them, the actively developing models aim at analyzing the ongoing changes in the permafrost, including its distribution pattern, thermal regime of deposits, etc. [*Pavlov, 2003; Vasiliev et al., 2008; Romanovsky et al., 2011; Streletskiy et al., 2014*]. At this, the vast majority of research to date has focused on the processes of permafrost degradation. This paper is primarily concerned with the fact that in parallel with permafrost degradation under subaeral conditions, the observed processes of its aggradation on the modern marine laidas of the Arctic seas remain largely overlooked. Marine laidas, the widespread relief forms on the Kara sea coast, are low coastal accumulative surfaces, periodically flooded during high tides, wind and storm surges. These comprise the Marre-Sal'skie Koshki and Sharapovy Koshki systems of low islands and sand spits, the area of Mys Skuratov, northern part of Bely island and other marine accumulative formations, e.g. low laidas with absolute elevations <1.5 m and high laidas >1.5–3 m asl. Beside the marine accumulative forms, accumulative alluvial-marine lowlands can also develop in river estuaries.

A unique series of annual field observations of the thermal regime of permafrost in the transition zone within the shallow part of the Mackenzie river delta (Canada) were conducted by S. Solomon in 2005–2006 [*Solomon et al., 2008*]. The mean annual temperatures in the upper permafrost horizons ranged between –2.4 and –3.7 °C. Remarkably, aggradation of new permafrost was observed in the shallow freshwater environment with temperatures of phase transitions close to 0 °C. In themselves, the measurement and data processing techniques are of great interest from the perspective of setting-up such observations in the marine conditions. The sediment temperature was measured in the 20-meter deep borehole (sea depth: ~4.5 m) in the shoal zone in the Marré-Sale area in 2014–2015 by V.A. Dubrovin and co-authors [*2015*]. The borehole was drilled into the talik at a distance about 800 m from the coast, which is partitioned by the talik from the massif of sub-sea permafrost. The reported temperatures are: –1.3 °C for a depth of 20 m; and –1.4...–1.8 °C for a phase transition temperature. In terms of their cryogenic state, the sediments are ranked as cooled. Modern marine sediments temperature and their freezup thickness within the Sharapovy Koshki and Marre-Salskie Koshki area on Western Yamal were determined by N.F. Grigoriev [*1987*] while drilling during the winter. The drilling results revealed relatively low temperatures (not more than –5 °C at a depth of 8–10 m) at permafrost thickness from 5 to 10 m, with alternating hard-and plastic-frozen interlayers in the section.

DESCRIPTION OF THE STUDY AREA

Two key sites (within the Kara low sea accumulative laidas) strikingly differing in freezing mode of the marine laidas were selected for investigating the processes of permafrost aggradation (Fig. 1).

The Marre-Sale observation site (69°42′ N; 66°49′ E) is located on the western coast of the Yamal Peninsula in the vicinity of the eponymous weather station (WS). According to the WS data, in the period from 1961 to 1990, the mean annual air temperature (MAAT) (climatic norm) was about –7.7 °C. The thickness of hard-frozen sediment reaches 100 m in the subaeral conditions, their mean temperature (mean annual ground temperature, MAGT) varies from –4.0 to –6.5 °C, depending on the landscape conditions [*Vasiliev et al., 2008*].

A low accumulative surface (laida) rising about 0.6 m asl is found in 12 km south of the weather station. The section of marine sediments within the laida is represented by the interbedding of not completely consolidated clay loams, sand loams and sands (Fig. 2). The degree of sediment consolidation shows an increasing trend with depth. The hard-frozen sandy horizons (0.2–0.4 m with thick) occurring beneath the active layer with thickness of about 1.5 m contain thin lenses and sporadic crystals of ice and negative-temperature sand-clay loamy plastic frozen horizons (thickness: 0.2–0.4 m) with no visible ice inclusions. Salt content of accumulative deposits (D_{sal}) of about 1.0–1.5 % corresponds to the marine sedimentation regime (salts composition is sodium chloride). The specificity of the cryotic state of deposits during permafrost aggradation in the Marre-Sale area was previously revealed by *N.F. Grigoriev* [*1987*]. The rate of modern sedimentation varies widely within the laida: normally, 1–6 mm/year of modern blanket sand-loam layer on the tidal flat surface, which incidentally was covered with a blanket sand layer (up to 0.4 m thick) after a storm of extreme duration and intensity in the fall of 2009.

