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The role of permafrost processes in the coastal dynamics of the Kara Sea

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ABSTRACT

The coastline of the Russian Arctic seas makes almost half of all Arctic coasts. In this study, to characterize the coastal dynamics of the western part of the Kara Sea region, we chose three key sites: the Ural and Yamal coasts of the Baydaratskaya Bay and the coast near Kharasavey settlement. These sites situated in the continuous permafrost zone with annual ground temperatures of -2..-8°C and permafrost thickness from 50-100 m to 200-300 m. The presence of permafrost in coastal bluffs is the driver of several erosional processes associated with thermal degradation of the soils during the period with positive air temperatures (thermo-denudation, thermokarst, thermo-abrasion, etc.). The estimation of coastal retreat rates was based on field studies including DGPS mapping of the coastal bluff edge position, and on analysis of high-resolution space images. We tried to estimate the role of permafrost processes and lithological composition of the bluffs in the coastal dynamics. Most of the cryogenic processes are easily identified on satellite images, for example, the area with predominance of gully landforms is easily recognized by the presence of a net of polygons coinciding with the ice wedges seen on the images. Coastal retreat rates were calculated for zones with prevalence of varying processes for different time intervals. Understanding the contribution of different permafrost processes to the coastal dynamics will provide a basis allowing to simulate and predict the evolution of a complex and sensitive Arctic coastal environment in the future.

KEY WORDS: Coastal dynamics; Thermo-denudation; Ice wedge degradation; Thermo-abrasion; Kara Sea.

INTRODUCTION

Since 1990-s in the Arctic region climate change is occurring much faster than anywhere else. Current assessment of coastal dynamics is a relevant task for the development of northern territories for natural resource exploration, for example, for construction of coastal facilities, drilling platforms, subsea pipelines, etc. Any activity in the Arctic region must be conducted taking into account the permafrost and its reaction to the changing climate. This is the most important for the coastal slopes composed of frozen unlithified sediments, as their stability depends on a number of factors and is sensitive to any changes in the environment. Usually, the main coastal destructive processes are thermo- abrasion and thermo-denudation (Reimnitz and Are, 2000; Günther, et al., 2013). Thermo-abrasion intensity depends on the energy (wind-wave) regime and the removal of the thawed material from the beach; thermo-denudation intensity depends on thermal regime of the territory (air temperature, sea water temperature, surface temperature) and provokes thawing of sediments composing the slope (Ogorodov, et.al, 2016). The presence of ground ice could provoke another permafrost erosion processes, which is related to ice wedge degradation within a gullying zone.

The retreat rates are usually assessed based on one or several factors (air and seawater temperature, surface temperature, waves, wind, coastal morphology, bathymetry, soils erodibility, cliff lithology, vegetation, etc). For different key-sites coasts of the Kara Sea, the long-term (30-50 years) average annual retreat rates range from 0.3 to 4.5 m/year (Vasiliev, et.al, 2006; Kizyakov, et.al, 2006; Novikova 2018; Belova 2017; Baranskaya et.al, 2021). In some years at local sites, for example, when the massive ice melting occurs in the coastal slope or at the low surface after a strong storm, the retreat rate can reach 7-14 m/year (Kizyakov, 2005; Kritsuk et al., 2014). However, no one identifies different coastal zones, which are exposed to different mechanisms of destruction. In this study we try to estimate the rate of development of a set of permafrost processes with different driving mechanisms for further simulations for chosen key sites of the Kara Sea coasts. In particular, we consider the lithology features of coastal slope and their influence on the coastal retreat.

MATERIALS AND METHODS

Study area settings

Coastal dynamics of the western part of the Kara Sea were investigated for three key-sites (Figure 1): Ural and Yamal coasts of Baydaratskaya Bay, and Kharasavey coast. The territory is situated in the continuous permafrost, with 50 to 200 m thickness and annual ground temperatures of -2..-8°C. Taliks are formed under lakes and rivers. Frozen saline soils are widely distributed along the western Russian Arctic coast, causing the occurrence of cryopegs.

