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CRYOGENIC PROCESSES IN THE ARCTIC SEAS SHELF AND ONSHORE AREAS

SOME RESULTS OF INTEGRATED STUDY OF THE KARA COASTAL DYNAMICS IN THE MARRE-SALE METEOROLOGICAL STATION AREA, WITH THE USE OF GIS TECHNOLOGIES

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The results of the 44-year long integrated observations of the Kara Sea coastal dynamics in the area of the VSEGINGEO Marre-Sale station have been presented. The multi-year on-ground surveys of the sea shoreline retreat to the distance of 4.5 km, in combination with the onshore drilling data and with remote sensing techiques, enabled the authors to reveal basic regularities and dynamics of the costal erosion and accumulation processes in the Marre-Sale station area. It was the first time that the use of GIS technologies allowed to obtain reliable qualitative data on the retreat distance of the edge and toe of coastal cliffs (average and threshold values) both for the total observation time and for particular periods. The shoreline actual position in the Marre-Sale station area and its dynamics have been clearly documented by large-scale aerial photos and video-images taken in different years. Relying on the Earth remote sensing data for the Station area, the geodynamic activity in the area of the Marre-Yakha river mouth has been ascertained.

Shore zone, materials of the Earth remote sensing, GIS technology, shoreline retreat, thermal abrasion, ground ice, river mouth

INTRODUCTION

Active development of oil and gas fields on the Yamal Peninsula has triggered a wide range of exogenous (primarily, cryogenic) geological processes that can compromise the environment of the region and, as further-reaching implications, will dramatically increase the cost of hydrocarbon production and transportation. The most challenging and complicated environmental problems of oil and gas fields operations are associated with the Arctic Sea shelf development, especially, its shallow coastal parts. This narrow strip of the offshore area and the adjacent coastal zone are subject to the most hazardous cryogenic and hydrodynamic processes, driven by storms and alongshore currents.

The processes related to the development of offshore oil deposits on the Western shelf of Yamal are considered the most perilous, including the coastal sediments reworking, as a rule, followed by the shoreline receding, lake draining, newly formed perennially frozen rocks at the bottom of young hasyreys and in the emerging topographic elements in the river estuaries.

There have evolved a complex of processes contributing to the Kara Sea coastline degradation including such phenomena as frost fissuring on the seashore crest (from where the snow cover is blown off); melting of ice bodies; thermosolifluction (both slow and fast) thermoabrasion, thermoerosion, thermokarst. Their interactions, along with processes of noncryogenic nature (abrasional and gravitational) have fashioned the sea shore of Western Yamal into unique landforms: scalloped permafrost disruptions (complicated by various features of thermal erosion: ravines, thermocirques, termokars, thermoterraces, wave-cut notches and silt pinnacles) alternating with laida beaches, large streams segments and estuarine areas.

Lengthy autumn storm events play an important role in the dynamics of the Kara Sea shoreline erosion, removing the ground material formed during the warm season from the shore and transported to the basal part of the slope, and washing out the collapsed blocks of frozen soil, as well as exposed ice bodies and ice-rich permafrost outcrops in the bedrock coast during the summer period.

This results in the formation of large thermoabrasive niches with depths from 1–2 up to several meters at the seashore bottom during the stormy periods, promoting the rapid and extensive destruction of the cliff the following year. Therefore, the mechanisms of these processes formation and development, studied by the authors in the vicinity of the Marre-Sale (MS) weather station, are of critical theoretical and practical importance.

OBJECT AND METHODS OF STUDY

The Marre-Sale weather station is one of the first three polar stations, established at the beginning of the XIX century by the Department of trading ports with the Trade and Industry Ministry of Russia, has been operating since September 1914. The Station enabled a long series of meteorological observations and one of the longest observations series of coastal edge receding on the Yamal Peninsula, which records have been published and are kept in archives [*Romanenko, 2008*].

The distance from the houses built in 1912 to the edge of coastal cliff 22–25 m high, composed of sand-clay deposits, including ground ice, was in 1914 about 40 sagenes (85.3 m). Until 1937 the researchers constantly observed the edge retreat, periodically moving various facilities (radio, radio tower and accommodations) further into the onshore area. By 1938 all the houses built in 1912 (except for baths, converted into housing) had been abandoned, and the location of the radio station erected in 1927, turned out to be only 2 meters from the cliff in 1948. In 1958, the stone houses built in 1912 collapsed into the sea. Thus, the retreat rates of the cliff edge of bedrock coast in the vicinity of the station averaged 1.9 m/year over the period of 44 years.

According to the data obtained by the analysis of archival materials, the retreat rates of the edge varied significantly in different years. Thus, in the period of 1946–1953 the coastal cliffs retreated by 8–35 m (1.0–4.4 m/year), and during one summer of 1950 – by 8 m [*Romanenko, 2008*].

In 1952, new premises were built at the station, with their locations as of 1969, according to a topographic map at a scale of 1:25 000, being at a distance of 200 m from the cliff edge. In 2013, the distance was reduced to 117 m, i.e. retreat rates of the cliff edge opposite the station averaged 1.9 m/year over the past 44 years.

In 1978, the VSEGINGEO Institute established a geocryological stationary observatory in the area of Marre-Sale meteorological station. Given that the Marre-Sale weather station provides a long series of meteorological observations, the observatory presents by itself a baseline monitoring operator for the entire central part of Western Yamal, currently intensively developed.

The main objective of the observatory operations was to study the dynamics of permafrost temperature and cryogenic processes, among them the processes associated with the degradation and retreat of the bedrock coast, as critical factors.

The goal of establishing the monitoring observations of coastal erosion processes consisted in the acquisition of evidence on the retreat rate of the sea, in the study of its interannual variability, and to assess the impact of the geocryological conditions on the rates and mechanism driving degradation along the permafrost-affected coast. The observations of the landward retreat of the coastal edge included: 1) measurements with rigidly mounted gauges, installed by Yu.L. Schur in 1978; 2) descriptions and photography of coastal outcrops; 3) aerovisual observations; 4) video-recording of the coastal zone; 5) processing of aerial imagery (AI) carried out in different years, including stereophotogrammetric survey data [*Gelman, 1994*].

