Proceedings of the 25th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2019, Delft, The Netherlands

Long-term geothermal monitoring of the Arctic coast for assessment of their stability

Osip V. Kokin[1,2], Aino V. Kirillova[2], Denis M. Frolov[1], Stanislav V. Godetskiy[2]
[1] Lomonosov Moscow State University, Moscow, Russia
[2] Zubov State Oceanographic Institute, Moscow, Russia

ABSTRACT

Sea coasts are the basis for the industrial facilities for oil and gas exploration in the Arctic. The establishment of a coastal geothermal monitoring station will provide the necessary recommendations on the magnitude of man-made deformations for the safe operation of designed facilities and engineering structures and avoid catastrophic events of coastal retreat and floods. It should be long-term year-round monitoring of the ground temperature in natural conditions prior to the economic development of the territory. In the present work, the results of long-term field measurements of ground temperatures which were carried out at Pesyakov island near Varandey settlement (Pechora Sea coast) in the period 2012–2018. Geothermal station consists of five boreholes with a depth of 2,3 to 6,5 m. Each borehole has GeoPrecision thermostrings with temperature sensors and wireless radio mini data loggers M-Log5W-DALLAS, which automatically record measurement data and store them. Thermostring have a length of 10 m and include 20 sensors located across 0,25–1 m. The boreholes are laid in various geomorphological positions along the line passing across the central part of Pesyakov island. It has been established that the episodic deviations of the ground thawing duration from the mean annual values do not directly affect the deformation of the coast. However, a directional increase in the duration of the warm period leads to an increase in the thickness of the active layer, reducing the thermodynamic stability of the sea coasts.

KEY WORDS: Sea coast; Ground temperature; Borehole; Pechora Sea; Stability.

INTRODUCTION

In recent decades, active development of oil and gas deposits located on the shelf and coast of the Arctic Ocean is underway. Some complex infrastructure projects with federal significance and strategic tasks have already been implemented. They are the oil-loading terminal and the Prirazlomnaya drilling platform in the Varandey area, the Bovanenkovo-Ukhta gas pipeline with an underwater segment that lie at the Baidaratskaya Bay seabed, as well as Yamal LNG with the port and airport in Sabetta. Ports (Arctur in Ust-Kara, Indiga), airfields (Amderma), railways and highways (Vorkuta – Ust-Kara, Sosnogorsk – Indiga, Bovanenkovo – Sabetta), production facilities (Arktik-LNG-2 plants on the Gydan Peninsula and Pechora LNG in Indiga), as well as boreholes and pipelines (Pesyakov Island in the Varandey area) are supposed to construction within the framework of currently planned infrastructure projects in the Arctic. In addition to the economic development of the Arctic, there is an increase in the military presence (construction of bases and airfields on Franz Josef Land and the New Siberian Islands), so some of the facilities are of military use.

One of the risks of the implementation of Arctic infrastructure projects in the report of the Agency for Political and Economic Communications is “the consequences of global warming”: “Because of the melting of the permafrost, the risks of collapse of facilities and railways increase, and the melting of ice requires modification of the existing navigation patterns (potential coastal flooding and the need for port transfer)” (Orlov, 2018).

In this regard, investigations of the ground temperature regime changes of the arctic sea coasts composed of frozen quaternary sediments which very sensitive to modern climate warming are very important. The Arctic sea coast is a transitional zone between the continental and subaqueous cryolithozone. The growth of the power of the active layer, as well as an increase in the ice-free period and storm activity, man-made effects accelerate the destruction of the coast by wave, slope and aeolian processes, which lead to deformations of the coastal zone topography, and accordingly to a change in the depth of penetration and redistribution of heat flows. The latter, in turn, may enhance positive feedback, which leads to the intensification of permafrost degradation, and, accordingly, threatens the sustainable safe operation of infrastructure facilities on the Arctic sea coasts.

The establishment of a geothermal coastal station for long-term year-round monitoring of the ground temperature in natural conditions prior to the economic development of the territory will provide the necessary recommendations on the magnitude of man-made deformations for the safe operation of designed facilities and engineering structures and avoid catastrophic events of coastal retreat and floods. In this work, the results of long-term field measurements of ground temperatures in the period 2012–2018 at such geothermal coastal monitoring station are presented.

