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CRYOGENIC PROCESSES AT ARCTIC SEAS' SHELF AND ON SHORE

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EROSION OF PERMAFROST COASTS OF KARA SEA NEAR KHARASAVEY CAPE, WESTERN YAMAL

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Analysis of multi-temporal satellite imagery and results of long-term field monitoring of coastal dynamics allowed to determine retreat rates of a 7-km coastal section between Kharasavey settlement and Cape Kharasavey, Western Yamal. Its bluffs, 7–12 m in height, are composed of permafrost and retreat at an average annual rate of 1.1 m per year (over a 52-year period). The highest mean annual retreat rates (>2 m per year) are typical for coasts composed by ice-rich fine silty clays, their cryogenic structure being the main factor of such fast retreat. In 2006–2016, average retreat rates increased to 1.2 m/year compared with the 1.0 m/year rate in 1964–2006, primarily due to the accelerated erosion rates of ice-rich silty clays in the coastal bluffs. The impact of hydrometeorological forcing on Kharasavey coastal area increased in the late XX–early XXI centuries, causing faster coastal retreat.

Western Yamal, permafrost, coastal dynamics, thermal abrasion, thermal denudation, ground ice, hydrometeorological forcing

INTRODUCTION

About half the length of the Russia's Arctic sea coasts is composed of perennially frozen dispersive sediments highly susceptible to the thermomechanical forcing. The mean coastal retreat rate along the Arctic Coast is found to be 0.5 m/yr [*Lantuit et al., 2012*], characterized by wide local and regional variation [*Are, 1980, 2012; Grigoriev et al., 2006; Kamalov et al., 2006; Kizyakov et al., 2006; Vasiliev et al., 2006; Lantuit et al., 2012, 2013; Kritsuk et al., 2014; Ogorodov et al., 2016; Pizhankova, 2016*]. In the context of natural conditions of the Russian Arctic seas, coastal erosion can have long-term average rates ranging from 0.1 to 5 m/yr and more. Given the ongoing active development of gas fields in the north of Western Siberia and construction of hydrocarbon storage and transportation facilities in the coastal zone (Sabetta and Kharasavey seaports, underwater pipelines crossing Baydaratskaya Bay), determination and prediction of coastal retreat rates have become of particular importance.

In the long-term perspective, the retreat of the Arctic seas' shoreline will be dictated by relative sea-level changes; on the scale of decades, coastal erosion rate is largely governed by the variability of hydrometeorological conditions and diversity of morphological properties of the coastal zone.

F.E. Are [*2012*] has identified three processes determining the coastal permafrost degradation dynamics: 1) thermal abrasion, which is defined as destruction of the coastal zone induced by the mechanical and thermal action of water; 2) thermodenudation, resulting from the combined influence of positive air temperatures and solar insulation causing coastal bluff erosion; 3) subsidence caused by permafrost thawing on the beach and underwater coastal slope. These processes are affected by both hydrometeorological factors (frequency and intensity of storms, wind direction, wave fetch, air and water temperatures, insolation), and in equal measure contributed by sediment composition, geomorphology and permafrost properties of the coastal zone.

Hydrometeorological forcing affecting the coastal dynamics consist of two main groups: 1) thermal factors associated with the thermal energy of air (and water) transferred to the coast; 2) wind and wave energy responsible for the mechanical destruction produced by action of waves onto the coast. Given that these appear the major driving forces behind coastal dynamics, the coastal systems' response to climatic fluctuations will be forthcoming. In recent decades, appreciable climate changes have thus been reported from the Russian Arctic [*IPCC, 2014; Alekseev, 2015; Romanenko et al., 2015*] along with affiliated rise in the mean annual air temperature (MAAT) showing a two-fold increase over the annually-averaged global temperature [*The second... report..., 2014; The 2016 re-*

port…, 2017]. Decreasing sea-ice extent and increasing ice-free period and wave fetch allow higher waves to develop, enhancing shoreline retreat [*Manson and Solomon, 2007; Forbes, 2011; Ogorodov et al., 2016*]. Numerous studies have provided evidence of increasing coastal erosion rates within the Alaskan and East Siberian Arctic coasts late in the 20th century and especially at the beginning of the 21st century, associated with the decreasing sea ice cover [*Lantuit et al., 2013; Pizhankova, 2016*]. Noteworthy, however, is that the hydrometeorological conditions shape the coastal erosion potential which may or may not be realized at a specific coastal site depending on its geological structure. Speaking of changes in hydrometeorological characteristics, we mean that more (or less)