The VSEGINGEO and Earth Cryosphere Institute SB RAS researchers carried out ground-based observations of the recession of the coastal cliff edge in different years. The results of these observations were processed and systematically published in different sources [*Vasiliev and Sautkin, 1992; Vasiliev et al., 2011; et al.*]. As the author suggests, the average long-term value of the retreat of the edge through 60 line gauges, located at a distance of 4.5 km between the Marre-Yakha and Yavar-Yakha rivers mouths, are likely to be indicative of the magnitude of the retreat of the coastal toe, and hence of thermal abrasion. Average retreat rates for coastal base over the period of 30 years (1978–2008) was estimated at 1.7 m/year [*Vasiliev et al., 2011*]. Represented either in graphical or tabular form, these data reflect the magnitude of the edge retreat by discrete points spacing at a distance of about 70 meters on average, so the results presented in the said papers can not be considered reliable.

Comparing the satellite images to aerial photographs and old topographical maps had become a key approach in obtaining quantitative data on the relief dynamics since the end of the last century. This method was first applied by *V.A. Troitskii* in the context of the Marre-Sale area [*1977*]. Unlike ground-based observations, the remote sensing observation allows to obtain an objective representation of continuous dynamics of a spatial process, whereas repeated observations supplement data with time.

The highly informative GIS technology enabled the authors to obtain reliable quantitative data on the rates of the coastal edge and base retreat, as well as to identify specific features of the dynamics development within the estuarine zone of the Marre-Yakha Rv. during 44 years.

To evaluate the Kara Sea coastal dynamics in the area of the observatory, the different-scale and time remote sensing (RS) data were used to generate topographic maps with scale factors 1:25 000 and 1:35 000 on the basis of the ALS data of flights piloted by L.I. Vaisman in 1969, and in 1978 (two maps with scale 1:6 000 and 1:12 000), supplemented by high-resolution satellite images of 2009, and video-photo survey data obtained during the resurvey (1:3 000 scale map), periodically carried out by V.A. Dubrovin.

RESEARCH RESULTS

In the context of coastal dynamics developments in the observatory area two types of coastal zones have been established for Western Yamal. The first type comprises terrace surfaces (absolute marks: from 10–15 to 20–25 m), the second type – estuarial parts of the Marre-Yakha and Yavar-Yakha rivers (absolute mark: 1–3 m). According to long-term on-ground observations, the coastal cliff edge retreat rates near the Marre-Sale observatory varies widely both in time and along the strike. Given the retreat rates averaged about 1.7 m/year [*Vasiliev et al., 2011*] their maximum values exceeded 10 m in some years, while minimum values equaled zero.

Fig. 1 shows the results of observations spanning 44 years (1969–2013) carried out at the Marre-Sale station with the use of variously timed and multi-scaled ERS data (Earth remote sensing) decoding methods, aimed at documenting any changes in the coastal zone of the Kara Sea (with length over 5 km). The satellite picture of 2009 with a resolution of 1–2 m was laid as a basis for the decoding, with the overlapping application of all the other photographs of the shoreline and topographic maps scaled 1:25 000 (1969) by georeferencing (ArcGIS software). In order to increase the picture visibility and make it more susceptive to the digital processing it was divided into two variously-scaled parts, showing the dynamics of the coastal cliff edge and toe, respectively.

Table 1 presents values for the edge and toe retreat on the Marre-Yakha and Yavar-Yakha rivers interfluve area with a length of about 4.5 km, for different periods of time, using 22 transects (profiles) selected by the authors, given their maximum coverage of sites with different rates of the processes development (through 200 m spacing alongshore profiling). The retreat distance was determined using ArcGIS software between the shore-lines in different years.

Table 1 (lines 1 and 3) presents the results of all transect-based measurements allowing to identify the features of dynamics developments both in time and in space.

It follows from Table 1, primarily, that the retreat rates of the coastal edge appear much higher than that of the cliff toe in different periods of the observations and over the entire cycle, and therefore, it can not serve as an indicator of the sea thermoabrasion rates.

Understandably, both the time-dependent coastal erosion processes and the coastal edge retreat rates are controlled by the variability of climatic parameters in different years. Their values were markedly higher in the on-ground surveys either during warmer summer periods or with greater sums of summer precipitations, and their maximum accounted for the combination of both. The highest relative values of the coastal edge retreat rates over the observation period were recorded in 1989, 2000, 2005 and 2012 (Fig. 2).