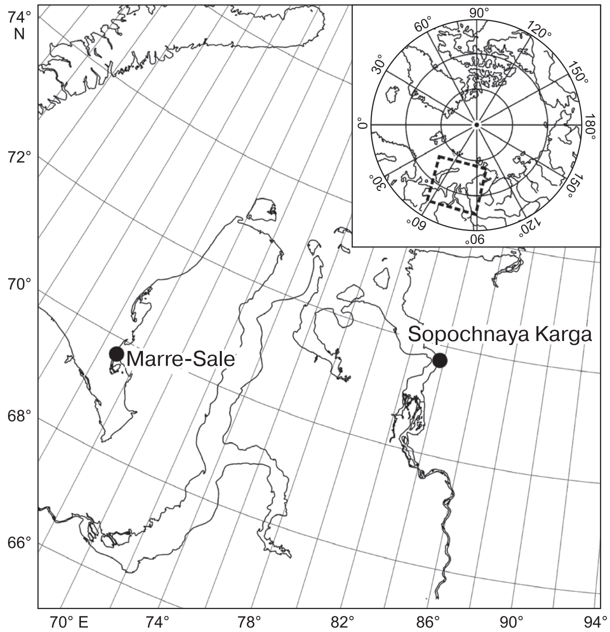

Fig. 1. Location map of observation sites.

The Sopochnaya Karga observation site (71°53′ N; 82°42′ E) encompasses the area on the western Taimyr Peninsula in the southern part of the Yenisei Gulf on the border between the Yenisei River and Yenisei Gulf. It represents a low sand-gravel-pebble spit which extends out into the sea (Fig. 3). The two types of laidas formed on the accumulative spit are: low laida, or low lying coastal laida (tidal flat) not more than 0.3 m in height above the Yenisei Bay water level, and high laida corresponding to an indistinctly expressed beach bar up to 1.5 m in height, where the Sopochnaya Karga weather station is located. The tidal flat (low laida) is composed by sand loams with inclusions of gravel-pebble material, whereas the high laida is composed exclusively by medium-grained well-sorted sands. The modern sedimentation rate at Cape Sopochnaya Karga is ranked lower compared to the Marre-Sale site and probably rarely reaches first millimeters per year. The water in this part of the Yenisei Bay is almost fresh, characterized by short-term slight increase in its salinity, only during the period of strong northern surges. The modern marine accumulative deposits are therefore practically fresh ($D_{sal} \leqslant 1$ %). According to the Sopochnaya Karga WS data, the MAAT was –11.1 °C (climatic norm) during the period of 1961–1990. The thickness of permafrost is about 300 m at the watershed (up to 35 m high), with the MAGT varying from –7.5 to –9.7 °C in the subaeral conditions (depending on the landscape). The seasonal thaw depth differs for the main watershed surface (about 0.5 m), the low laida (not exceeding 0.7 m), and the high laida (1.5 m). Permafrost aggradation on the laida begins in shallow water at a sea depth less than the thickness of sea ice, reaching 1.5 m. Frozen deposits are encountered in the modern marine lagoon at a sea depth of about 0.5 m. Geological section on the laidas and in the lagoons near the Sopochnaya Karga is represented by hard-frozen sediment, with no cooled interlayers.

OBSERVATIONAL TECHNIQUES

Given that permafrost aggradation on the marine laidas occurs concurrently with the sediment freezeup from above, long-term observations were set up for the thermal regime monitoring in the upper horizons of the freezing strata. To that end, in 2007, a borehole was drilled and cased with a metal pipe (76 mm in diameter) on the surface of the low marine laida (Marre-Sale site) to a depth of 3.2 m.

