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# THERMAL REGIME OF THE UPPER PART OF PERMAFROST IN THE TRANSITION ZONE FROM LAND TO SEA, WESTERN YAMAL

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This paper analyzes specific features of thethermal regime evolved in the upper portion of permafrost in the transition area between land and sea in western Yamal Peninsula. Based on direct observations, the mean annual temperature of saline sediments is found to be about freezing point in areas where permafrost is subject to degradation, with the depth of zero annual amplitude occurring at 2.5–3.5 m. Permafrost continues to form at low marine laidas, where mean annual temperature of sediments average –3.9 °C. The depth of layer with zero annual amplitude in this area is less than 3–4 m.

*Thermal regime of permafrost, climate, coastal zone, Western Siberia, Yamal*

## INTRODUCTION

The problem of studying the permafrost zone response to climate changes has become one of the critical environmental issues in recent decades. Apart from the conducted extensive research on the permafrost temperature regime [*Anisimov and Belolutskaya, 2002; Pavlov, 2003; Romanovsky, 2006; Romanovsky et al., 2011*], there were initiated a permafrost temperature monitoring system (the Global Terrestrial Network for Permafrost, GTN-P), and the CALM (Circumpolar Active Layer Monitoring) Program with a focus on the seasonal freeze and thaw depth monitoring. In addition, new approaches and methods for assessing the permafrost response to climate changes have been developed [*Streletskiy et al., 2014*]. Given that that the permafrost temperature is found to be increasing in the context of climate warming, the upper permafrost horizons experience downward thawing, which locally causes their complete degradation [*Pavlov and Malkova, 2005; Oberman, 2006*]. All these dedicated works and inferences made are related primarily to the terrestrial permafrost.

At this, the thermal regime of the subsea permafrost remains practically unexplored, though, which is evidenced by scant temperature measurements in the boreholes penetrated submarine permafrost [*Melnikov and Spesivtsev, 1995; Rokos et al., 2009*]. Its thermal regime is governed by the near-bottom seawater temperature variability, whose pattern can be largely influenced by climatic and hydrological conditions. The established two types submarine permafrost are represented by: 1) relic permafrost, formed during the last cooling period and extensive regression of the sea 21–12 ky BP; 2) submarine stock-like frozen bodies whose formation was conditioned by jet degassing and supercooling of the cooled bottom deposits [*Melnikov and Spesivtsev, 1995*]. At sea depths more than 20 m, the temperature of submarine permafrost is found to be close to the phase transition temperature [*Vasiliev et al., 2015*] and usually ranges between –1.0 and –1.5 °C. Inasmuch as subaqueous permafrost in the shallow offshore parts has a lower temperature and is subject to warming from above, its temperature profile shows a decreasing trend with depth. As such, the temperature of shallow-occurring submarine permafrost can reach –4...–5 °C [*Nixon, 1986; Vasiliev et al., 2015*]. The temperature regime of subsea permafrost can therefore be subdivided into two types: "quasi-equilibrium gradientless", with a temperature close to the phase transition temperature, and "non-equilibrium low-temperature", with inverse gradient.

In the coastal-marine zone, terrestrial and submarine permafrost deposits are separated by a transition zone. After *T. Osterkamp* [*2001*], the authors interpret the transition zone to be subsumed into that stretch of the sea coast (including the onshore and offshore parts) where permafrost is affected by the interplay of climatic and hydrological conditions. A unique, year long cycle of field observations of the thermal regime of permafrost in the transition zone within the shallow part of the Mackenzie river delta (Canada) was conducted by S. Solomon [*Solomon et al., 2008*] in 2005–2006, where the shallow freshwater deposits have temperatures of phase transitions close to 0 °C. The mean annual temperatures in the upper permafrost horizons ranged between –2.4 and –3.7 °C.

The temperature was measured by V.A. Dubrovin and his colleagues [*Dubrovin et al., 2015*] during one year within the period 2014–2015, in a 20-m deep borehole at the sea depth of about 4.5 m in the area of the Marre-Sale weather station (WS), Western Yamal. The borehole was drilled into a talik separating the terrestrial permafrost from the subsea permafrost deposits, at a distance of ca. 800 m from the coast. The temperature at a depth of 20 m was –1.34 °C; the temperature of phase transitions varied from –1.4 to –1.8 °C. Thickness of the annual thermal cycle layer reached 5.5 m. In the Western Yamal conditions, two types of transition zones are established, with the first developed on thermoerosion-affected stretches of the coast comprising the beaches and adjacent underwater slope, to the sea depth of about 6–8 m. This type of transition zone is featured predominantly by degradation of permafrost deposits, down to their transition to the cooled state, as the coast retreats.

The second type of transition zone is inherent in the low accumulative laidas (tidal flats) in the areas of modern marine sediments accumulation. It encompasses the laida-zone proper and the adjacent underwater slope to the depth of the sea bounded by the zone of sea-ice adfreezing to the bottom. According to the long-term observations at the Marre-Sale WS, the maximum thickness of the sea-ice cover reaches 1.6 m. This depth is delimiting the outer boundary of the second type transition area featured by new permafrost aggradation.