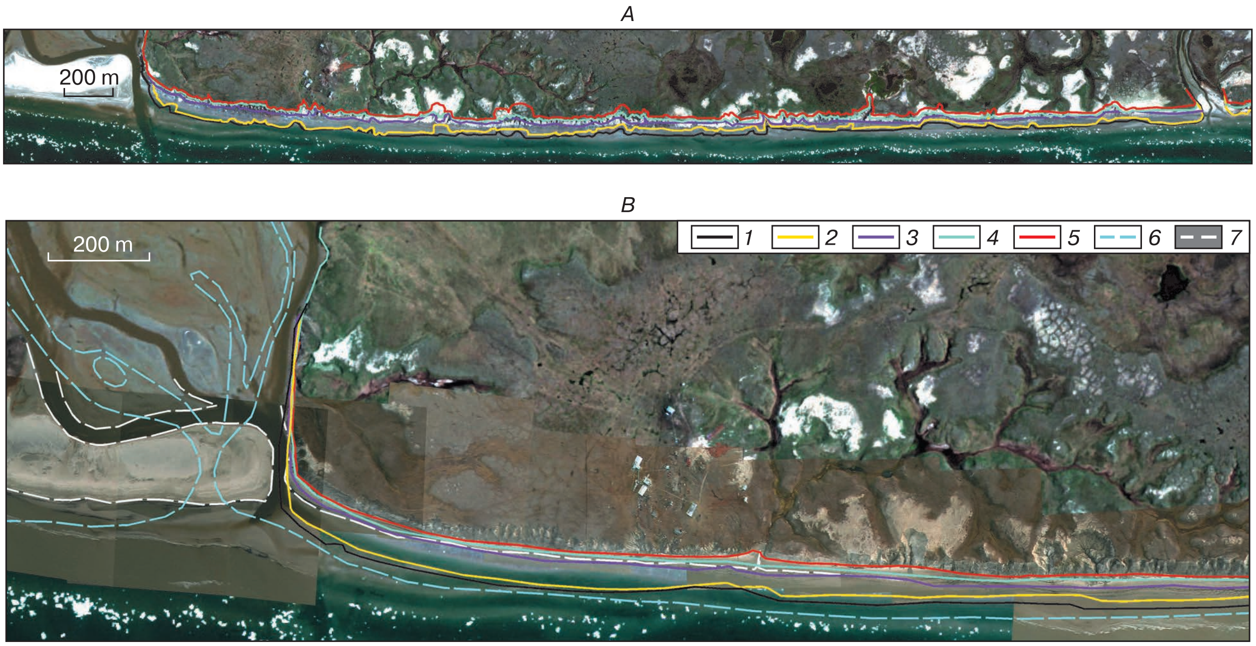

Fig. 1. Dynamics of the Kara Sea coast in the Marre-Sale polar station area, the Marre-Yakha–Yavar-Yakha rives interfluve area, during a 44-year period (1969–2013).

A – coastal edge (~4.5 km); *B* – toe of slopes (~2.0 km); *1* – 1969; *2* – 1978; *3* – 1999; *4* – 2009; *5* – 2013. Seashore-line: *6* – 1969; *7* – 2013.

Table 1. **Dynamics of the Kara Sea bedrock coast within the Marre-Sale station area during a 44-year period**

No.	Retreat distance*, m	1969–1978 (9 years)	1978–1999 (21 years)	1999–2009 (10 years)	2010–2013 (4 years)	1969–2013 (44 years)
1	Coastal edge	1–20; 2–20; 3–9; 4–12; 5–15; 6–9; 7–11; 8–41; 9–14; 10–18; 11–29; 12–13; 13–12; 14–20; 15–20; 16–10; 17–11; 18–13; 19–12; 20–12; 21–3; 22–5	1–45; 2–50; 3–53; 4–42; 5–44; 6–34; 7–36; 8–15; 9–70; 10–40; 11–38; 12–35; 13–30; 14–24; 15–29; 16–23; 17–19; 18–17; 19–14; 20–32; 21–42; 22–13	1–13; 2–12; 3–26; 4–27; 5–43; 6–15; 7–24; 8–32; 9–12; 10–5; 11–12; 12–5; 13–20; 14–25; 15–7; 16–27; 17–19; 18–7;19–17; 20–23; 21–17; 22–20	1–10; 2–13; 3–17; 4–15; 5–15; 6–11; 7–21; 8–44; 9–3; 10–40; 11–56; 12–16; 13–6; 14–31; 15–12; 16–21; 17–18; 18–19; 19–13; 20–16; 21–6; 22–8	88; 95; 105; 96; 117; 69; 92; 132; 99; 103; 136; 69; 68; 100; 68; 81; 67; 56; 56; 83; 68; 46
2	Mean values for the period	329:22 = 14.9	745:22 = 33.9	411:22 = 18.7	411:22 = 18.7	1894:22 = 86.1
3	Retreat rates, m/year	1.7	1.5	1.9	4.7	2.0
4	Foots of bluffs	1–12; 2–20; 3–6; 4–4; 5–14; 6–15; 7–10; 8–8; 9–11; 10–6; 11–13; 12–5; 13–21; 14–13; 15–11; 16–16; 17–10; 18–14; 19–18; 20–20; 21–13; 22–8	1–46; 2–49; 3–48; 4–31; 5–30; 6–26; 7–40; 8–22; 9–14; 10–27;11–21; 12–29; 13–18; 14–38; 15–33; 16–36; 17–17; 18–21; 19–17; 20–21; 21–18; 22–15	1–10; 2–7; 3–21; 4–15; 5–10; 6–15; 7–17; 8–12; 9–21; 10–12; 11–10; 12–22; 13–14; 14–5; 15–5; 16–15; 17–12; 18–9; 19–12; 20–16; 21–5; 22–12	1–6; 2–6; 3–9; 4–10; 5–11; 6–18; 7–9; 8–12; 9–17; 10–11; 11–9; 12–22; 13–22; 14–16; 15–16; 16–11; 17–17; 18–8; 19–6; 20–12; 21–17; 22–8	74; 82; 84; 60; 65; 74; 76; 54; 63; 56; 53; 78; 75; 72; 65; 78; 56; 52; 53; 69; 53; 43
5	Mean values for the period	268:22 = 12.18	617:22 = 28.0	277:22 = 12.6	273:22 = 12.4	1435:22 = 65.23
6	Thermoerosion rates, m/year	1.4	1.3	1.3	3.1	1.5

* Data from 22 linear transects between the lines of Fig. 1, measured with ArcGIS software.

Table 2 contains the summarized weather data for different periods of observations, attesting to a significant increase in totaled average summer air temperatures and precipitations for the period from 1969 to 2009. In the most recent period (2010–2013) the sums of average summer temperatures and precipitations showed a slight decrease, whereas during that period (as follows from Table 1) the retreat rate of both the coastal cliff edge and toe have proven to be the highest. According to Fig. 2, the sums of summer temperatures and precipitation bear evidence of anomalies during the warm period of 2012, that was why the generalized indicators have dramatically increased for this period.