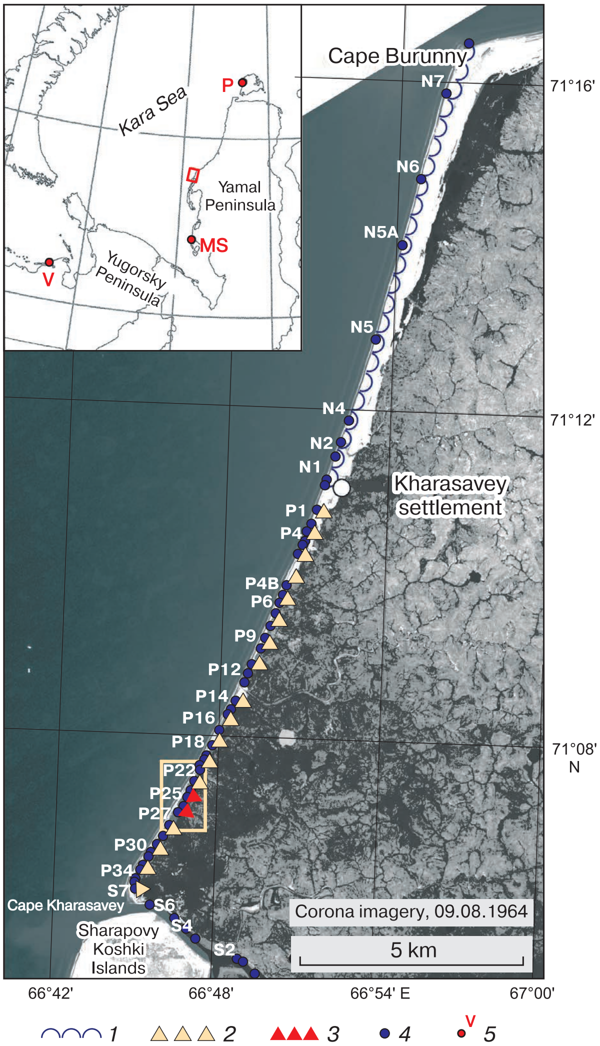

Fig. 1. Type of shorelines between Burunny Cape and Kharasavey Cape.

1 – accumulative coasts; thermal abrasion-affected coasts: *2* – retreating at a rate of 0.4–1.9 m/yr; *3* – retreating at a rate of >2 m/yr; *4* – coatal dynamics monitoring profiles; *5* – weather stations: V – Varandey, MS – Marre-Sale, P – Popov WS. Rectangular delineates the coastal site shown in Fig. 3.

favorable conditions for coastal erosion are created, which determine the probability of more (or less) intensive coastal retreat; however, these processes are not directly dependent.

The rate of thermal abrasion, other conditions being equal, is determined by the area-specific topography and permafrost properties, including the shoreface profile, sediment composition, total ice content, and the presence of massive ice: tabular, ice wedges, and intrusive ice. Exposure of large ice bodies in the retreating bluffs triggers thermal denudation and thermal erosion. Besides, degradation of coastal bluffs with high ice content results in smaller volumes of thawed material sliding onto the beach, contributing both to its accelerated removal by waves and to coastal erosion.

The objectives of the present study include: 1) determining the mean annual coastal retreat rates in an area of industrial development (in the vicinity of Kharasavey settlement, Western Yamal) from satellite imagery interpretation and long-term field monitoring data; 2) characterization of the features determining the retreat rate variability along the investigated coastal segment, and 3) quantifying the variations in hydrometeorological factors affecting the coastal retreat rate.

STUDY AREA AND RESEARCH METHODS

Properties of permafrost in the coastal bluffs

A network for coastal dynamics monitoring set up in the area of Kharasavey settlement by the team of research laboratory of Geoecology of the North (affiliated with the Faculty of Geography, Moscow State University), covers a 20-km coastal segment stretching from Cape Kharasavey in the south to Cape Burunny in the north. The northern part of the area is represented by a flat, retreating accumulative coast. Coastal dynamics were investigated at an illustrative 9-km segment of the southern thermal abrasion-affected coast, its cliff height ranging between 7 and 12 m.

Within a 9.5 km – segment between Kharasavey settlement in the north and Cape Kharasavey in the south (Fig. 1), the coastal bluffs are composed of perennially frozen Quaternary sediments (Fig. 2). Both the deposits and massive ice beds hosted by them were discussed in numerous studies [*Kaplyanskaya, 1982; Velikotsky and Mudrov, 1985; Grigoriev, 1987; Cryosphere…, 2006; Yuriev, 2009; Vasil'chuk, 2012; Belova, 2014*]. Most of them suggest the marine origin of sediments composing most of the outcrops, as inferred from soil texture and chemical analyses' results, soil fauna and microfauna data (composition, abundance and distribution). Coasts of 7–12 m height are generally composed of silty and sandy marine sediments with inclusions of boggy, lacustrine-boggy, lacustrine-alluvial deposits represented either by peat, sands or interbedded sands, sandy loams,

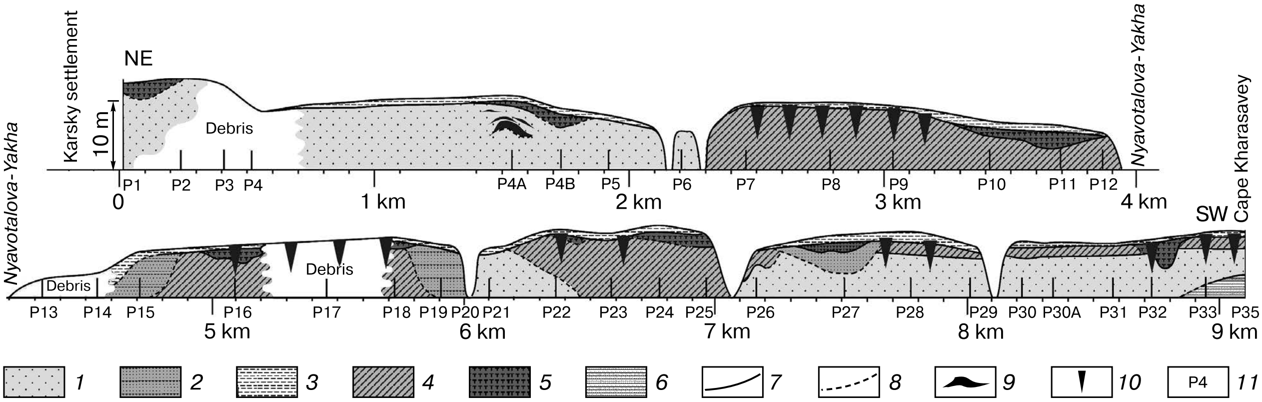

Fig. 2. Sediment release from the retreating coastal bluffs between Kharasavey settlement and Kharasavey Cape.