## THE IMPACT OF CHANGING CLIMATE AND MARINE HYDROLOGICAL CONDITIONS ON THERMAL REGIME OF PERMAFROST DEPOSITS

The permafrost temperature dynamics in the transition zones of both types is controlled by climate changes and marine hydrological conditions. Analysis of the air temperature variations versus time is of particular importance, inasmuch as this dependence has always determined the dynamics and extent of permafrost development. The trend analysis of the air temperature variations in the Russian Arctic was carried out by *A.V. Pavlov* [*2003*]. According to his data, climate warming has been most strongly expressed in the north of Western Siberia since the 1970s, which affected the onshore areas to far greater extent, than the sea coasts [*Pavlov and Malkova, 2005*].

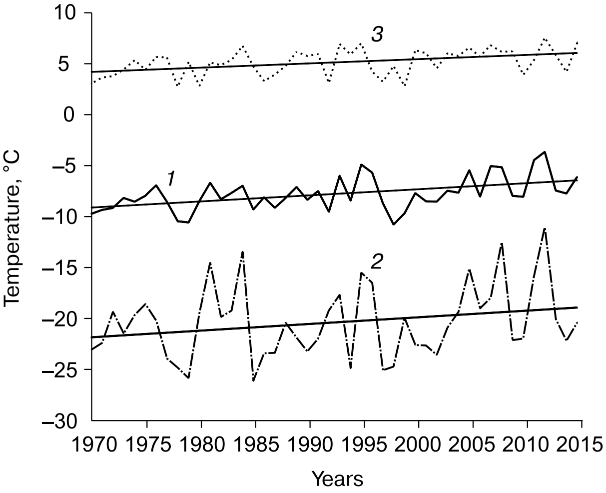

**Fig. 1. Variations of mean annual (*1*), mean winter (*2*) and mean summer (*3*) air temperatures according to the Marre-Salé weather station.**

To assess trends in evolution of the permafrost areas, it is critical to know if climate warming occurs due to the increasing mean winter temperature alone, or whether the mean annual air temperature also tends to rise. To investigate behavior trends of temporal air temperature variations after 1970, we analyzed the Marre-Salé WS data. The diagrams for mean annual and mean winter/summer air temperature variations derived from the weather station data (Fig. 1) demonstrate a clearly manifested increase in both the mean annual and mean summer temperatures, beginning from the 1970s.

For the Marre-Salé area, an increase in the mean annual air temperature over the period of 1970–2015 constituted 2 °C, which is 0.04 °C/year. A rise in the air temperature was also accompanied by a shift in the dates of stable transition through 0 °C (Fig. 2), which, however, shows no pronounced trend for the spring-time (Fig. 2, *a*).

On average, the temperature transition from negative to positive values occurs around June 10. Whilst in autumn, the transition from positive to negative values tends to be shifted to later dates, from October 5 to October 16 (Fig. 2, *b*). In other words, the period with negative air temperatures sets in increasingly later. Accordingly, the mean annual dates of stable snow cover formation exhibit a delay of 10–12 days.

The permafrost temperature field evolution in the transition zone is largely governed by the sea-ice thickness and water temperature in the shallow sea zone.

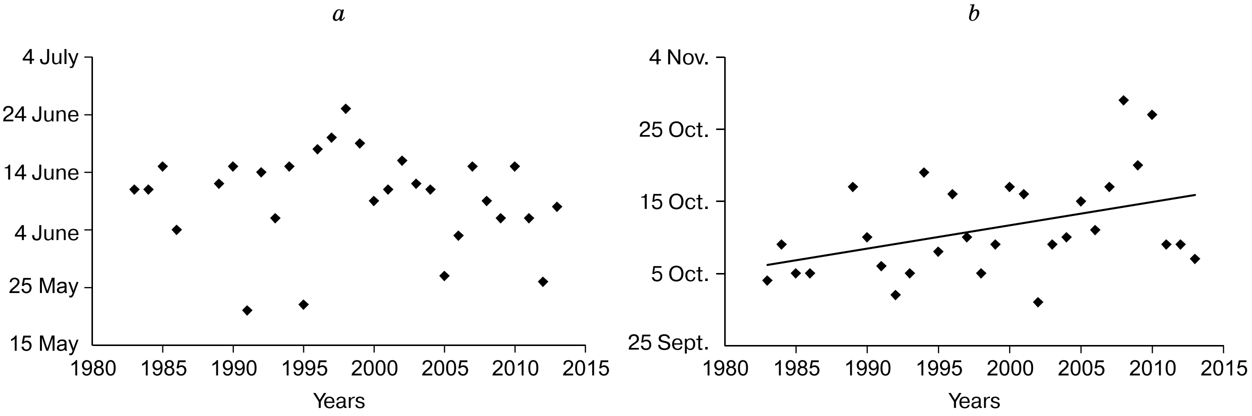

**Fig. 2. Shift in dates of the steady transition of the air temperature through 0 °C (*a* – spring, *b*– autumn).**

Based on the Marre-Salé WS observation data, it was establish that the formation of the sea-ice cover begins in the second and third decades of October, with the ice thickness reaching its maximum in late April–early May. Destruction of coastal fast ice usually begins in the second and third decades of July. The appearing rise in the seawater temperature driven by climate warming diminishes the thickness of the sea-ice cover [*Willis et al., 2004*]. In the currents conditions of Western Yamal (the Marre-Salé WS data), the maximum thickness of seasonal sea-ice has decreased from 150 cm in 1998 to 125 cm in 2015 (Fig. 3).