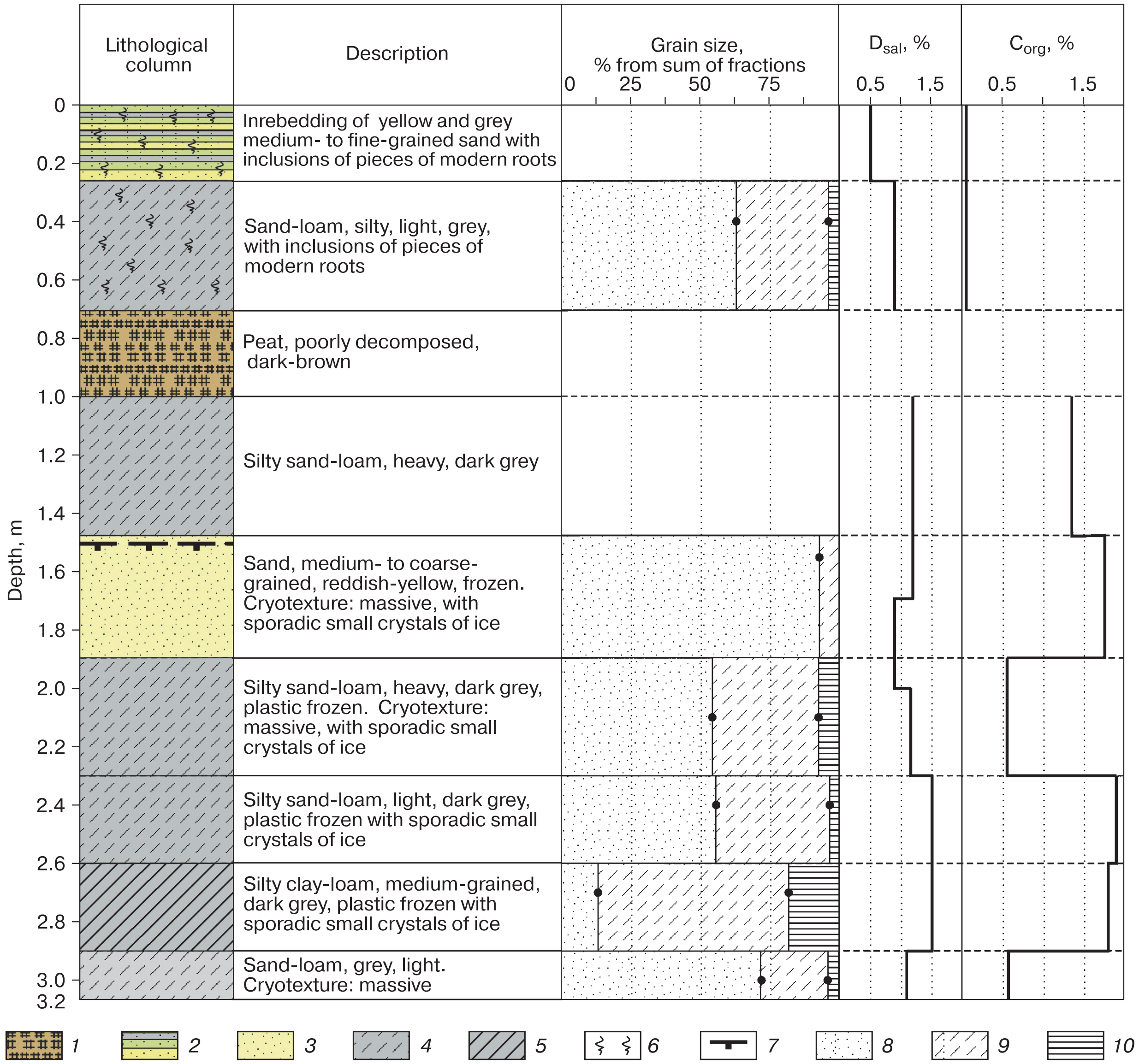

Fig. 2. Section of sediments on the low marine laida in the Marre-Sale area supplemented with the data on grain size distribution, contents of organic carbon (C_{org}) and water soluble salts (D_{sal}).