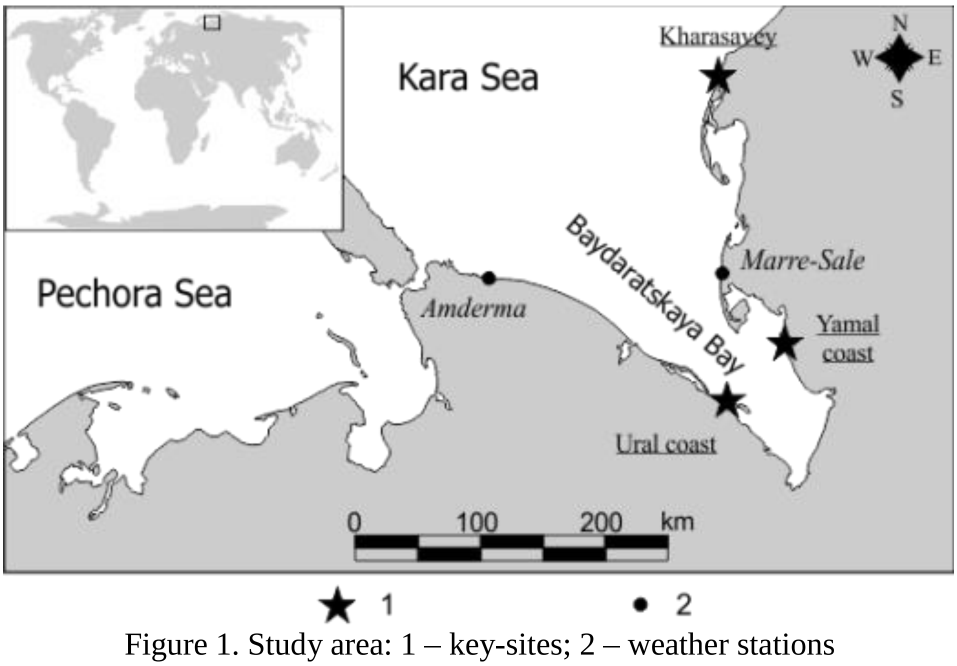

Figure 1. Study area: 1 – key-sites; 2 – weather stations

Ural coast site is located on a 5-kilometer-long coastal segment between Torasavey and

Levdiyev islands. The elevations of the coastal plain vary from 4 to 6 m (low surface) in the eastern part of the studied coastline to up to 12-17 m (high surface) in the western part. All these surfaces are separated by laida (lowland surface flooded by tides) 1.3 km along the sea coast with 1-2.5 m high berms. High surface is mainly composed of sands with low ice content (20-30%). The western part of the low terrace is dominated by ice-rich silt and clay with ice wedges.

Yamal coast site is situated at a 8.5-kilometer-long coastal segment NW from Yara-Yaha river on the opposite site of Baydaratskaya Bay, near the gas pipeline. Topography levels vary from laida (near pipeline) in the southeast part to the elevated surface up to 12 m in the northwest part of the territory. All surfaces are mainly composed of sands with low ice content.

Kharasavey coast is located on a 8.5-kilometer-long coastal segment between cape Kharasavey and Kharasavey settlement at the western Yamal Peninsula, 105 km north-west from Bovanenkovo gas field and 170 km north from the Marre-Sale weather station. The coastal plain is mainly situated on a high surface 6-10 m with gulleys and deltas of small streams. The central part of the coast is composed of saline clays with the ice content of more than 40%. Sandy sediments with the ice content of 20-30% compose the other part of the coast (Belova, et.al., 2017).

Methods

Investigation of coastal dynamics was conducted by standard well-developed methods based on an interpretation of space images obtained in different years (Kritsuk et al., 2014, Jones, et.al., 2009). For our study area, the available images were: Corona 1968, the aerial photographs obtained of 1970s and 1980s, Landsat or/and ALOS Prism QuickBird-2, WorldView-2 and WorldView-3. The space images were provided with the reference files containing the satellite’s orbit parameters, but the accuracy of the georeference was not enough to analyze the annual variability of the coastal dynamics. The images had to be georeferenced with ground control points, collected during the field work. As a control points, in the field we chose objects with a stable position which were well distinguishable on the images, for example, buildings, coastline of thermokarst lake and drained lake basin, the confluence of two rivers or few ground roads, etc.

Estimation of the coastal retreat rates at the key-sites was conducted based on field work observations and the analysis of the satellite imagery. Data processing was performed using ArcGIS 10.2 software. Comparison between the cliff position from DGPS mapping and the cliff contour obtained from space images allowed us to determine the general pattern of coastal destruction within the studied key-sites and to estimate quantitatively the coastal retreat rates at the different time periods. The coastal retreat rates were calculated as the proportion of the retreating area (m^2) to the shoreline length on the transections perpendiculars (every 10 m) to the general direction of the shoreline. The retreated area was determined as the area between the two parallel lines (transects) and two lines of coastal position at different times.