1 – sands, fine and meduim-grained, with interlayers and lenses of loams, marine; *2* – sands, fine-grained, with loam and peat interlayers, lacustrine-alluvial; *3* – loams, sand-loams; *4* – loams, marine (to the south of profile P26 – of unspecified origin); *5* – peat, locally with loam and sandy interlayers; *6* – clays; contacts between lithologies: *7* – established, *8* – asumed; *9* – tabular ground ice; *10* – ice-wedges; *11* – Profile No. of network monitoring.

loams and alluvial detritus [*Belova, 2014*]. Flat, terrace-like coastal lowlands with similar elevations can in fact be composed by different geological bodies, while steeply dipping contacts between them are not seen in the modern topography.

On two coastal sites (profiles P7–P10 and P22–P26, Fig. 1), predominantly ice-rich loams with epigenetic ice wedges are exposed in the coastal bluffs. In this way, 2.5 km to the north of Cape Kharasavey (profiles P22–P26, Fig. 1, 2), a 9 m-high bluff is found to be almost completely composed of gray splintered and slabby loams, with increasing sand content in the upper 1–3 meters. The heavy silty loams, contain numerous shells of marine and continental-shelf mollusk species, along with spicules of sponges (determined by S.D. Nikolaev) [*Belova, 2014*]. The loams have a reticulate cryogenic structure and contain on average more than 40 % ice by volume.

Ice content of sandy deposits is generally lower (not more than 30 %), compared to ice-rich loams. Coastal sections with ice wedges in the upper parts of the coastal bluffs and with the presence of massive ice beds are an exception. Massive ice beds largely outcrop in the northern part within a 2 km-stretch of the investigated coastal site, lying to the south of Kharasavey settlement (formerly, Karsky and Pionerny settlements). Tabular ground ice is represented by a series of ice lenses with a total thickness of 1–2 m and a length of first tens of meters. Varying from year to year, massive ice is exposed at different coastal segments; tabular ground ice typically lie in the upper part of sandy layer and mainly outcrop in areas where this layer is located above sea-level. Fine-grained silty sands (locally with fauna remains, including mollusk shells) contain layers with high plant debris content.

A field study of coastal dynamics near Kharasavey settlement

The observations of coastal dynamics near Kharasavey settlement conducted by the researchers from Laboratory of Geoecology of the North (Moscow State University) were launched back in 1981, with 10 profiles laid within the accumulative coastal segment, and 33 profiles on the thermal abrasion-affected coastal segment. In the years to follow, intermediate profiles were set on the thermal abrasion-affected coast including those intended to substitute the missing ones. The network monitoring profiles were laid on the coastal segments differing in permafrost properties (sediment composition and ice content) and morphology (bluff height, beach and tidal-flat width, etc.). Direct measurements were carried out by repeated trigonometric levelling normally to the shoreline, from pegs serving as benchmarks (at least three benchmarks installed every 10 m for each profile), which allowed monitoring coastal profile changes. The coastal bluff edge retreat rate was used in estimates of coastal erosion rates.

According to the field monitoring results, the mean retreat rate of the investigated coastal site is 1 m/yr (averaged over 31 years, from 1981 to 2012). However, depending on the coastal morphology and permafrost properties of a given section, mean annual erosion rates at different segments varied from almost zero to 2.7 m/yr. Despite the high accuracy of direct measurements, the field monitoring data can not always be adequate for calculating the mean annual retreat rates of individual coastal segments. Given the long interval between observations at the representative rapidly retreating segments, some of the reference benchmarks were missing due to erosion; others were lost as a result of human activity. Therefore, we used the observations along profiles to characterize the interannual variability of the coastal retreat rates, whereas the average rates were derived from the satellite imagery interpretation.

A.A. Vasiliev estimated the average rate of coastal erosion in the Kharasavey Cape area to be as high as 1.4 m/yr (between 0.5 and 3.0 m/yr) over the period of 1978–2001 [*Vasiliev et al., 2006, 2011*]. Based on the analysis of aerial imagery from different years (1976, 1990, 2001), tachymetric measurements (2006) and remote sensing results using digital airborne (helicopter) equipment (2007), the Gazprom Dobycha Nadym employees obtained the data on the coastal retreat rate between Cape Kharasavey and Kharasavey settlement: the coastline retreated over 31 years (1976–2007) at a mean rate of 1.1 m/yr for the entire segment, with a minimum of 0.5 m/yr and a maximum of 2.3 m/yr [*Yuriev, 2009*]. However, more detailed information on spatial and temporal variability of the retreat rates is not provided here.

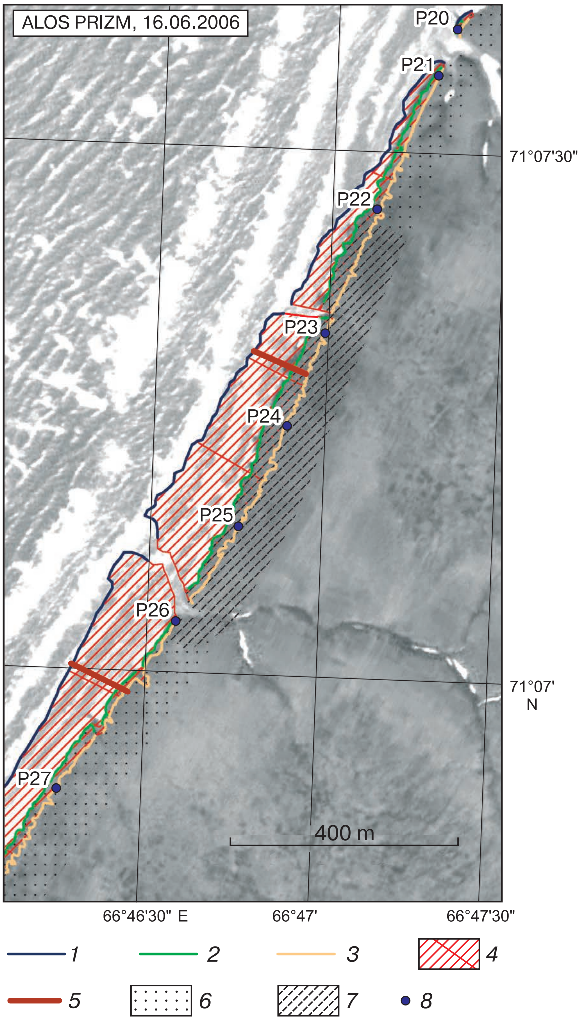

Fig. 3. Coastal bluff edge retreat rate over a 52-year period.