Moreover, there is a remarkable shift in the dates of the onset of sea-ice formation to later periods and, conversely, the destruction of the ice cover increasingly tends to be shifted to earlier date. Over the past 20 years, the date of the sea-ice formation is reported to have shifted 14 days later, while the ice cover degradation – approximately 10 days earlier. The duration of ice-free period has thus increased by 20–25 days in the last 20 years.

Depending on the adjacent underwater coastal slope morphology and taking into account the thickness of fast ice, the width of the stretch experiencing freezing within the thermoerosion-affected coasts is 80–100 m, while within the coastal aggradation zones it is 150–200 m, and both tend to decrease from year to year. Within the thermoerosion-affected coasts, the sea ice adfreezing to the bottom precludes degradation of the terrestrial permafrost in the shallow coastal zone, whereas near the accumulative coasts, the permafrost aggradation begins already in the adfreezing zone on the underwater slope. Due to climate warming, at least in the last 30 years, there have been observed accelerated rates of permafrost degradation on the thermoerosion-affected coastline and deterioration of permafrost-forming conditions within the accumulative coasts.

Another important factor that favor permafrost development in the transition zone is the sea-water temperature. Temperature monitoring of the near-bottom water layer were conducted at the Marre-Salé

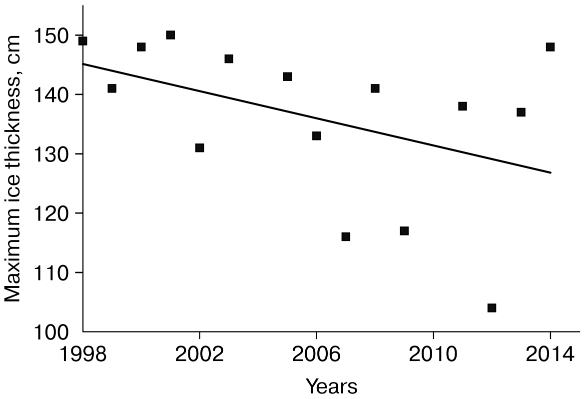

**Fig. 3. Change in maximum thickness of seasonal sea-ice according to the Marre-Salé weather station data.**

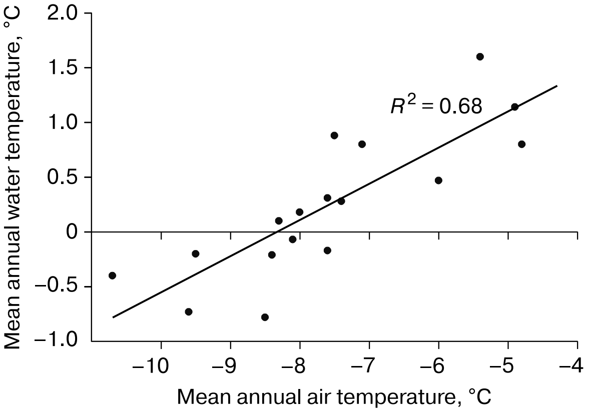

**Fig. 4. Relationship between mean annual seawater temperature and mean annual air temperature according to the Marre-Salé weather station data (1988–2015).**

WS in the shallow water zone during the summer season, and under ice in the winter. The mean annual water temperature in the near-bottom layer was calculated on the basis of fixed-time observational data.

A good correlation was established between the mean annual values for water and air temperatures (Fig. 4). The correlation coefficient $R^2$ is 0.68. Given that the air temperature has been rising since the 1970s, one can expect an increase in the mean annual water temperature in the near-bottom layer. Based on the available observational data from the Marre-Salé WS, an increase in the sea-water temperature in the period from 1988 to 2015 is estimated to be 0.03 °C/year, in the first approximation.

The satellite observational data show that in recent decades, the temperature of the oceanic waters in the near-surface layer has been increasing at a rate of about 0.05 °C/year in the North Atlantic [*Willis et al., 2004*]. The temperature of the near-bottom water layer in the Kara Sea near the Western Yamal coast is thus rising due to both the water column warming in shallow waters driven by climate warming, and because of the arrival of increasingly warmer Atlantic waters in the Kara Sea.

## METHODS APPLIED TO DEPOSITS TEMPERATURE OBSERVATION IN THE TRANSITION ZONE

The thermal regime monitoring in the transition zone from land to sea is technically challenging, inasmuch as the coastal zone is largely influenced by tides, surges and storms. It is therefore all but impossible to equip a dry borehole there, so using autonomous loggers to measure deposits temperature is most appropriate. The observations at the Marre-Salé WS are carried out in two boreholes.