The estimation of a role of permafrost processes was based on the division of the territory according to the prevailing cryogenic processes, as recognized on images. The leading process was identified for each site. As a result, each key site was divided into following “visual” zones in accordance with the prevailing type of cryogenic processes at the coastal cliff and on the adjacent surface of the coastal plain: 1 – zones with the predominance of thermo-denudation processes; 2 – zones with the predominance of thermo-abrasion processes (for low topography levels); 3 – zones with the predominance of gully landforms which actively evolves during ice wedges thaw (as a linear process).. Lithological features were studied at the outcrops and according to the published data for the chosen key sites (Aleksyutina, Motenko, 2017; Belova, et.al., 2017). This data was analysed and the statistical parameters of the coastal retreat rates depending on the lithological characteristics of the sediments were obtained.

RESULTS AND DISCUSSION

The thermo-denudation process is the most widely developed at the Ural and the Kharasavey coast, occupying 60.4% and 74.9% of the coastline, respectively. On the Yamal coast, thermo-denudation is developed at 26.6% of the territory. For the Ural coast (Figure 2 A-B) and the Kharasavey section (Figure 2 D), the conditionally normal distribution of the retreat rates appears only for a long period of time (1988-2005). This underlines the influence of a huge number of factors on the coastal retreat. Perhaps this confirms the assumption of A.A.Vasiliev (2011) on the cyclical nature (with a period of about 20 years) of the characteristic retreat rates for one site. At the Ural coast for a shorter time period (2005-2012 Figure 2A), the influence of the geomorphological factor is observed. The coastal retreat values due to thermo-denudation have a conditionally lognormal distribution for other periods at all key-sites. At the Ural coast, the retreat rates due to thermo-denudation are on average 0.6-1.8 m/year, in some local profiles they reach 10-12.2 m/year. At the Yamal coast, the rate of coastal retreat increased from 0.2 to 0.9 m/year from 1968 to 2016 (Figure 2C), with a maximum of 2.4-4 m/year at local areas. The retreat rates in the Kharasavey coast slowed down on average from 1.5 to 0.95 m/ year (the maximum values – from 9 to 3.8 m/year).