Coastal bluff edge position: *1* – in 1964 (from the Corona KH-4 satellite imagery); *2* – in 2006 (from the ALOS PRIZM satellite imagery); *3* – in 2016 (from the WorldView-2 imagery); *4* – eroded area over the 1964–2016 period, thin cross-lines delineate boundaries of coastal segments used for calculating the mean retreat rates; *5* – boundaries of rapidly retreating coastal site coastal (>2 m/yr over the 1964–2016 period); deposits dominating in the coastal bluf structure: *6* – sands, *7* – ice-rich clay-loams; *8* – network monitoring profiles.

In this way, given the diversity of the implemented methods and high spatial and temporal variability of coastal erosion processes in permafrost areas [*Vasiliev et al., 2006*], the retreat rates values resulting from earlier research efforts vary widely.

Compared with previous studies, we have analyzed a longer time interval – spanning 52 years (1964–2016). We used satellite imagery to obtain the mean annual coastal retreat rate values. Temporal variability of the coastal erosion rates was estimated from satellite imagery and field monitoring data (until 2012). A comparative analysis of multitemporal satellite imagery was performed: Corona KH-4A (09.08.1964, 5 m-spatial resolution; interpolation by the cubic convolution method in the ArcGIS up to 4 m was performed for the convenience of interpretation), the ALOS PRIZM imagery (16.07.2006; 2 m-resolution) and the WorldView-2 imagery (15.07.2016, 0.5 m-resolution; provided by the © Digital Globe Foundation). In the course of the imagery interpretation, the coastal bluff edge was traced, seeing as its position, contrarily to the coastline, does not depend on the tidal and wind-induced phenomena. The mean uncertainty in coastal retreat rate calculation is 0.1 m/yr; the largest possible uncertainty is 0.2 m/yr. These uncertainties were derived from satellite imagery resolution, as well as georeferencing and interpretation accuracy. The site with disputable bluff edge position on the Corona image (north of the P4B profile, Fig. 1) was excluded from the calculations. The mean coastal retreat rates were calculated for the coastal segments of 100–500 m length (250 m on the average), homogeneous in terms of morphology and permafrost properties (Fig. 3), each having a ground network monitoring profile.

Evaluation of hydrometeorological factors of coastal dynamics

There are different methods of quantifying the thermal and wave-energy factors of coastal dynamics [*Razumov, 2001; Leontiev, 2003; Vasiliev et al., 2006; Jones et al., 2009*]. The Popov–Sovershaev method developed at the Laboratory of Geoecology of the North (Moscow State University) has been successfully applied to calculations of wave energy fluxes [*Popov and Sovershaev, 1981, 1982; Ogorodov, 2002; Ogorodov et al., 2016*]. The wave energy flux (*WE*) per meter of wavefront length is directly related to the wind speed third degree polynominal, frequency of wind of a given speed and direction, wave fetch and ice-free period duration . The unit of measurement of wind and wave energy flux is tons per unit of time (in our case, over the ice-free period); its physical meaning is the mass of water crashing against 1 m of the coastline during the ice-free period. For calculations, winds of hazardous wave directions with speeds exceeding 5 m/s are used; the contribution of lower speeds to the total wind and wave energy flux is shown to be negligible [*Popov and Sovershaev, 1982*].

The ice-free period duration was determined based on data derived from satellite imagery, using the product of the Danish Meteorological Institute [*EUMETSAT, 2015*] characterized by the greatest temporal coverage (1979–2014) and the best spatial resolution (about 12 km) in comparison to other sources of satellite data.

The thermal factor can be estimated according to the US Geological Survey recommendations [*Andersland and Ladanyi, 2004*], using positive and negative mean daily temperatures accumulated during the year, termed the "thawing index" and the "freezing index", respectively.

Wind and air temperature data were obtained from the ERA Interim [*Dee et al., 2011*] and ERA-20C [*Poli et al., 2016*] reanalyzes, supplemented with the Kharasavey weather station (WS) data (1973–1987, from the N.N. Zubov State Oceanographic Institute archive). The application of atmospheric modeling (reanalyzess) data was required because of the lack of observational data (above all, wind data), inasmuchas the Kharasavey WS was closed in the 1990s, leaving the past (most dynamic) two decades without observations.

With land surface temperature field representing a smooth natural surface, the long-term temperature trend can be analyzed using the Marre-Sale WS data (in operation, located 150 km south of Kharasavey Cape, its temperature observations available from 1914). However, although these observations cover a long time period, significant gaps in the data series require restoration.

A comparative analysis of the ERA data and observations at meteorological (weather) stations (Popov WS on Bely Island, Marre-Sale WS, and Varandey WS in the Pechora Sea, Fig. 1) has shown that the reanalysis with systematic deviations from observational data will adequately reproduce interannual thawing and freezing index variability: the correlation coefficient of the reanalysis series adjusted for systematic deviation and observations is on average 0.87–0.89 and 0.94–0.96 for the freezing and thawing indices, respectively [*Shabanova et al., 2017*]. We used the reanalyzes for estimation of the interannual variability of thermal factor in the coastal dynamics in the Kharasavey settlement area, in comparison with the available observational data.