The magnitude of the cliff edge retreat over the 44-year period reached 86 m, while the toe of the cliff over the period receded by 65 m on average. The retreat rates over the period averaged 2.0 m/year for the edge, and 1.5 m/year for the toe.

Table 1 pronouncedly demonstrates diversity in the edge retreat rates through different transects, both over the observation periods and at different points in one period. The differences are determined, primarily, by the permafrost cryolithological struc-

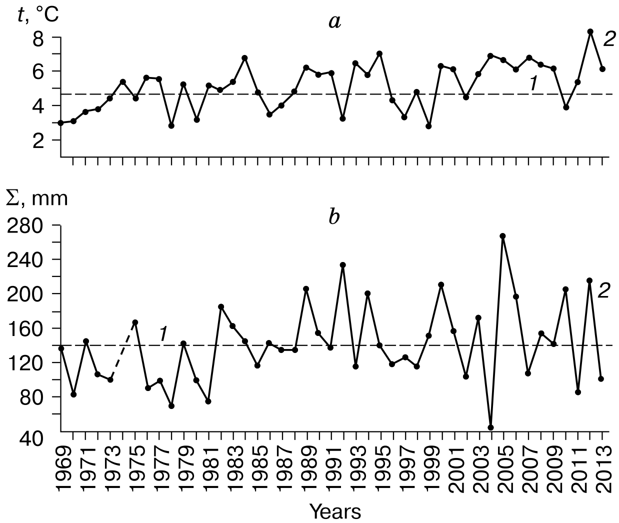

Fig. 2. Dynamics of climatic parameters for the period of 1969–2013 (according to the Marre-Sale meteorological station data).

a – mean summer air temperature; *b* – sum of atmospheric precipitates during the warm season (June–September); *1* – mean multiyear values; *2* – year-to-year value.

Table 2. **Climatic parameters dynamics according to the Marre-Sale meteorological station data**

Meteorological data	1969–1978 (10 years)	1979–1986 (8 years)	1987–1999 (13 years)	2000–2009 (10 years)	2010–2013 (4 years)
Mean summer air temperature over the period, °C	167.2	153.0	261.1	248.0	91.6
Idem, during one season	16.7	19.5	18.6	24.8	22.9
Weighted average precipitates sum during the summer period, mm	1005*	921*	1863	1544	609
Idem, during one season	111.7	131.6	143.3	154.4	152.3

* The incomplete period means the lack of data during one season.

ture and, above all, by the presence and occurrence mode of massive ground ice and very ice-rich soils in the MS station area. The maximum values of the edge retreat in 44 years (within thermocirques with thawed ice) totals 133–136 m, and their minimum is 46 m accounted for the areas with ice-free soils. Therefore, the matter of the spatial distribution patterns of ice bodies is not only of scientific, but of great practical importance either, because until present no engineering solutions exist for strengthening high marine terraces (plains) shoreline on the Arctic seas coast.

Widely extending thick massive ground ice is known to be developing in the vicinity of the Marre-Sale polar station. Coastal outcrops, which included icy bodies of different shapes and sizes, have been studied by many researchers, providing different interpretation of massive ice origin – from glaciers [*Kaplyanskaya and Tarnogradskii, 1982; Tarnogradskii, 1982; Gataullin, 1992*] to seawater ice [*Shpolyanskaya, 1993; Danilov, 1997; Vasiliev and Rogov, 2001*], while the thick ice veins are considered to be syngenetic bodies.

Since the organization of the VSEGINGEO observatory in 1978 the coastal outcrops of ground ice have been the subject of the authors' attention. During the observation period, various icy and ice-soil bodies of different morphology and size enclosed in the coastal cliffs of the Kara Sea bedrock coast had outcropped and thawed [*Kritsuk and Dubrovin, 2000; Kritsuk, 2010*]. The numerous boreholes drilled (with reconnaissance, exploration and observation purpose) in the Marre-Sale observatory area revealed a large number of discrete ice bodies (with thickness ranging from 1 to 10 m) in the upper 10–12 meters of the geological section, associated with the specific cryohydrogenic morphostructures (circular or linearly extended), and were pronouncedly decoded on the remote sensing (RS) data (large-scale air-photography, video and high resolution satellite imagery) [*Kritsuk, 2001, 2010*].

In 1986, within the largest of these morphological structures (with length along the beach about 1 km) the VSEGINGEO researchers carried out integrated permafrost and geophysical surveys. Their aim was to identify patterns of spatial distribution of thick ground ice exposed in the coastal cliffs, as well as their origin and impact on the coastal dynamics.

These studies specified the second intraground nature of massive ground ice commonly occurring at the observatory site, and genetic link of ground ice with the investigated morphostructures, and cryohydrotectonic nature of the morphological structure proper [*Kritsuk, 2001*]. According to *L.N. Kritsuk* [*2010*], ground ice formed in the harsh climatic epoch during the freezing of various natural waters: groundwater (different horizons, sub-channel and sub-bottom lake taliks, deep circulation water) and surface water (in rivers and lakes).

In the course of their freezing in closed systems a super high hydraulic pressure was created, causing disrupture of the thick frozen layers and thus giving way to water input, which was subject to congealing. Later, E.A. Slagoda came up with an inference on the repeated injections nature of thick ice veins in the Marre-Sale coastal outcrops [*Slagoda et al., 2010*].

In the years to follow, the observations of ice bodies opened within the morphological structure were carried out by A.A. Vasiliev, I.D. Streletskaya, M.Z. Kanevskii et al.

Fig. 3 reflects the specificity of the coastal processes within the semi-circle morphostructure on the Kara Sea shore. The photographs of the outcropping ground ice, studied by the authors in 1986, are shown in Fig. 4, *A*. Fig. 4, *B* shows a view of a giant outcrop of thick ground ice actively thawed from 2009 to 2012 within the young thermocirque (opened only in 2000).