STUDY AREA

Geothermal monitoring station is located at the coast of Pesyakov Island (Figure 1), west of Varandey settlement (coastal area of Pechora Sea, Nenets Autonomous District) in a zone of continuous permafrost near its south border. Varandey settlement is a large oil and gas development base in the Russian Arctic. Oil storage and loading terminal and weather station are located here. Coastline at monitoring site is oriented eastnortheast-westsouthwest (75°N).

Pesyakov Island is a coastal barrier island which consists from fine sands with low ice content (Novikov, Fedorova, 1989; Ogorodov, Kokin, 2012). Barrier looks like a flat terrace with a height approximately 3–5 m a.s.l. There is a narrow strip of dune belt at the surface of terrace. The height of the dune belt varies from 5 to 12 m. The marine slope of dune belt sometimes has a steep bluff (Figure 2). The width of beach and surge berm can reach 80–100 m.

The climate in the region is subarctic and marine, characterized by long, cold winters and short, cool summers. The cold period when average monthly air temperatures remain negative lasts 8 months (from October until May). The warm period lasts 4 month (from June until September). The mean annual air temperature at Varandey weather station according to observations before 1980 is -5,6 °C (Scientific …, 1989). Total annual precipitation at

Varandey averages 409 mm, with 161 mm falling as snow. Precipitation is typically heaviest in late summer and early fall (August-October).

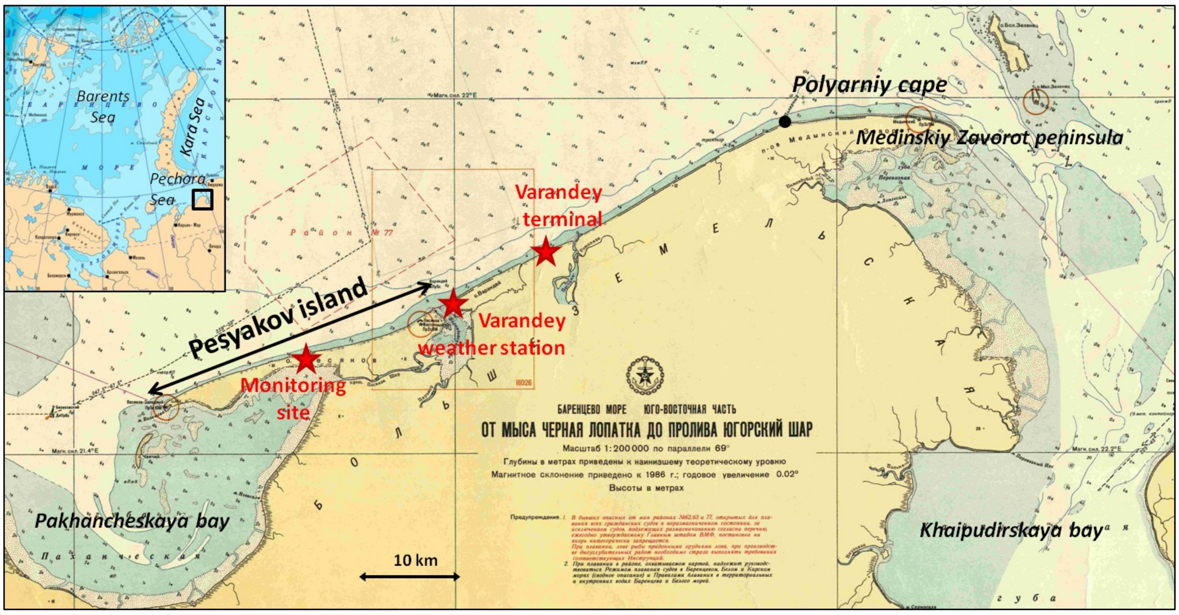

Figure 1. Location of study area and monitoring site

Figure 2. The view of the dune belt along the coast of Pesyakov island near monitoring site

MATHERIALS AND METHODS

The geothermal station at Pesyakov Island was established in July 2012 and consisted of six boreholes with a depth of 2,3 to 6,5 m (Figure 3). Each borehole has GeoPrecision thermostrings with temperature sensors and wireless radio mini data loggers M-Log5W-DALLAS, which automatically record measurement data and store them. Thermostring have a length of 10 m and include 20 sensors located across 0,25–1 m. The boreholes are laid in various geomorphological positions along the line passing across the central part of Pesyakov island: the upper part of the beach at the foot of the coastal bluff, the top of the dune belt near the edge of the coastal bluff, the surface of the terrace behind the dune belt (3 boreholes), layda.