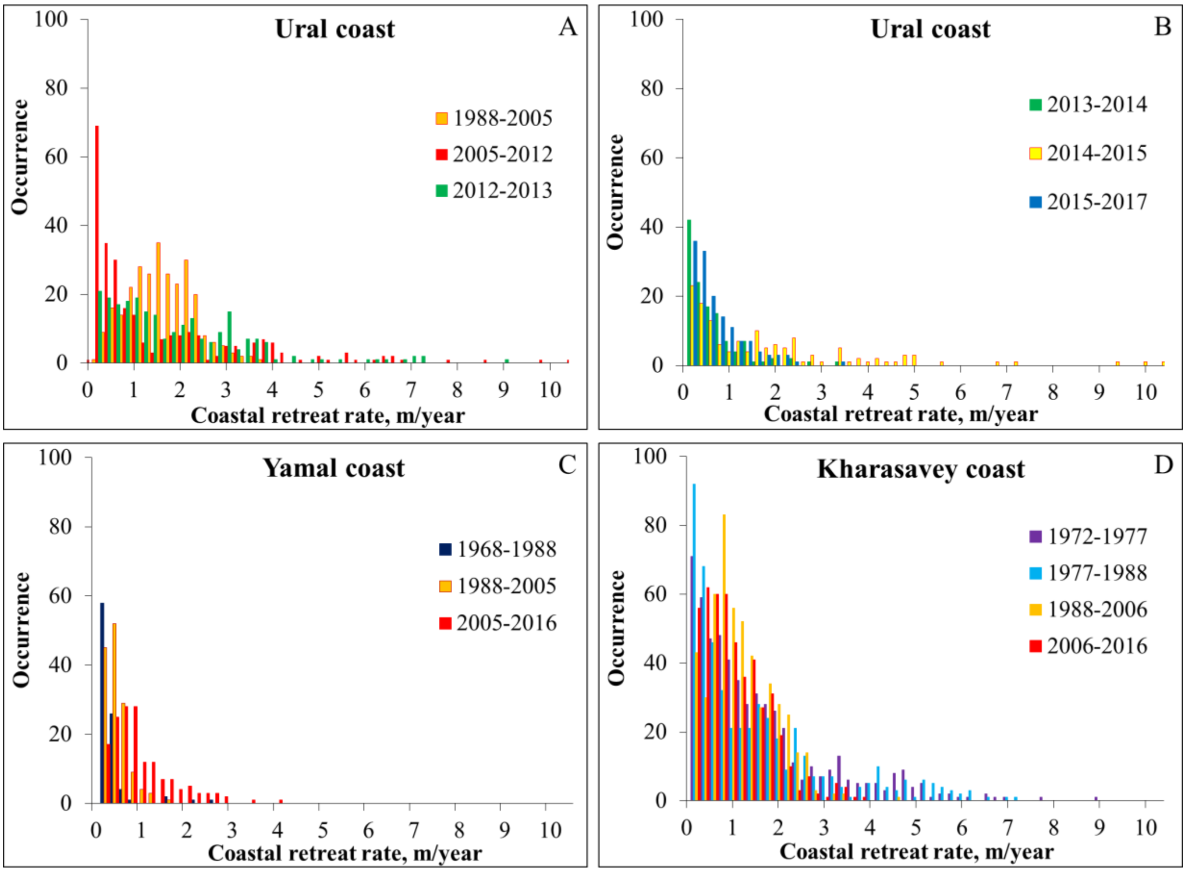

Figure 2. The distribution of coastal retreat rates due to thermo-denudation for chosen key sites

The thermo-abrasion process on the Yamal coast occupies 60% of the coastline, on the Ural coast - 25.6%, on the Kharasevey - 5.4%. On the Yamal coast, for the period 1960s-2000s, the retreat rates due to the thermo-abrasion are the same due to the thermo-denudation – 0.2-0.4 m/year, maximum values 1.1-1.6 m/year. In the period 2005-2016, the coastal retreat significantly increased up to 1.6-6.6 m/year, with maximum values up to 15.4 m/year. Figure 3C shows two peaks characterizing different coastal topography levels (lower and higher as 1 m), which are being eroded with the different rates. Similar peaks are visible for the same time period on the Ural coast (Figure 3A), but for this area this is related to the drainage of several thermokarst lakes on the laida. In this case, the thermo-abrasion was up to 14.4 m/year. B. Jones et.al. (2009) also observed the highest coastal retreat in the area of recently drained lake basins. The rates are determined primarily by the size of the termokarst lake. The thermo-abrasion on this coast decreased over the next periods (Figure 3A and 3B), and after a significant retreat of the coast reached the average of 0.4-0.9 m/year. At the Kharasavey site, the thermo-abrasion occurs at the bottoms of ravines and the deltas of streams flowing into the Kara Sea. The rates of the thermal abrasion at these sites are 0.75 to 3.3 m/year with maximum values of 6 -7 m/year (Figure 3D).