Both Fig. 1, Fig. 3 are high-resolution satellite images of 2009, with the imposed video-photographic panorama (2013) of the coastal zone, where the thermocirques have been clearly decoded. Fig. 3 shows that the photographs of the morphostructure area taken from a helicopter in 1986 enabled the authors to divide a long period (1978–1999) into two parts.

For convenience in conducting the quantitative analysis of the coastal zone dynamics, as well as analysis of data from other research with the observations of ice bodies melting in the Marre-Sale outcrops, Fig. 3 provides transects through which the calcula-

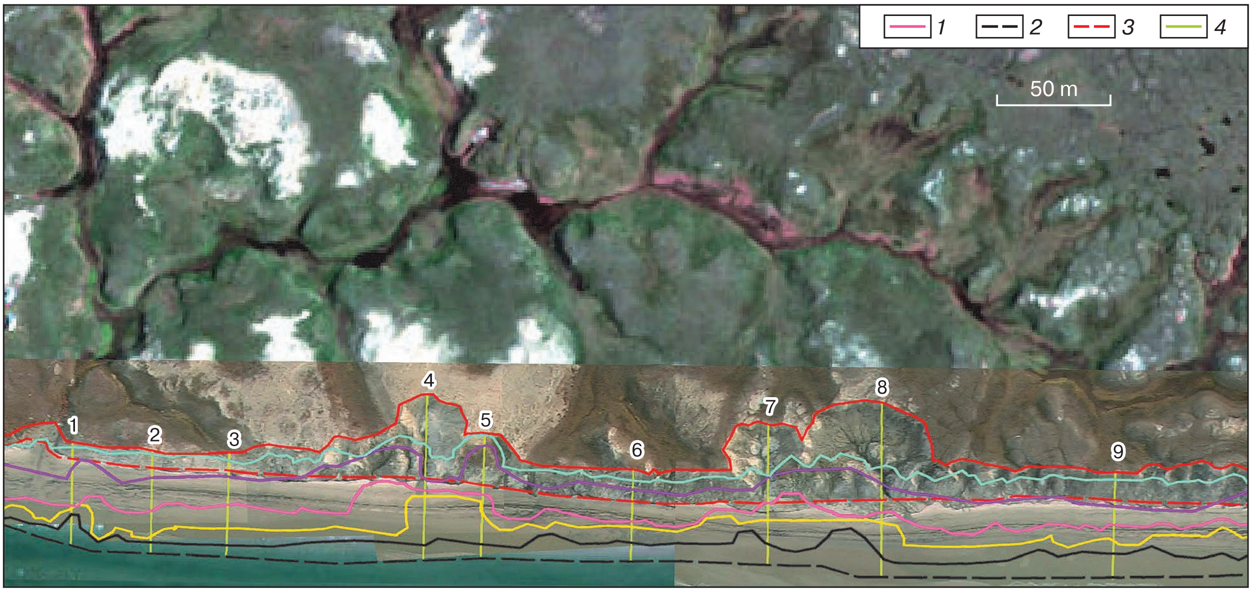

Fig. 3. Dynamics of bedrock coast within the semicircular morphostructure.

1 – coastal edge, 1986; *2* – toe of cliff, 1969; *3* – toe of cliff, 2013; *4* – linear transects with numbers (Table 3). Other notations are given with Fig. 1.

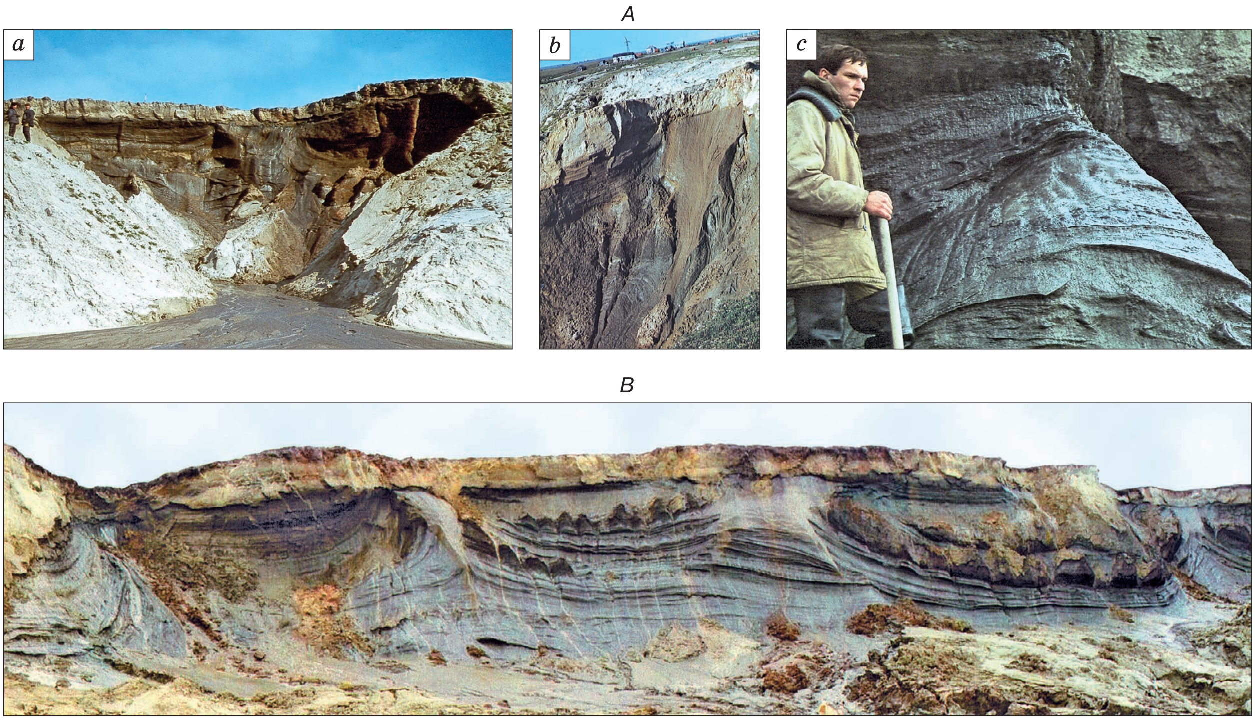

Fig. 4. Outcrops of ground ice in thermocirques of semicircular morphostructure.