Borehole SB 01 (69°42′ N, 66°48′ E) was drilled in 2006 on the beach at the thermo-erosion gully to a depth of 2.5 m, to enable the permafrost temperature measurements below the active layer. The borehole is cased with a metal pipe, 76 mm in diameter. The height of the wellhead is 0.1 m a.s.l. The HOBO Water Temp Pro v2 loggers are installed in SB 01 at depths of 0.03, 0.5, 1.0, 1.5 and 2.1 m.

The measurements are taken 4 times a day. At the end of the warm season, the temperature loggers are retrieved from the borehole, to take the readings (i.e. the accumulated data), and then they are installed back to the preset depths.

The geological section of the beach within the thermoerosion-affected stretch of the coast in the Marre-Salé area from the surface to a depth of 0.6 m is represented by sediments of the modern beach facies, composed of fine-grained sands. The layer of pebbles and gravel established at a depth of 0.6–0.8 m delimits the lower boundary of the facies.

From a depth of 0.8 m, the section is represented by the Late Neo-Pleistocene gray stratified clays of marine origin. From a depth approximating 1.5–1.8 m, the clays are in the permafrost state. The total ice content of clays reaches 30–35 % [*Kanevsky et al., 2005*]. Given that all deposits are saline, the contents of water-soluble salts are varied and account for 0.1–0.4 % in sands, while they average 0.8 % in clays. The freezing temperature of sands with a given salinity is −0.2...−0.6 °C, and that of clays is about −1.5 °C.

Borehole SB 03 (69°36′ N, 66°49′ E) was drilled in 2007, about 12 km south of the Marre-Salé WS on the surface of the marine laida, within the accumulative beach. The borehole cased with a 76 mm metal pipe was drilled to a depth of 2.5 m. The wellhead height is 0.2 m a.s.l. During high tides, storms and surges, the laida surface is flooded with water. Until 2014, observations with the use of autonomous loggers were conducted at depths of 0.03, 0.6, 1.1, and 1.6 m. In August 2014, temperature loggers were additionally installed to depths of 2.0 and 2.5 m. Similarly to their function in the borehole at the thermo-erosion-affected coast, the measurements are taken four times a day.

The geological section of Holocene marine deposits within the accumulative laida is represented by medium-grained sand from the surface to a depth of 0.2 m. Then it is succeeded by a 0.2 m-thick layer of allochthonous, decomposed peat formed as a result of accumulation of vegetable detritus under lagoon conditions. Peat is underlain by brown, muddy, not completely consolidated deposits of sand-loamy clay-loamy composition with the inclusion of organic detritus. Consolidation of the deposits is found to be increasing with depth. Beginning from a depth of 1.5 m downward, the section is composed of gray heavy clay-loams and clays. The deposits are completely water-saturated. Moisture (ice content) of sediments varies between 30 and 45 %. The deposits are saline, the content of water-soluble salts in surface sands is 0.1–0.4 %, and 0.4–2.0 % in clays. As such, salt content of clays affects their freezing which proceeds in the temperature range from −1.1 to −3.8 °C.

The permafrost structure is represented by alternation of hard-frozen horizons with a thickness of 0.02–0.2 m and 0.2–0.5 m thick negative-temperature, plastically frozen layers. The specific physical state of deposits under the conditions of permafrost aggradation in the Marre-Salé area were earlier characterized by *N.F. Grigoryev* [*1987*]. In addition to the observations of the transitional zone in the Marre-Salé area, permafrost temperature monitoring is well underway in six observational boreholes drilled to a depth of 10 m on the surface of the third (3rd) marine terrace (MT).

## RESULTS AND DISCUSSIONS

Results of measurements in borehole SB 01 located on the thermoerosion-affected coast are shown in Fig. 5 as remarkable temperature curves of unusual