1 – peat; *2* – interbedding of fain-grained sand; *3* – coarse-grained sand; *4* – sand-loam; *5* – clay-loam; *6* – inclusions of modern roots; *7* – frozen/unfrozen sediments boundary; *8–10* – composition of grain-size fractions after the V.V. Okhotin classification: *8* – sandy fraction; *9* – silty fraction; *10* – clayey fraction.

The temperature measurements were taken using autonomous HOBO Water Temperature Pro v2 data loggers at depths of 0.03, 0.6, 1.1, 1.6, 2.0, 2.5 and 3.0 m (the error of measurement with this type logger is ±0.2 °C). The temperature was measured four times per day. In some years, when the lower loggers were "captured" in the borehole, making it impossible to take them out, they were drilled out, removed and replaced by new ones. Sediments were sampled while drilling (the Marre-Sale laida) for determination of the moisture content, grain size composition, concentrations and composition of salts, and the total organic carbon (TOC) content. Temperature monitoring of the freezing sediments at the Sopochnaya Karga site was also launched in 2007 in the uncased well drilled to a depth of 1.5 m on the surface of high laida, where a 4-channel HOBO U12 Outdoor data logger was installed. The measurement error for this type temperature loggers is ±0.2 °C. The logger sensors are located at depths of 0.2, 0.5, 0.8 and 1.1 m, i.e. within the active layer. The measurements launched in 2009 (ceased in 2010) were taken four times per day and

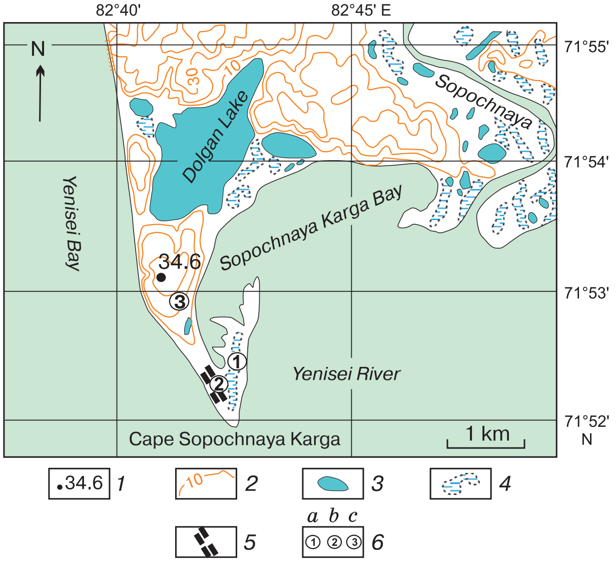

Fig. 3. Schematic map of loggers location in the Sopochnaya Karga area.

1 – elevation mark; *2* – height contours; *3* – lakes; *4* – low marsh surface areas; *5* – weather station buildings; *6* – location of boreholes with loggers: *a* – on the low laida surface, *b* – within the beach bar (of the high laida), *c* – on the watershed surface.

reported from the borehole drilled on the tidal flat to a depth of 0.8 m into gravel-pebble sediments filled with sand loam. The well was cased with a plastic pipe 40 mm in diameter. The HOBO Water Temperature Pro v2 loggers were installed at depths of 0.15, 0.32, 0.53 and 0.75 m. The temperature was measured four times per day. At this, the lower sensor was installed below the active layer base. Additionally, in September 2010, four autonomous loggers were installed within the active layer on the watershed surface, to compare the pattern of the formation of thermal regime in the conditions of modern permafrost aggradation. The logger installation depths were 0.06, 0.27, 0.4 and 0.6 m, with the lower sensor placement below the seasonal thaw depth. A comparative study of the thermal regime on the laida and watershed was completed in the summer of 2014.