The monitoring site was chosen on the island of Pesyakov, which did not experience the effects of economic activity. This makes it possible to study the effect of fluctuations of meteorological parameters on the thermal regime of coastal grounds in their natural form, while on Varandey this is also subject to a factor of technogenic activity (Sinitsyn et al., 2013) that would be difficult to separate from each other. Nowadays, observational data for the period 2012–2018 have been obtained with an interval of 12 hours. However, the station continues to function to the present.

In the present work, the variability of average annual and seasonal ground temperatures of two boreholes closest to the coast is considered in comparison with average annual and seasonal air temperatures according to the Varandey weather station (Weather schedule, 2019). The beach borehole has a depth of 3,25 m and is located in the upper part of the beach, at the foot of the coastal bluff of the dune belt at an altitude of 2,85 m relative to sea level. The dune borehole (6,5 m deep) is located on the top of the dune belt at a height of 6,5 m relative to sea level.

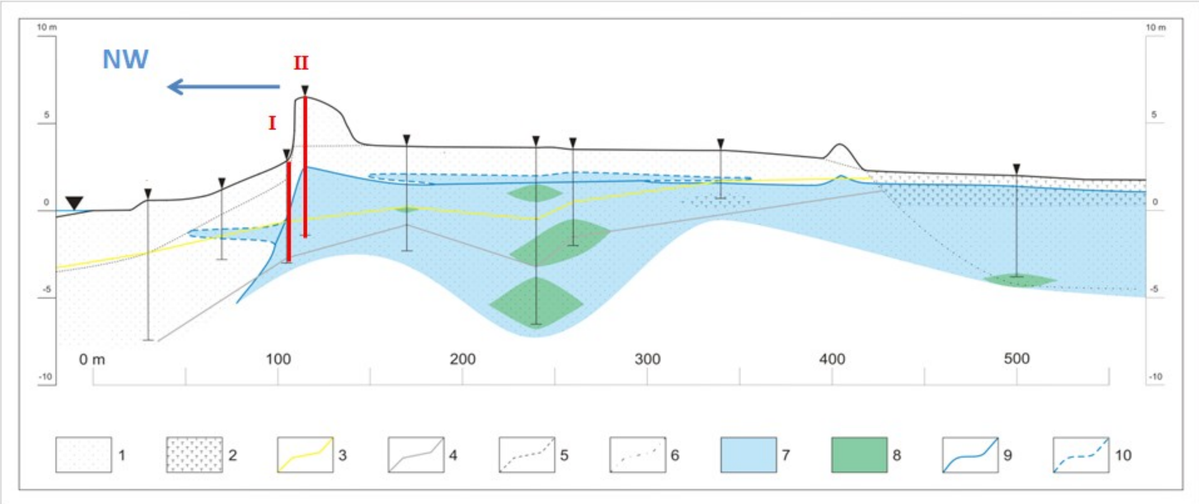

Figure 3. The geocryological profile and location of boreholes (after Guégan et al., 2016): 1 – fine sand; 2 – peat and sand with remains of peat; 3 – foot of yelow sand; 4 – foot of gray sand; 5 – supposed boundaries between sands of different genetically-age facies; 6 – boundary between silty sands of laida and washed sands of barrier terrace; 7 – well bonded frozen ground; 8– probable lenses of cryopegs;); 9 – permafrost table; 10 – probable boundary of seasonally frozen ground. I – the beach borehole; II – the dune borehole

Data analysis was carried out in annual cycles from October to September. The annual cycle 2017–2018 of ground temperatures has an incomplete series of observations ending in early August when the last data downloading have been performed during field work.