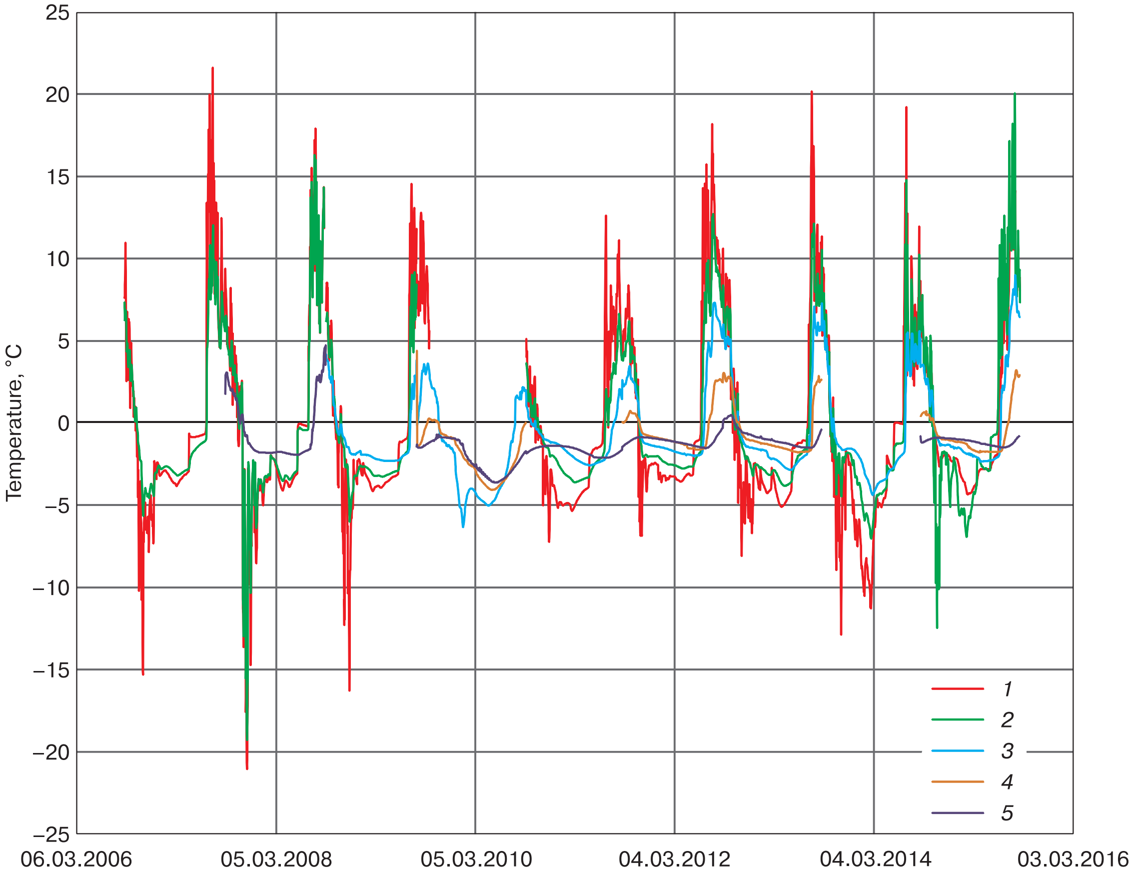

**Fig. 5. Temperature dynamics in borehole SB 01 on the beach at the thermoerosion-affected coast at different depths:** *1* – 0.03 m; *2* – 0.5 m; *3* – 1 m; *4* – 1.5 m; *5* – 2 m.

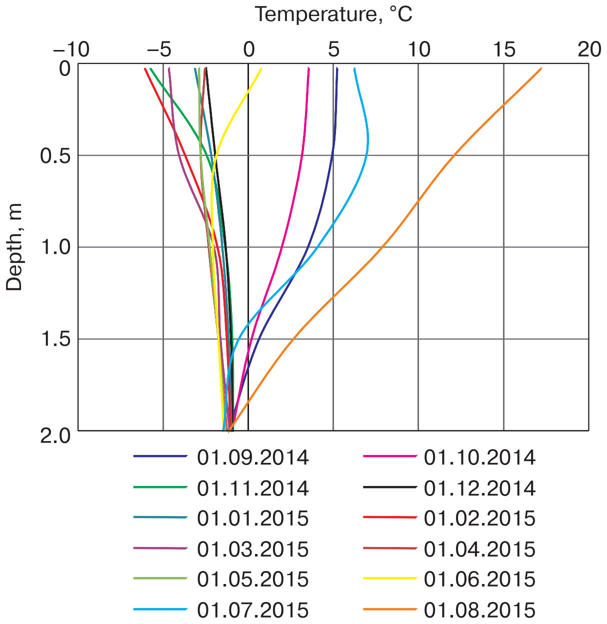

**Fig. 6. Temperature distribution through permafrost deposits at a depth reported for beginning of each month (September 2014 through August 2015) in borehole SB 01 01 on the beach at the thermoerosion-affected coast.**

(asymmetric) shape, indicating that in the period from early December through early June, the surface (0.03 m) temperature has increased dramatically. This is likely to be caused by a thick layer of snow accumulated on the beach, which does subdue daily amplitudes of temperature fluctuations on the beach surface.

This is also confirmed by the snow cover accumulation dynamics during the winter according to the Marre-Salé WS data. The beginning of December is pointedly marked by a rapid increase in the snow cover depth and the formation of snow drifts up to 2 m thick. Loss of snow cover takes place in the first and second decades of June. The average daily air temperature rises sharply in the second decade of June, which is reflected in the surface temperature variability. As a result of substantial rise in the surface temperature, the annual course of soil temperature is marked by appearance of subhorizontal zones at all the depths. Figure 6 shows temperature distributions at the beginning of each month over the period from September 2014 to August 2015. Relying on this representation, the average annual temperature of permafrost is inferred to be (–1.15 ± 0.25) °C at a depth of 2.0 m. The depth of the layer annual of