The scope of the studies included collection of samples at the logger installation points for determinations of sediment moisture content, particle size distribution, contents and composition of salts.

ANALYSIS OF DATA OBTAINED

Analysis of the long-term climate data from the Marre-Sale and Sopochnaya Karga weather stations has shown an explicit trend for climate warming since the 1970s on the Kara sea coast (Fig. 4). Averaged over the 45 years' period, the increase in MAAT constituted about 2.6 °C for the Marre-Sale WS, and about 2.4 °C for the Sopochnaya Karga WS. Figure 4 provides an insight about the growth rate of MAAT since 2000. The rate of MAAT increase (averaged for the region over the period since 1970 till the present day) is approximately 0.06 °C/year. As such, the high real rate of warming is consistent with the worst case scenarios for climate warming in the western sector of the Arctic [*Anisimov and Belolutskaya, 2002*]. According to the borehole measurements, climate warming in the studied areas does not actually arrest the freezeup process and modern permafrost aggradation, acting rather as a brake on them (Fig. 5).

As a result of long-term thermal regime monitoring in the active layer and upper permafrost horizons in boreholes drilled into the laidas within the Marre-Sale and Sopochnaya Karga areas, long series of per-

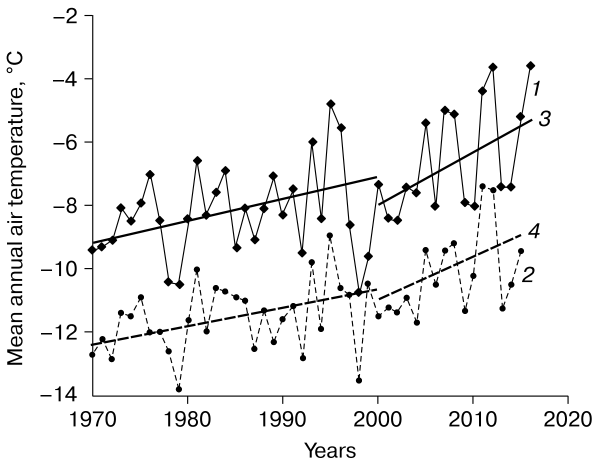

Fig. 4. Mean annual air temperatures (*1*, *2*) and their linear trends (*3*, *4*) after 1970, according to the weather stations data: Marre-Sale (*1*, *3*) and Sopochnaya Karga (*2*, *4*).

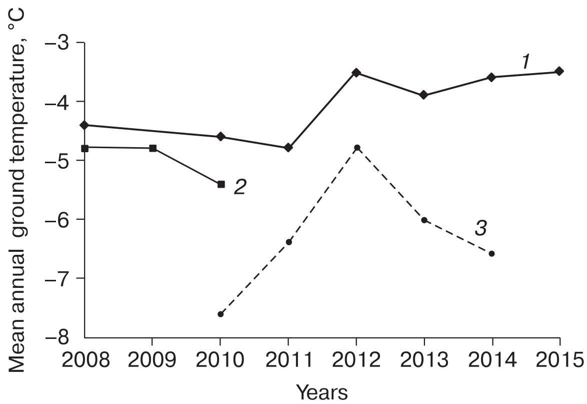

Fig. 5. Interannual coarse of mean annual temperatures in the upper permafrost horizons:

1 – Marre-Sale, low laida (depth: 1.6 m); *2* – Sopochnaya Karga, high laida (depth: 1.1 m); *3* – Sopochnaya Karga, low laida (depth: 0.65 m).

mafrost temperature variations have been obtained for different depths. The data with such level of detail provided insights into the main features of the thermal regime variability.