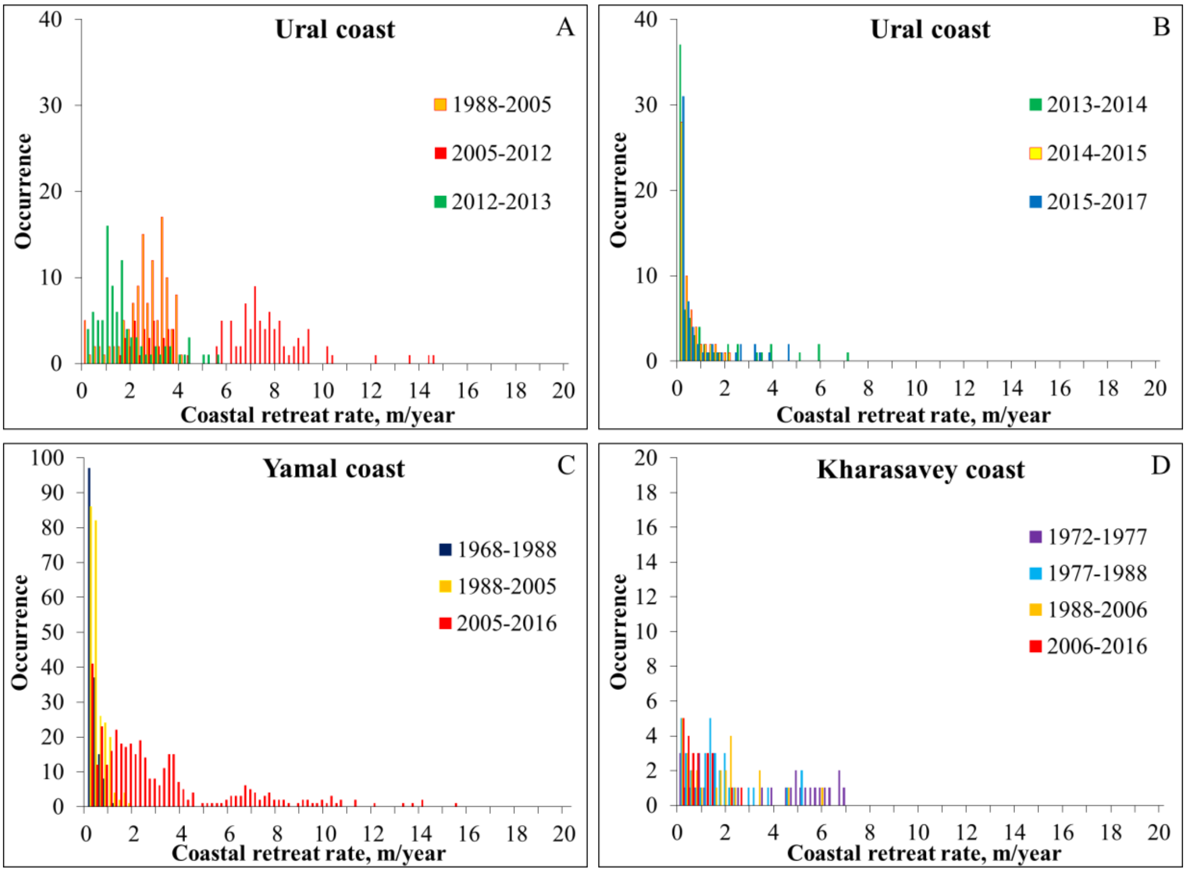

Figure 3. The distribution of coastal retreat rates due to thermo-abrasion for chosen key sites

The linear process associated with ice wedges thawing covers 14% of the territory on the Ural coast, on the Yamal - 14.8%, on the Kharasavey - 19.7%. For the Ural coast (Figure 4A) the coastal retreat values have a conditionally normal distribution only for a long-term period (1988-2005). The average rates of the thermo-erosion are slightly higher than for the thermo-denudation process and the values are close to the retreat rates due to the thermo-abrasion. At the Ural coast, with the exception for the period 2015-2017, the coastal retreat varied from 1.2 to 3.4 m/year, with a maximum value of 4.2-9 m/year. However, unlike the thermo-abrasion, the thermo-erosion rates do not decrease quickly, and after a year with high values a period with slightly smaller rates comes. For the Yamal coast and Kharasavey area, the coastal retreat values are characterized by a conditionally lognormal distribution. The rate of the coastal retreat due to the thermal denudation in Yamal increases from 1968 to 2016 from 0.4 to 0.6 m/year (Figure 4C), with a maximum of 1.3-1.6 m/year. The rate of coastal retreat due to thermal erosion for the Kharasavey area (Figure 4D) is on average 0.8-1.4 m/year, the maximum values 2.1-5.4 m/year.