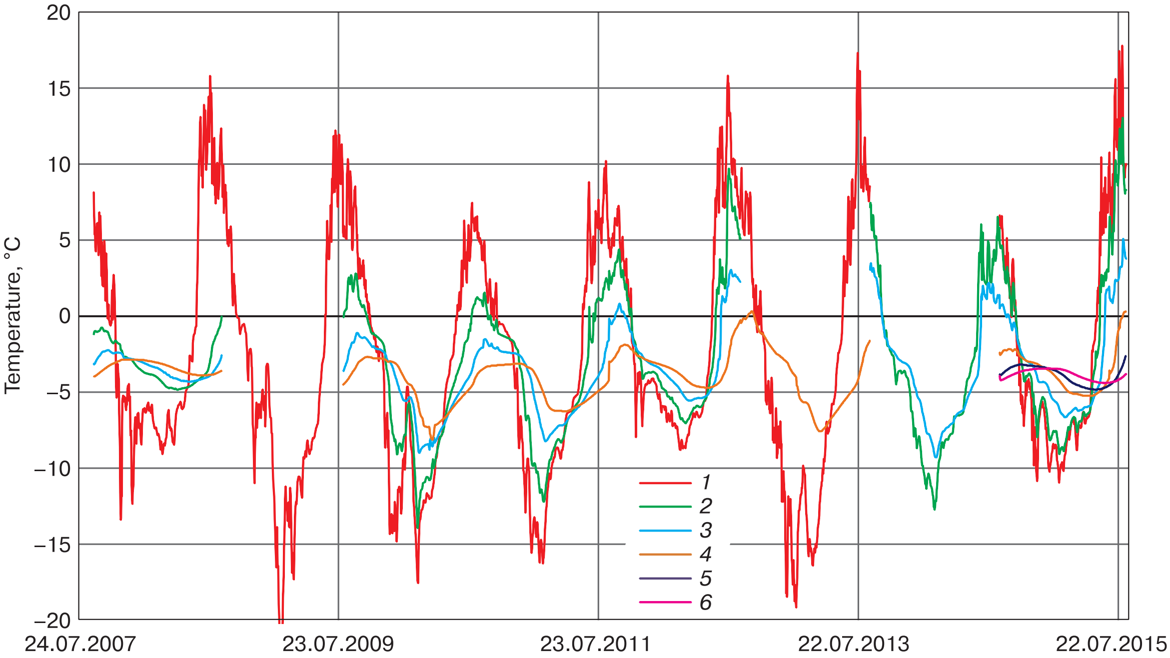

**Fig. 7. Temperature dynamics in borehole SB 03 on the marine laida surface within contemporary marine accumulation zone at different depths:**

*1* – 0.03 m; *2* – 0.6 m; *3* – 1.1 m; *4* – 1.6 m; *5* – 2 m; *6* – 2.5 m.

zero amplitudes is estimated at 2.5–3.5 m. Notably, its depth on the surface of the 3rd MT is found to be greater than 10 m, and the temperature at this depth equals −4.5 °C. Such a shallow depth of the layer of zero annual amplitudes of the degrading permafrost in the first type transition zone is explained by the absence of winter cooling of the permafrost strata at the expense of the extremely deep snow cover.

The transition from the continental to the subsea permafrost, taking place in the first type transitional zone is thus marked by an abrupt change in the mean annual temperature of deposits from −4.0...−5.0 to −1.0...−1.5 °C.

The long-term temperature variations observed in borehole SB 03 on the laida surface within modern marine accumulative zone with permafrost development is shown in Fig. 7. Given that snow accumulation conditions are not anomalous here, the temperature distribution curves in time exhibit a symmetrical character. Figure 8 shows the temperature distribution through depth at the beginning of each month in the period from September 2014 to August 2015. The mean annual temperature of frozen deposits at a depth of 2.5 m is −3.9 °C, which is 1.5 °C higher than on the 3rd MT surface. The depth of zero annual temperature amplitudes is assumed to be 3–4 m.

However, unlike temperatures in the first-type transition zone, the low depth of the layer of zero annual amplitudes here is accounted for the heat loss during a phase change of the freezing deposits. According to the data obtained by *N.F. Grigoriev* [*1987*],

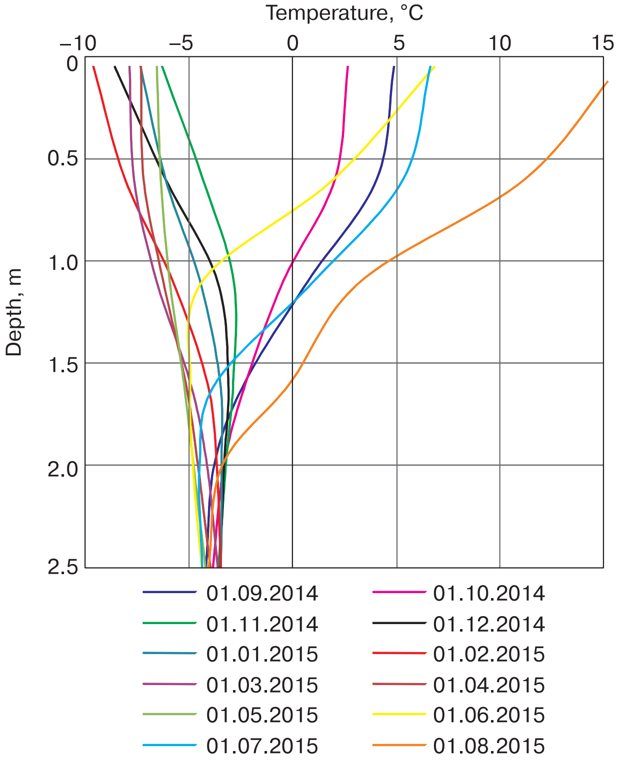

**Fig. 8. Temperature distribution through permafrost deposits at a depth reported for beginning of each month (September 2014 through August 2015) in borehole SB 03 on the marine laida surface within contemporary marine accumulation zone.**