RESULTS AND DISCUSSION

Air temperature

Variation of mean air temperature at Varandey weather station is shown on the Figure 4. Mean annual air temperature vary from -4,9 to -0,9 °C. These values are warmer than the mean annual temperature until 1980 (-5,6 °C). Mean air temperature for warm period vary from +6,2 to +12,0 °C and for cold period – from -10,6 to -7,3 °C. The coldest annual cycle is 2013–2014 and warmest is 2015–2016. The mean annual air temperature is closer to the mean cold period air temperature due to longer duration of cold period during annual cycle. There is a weak trend to increase of mean annual air temperatures due to the increase in mean temperatures of the cold period.

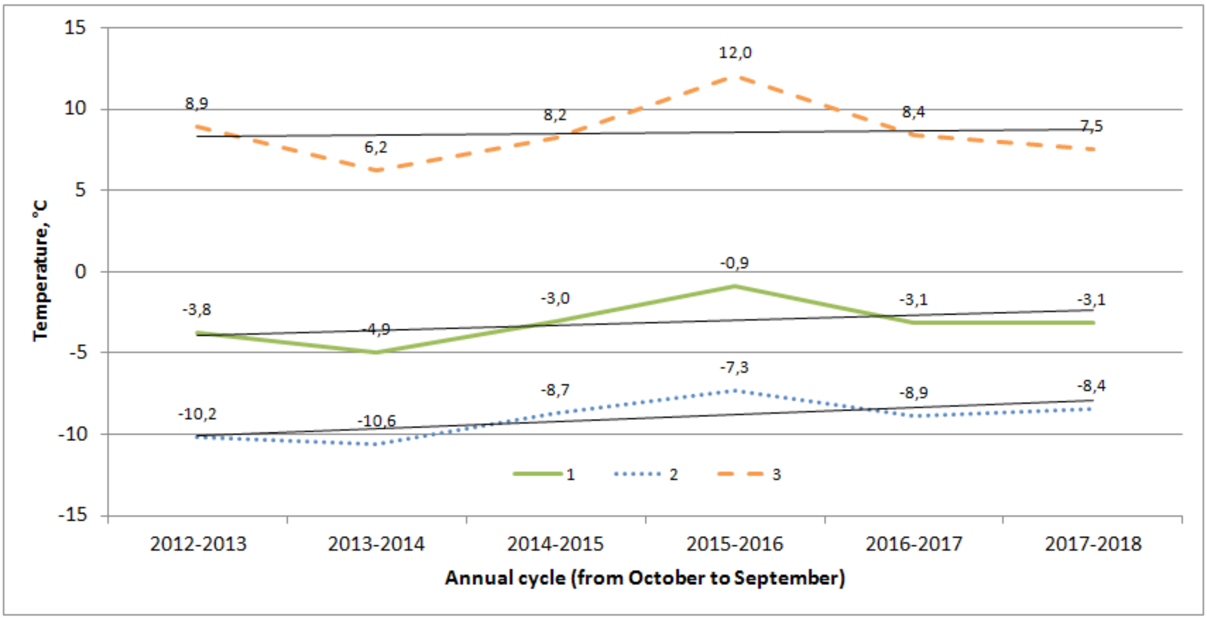

Figure 4. Mean annual (1), cold (2) and warm (3) periods air temperature at Varandey weather station for annual cycles from October 2012 to September 2018

Ground temperature on the beach

Variation of mean ground temperature distribution with depth is shown on the Figure 5 (left). Mean annual ground temperatures are positive. Its variation decreases from +1…+2,8 °C at a depth of 0,5 m until +0,1…+0,5 at a depth of 3 m. The results of 2017–2018 are not taken into account, because there is an incomplete series of observations for this annual cycle and are given for information as empty dots. The coldest annual cycle is 2013–2014 and warmest is 2015–2016 like air temperature which is shown in the graphs as values at a height of 2 m.

Mean cold period ground temperatures until the depth 1 m has negative values and vary from -1,3…-0,6 °C at a depth of 0,5 m until -0,5…-0,1 at a depth of 0,75 m. Deeper than 1 m ground temperature in cold period stay positive and almost the same (between +0,1 and +0,5 °C) throughout the thickness up to 3,25 m. Such distribution is due to the accumulation in winter of a thick snow pack in the upper part of the beach at the foot of the coastal bluff (Guégan et al., 2016). This snow pack has a warming effect on ground temperatures here.