Given that the surface wind field is a discontinuous surface, description of the wind conditions near Kharasavey settlement and Cape Kharasavey based on the data of a weather station located 150 km to the south will most likely contain significant errors. Therefore, the atmospheric modeling (reanalysis) data serve as an indispensable source of wind-related information in evaluating the long-term variability of the thermal abrasion potential of the Arctic coastal dynamics. The speed and directions of surface wind and temperature series were obtained from the nearest reanalysis network nodes: 71°25′ N, 67°05′ E for ERA Interim (grid spacing: 0.75°) and 71° N, 68° E for ERA 20C (grid spacing: 1°).

COASTAL RETREAT RATES

The coastal segment from Kharasavey settlement to Cape Kharasavey has an almost straight coastline stretching from NNE to SSW. Despite similar wind-and-wave conditions and slope aspect, retreat rates of individual coastal segments differ greatly. The rate of coastal bluffs' erosion is determined by their structure and the resulting sediment fluxes and their deposition on the beach and shoreface. The most stable coastal segments are confined to areas with wide beaches and tidal flats, formed either due to the river sediment load or long-shore sediment transport.

Of the 7-km coastal stretch between profiles P5 and P35 with a well-expressed coastal bluff, the mean annual coastal retreat rates exceed 1 m/yr only within segments with a total length of about 3 km (hereinafter the retreat rates are given for a 52-year period, unless otherwise specified). To characterize spatial variability of the coastal dynamics, the mean annual retreat rates were calculated for several coastal sites, consisting of segments with a similar cryostructure of permafrost deposits (Table 1).

Table 1. **Long-term mean annual coastal bluff edge retreat rate obtained from the sattelite imagery interpretation**

Profile	Deposits of the coastal bluff	Coastal segment length, km	Retreat rate, m/yr		
			1964–2006	2006–2016	1964–2016
P5–P6	Sands	0.8	0.4	0.4	0.4
P7–P9	Ice-rich clay-loams	0.9	0.5	**1.4**	0.7
P10–P12	Clay-loams	0.6	0.8	0.7	0.8
P22–P25	Ice-rich clay-loams	0.8	**1.8**	**2.7**	**2.0**
P26–P35	Sands	2.1	**1.5**	**1.5**	**1.5**

Note. Retreat rates exceeding 1 m/yr appear in bold font, and those greater than 2 m/yr are marked by shaded fill.

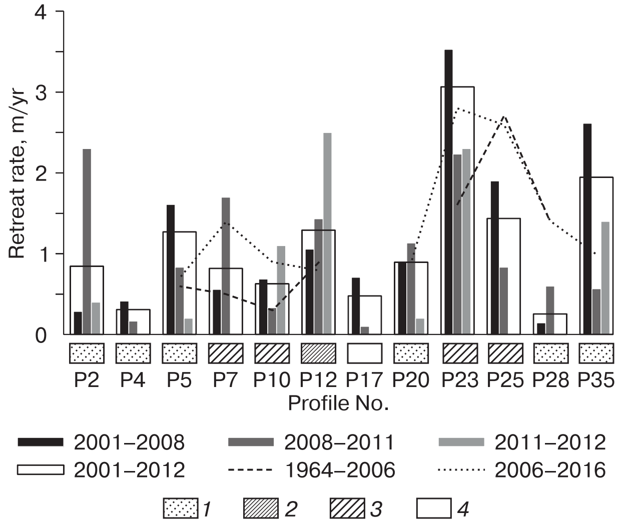

Fig. 4. Coastal bluff retreat rates near the Kharasavey settlement village from field monitoring data (2001–2012) and results of satellite imagery analysis from different time periods (1964–2006 and 2006–2016).

Deposits dominating in the coastal bluf structure: *1* – sands; *2* – loams; *3* – ice-rich loams; *4* – talus material.
Satellite photographs show the mean retreat rates for coastal segments controlled by respective profiles.

The greatest average annual retreat rates (>2 m/year, Fig. 3, Table 1) were observed at profiles P22–P25,where the 0.8 km-segment includes shores with narrow (10–15 m) beaches and coastal bluffs composed of ice-rich (>40 %) loams. At this segment, even more significant erosion rates were reported in 1981–1987: the retreat rate on individual profiles reached 4.2–4.5 m/yr, peaking at 11.8 m/yr [*Sovershaev and Kamalov, 1992*]. Over the decade of 2006–2016, the mean retreat rate of this coastal segment showed a 1.5-fold increase compared to the period of 1964–2006 (from 1.8 to 2.7 m/year, Table 1). Even higher erosion rate increase (trippled for the same periods) was observed at another segment where ice-rich loams outcrop (P7–P9, Table 1), although the absolute values of coastal retreat rates appear not so high (from 0.5 to 1.4 m/year, respectively).

On coastal segments composed of either sandy or ice-poor loamy sediments, the mean annual retreat practically did not change over the period of 2006–2016 in comparison with the longer preceding time period between 1964 and 2006. Along with this, field monitoring data (Fig. 4) indicate a significant interannual variability of coastal retreat rates at these coastal sites. In this way, high erosion rates were observed in some years at Cape Kharasavey (P35), for which reason the polar station built in 1953 and the lighthouse were under threat of destruction in 30 years' time, and were therefore dismounted and moved to a safer place [*Sovershaev and Kamalov, 1992*]. As such, high erosion rates of beach deposits were largely accounted for by their repeated withdrawal for the needs of the sea-port construction, rather than their position near the cape. However, in recent years, coastal recession in the area of Cape Kharasavey has significantly decreased, which may be explained by the dredging of the Kharasavey river mouth, resulting in abundant suspended material transport by the shallow water flow, with its subsequent accumulation on the beach.