A – thermocirques with outcrops of ground ice, 1986; *a–c* – transects 4, 5, 7. *B* – an outcrop in thermocirque (transect 8), 2011 [*Kurchatova et al., 2012*].

Table 3. **Dynamics of the Kara Sea bedrock coast within the semicircular morphostructure (in the area of Marre-Sale meteorological station)**

No.	Retreat distance*, m	1969–1978 (9 years)	1978–1986 (8 years)	1986–1999 (13 years)	1999–2009 (10 years)	2009–2013 (4 years)	1969–2013 (44 years)
1	Coastal edge	1–2; 2–7; 3–15; 4–42; 5–28; 6–14; 7–21; 8–30; 9–11	1–6; 2–21; 3–20; 4–6; 5–16; 6–5; 7–15; 8–9; 9–15	1–32; 2–29; 3–25; 4–10; 5–42; 6–28; 7–12; 8–26; 9–16	1–20; 2–21; 3–14; 4–30; 5–10; 6–8; 7–12; 8–15; 9–24	1–5; 2–3; 3–8; 4–45; 5–2; 6–8; 7–45; 8–56; 9–14	1–65; 2–81; 3–82; 4–133; 5–98; 6–63; 7–105; 8–136; 9–80
2	Mean values over the period	170:9 = 18.89	113:9 = 12.56	220:9 = 24.44	154:9 = 17.11	186:9 = 20.67	843:9 = 93.67
3	Mean annual values, m/year	2.1	1.6	1.9	1.7	5.2	2.1
4	Coastal toe	1–16; 2–11; 3–15; 4–13; 5–11; 6–13; 7–16; 8–20; 9–16	1–9; 2–19; 3–15; 4–19; 5–17; 6–15; 7–12; 8–18; 9–13	1–19; 2–21; 3–23; 4–18; 5–16; 6–6; 7–5; 8–3; 9–4	1–18; 2–16; 3–13; 4–5; 5–6; 6–10; 7–15; 8–16; 9–13	1–14; 2–9; 3–11; 4–17; 5–15; 6–9; 7–6; 8–11; 9–13	1–76; 2–76; 3–77; 4–72; 5–65; 6–53; 7–54; 8–68; 9–59
5	Mean values over the period	131: 9 = 14.56	137:9 = 15.22	115: 9 = 12.78	112: 9 = 12.44	105: 9 = 11.67	600:9 = 66.67
6	Thermoabrasion rates, m/year	1.6	1.9	1.0	1.2	2.9	1.5

Note. The first digit in front of the retreat value is the transect number. The last column of Table 3 shows sums of the cliff edge and toe retreat over the 44-year period for each profile, following the same sequence, as in the previous columns. Mean weighted values and mean edge and toe retreat rates are provided in the respective lines of Table 1.

* Measured with the use of ArcGIS program for the nine transects in Fig. 3.

tions were performed. The scale of this figure being larger (as compared with Fig. 1), this allowed to overlap data on the edge retreat and the position of the coastal cliff toe in 1969 and 2013. The results of calculations are shown in Table 3.

Unlike Table 1, Table 3 does not present any explicit dependency of the mean values of the coastal cliff edge retreat on mean climatic parameters, because during the entire period thick discrete ice bodies opened and melted off in different parts of the morphostructure. The cliff edge retreat rates within thermocirque 1-86 (transect 4) over the 44-year period averaged about 3 m/year, while in the last four years (2009–2012), it equaled 11 m/year. Ice melting rates during this period within the young thermocirque (transect 8) proved even greater – 14 m/year. The coastal edge retreat rates in the areas where thick ice inclusions are absent (transects 1–3, 6, 9) averaged 1.7 m/year. Total in 44 years the edge retreat distance within these areas varies in the range of 63–82 m, depending on lithology and ice content of perennially frozen rocks (permafrost).

The retreat rates of the coastal cliff toe within the morphological structure (Table 3, Fig. 3) are higher than in the entire interfluve area of the Marre-Yakha and Yavar-Yakha rivers, but proved significantly less than the edge retreat rates.

Adding the data for 1986 to Table 3 allowed to refine the specific features of the bedrock coast retreating landward over a 21-year period. In 1986–1999, when the edge recession varied from 10–12 to 32–42 m, the cliff toe retreat in the four transects was 3–6 m. As a result, the average retreat rate of the edge has increased to be 1.9 m/year, and the cliff toe retreat rate reduced to approximately 1 m/year. A similar recession pattern was observed in the period of 1999–2009, while in 2009–2013 both the cliff toe and edge, were retreating at abnormally high rates (2.9 m/year), which might have been caused either by a large volume of sandy-clayey material thawed in the summer and accumulated at the foot of slopes, or by a more intense storm activity of the sea.

The edge retreat rates within the semicircular morphological structure averaged 2.1 m/year, and the toe – 1.5 m/year during the 44-year period. The total magnitude of the edge retreat within the morphological structure during this period was significantly greater, than for the shoreline – 93.7 m (against 86 m), and for the cliff toe it was 66.7 m, i.e. it was close to the average for the entire shoreline (65.2 m).