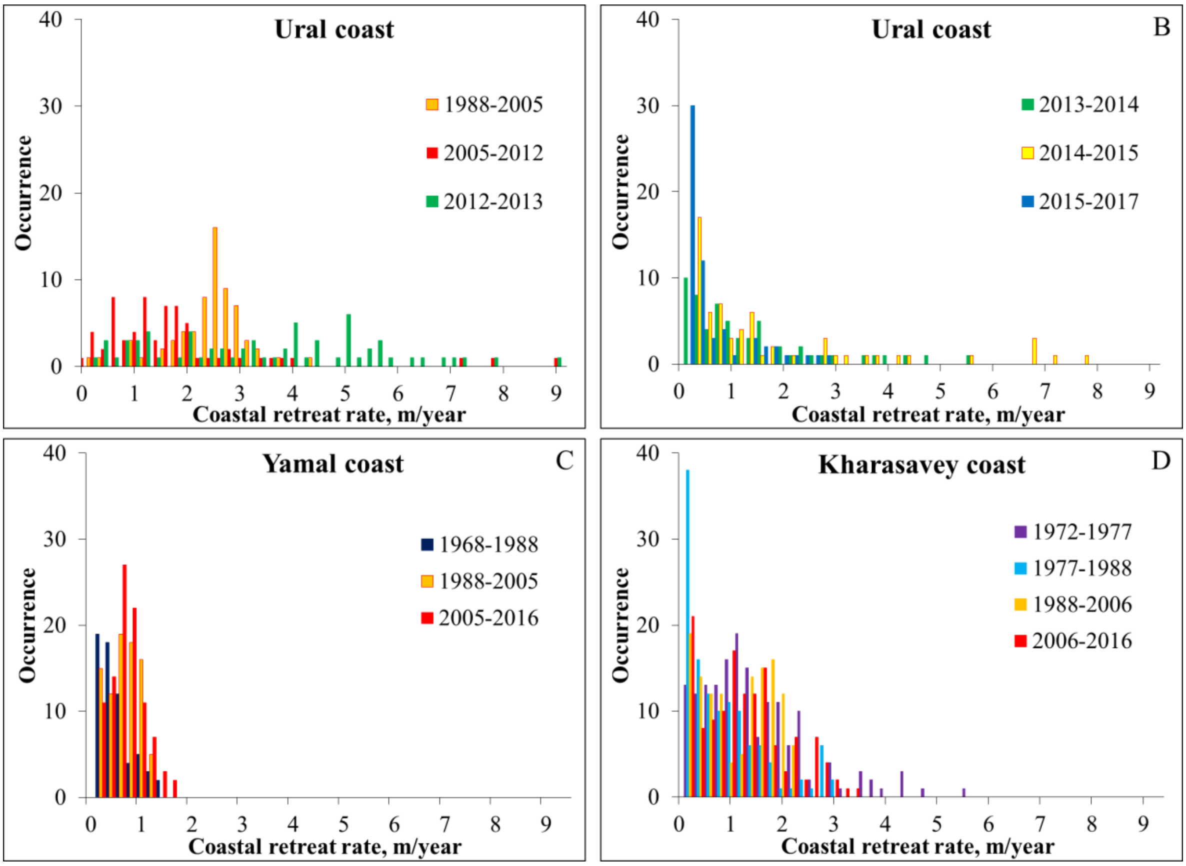

Figure 4. The distribution of coastal retreat rates due to gully landforms with active evolution of erosion for chosen key sites

Thus, various types of permafrost processes are developed at all three key sites. These processes occur at approximately the same rates, however, behavior of these processes at different time periods is slightly different, for example, the thermo-abrasion slows down (or even can cease) after a year with a strong storm, while the thermo-denudation and the thermo-erosion do not slow down after an extremely warm year.

Since the coastal destruction rates due to the thermo-abrasion directly depend on the wave-energy regime for a specific period, which is partly a random value, we analyzed the effect of sediment composition on the coastal retreat for more constant (monotonic) cryogenics processes, excluding low coastal areas exposed to waves.

The main statistical parameters of the coastal retreat rates for all key sites are presented in Tables 1-3. For the Ural (Table 1) and Kharasavey (Table 3) coasts, coastal erosion in sandy cliff varies from 0.7 to 2 m/year, with maximum values up to 9 m/year. The Yamal sandy cliff retreats slightly slower, with average annual rates of 0.3-0.8 m/year and maximum values of 4 m/year (Table 2). The coast composed of loamy deposits retreats slower than the sandy coast: the Urals – with an average value of 0.3-4.1 m/year; Kharasavey - 1-1.5 m/year. Such large ranges in the retreat values for the Ural coast is associated with remarkable differences in soil ice content and, accordingly, heat capacity (Aleksyutina, Motenko, 2017), resulting in different reactions to the thawing during a warm season.