Hydrometeorological factors: periods and tendencies

The reconstruction of thermal factors of coastal dynamics in the late 20th–early 21st century using the ERA-20C reanalysis [*Poli et al., 2016*] and ERA Interim data [*Dee et al., 2011*] shows that the thawing and freezing indices have undergone significant alterations (Fig. 5).

The freezing index is characterized by a variability consistent with secular variation in the MAAT (mean annual temperature) with a maximum in the 1940s, a minimum in the 1960s, and an increase since the 1980's (Fig. 5, *a*). Some winters of the 21st century were unprecedentedly warm, breaking the records of the 1940s. In the context of coastal dynamics, this means their freezing through to smaller depths and at higher temperatures. Under these conditions, transition of permafrost deposits composing the coastal bluffs into a thawed state during the warm season will require less thermal energy, while thawed material is effectively removed by waves (in case of sufficient storm strength). Recent warming has thus enhanced the likelihood of more intense thermal denudation (compared, e.g., with the 1960s). However, the driving factor in thermal denudation process is the amount of thermal energy consumed by thawing permafrost, which can be estimated by the thawing index (Fig. 5, *b*).

The thawing index demonstrates a trend differing from that for the freezing index and MAAT values. The most pronounced warming episodes happened in the 1920s' of the 20th century, and at the turns of the 1950–1960s, the 1980–1990s and the 21st century. Specifically, in the 20th century, the 40s and 70s summer seasons were the coldest in Kharasavey area (just as in the entire Barents-Kara region). The freezing and thawing index trend analysis has shown that winter and summer temperatures changed in antiphase before the 1980s. The recent warming, however, doesn't follow this rule, demonstrating unprecedentedly high values for both winter and summer seasons. This means that the hydrometeorological potential of thermal denudation has significantly increased in the late 20th–early 21st century compared with the past periods. Noteworthy is also

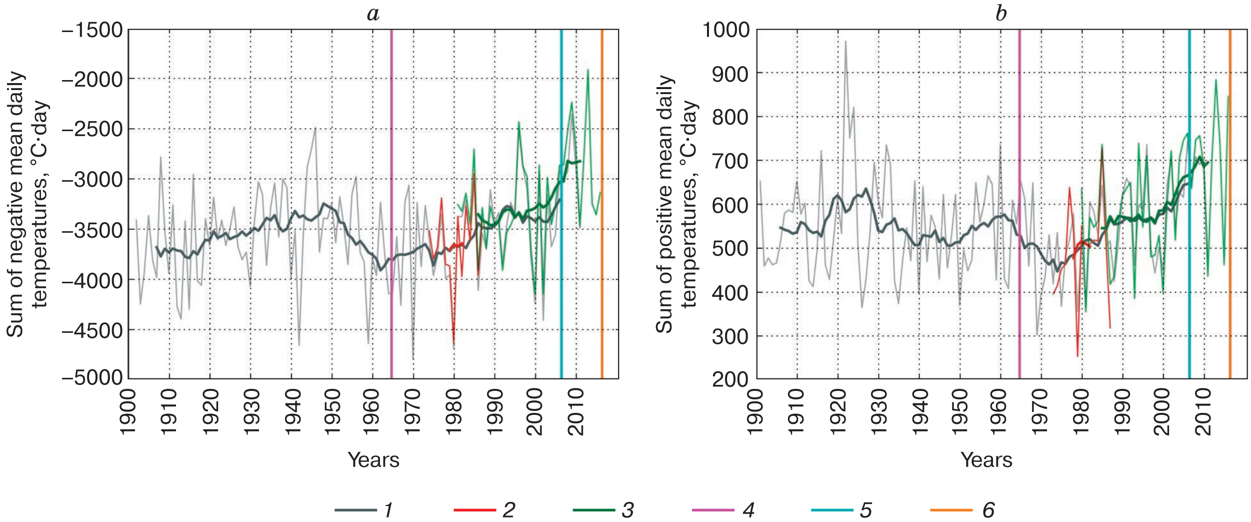

Fig. 5. Thermal factor variability in the coastal dynamics near the Kharasavey settlement in the 20th–21st centuries, according to the ERA Interim and ERA-20C reanalyses data and the Kharasavey WS observations:

a – sum of negative mean daily temperatures over a year (freezing index); *b* – sum of positive mean daily temperatures over a year (thawing index). Bold lines – 11-year moving average, vertical lines are the dates of photographs. Temperature data from: *1* – ERA 20C reanalysis, *2* – Kharasavey WS observations, *3* – ERA Interim reanalysis; dates of photographs: *4* – Corona 09.08.1964, *5* – ALOS PRISM 16.06.2006, *6* – WorldView 15.06.2016.

that the data obtained for Kharasavey are characterized by high variability in the 2000s, with record high values changing for anomalously low (the "cold" years of 2011, 2013 and 2014, and the "warm" years of 2009 and 2012).

A quantitative assessment of the trends shows that the observed increase in the thawing index is statistically significant at the 0.01 level (Table 2), while the freezing index is statistically significant at the 0.02 level (p-values are 0.0074 and 0.014, respectively). Over the period spanning 35 years (from 1980 to 2014), summer temperatures have increased by 30 % (compared with average values for 1981–1990), while winter temperatures have increased by 21 %. During these years, the duration of the ice-free period (N), i.e. the time of the shore exposure to waves (Fig. 6), increased considerably: from 80–90 days in the 1980s to 100–180 days after 2005. The duration of the ice-free period increased by 50 days (Table 2) over 35 years is statistically significant at the 0.05 level.