Analysis of the MAGT distribution with depth for the Marre-Sale area (Fig. 6) shows that the depth of zero annual amplitudes of the freezing sediment temperature does not exceed 3–4 m. The mean annual temperature of permafrost at a depth of 3.5 m averages –3.5...–4.5 °C, which is approximately 1.5 °C higher than in boreholes drilled on the surface of the third (3rd) marine terrace [*Vasiliev et al., 2008*]. The thickness of the layer of zero annual amplitudes being small is explained by the heat consumed during phase transitions in the freezing saline sediment strata with the phase transition temperatures averaging about –4 °C. According to the data obtained by *N.F. Grigoriev* [*1987*], on the Bolotny island laida, located a few kilometers from the borehole, the average annual sediment temperature at a depth of 5 m constituted –4.0...–5.0 °C. The depth of zero annual amplitudes (after N.F. Grigoriev) reaches 4–5 m, while the permafrost thickness varies from 5 to 10 m. This allowed an inference that a relatively low-temperature permafrost formed at a mean annual temperature below –4 °C on the marine laidas in the Marre-Sale area.

The long-term observations data enabled estimation of MAGT from the temperature loggers for each logger depth. This allows to determine (for each year of observation) the MAGT gradients for the active layer within upper permafrost horizons and the heat fluxes averaged over the year. A linear interpretation is used as a first approximation for calculations of temperature gradients.

As follows from Fig. 6, the difference in MAGT (gradient) varies with depth for different years, with the maximum gradient (1.6 °C/m) reported for the Marre-Sale area in 2008. The minima in the average annual ground temperature gradients were reported for 2010, 2013 and 2014, with temperatures having negative values either in fractions of a degree or close to zero. Remarkably, MAAT was close to the climatic norm specifically in these years. The heat flux is calculated as the product of the temperature gradient grad T [°C/m] by the thermal conductivity coefficient λ [W/(°C·m)]. The initial data for the calculation of air temperature anomalies (as the difference between the MAAT for a particular year and the climatic

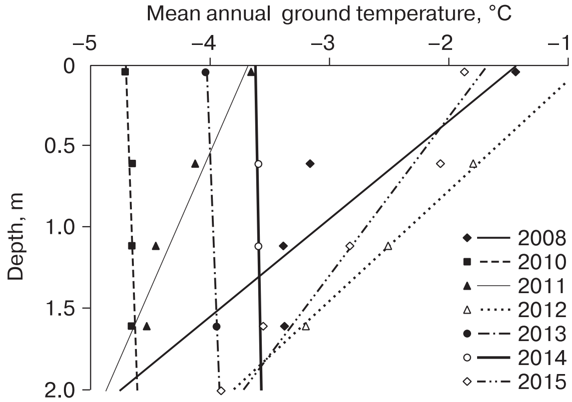

Fig. 6. Distribution of mean annual temperatures in the upper permafrost horizons with depth, Marre-Sale (low laida).

norm) and temperature gradients in the upper horizons of the freezing sediment in the taidal flats for the Marre-Sale and the Sopochnaya Karga areas are given in Table 1. The temperature gradients are determined from the trends for MAGT (Fig. 6, 7, *a*). The thermal conductivity coefficient values are derived from the reference data [*SNiP 2.02.04-88, 2001*]. The value of λ_f for frozen water-saturated sand loams is 1.98 W/(°C·m), and λ_m = 1.86 W/(°C·m) for unfrozen. The estimation of heat fluxes requires taking into account the fact that the sediments in the upper layer are in the frozen state during about nine months a year, and are accordingly unfrozen during only three months. The calculations employed the weighted average (for the year) value of the thermal conductivity coefficient λ_{av} = 1.96 W/(°C·m).

The descending heat flux, which is consumed for warming up the upper horizon of permafrost in the Marre-Sale area, in the warmest years is more than 50 times higher than the ascending heat flux, which is equal to 0.045–0.058 W/m^2 in the shallow offshore Kara sea [*Melnikov and Spesivtsev, 1995*]. During the observation period, the heat flux in the upper part of the freezing sedimentary strata generally varied from –0.4 to 3.4 W/m^2. The formation of even lower-temperature permafrost proceeds in more severe climatic conditions in the Sopochnaya Karga area, owing to wide distribution of non-saline marine sediments. The inception of permafrost aggradation takes place in shallow water. During the observation period, the