Table 1. Main statistical parameters of the coastal retreat rates depending on lithological characteristics of the sediments at the Ural coast

Soils	Data or Parameters	1988-2005	2005-2012	2012-2013	2013-2014	2014-2015	2015-2017
Sandy sediments	Average, m	1.49	0.79	1.96	0.71	1.57	0.67
	Median, m	1.43	0.44	1.40	0.43	1.40	0.52
	Std. deviation	0.70	0.88	1.76	0.81	1.34	0.59
	Minimum, m	0.18	0.00	0.02	0.00	0.00	0.00
	Maximum, m	3.64	3.86	8.95	3.62	5.48	3.24
Loamy sediments	Average, m	2.52	4.07	2.01	0.47	0.57	0.28
	Median, m	2.54	3.78	1.57	0.23	0.33	0.14
	Std. deviation	0.79	3.03	1.68	0.55	0.75	0.40
	Minimum, m	0.81	0.00	0.05	0.00	0.00	0.00
	Maximum, m	4.28	12.66	8.87	2.63	4.04	2.06
Peats	Average, m	1.99	3.06	2.91	1.68	5.38	1.02
	Median, m	2.14	2.56	2.77	0.77	5.29	0.55
	Std. deviation	0.62	2.04	1.93	1.76	2.73	0.87
	Minimum, m	0.00	1.16	0.34	0.06	0.46	0.02
	Maximum, m	2.60	8.96	6.01	5.44	10.42	2.60

Cliffs composed of interbedding sediments with different gran-size distribution retreat with an average value of 0.7-1.7 m/year and a maximum value of 4.1 m (Table 1). The occurrence of peat at the upper part of the coast causes different effects: at the Ural site such coasts retreat on average at 1-5.4 m/year and maximal up to 10.4 m/year; at the Kharasavey site, otherwise, the retreat rates are the smallest, of 0.7-1 m/year and maximum of 2.3 m/year. While peat can block the ice wedges and protect them from thawing on both sites, perhaps this phenomenon is more pronounced at the Kharasavey site, as the coast at the Ural area has a narrower beach and is actively exposed to the sea. The thawed material might be therefore quickly washed away by the sea, and the next part of the wedge might be exposed to thawing.

Table 2. Main statistical parameters of the coastal retreat rates depending on lithological characteristics of the sediments at the Yamal coast

Soils	Data or Parameters	1968-1988	1988-2005	2005-2016
Sandy sediments	Average, m	0.30	0.42	0.77
	Median, m	0.21	0.37	0.62
	Std. deviation	0.37	0.30	0.60
	Minimum, m	0.00	0.00	0.00
	Maximum, m	2.44	1.56	3.98

Table 3. Main statistical parameters of the coastal retreat rates depending on lithological characteristics of the sediments at the Kharasavey coast

Soils	Data or Parameters	1972-1977	1977-1988	1988-2006	2006-2016

Sandy sediments	Average, m	2.00	0.85	1.28	0.66
	Median, m	1.48	0.73	1.34	0.67
	Std. deviation	1.75	0.72	0.83	0.41
	Minimum, m	0.00	0.00	0.00	0.00
	Maximum, m	8.99	3.76	4.52	2.10
Loamy sediments	Average, m	1.53	1.48	0.95	1.03
	Median, m	1.21	0.47	0.81	0.81
	Std. deviation	1.25	1.86	0.61	0.84
	Minimum, m	0.00	0.00	0.00	0.01
	Maximum, m	6.98	7.10	2.44	3.76
Interbedding of sandy and loamy sediments	Average, m	0.71	1.65	1.21	1.33
	Median, m	0.59	1.63	1.18	1.32
	Std. deviation	0.63	0.88	0.64	0.55
	Minimum, m	0.00	0.00	0.00	0.03
	Maximum, m	2.75	4.11	2.58	2.46
Peats	Average, m	0.68	1.03	0.74	0.84
	Median, m	0.47	1.17	0.78	0.59
	Std. deviation	0.63	0.72	0.45	0.66
	Minimum, m	0.01	0.01	0.02	0.00
	Maximum, m	2.25	2.20	1.50	1.88

CONCLUSIONS

The study revealed that long-term (30 years or more) average annual retreat rates for coasts of different key-sites ranged from 0.5 to 1.3 m per year: at the Ural coast of Baydaratskaya Bay – 1.1-1.3 m/year (maximum 5.3 m/year), at the Yamal – 0.5-1.1 m/year (maximum 3.6 m/year), at the Kharasavey coast – 1 m/year (maximum 4.3 m/year). We estimated the role of different permafrost processes and lithological composition of the cliffs in the coastal dynamics on three key sites in the Western sector of Kara Sea. The development of these processes occurs at approximately the same rates, however, behavior of these processes at different time periods is slightly different. Our data provide the basis for modelling, simulation, and prediction of the coastal dynamics in similar environments, and may be used for planning and conducting of the industrial activities in the Arctic region.

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