The wind-and-wave load on the coasts at the investigated site has also been increasing in the recent years (Fig. 6); the observed trend is, however, statistically insignificant (Table 2), as the wind-wave (*WE*) energy variance is high, and the linear trend value does not exceed 65 % of the standard deviation (SD). Within the *WE* multiannual fluctuations, the distinct low value periods are 1998–2003 and 2013–2014. Fairly small wind-and-wave energy fluxes in these years are explained by a short ice-free period. However, besides the severe ice conditions during these years, the frequency of storms of hazardous wave directions (NW and W) also declined, together with a decrease in summer temperatures (Fig. 5, *b*).

Table 2. **Analysis of hydromeorological parameters' trends over the 1980–2014 period**

Hydromeorological parameter	Trend value	Increment over 35 years			p-value
		Absolute value	% of mean 1981–1990	Standard deviation (SD) for 1981–1990	
Thawing index, °C·day/yr	***4.7***	***165***	***30***	***2.3***	***0.0074***
Freezing index, °C·day/yr	*20*	*696*	*21*	*2.5*	*0.014*
Ice-free period duration, day/yr	*1.4*	*50*	*53*	*1.85*	*0.02*
Wind- wave energy, thou. t/yr	6.35	222	34	0.62	0.27

Note. Trends, statistically significant at the 0.01 level are shown in bold, and those significant at the 0.05 level appear in italics.

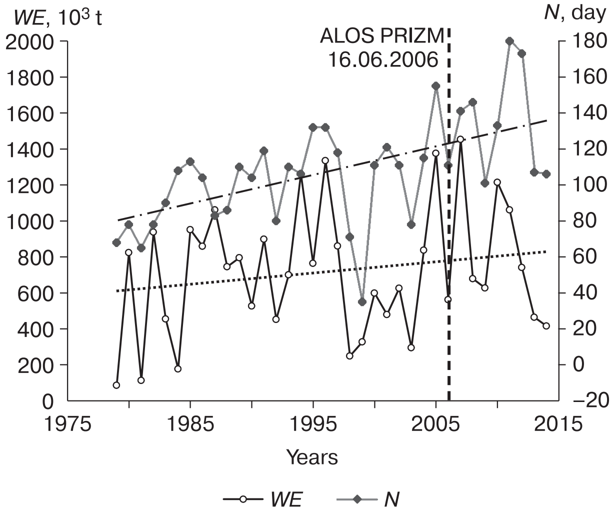

Fig. 6. Long-term wind-and-wave energy (*WE*) flux variability and duration of ice-free period (*N*) near the Kharasavey settlement according to the ERA Interim reanalysis and satellite data [*EUMETSAT, 2015*].

Dashed and dash-and-dot lines are linear trends; vertical dashed straight line s the date of ALOS PRIZM photograph.

Spatial and temporal variability of coastal retreat rates

The presence of ground ice determines the geoecological instability of permafrost [*Solomatin, 2013*] and the Arctic coasts composed by permafrost, in particular. Ice-rich permafrost exposed in the coastal bluffs is highly sensitive to warmer temperatures of air and near-surface layers of sea water, enhancing thermal denudation and thermal abrasion.

Different types of ground ice types are unevenly distributed in the permafrost areas; the spatial distribution of ground ice is determined by the region's history and paleogeography, including the conditions of permafrost aggradation. The contribution of ground ice to coastal retreat is also nonuniform and is determined in equal measure by the geological and geomorphological structure of the coast, rather than by cumulative ice content of sediments alone. Earlier attempts have been made to establish a statistical relationship between the Arctic coastal erosion rates and ground ice content [*Héquette and Barnes, 1990; Lantuit et al., 2008*]. The presence of ground ice was initially assumed to lead to an increase in the coastal retreat rates; however the correlation between them proved to be weak. The reason is that both of these studies analyzed the retreat rates of coasts extremely inhomogeneous in terms of geological and geomorphological structure and hydrometeorological conditions, relying either on the data for an entire region or for all Arctic coasts in general.

In contrast to the above examples, a distinct relationship between the cryostructure and coastal erosion rates is observed within the investigated coastal site (Kharasavey settlement area), where the coastal bluffs have fairly similar heights and are therefore affected by hydrometeorological factors in a similar way; separate segments of the coastal site differ only in ice contents and sediment dispersity.

The maximum average annual retreat rates (up to 3 m/yr over a 52-year period) induced by the intensive thermal abrasion are controlled by the permafrost properties of the cliff, its sediment composition and the site position within the divergence zone of the longshore sediment fluxes (profiles P24–P26), where the 9–10 m-high bluff is composed of ice-rich marine silty clays (loams) with a reticulate cryostructure, and ice wedges in the upper part of the section (Fig. 2). When eroded, the loams do not supply material suitable for beach formation, while small beach width and ice-rich sediments of the bluff contribute to the development of deep wave-cut notches. As a result, the coastline recedes as separate blocks, with more rapid thermoerosion along ice wedges.

Despite the forecasted increase in the Arctic coastal retreat rates, in the recent decades, even coasts composed of ice-rich permafrost, have been receding faster only locally. On the Yukon coast (SW Beaufort Sea), characterized by the highest permafrost ice content in the Canadian Arctic, investigations have shown slightly decelerating mean annual erosion rates: from 1.4 m/yr between 1951 and 1972 to 1.2 m/yr between 1972 and 2009, although this trend is not statistically significant [*Konopczak et al., 2014*]. There is a general spatial pattern of decreasing erosion rates from the west to the east along the Arctic Coast of Alaska and Yukon.