Mean warm period ground temperatures are positive and vary from +4,6…+9,5 °C at a depth of 0,5 m until +0,3…+1,2 °C at a depth of 3,25 m. The results of 2017–2018 are not taken into account, because there is an incomplete series of observations for this annual cycle and are given for information as empty dots. The coldest annual cycle is 2013–2014 and warmest is 2015–2016 like air temperature. On the beach the mean warm period ground temperature determines the mean annual ground temperature despite the short duration.

Relation between air and ground temperature at separate depth (0,5; 1 or 2; 3 m) on the beach is shown on the Figure 5 (right). Trend lines are based on 4 annual cycles (2012–2016). Values of 2016–2017 annual cycle are shown as empty points because they deviate significantly from the linear trend especially for the depth of 0,5 m. The results of 2017–2018 are not taken into account, because there is an incomplete series of observations for this annual cycle. A regression coefficient of about 0,9 or more is noted for mean annual and warm period temperature. So in winter period another factor is more important than air temperature. Obviously this is snow cover. The anomaly of 2016–2017 when lower ground temperature is observed than should be at the same air temperature is also apparently related to snow cover. Probably it was less thickness in this year than usual or it was established later than usual. With increasing depth, the temperature anomaly fades.

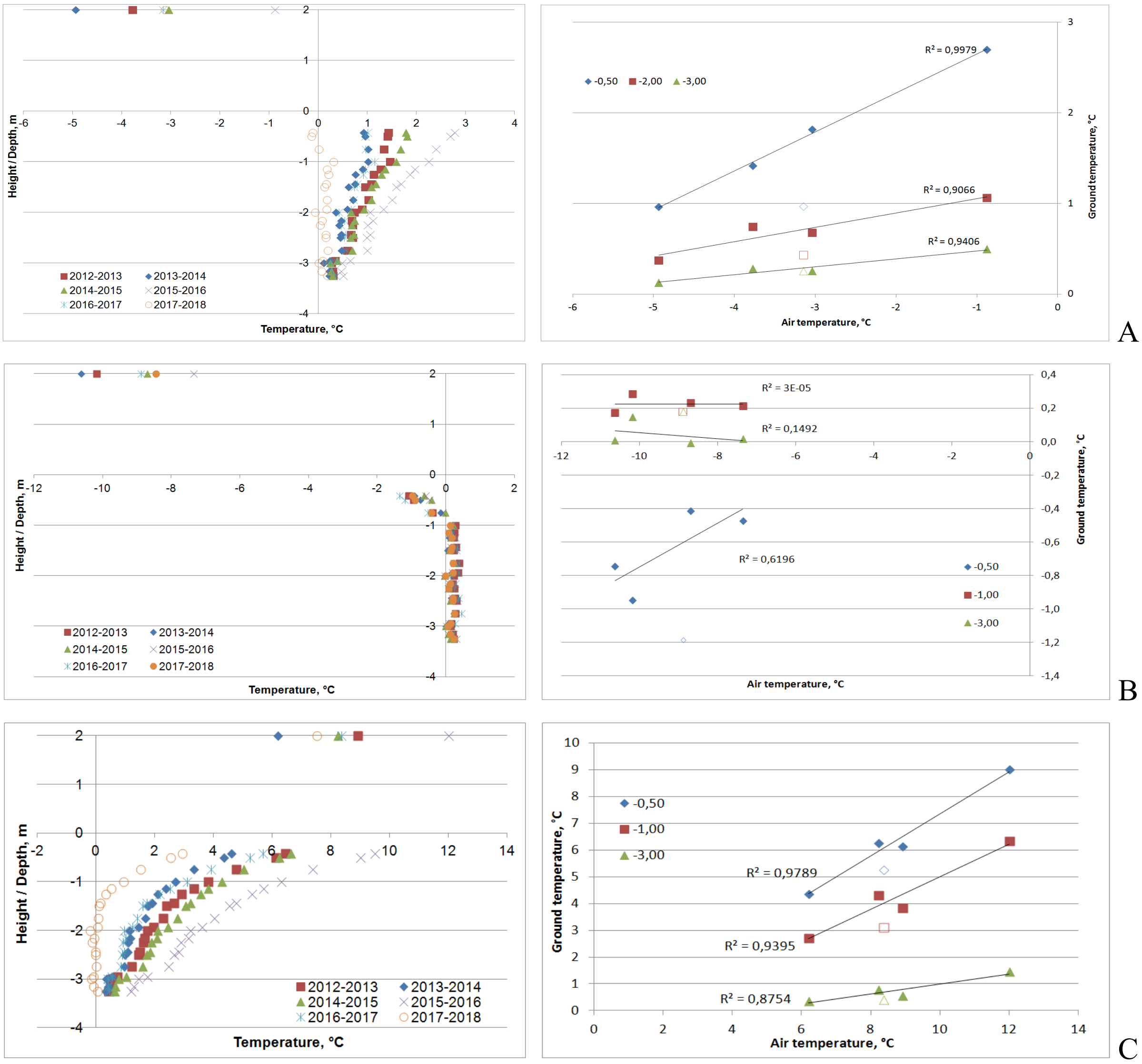

Figure 5. The beach borehole: ground temperature distribution with depth (left) and relation between air and ground temperature at separate depth (right): mean annual (A), cold (B) and warm (C) periods

Ground temperature on the dune

Variation of mean ground temperature distribution with depth is shown on the Figure 6 (left). Mean annual ground temperature are negative until the depth 2,25–3 m. Deeper there are mean annual ground temperatures near zero. The exceptions are the values of the annual cycle 2015–2016, when mean annual temperatures were positive until the depth of 4 m. Variation of mean temperatures decreases from -2…+0,6 °C at a depth of 0,5 m until -0,3…+0,2 at a depth of more than 4 m. The results of 2017–2018 are not taken into account, because there is an incomplete series of observations for this annual cycle and are given for information as empty dots. The coldest annual cycle is 2013–2014 and warmest is 2015–2016 like air temperature which is shown in the graphs as values at a height of 2 m.