Table 1. **Mean annual temperatures (°C) of permafrost deposits in the transition area from land to sea: type 1 (borehole SB 01) and type 2 (borehole SB 03) over the period of 2007–2015**

| Year | Depth of temperature loggers installation, m | | | | | | | | | | Mean annual air tempera-ture, °C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Borehole SB 01 | | | | Borehole SB 03 | | | | | | |
| | 0.03 | 0.5 | 1.0 | 2.1 | 0.03 | 0.6 | 1.1 | 1.6 | 2.0 | 2.5 | |
| 2007 | 0.13 | −0.1 | −0.1 | −0.9 | – | – | – | – | – | – | −5.0 |
| 2008 | −0.4 | −0.2 | −0.2 | −1.0 | −1.4 | −3.2 | −3.4 | −3.4 | – | – | −5.1 |
| 2009 | −0.7 | −1.3 | −0.9 | −1.1 | −3.6 | – | – | – | – | – | −7.9 |
| 2010 | – | – | −2.2 | −2.0 | −4.2 | −4.7 | −4.7 | −4.7 | – | – | −8.0 |
| 2011 | −0.9 | −1.0 | −1.2 | −1.6 | −3.7 | −4.1 | −4.4 | −4.5 | – | – | −4.4 |
| 2012 | 1.2 | 1.0 | 0.4 | −1.1 | −0.9 | −1.8 | −2.5 | −3.2 | – | – | −3.6 |
| 2013 | −0.4 | −0.2 | −0.3 | −0.9 | −4.0 | – | – | −4.0 | – | – | −7.4 |
| 2014 | −1.8 | −1.0 | −0.8 | – | – | −3.6 | −3.6 | – | – | – | −7.7 |
| 2015 | 0.2 | 0.2 | 0.1 | −1.1 | −1.9 | −2.1 | −2.9 | −3.6 | −3.9 | −3.9 | −5.3 |

the mean annual temperature on the laida-zone of Bolotny island, in the vicinity of borehole SB 03, also approximates −4 °C, while the depth of zero annual amplitudes reaches 4–5 m. The permafrost thickness is 2–10 m.

Aggradation of the comparatively low-temperature permafrost with average annual temperature of about −4 °C, thus, occurs in the second type transition zone.

Despite the specific heat exchange conditions, a pronounced response of the average annual sediment temperature to climatic changes is manifest in both types of transition zones. Table 1 shows the mean annual air and permafrost temperatures in both identified types of transition areas from land to sea at different depths. The data from Table 1 indicate a correlation between the air temperature variations and the upper horizons of frozen deposits: an increase in the mean annual air temperature prompts an appreciable growth of the average annual temperature of the deposits at all the depths. This allows us to infer that climate has an imperative influence on the formation of the onshore permafrost thermal regime in the transition zone both within the thermoerosion-affected coasts and on the accumulative beaches. In the subsea portion of permafrost, on the contrary, the determining role is played by the changes in hydrological characteristics, primarily, in temperatures of the near-bottom layer of sea-water.

Another important feature of the permafrost thermal regime is the mean annual temperature reducing with depth, which indicates a climate-driven long-term warming of the permafrost strata. The same trend is also observed in the onshore conditions [*Vasiliev et al., 2011*].

## CONCLUSIONS

Monitoring observations of the thermal regime of the upper horizons of permafrost were conducted in the transition zone from land to sea. The processes of permafrost degradation and submergence of its upper horizon seawards feature the base of thermo-erosion-affected coast. Whilst permafrost development occurs on the laidas of accumulative beaches.

The mean annual temperature of deposits near the thermoerosion-affected coast is −0.9...−2.2 °C, which is 2–3 °C higher than in typical continental conditions. The thickness of the layer of zero annual amplitudes averages 2.5–3.5 m, as is determined primarily by the heat-insulating effect of a thick snow drift, which forms annually at the base of thermal erosion gully. Given that the mean annual temperature of deposits in this zone is higher than the temperature of phase transitions, this enabled the upper layer of the degrading frozen deposits to be assigned to seasonally frozen deposits (active layer). While only lower horizons can be ranked as permafrost.

The present-day aggradation of permafrost proceeds on the marine laidas, where average annual temperature is about −4 °C; the depth of zero annual amplitudes does not exceed 4–5 m, which is associated with the heat losses attributed to phase transitions in the freezing zone.