The coastal bluffs composed of permafrost (silty clays) along the Alaskan Beaufort Sea retreated with the mean rate of 14 m/yr in 2002–2007, which is doubled compared to the period between 1955 and 1979 [*Jones et al., 2009*]. As such, the enhanced erosion rate is associated there with a rise in the near-surface sea water temperature, which facilitates thermal abrasion and formation of thermoabrasive (wave-cut) notches in the lower part of the coastal bluff. The increasing ice-free period, making the coasts particularly vulnerable to autumn storms makes a smaller contribution to the coastal retreat rates compared to intensified summer warming. As an example, the shoreline retreated by 25 m in 2007 during a period without storms of wave-dangerous directions.

The rate of thermal denudation is determined by air temperature, determining the rate of thawing of ground ice and frozen sediments in the costal bluffs [*Are, 2012; Günther et al., 2013; Kizyakov and Leibman, 2016*]. For ongoing thermal denudation to continue, the thawed material of the cliff has to be further removed by waves.

If thermal denudation prevails over thermal abrasion, the upper part of the bluff recedes faster than its bottom. This mechanism forms thermal denudation terraces in the outcrops of the Ice Complex. In the Marre-Sale weather station area, Western Yamal, ice content is one of the most important factors determining the rate of thermal denudation and coastal retreat: with the increasing volumetric sediment ice content from 25 to 45 %, the total retreat of the upper edge of the coastal bluff nearly doubled between 1978 and 2002 [*Vasiliev et al., 2006*].

Coastal retreat rates in the area of massive ice beds' exposure near Kharasavey settlement (P2–P4B) appear rather slow. The reason for slower retreat of the segment with tabular ground ice compared to the bluff composed by ice-rich loams, besides the location of the latter in the zone of divergence of the longshore sediment flux, can be the different sediment composition of the coastal bluff. Thin beds of massive ground ice outcrop in the upper part of the sandy layer; their degradation provides sediment supply for accumulation on the beach. Moreover, ice content of sediments hosting massive ice beds tends to be less than that of the ice-rich loams, causing slower rates of thermal abrasion and thermal denudation.

Temporal variability of coastal retreat

Analysis of the variability of hydrometeorological factors affecting coastal dynamics has revealed periods of increased hydrometeorological load on the coast. Unfortunately, the dates of the available satellite images do not coincide with the limits of these periods, and the coastal retreat rates determined with the help of these images reflect average hydrometeorologic conditions. This concerns, above all, the retreat rates obtained from the satellite images of 1964 and 2006. The period of 2006–2016 may be conventionally interpreted to be a period of enhanced hydrometeorological load, although no data are available for 2015 and 2016.

The monitoring network profiles have shown that the retreat rates at the investigated site don't increase simultaneously in different coastal segments (Fig. 4). When comparing the retreat rates for 1964–2006 and 2001–2012, on profiles P5, P23 and P35, the coastal bluff edge retreated faster in 2001–2012, while in the area with profiles P25 and P28 an increased erosion rate was observed in 1964–2006 (Fig. 4). Local variability of retreat rates over short time intervals (at the decennial scale) is largely associated with the inhomogeneity of deposits composing the coastal bluff, with the shape of its cross-section, as well as with direct human impact (withdrawal of sediments from the beach/tidal flat).

A 42-year period between the space images of 1964 and 2006 has revealed an increase in the thawing/freezing index values (Fig. 5). During this period, both favorable (early 1990s and after 2002) and unfavorable (e.g., 1969–1981 and 1997–2002) conditions for thermal denudation were observed. The potential of thermal abrasion also changed from relatively low values in 1979–1984 and 1998–2003 to high values in 1994–1997 and after 2004 (Fig. 6). The coastal retreat rates calculated from the satellite imagery analysis show the mean values for the whole time interval between the surveys. However, given the described fluctuations of hydrometeorological conditions, a great temporal variability of coastal retreat rates within these periods can be assumed.

The period of 2006–2016 was characterized by increased potential for thermal denudation and thermal abrasion activation (635 thou. t in 2006–2014 vs. 450 thou. t in 1981–2005, implying their rise by 40 %) compared to the period between 1964 and 2006. At the same time, this period is characterized by significant interannual variability of both factors. Since 1900, the sum of positive temperatures has reached the extremely high values several times: in 2006, 2009, 2012 and 2015. However, 2011 and 2014 fall into the 25%-group of the years with record low temperatures. In 2007 and 2010, the shorelines experienced the greatest wind-and-wave load since 1979, while in 2008, 2013 and 2014, it was equal to the "calm" period of 1998–2003. Such alternation of active and calm years likely reduces the generally growing coastal retreat rates.

In this way, a case study of the coasts in the Kharasavey settlement area has shown that thermal abrasion-affected coasts respond differently to changes in hydrometeorological parameters. Coasts composed of ice-rich permafrost with finely dispersed sediments have proven most sensitive to such changes. During their retreat, the hydrometeorological potential of thermal abrasion and thermal denudation is completely fulfilled.

CONCLUSIONS

1. The long-term mean annual coastal retreat rate within a 7-km coastal segment near Kharasavey settlement reached 1.1 m/yr over the 52-year period (between 1964 and 2016).

2. The greatest retreat rates (2–3 m/yr over the 52-year period) primarily driven by intensive thermal abrasion, were observed at the divergence zone of the longshore sediment fluxes, where the coastal bluffs are composed of heavy loams with high volumetric ice content (>40 %).

3. The late 20th–early 21st century were characterized by an increased hydrometeorological potential of coastal erosion near Kharasavey settlement, including both thermal denudation (the thermal factor of coastal dynamics) and thermal abrasion (the wave-energy factor). The growth of the hydrometeorological component of the coastal erosion potential is likely to have played a major role in the dramatic

increase in the coastal retreat rates (showing a 1.5–3-fold increase in 2006–2016 compared with 1964–2006) of the coastal bluffs composed by ice-rich loams.

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