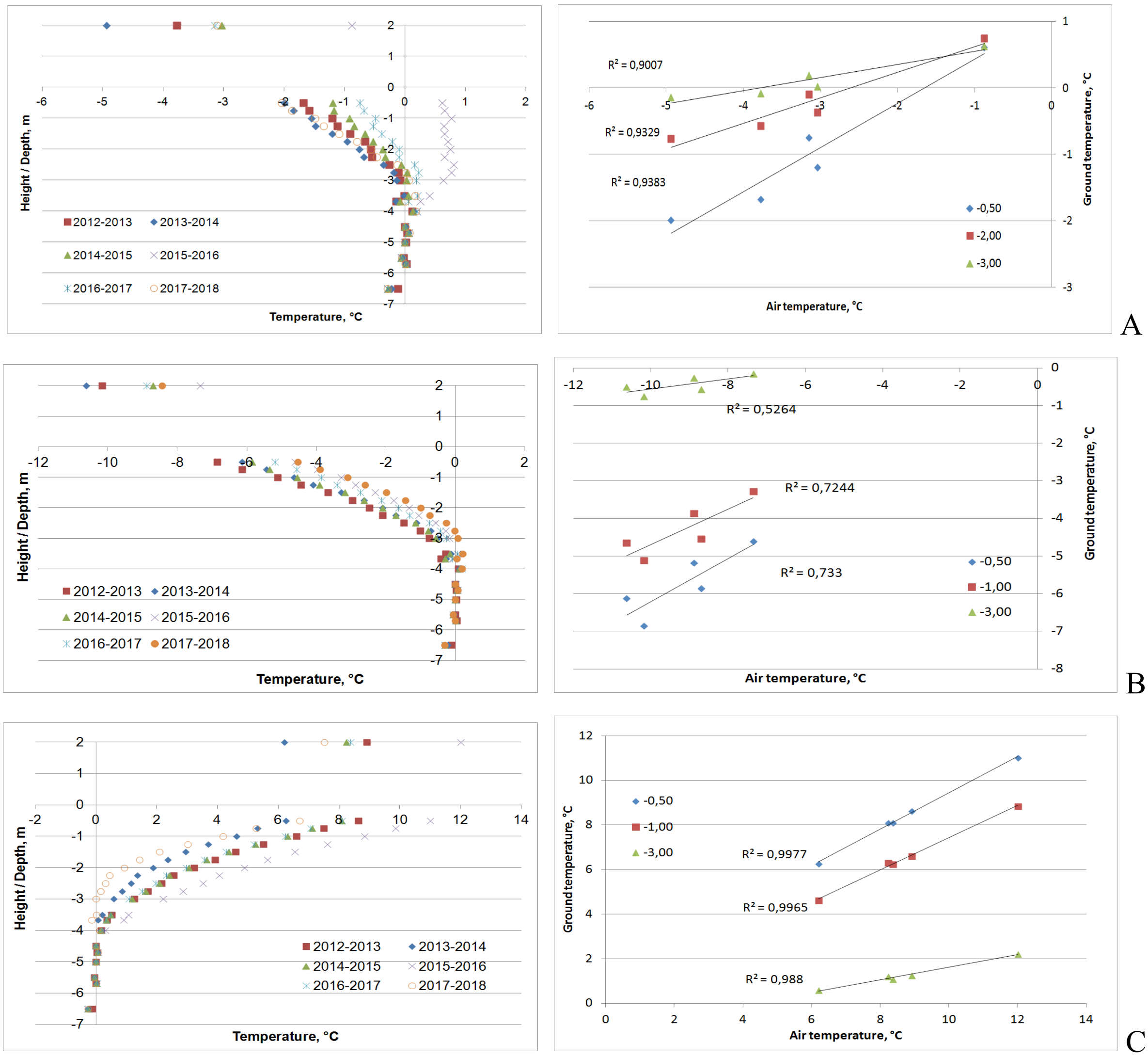

Figure 6. The dune borehole: ground temperature distribution with depth (left) and relation between air and ground temperature at separate depth (right): mean annual (A), cold (B) and warm (C) periods

Mean cold period ground temperatures until the depth 3–4 m has negative values and vary from -6,9…-4,6 °C at a depth of 0,5 m until -0,3…+0,1 at a depth of 3,5 m. Deeper than 3–4 m ground temperature in cold period fluctuate around zero. In contrast to the foot of the coastal bluff there is thin snow cover accumulate in winter due to the exposure to the wind and blowing snow from the top of dune belt. On the dune the mean cold period ground temperature determines the mean annual ground temperature due to the long duration.

Mean warm period ground temperatures until the depth 4 m has positive values and vary from +6,3…+11 °C at a depth of 0,5 m until +0,1…+0,2 °C at a depth of 4 m. The results of 2017–2018 are not taken into account, because there is an incomplete series of observations for this annual cycle and are given for information as empty dots. The coldest annual cycle is 2013–2014 and warmest is 2015–2016 like air temperature.

Relation between air and ground temperature at separate depth (0,5; 1 or 2; 3 m) on the dune is shown on the Figure 6 (right). Trend lines are based on 5 annual cycles (2012–2017). The results of 2017–2018 are not taken into account, because there is an incomplete series of observations for this annual cycle. A regression coefficient of about 0,9 or more is noted for mean annual and warm period temperature. For the cold period, the regression coefficient is less (0,5–0,7), but still quite significant. There are no big anomaly due to non-thermal factors exept air temperature.

Thermal stability of the Arctic sea coasts

Thermal stability of the Arctic sea coasts manifested in changing the active layer thickness. The growth of mean temperatures at a certain depth leads to an increase of the active layer thickness. Changes in mean temperatures from negative to positive are especially important.

Changes in ground temperatures can be caused by both the air temperature factor and others non-temperature factors (for example, precipitation both in winter and in summer). The temperature factor affects the expansion or displacement of the range of fluctuations in ground temperature along the trend line of the relation of air and ground temperatures when the critical values of mean annual air temperature are exceeded.

Non-temperature factors affect the anomalies in the relation of air and ground temperatures. In such cases, a rebound of values from trend lines of air and ground temperatures can be observed. Increasing the frequency of critical values of mean air temperature and non-temperature anomalies can bring the temperature regime out of balance.