Recent climate warming is reflected in the declining mean annual temperature of the deposits with depth, which is observed near the thermoerosion-affected coasts within the permafrost degradation area, and in the zone of modern marine accumulation where permafrost is present. Therefore, climate warming contributes to the permafrost degradation in the former case, and slows down permafrost development in the latter.

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## References

Anisimov, O.A., Belolutskaya, M.A., 2002. Estimation of effects of climate change and permafrost degradation to infrastructure in northern regions of Russia. Meteorologia i Gidrologia, No. 6, 15–22.

Dubrovin, V.A., Kritsuk, L.N., Polyakova, E.I., 2015. Temperature, composition and age of the Kara Sea shelf sediments in the area of the Marre-Salé geocryological station. Earth's Cryosphere (Kriosfera Zemli), XIX (4), 3–16.

Grigoriev, N.F., 1987. Permafrost Coast of the Western Yamal. Izd-vo IMZ SO AN SSSR, Yakutsk, 112 pp. (in Russain)

Kanevskii, M.Z., Srtreletskaya, I.D., Vasil'ev, A.A., 2005. Formation patterns for cryogenic structures of Quaternary deposits of the Western Yamal (Evidence from the Marre-Salé area). Kriosfera Zemli, IX (3), 16–27.

Melnikov, V.P., Spesivtsev, V.I., 1995. Engineering-geological and Geocryological Conditions of the Barents and Kara Shelves. Nauka, Novosibirsk, 198 pp. (in Russian)

Nixon, J.F., 1986. Thermal simulation of subsea saline permafrost. Can. J. Earth Sci., vol. 23, 2039–2046.

Oberman, N.G., 2006. Multi-year trends in natural evolution of permafrost in the northeast of European Russia. Proceedings of the International Conference "Theory and practice of an estimation of the Earth's Cryosphere state". TyumGNGU, Tyumen, vol. 1, pp. 93–96.

Osterkamp, T.E., 2001. Subsea permafrost, in: Encyclopedia of Ocean Sciences. J.H. Steele, S.A. Thorpe, K.K. Turekian (Eds.). Cambridge, Massachusetts, Acad. Press (Elsevier), pp. 2902–2912.

Pavlov, A.V., 2003. Permafrost-climatic changes in northern Russia: observations, forecast. Izv. RAN, Ser. geogr., No. 6, 22–29.

Pavlov, A.V., Malkova, G.V., 2005. Contemporary Climate Changes in Northern Russia. Geo Academic Publishing House, 54 pp. (in Russian)

Rokos, S.I., Dlugach, A.G., Loktev, A.S., Kostin, D.A., Kulikov, S.N., 2009. Permafrost deposits of the Pechora and Kara shelves: genesis, composition, distribution and occurrence character. Inzh. Geologia, No. 10, 38–41.

Romanovsky, V.E., 2006. Thermal regime of the permafrost in Alaska in the last two decades, in: Proc. of the International Conference "Theory and practice of an estimation of the Earth's Cryosphere state". TyumGNGU, Tyumen, vol. 1, pp. 96–101.

Romanovsky, V., Drozdov, D., Oberman, N., Malkova, G., Kholodov, A., Marchenko, S., Moskalenko, N., Sergeev, D., Ukraintseva, N., Abramov, A., Gilichinsky, D, Vasiliev, A., 2011. Thermal state of permafrost in Russia. Permafrost and Periglacial Processes. Spec. Iss.: The International Polar Year, 21 (2), 136–155.

Solomon, S.M., Taylor, A.E., Stevens, Ch.W., 2008. Nearshore ground temperatures, seasonal ice bonding, and permafrost formation within the Bottom-Fast Ice Zone, Mackenzie Delta, NWT, in: Proc. of the Ninth Intern. Conf. on Permafrost (Fairbanks, June 29–July 3, 2008). Fairbanks etc., Institute of Northern Eng., Univ. of Alaska Fairbanks, vol. 2, pp. 1675–1680. (in Russian)

Streletskiy, D., Anisimov, O., Vasiliev, A., 2014. Permafrost degradation, in: Snow and Ice-Related Hazards, Risks and Disasters. Elsevier, N.Y., pp. 303–343.

Vasiliev, A.A., Oblogov, G.E., Rekant, P.V., Srtreletskaya, I.D., 2015. Thermal regime of subaqueous permafrost in the Kara Sea, in: Proc. of the third International Conference "Arctic, Subarctic: Mosaic, Contrast, Variability of the Cryosphere" (Tyumen, 2–5 July 2015). Epokha, Tyumen, pp. 44–45. (in Russian)

Vasiliev, A.A., Srtreletskaya, I.D., Shirokov, R.S., Oblogov, G.E., 2011. Evolution of the permafrost of the coastal marine area of Western Yamal under changing climate conditions. Kriosfera Zemli, XV (2), 56–64.

Willis, J.K., Roemmich, D., Cornuelle, B., 2004. Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scale. J. Geophis. Res., vol. 109, 13–26, DOI: 10.1029/2003JC002260.

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