Fig. 1, *B*, apart from theremodestructive and thermoabrasive processes within the Kara Sea bedrock coast, the geodynamic processes are clearly visible in the estuary of the Marre-Yakha Rv. floodplain. Along with the sea progression (due to its eating into the bedrock coast), the following processes were taking place: active lateral movement of the river channel within the delta front; the river bend changing;

a *b* *c* *d* *e*

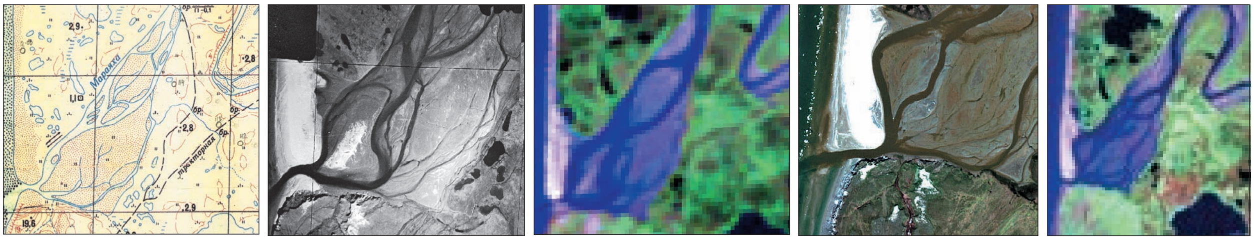

Fig. 5. Marre-Yakha Rv. mouth in various years, on the basis of data on remote sensing (RS) of the Earth surface.

a – map, 1969; *b* – aerophotograph, 1978; satellite imagery: *c* – 1986; *d* – 2009; *e* – 2013.

Table 4. **Bedrock coast dynamics in the estuary of the Marre-Yakha river**

Edge/Toe retreat distance*	1969–1978	1978–1999	1999–2009	2009–2013	1969–2013
Sea/river boundary	19/19	50/40	11/16	4/5	84/80
50 m from sea	20/10	26/39	9/20	8/5	63/74
100 m	14/12	5/28	9/20	4/6	32/66
150 m	19/11	4/4	3/11	0/1	26/27
200 m	5/13	1/2	1/4	1/2	8/21

* Distanced were measured, using 5 transects.

and accumulation of sand deposits associated with both the activity of waves and, perhaps, with aufeis formation. During the period of 1969–2013 the Marre-Yakha Rv. mouth pattern prove to have been ever-changing in the river valley, as well as the amount and width of the river arms and its main channel. Concurrently with these, the shape and size of the sand spit, partitioning the mouth of the Marre-Yakha Rv., changed and its left (bedrock) bank was subjected to degradation (Fig. 5).

Table 4 provides the estimates of recession of the left bank edge and slope toe the Marre-Yakha Rv. in the estuarial part at 200 m from the sea. As it follows from Table 4, the Marre-Yakha Rv. estuary and the surrounding coastal area was characterized by an progressively retreating edge and toe of the coastal bluff within a distance of about 100 m during 44-year period, which resulted in the river's left bank receding by 84–32 m, and its slope toe – by 80–66 m. Maximum retreat measurements at the river/sea boundary and in the immediate vicinity, are very much likely to be linked with the melting of thick massive ground ice (responsible for the bank edge recession) and thermoabrasive developments both in the sea and river (responsible for the slope toe retreat). At a distance of 150 m from the sea coast the river's bank edge almost ceased receding after 1999, while the toe is gradually eating into the mainland.

The Marre-Yakha river channel receded into its mouth from 1969 (topographic map) through 2013 (video-recorded imagery) by about 160 m, i.e. averaging 3.6 m/year. Over the 44 years of observations, the shape of the present-day sand spit that partition the Marre-Yakha river valley from the sea has changed dramatically. The sand spit length increased by 140 m (~4.7 m/year) from 1969 to 1999, while its width (at the river gorge) decreased from 247 to 108 m, and in the marginal (southernmost) part, on the contrary, increased from 150 up to 181 m. From 1999 through 2013, however, the sand spit length showed no increase. The distances were measured through the schematics of Fig. 1, *B* using ArcGIS software.

ANALYSIS OF DATA OBTAINED

The active development of cryogenic and geodynamic processes in the Marre-Sale station area, in our opinion, has been largely conditioned by the site sitting in the area of the ongoing geodynamic activity, at the crossing of two faults. Fig. 6 presents a topographical map of the Marre-Sale Cape coastline pronouncedly exhibiting semicircular neotectonic morphostructures, with local structure of the platform cover being confined to the southernmost edge at the top of Mesozoic sediments, revealed by seismic and gravimetric surveys [*Explanatory notes..., 2000*].

Apparently, the key role in the Marre-Yakha river 'wandering about' and active sedimentation on the laida area belongs to annual aufeis growth during the river and taliks freezing, and the presence of deep groundwater with high-pressure. The evidence of aufeis development in the Marre-Sale station area was

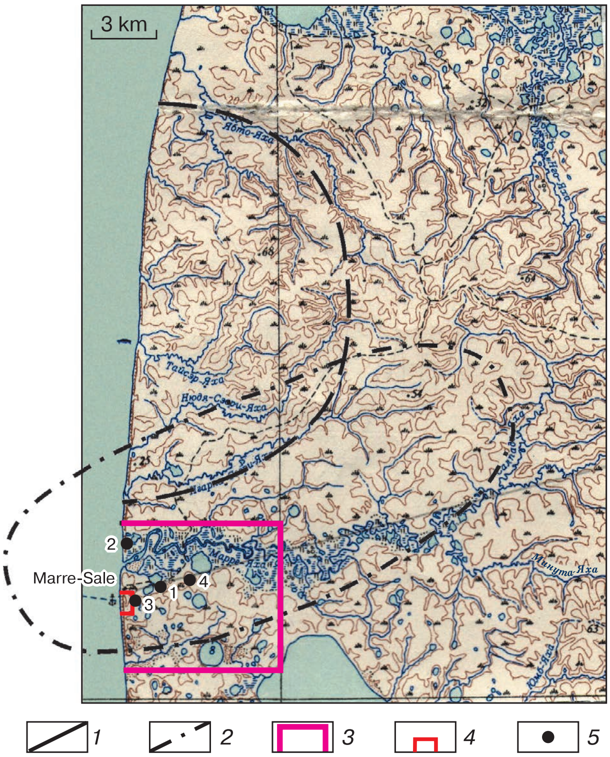

Fig. 6. Structural pattern of the Marre-Sale station area.