During the 2012–2018 period, the geothermal station coastal ground were in a stable condition, apparently due to the weak trend of rising winter air temperatures and the stable trend of summer air temperatures. Non-thermal anomaly of beach temperatures was observed only in 2016–2017, when the ground was colder than it should be at the observed mean air temperature. This was probably due to the lower than usual thickness of the snow pack, or due to its late formation. The depth of winter freezing on the beach remained constant throughout the study period (between 0,75 and 1 m).

No anomalies associated with non-thermal factors were observed on the dune belt. However, in the 2015–2016 annual cycle, the mean annual temperatures had positive values due to exceeding the mean annual air temperature critical values (above -1,6...-1,7 ° C for a depth of 0,5 m).

It is worth noting that the stability of the coastal grounds in the study period is also manifested in the stability of the coastal bluff, which is established by repeated geodetic surveys.

CONCLUSIONS

Mean annual air temperature during 2012–2018 period vary from -4,9 to -0,9 °C. These values are warmer than the mean annual temperature until 1980 (-5,6 °C). There is a weak trend to increase of mean annual air temperatures due to the increase in mean temperatures of the cold period.

Mean annual ground temperatures on the beach are positive due to the accumulation in winter of a thick snow pack in the upper part of the beach at the foot of the coastal bluff. The non-thermal anomaly of 2016–2017 when lower ground temperature is observed than should be at the same air temperature is also apparently related to snow cover. Probably it was less thickness in this year than usual or it was established later than usual.

Mean annual ground temperature on the dune are negative until the depth 2,25–3 m. Deeper they are near zero. The exceptions are the values of the annual cycle 2015–2016, when mean annual temperatures were positive until the depth of 4 m. It was due to exceeding mean air temperature critical value (above -1,6...-1,7 ° C for a depth of 0,5 m).

The coldest annual cycle for air and ground temperatures (in both boreholes) is 2013–2014 and warmest is 2015–2016.

During the 2012–2018 period, the geothermal station coastal ground were in a stable condition, apparently due to the weak trend of rising winter air temperatures and the stable trend of summer air temperatures. Increasing the frequency of critical values of mean air temperature and non-temperature anomalies can bring the temperature regime out of balance.

ACKNOWLEDGEMENTS

The work was supported by the Russian Science Foundation (project №17-77-10140).

REFERENCES

Guégan, E., Sinitsyn, A., Kokin, O., & Ogorodov, S., 2016. Coastal geomorphology and ground thermal regime of the Varandey area. *Journal of Coastal Research*, 32(5), pp. 1025–1031.

Novikov, V.N., & Fedorova, E.V., 1989. Destruction of coasts in the southern Barents Sea. *Vestnik MGU, Geografiya*, 5(1), pp. 64–68. In Russian.

Ogorodov, S.A., & Kokin, O.V., 2012. Geomorphological structure and dynamics of barrier islands in the Barents Sea. In: Pascucci, V., Coltorti, M., Stefano, A., Pieruccini, P., Laura S. eds., At the edge of the sea: sediments, geomorphology, tectonics, and stratigraphy in Quaternary studies *INQUA SEQS 2012 Meeting*, pp. 74–75.

Orlov, D., 2018. *The development of the Arctic zone of Russia and the main challenges for its exploration* [Online] Available at: https://regnum.ru/news/2407690.html [Accessed 13 March 2019]. In Russian.

Scientific and Applied Handbook on the Climate of the USSR, 1989. Series 3. Long-term data. Parts 1-6. Issue 1. Book 1. Leningrad: Gidrometeoizdat, 483 p. In Russian.

Sinitsyn, A., Guegan, E., Kokin, O., Vergun, A., Udalov, L., &Ogorodov, S. (2013). Investigations of coastal erosion processes in Varandey area, Barents sea. In: Society of Petroleum Engineers - SPE Arctic and Extreme Environments Conference and Exhibition, , *Proceedings of the AEE 2013*, 3, pp. 2083–2099.

Weather schedule, 2019. Weather archive in Varandey [Online] Available at: https://rp5.ru [Accessed 13 March 2019]. In Russian.