Table 1. **Air temperature and temperature gradients anomalies values for the upper horizons of the freezing sedimentary strata**

Observation site	Parameter	2008	2010	2011	2012	2013	2014	2015
Marre-Sale	Air temperature anomalies, °C	2.6	–0.3	3.3	4.1	0.3	0	2.4
	Sediment temperature gradient, °C/m	1.7	–0.2	0.6	1.6	–0.1	0	1.0
Sopochnaya Karga	Air temperature anomalies,°C	–	1.0	3.8	3.7	0	0.7	–
	Sediment temperature gradient, °C/m	–	0.38	0.81	1.0	0.25	0.5	–

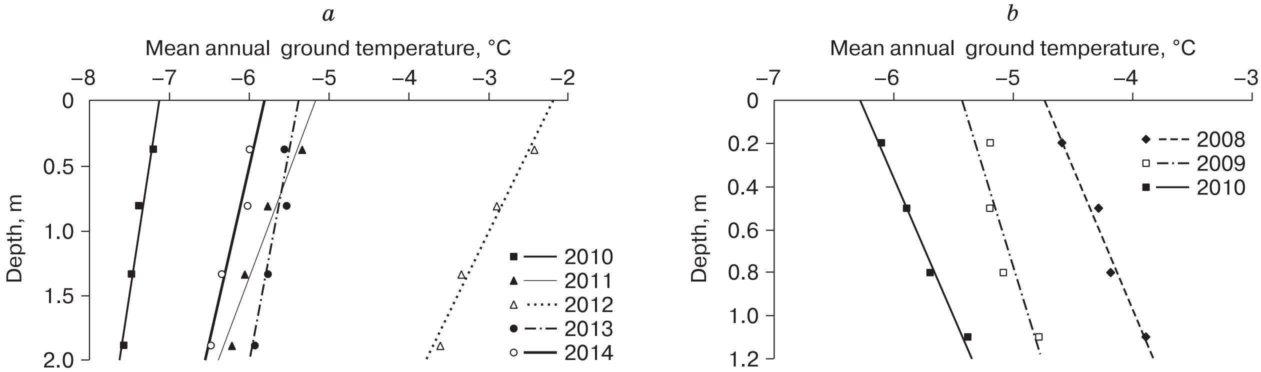

Fig. 7. Distribution of mean annual temperatures in the upper permafrost horizons with depth, Sopochnaya Karga.

a – low laida; *b* – high laida.

MAGT values varied from –4.8 to –7.7 °C (upper permafrost horizon within low laida), and from –4.8 to –5.4 °C (within high laida). The specific geological settings of the Sopochnaya Karga site disabled measurements of the depth of zero annual amplitudes.

The distribution and gradients of mean annual ground temperatures with depth for each year of observation, separately for the Sopochnaya Karga low and high laidas are shown in Fig. 7, *a*, *b*, respectively. The difference in the gradients' values for low and high laidas is remarkable, i.e. given different types of landscapes the temperature gradients values may vary. Low lidas (tidal flats) are characterized by positive or close to zero gradients during the whole period. Whereas in the case of high laida, gradients of mean annual temperature with depth are ubiquitously negative. In 2010, the mean annual temperatures slightly warmed (0.38 °C/m) accompanied by small positive gradient within the low laida, while negative gradient produced by mean annual temperatures (–0.4 °C/m) was observed within the high laida.

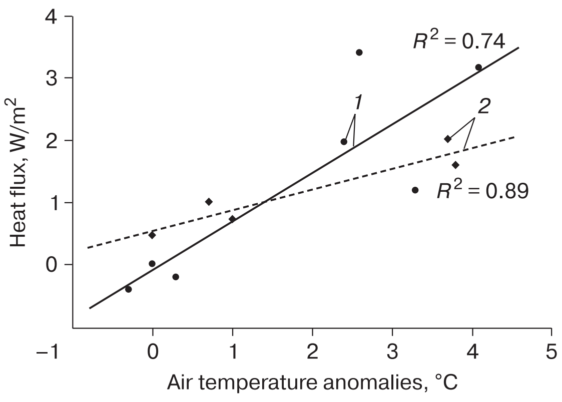

Fig. 8. Correlation between air temperature anomalies and heat fluxes on the low laidas.