1 – neotectonic morphostructure; *2* – local structure of the platform mantle at the top of Mesozoic sediments; *3* – contour line of the Marre-Sale geocryological center area; *4* – area of site for detailed comprehensive investigations; *5* – deep borehole drilled by VSEGINGEO, and its number.

documented at the end of the last century at the result of mass chemical and isotopic analysis of surface and ground waters and ice-covered area, and tritium content determinations [*Kritsuk and Polyakov, 2003*]. The Marre-Yakha Rv. water in the spring season proved to be the heaviest in terms of tritium content (20.1 tritium unit), which suggests surface discharge of large amounts of groundwater retained after the nuclear tests in the 1950s (interpermafrost or deep subpermafrost layers).

The inferences made on the evidences of aufeis formation processes at the observatory site [*Kritsuk, 1989*] have been ascertained by the materials on satellite imagery 2013 re-decoding (Fig. 7). The dimensions of the aufeis field (1.5 km × 600 m) were determined using ArcGIS software.

Fig. 8 shows aerial photographs of different years, prompting ideas on possible sources of water feeding the aufeis patches. The arrows in the images mark the river channel deepening, looking like an orifice of "hydrovolcano", which is likely to have formed that large aufeis field. Given the pictures was taken at the end of October 2013 (Fig. 8, *b*), it represents by itself open water (polynya) amidst the frost-bound river channel.

At the mouth of a small Yavar-Yakha river delimiting the Marre-Sale station area from the south, similar cryogenic and geodynamic processes of lesser intensity, though, have been documented. The river is positioned at the margin of a local structure in the platform cover, where (as in the middle) the permafrost is assumed to be highly prone to frost fissuring. The aufeis development in the river mouth was documented by the VSEGINGEO researcher L.P. Kharitonov in June 1999.

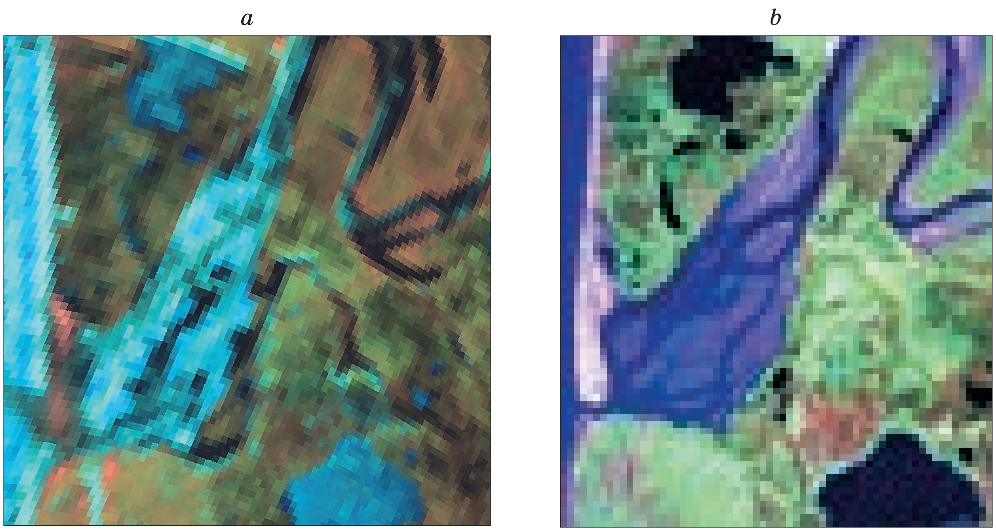

Fig. 7. Large body of flood icing (naled) in the area of the Marre-Yakha Rv. mouth.

Landsat satellite imagery: *a* – 10.06.2013; *b* – 19.07.2013.

a *b*

Fig. 8. Marre-Yakha Rv. mouth.

Aerophotograph (from helicopter): *a* – 20.09.1999; *b* – 23.10.2013.

CONCLUSIONS

Long-term integrated geocryological research and the use of remote sensing materials from different years revealed the key features of the Kara Sea coastal dynamics in the area of Marre-Sale station over the past 44 years. Widely applying GIS technology to get objective quantitative data on the retreat rates of the coastal cliffs edge and toe (average and limit values) for the entire observation period, as well as for separate time intervals.

It has been established that the retreat rates of the coastal cliff toe, and hence the rates of thermal abrasion are significantly lower than the retreat rates of coastal edge. The average retreat rate of the bedrock coast edge in the watershed of the Marre-Yakha and Yavar-Yakha rivers over the observation period was 2.0 m/year, while average rates of thermal abrasion (coastal cliff toe retreat) equal 1.5 m/year.

The coastal edge retreat distances and rates vary widely, both in time and in space. Over the 44 years the bedrock coast retreated an average 86 m, with the values ranging from 46 to 136 m. The maximum retreat rates accounted for 3.0 m/year, while the minimum was 1.0 m/year. Average retreat rates of the coastal cliff toe constituted 65 m, ranging within 43–84 m, i.e. the interval of average values of the recession rates was 1.0–1.9 m/year.

The main factor suggesting uneven pattern of the edge retreat rates is believed to be spatial variability of the cryolithologogical section and discrete location of extensive massive ground ice in the vicinity of the observatory. The maximum edge retreat rates (within thirmocirque with the ice melting off) during four-year period was 56 m, or 14 m per year, on average. Average retreat rates of the coastal areas, not including massive ice beds equaled 1.7 m/year.

Analysis of variously timed remote sensing data allowed to establish the evidence of ongoing geodynamic and cryogenic processes in Marre-Yakha River valley and linked with geological and structural factors. A huge aufeis body (length: 1.5 km; width: 0.6 km) was identified in the estuary portion of the river valley in June 2013, and lateral drifting of the river channel at rates of 3.6 m/year was established, as well as the growth of sand spit partitioning the mouth of the river from the sea, at rates of 4.7 m/year.

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