1 – Marre-Sale; *2* – Sopochnaya Karga.

As is the case with the Marre-Sale, the maximum values for the descending heat flux exceed the ascending heat flux and are subject to variations from year to year within 0–2 W/m^2.

Analysis of changes in the mean annual temperatures and their gradients within the freezing strata of saline and non-saline sediments allows an inference that the thermal regime during the permafrost aggradation is generally consistent with the climatic norm. While the exceedance of the norm implies warming and slower aggradation of permafrost, with the latter, alternatively, experiencing cooling and accelerated freezup when the climatic norm is lowered.

The comparison of the heat flux values with the MAAT anomalies calculated as the difference between MAAT for the current year and the climatic norm shows their fairly high correlation (Fig. 8). The correlation radius (R^2) values are 0.74 (for Marre-Sale), and 0.89 (for Sopochnaya Karga). The conducted observations thus allow estimation of the heat fluxes into the permafrost in the area of permafrost aggradation depending either on actual or predicted anomalies of air temperature.

This allowed to simplify the model of calculations for the thermal state of the freezing strata. Typically, temperature on the day surface is used in modeling the thermal state of permafrost i.e. a first-type boundary conditions. The impact from the vegetation and snow covers is taken into account by introducing a layer with a given thermal resistance. However, in view of unavailability of data on properties and patterns of changes in vegetation and snow cover over time, the use of first-type boundary conditions for the calculations of permafrost aggradation appears problematic. Application of the heat flux values as a second-type boundary condition allows to avoid this problem, since the heat flux coming into the ground is controlled solely by the MAAT anomalies.

CONCLUSIONS

The long-term observations of the thermal regime of the upper horizons of saline and non-saline freezing deposits were carried out in the conditions of the modern marine laidas of the Kara sea at two sites (Marre-Salé in Western Yamal and Sopochnaya Karga in Western Taimyr) differing in the freezing conditions.

Against the backdrop of generally warming air temperatures in the Arctic, permafrost aggradation is ranked as syngenetic type of cryogenesis at low marine laidas (tidal flats).

The series of detailed continuous observations obtained by the authors enabled estimation of the mean annual temperatures of the upper permafrost horizons. In the Marre-Sale area, the mean annual temperature of sediments on the laida is –3.5...–4.5 °C, with the depth of seasonal thaw reaching 1.8 m, and the thickness of the layer of zero annual amplitudes not exceeding 3–4 m. Permafrost thickness in areas of permafrost aggradation is less than 10 m. The section is represented by alternation of frozen saline deposits with thin lenses and nodules of ice, and cooled plastic ("flowing") sediments.

At the Sopochnaya Karga site, the modern permafrost aggradation begins in the shallow sea water at a sea depth <1.5 m, which corresponds to the maximum thickness of sea ice, where permafrost develops with the mean annual temperatures in the range from –4.8 to –7.7 °C (low laida) and –4.8...–5.4 °C (high laida). The section is composed by fresh monolithic permafrost with a microlens array in a layered arrangement.

The calculated values of heat fluxes descending into the subsurface in some years exceed the heat fluxes ascending from below by 50 times. It has been established that heat fluxes are close to zero if the mean annual air temperature corresponds to the climatic norm. This allows to infer that the thermal regime of freezing deposits is generally consistent with the climatic norm.

The established close correlation between the heat fluxes and temperature anomalies enables simplification of the calculus model for the thermal state of the freezing strata.

The work was financially supported by the Russian Foundation for Basic Research (Project No. 18-05-60004). The data on sediment physical properties were obtained within the scope of the RFBR Project (No. 16-05-00612 A).

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Received May 27, 2018