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Spatiotemporal variability of coastal retreat rates at Western Yamal Peninsula, Russia, based on remotely sensed data

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ABSTRACT

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The work aims at estimating coastal retreat at Western Yamal from 1972 to 2016, when significant climate change occurred in the Arctic. One fourth of the Kara Sea coasts are collapsing cliffs composed of permafrost, i.e. thermo-abrasional coasts. Although these coasts are bounded by sea ice for most of the year, they retreat with rates comparable to those of temperate latitudes, but only during the short ice-free period. Permafrost cliffs are not only eroded by waves; they also get destroyed by melting of the ground ice bounding the sediments (thermo-denudation). Arctic coasts are sensitive to climate change, as rising summer air temperatures lead to deeper thawing of frozen sediments, and longer ice-free periods extend the time of the wave impact on the coast. At Western Yamal, in the area of Kharasavey gas condensate field, the average long-term coastal retreat rate is 1.3 m/yr (1972-2016) for 5.9 km of the coastline, reaching mean annual rates of 3 m/yr in some areas. The greatest retreat rates are typical for coastal segments composed of permafrost with high ice content. Based on the analysis of multitemporal aerial and space images, the coastal retreat rates for four time periods between 1972 and 2016 were estimated. The retreat rates were brought into context with data on sediment composition and type (grain size, ice content, presence of massive ice), reconstructed evolution of hydrometeorological parameters and the history of economic development of Kharasavey area. Unlike other Kara Sea sites of coastal dynamics' monitoring, the strongest coastal retreat rates at Kharasavey were observed earlier in 1977-1988, when the hydrometeorological stress was low, implying vulnerability of the coasts to significant anthropogenic impact at the beginning of the gas field development.

ADDITIONAL INDEX WORDS: *Permafrost, icy coasts, thermo-abrasion, thermo-denudation, Kara Sea.*

INTRODUCTION

Arctic coasts are known to retreat fast despite sea ice and snow protecting them during most of the year. The average retreat rate for all Arctic coasts was estimated as roughly 0.5 m/yr (Lantuit *et al.,* 2013), with great variations in time and space (Jones *et al,* 2009; Günther *et al.,* 2015; Maslakov and Kraev, 2016; etc.).

The study aims to characterize retreat rates at a key site in the Western Russian Arctic and to determine whether the current climate warming enhances coastal erosion. The coasts of the Russian Arctic are almost exclusively composed of permafrost and subject to thermo-abrasion (Are, 2012), where mechanical wave erosion is strengthened by the thermal impact of air and water. Because of thawing, frozen deposits lose their strength and are easier removed. Currently increasing air temperatures should lead to faster permafrost thawing, and a longer ice-free period increases the duration of the wave impact, tentatively leading to greater mechanical erosion. To check whether these changes affect the patterns of thermo-abrasion, data on the spatial and temporal variability of shoreline retreat for a key site on the west of Yamal Peninsula were obtained, and changes of hydrometeorological parameters during several decades of the recent climate change were assessed, allowing a comparative analysis of coastal retreat rates' response to natural and human-induced environmental changes.

Background

Thermo-abrasional coasts make up to one-fifth of the Kara Sea coastline (Vasiliev *et al.,* 2006). Such coasts host a great number of settlements and infrastructure, Kharasavey on the northwestern coast of the Yamal Peninsula (Figure 1) being an example. The research area is characterized by severe climatic conditions. The average long-term air temperature is -9.8°C (according to observations at the Kharasavey weather station. 1961-1989, now closed). From October to May, the average monthly temperature

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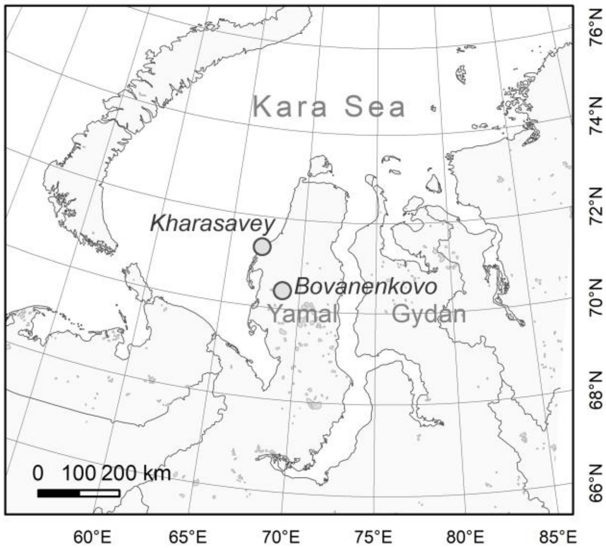

Figure 1. Study area.

is negative (Baulin *et al.*, 2003). High wind activity and a pronounced seasonal change in the direction of the prevailing winds is observed. During winter months, southern winds with average velocities of 6-8 m/s prevail. In summer, northern winds with average velocities of 5-7 m/s prevail (Baulin *et al.*, 2003). The duration of the ice-free period is 100-180 days (for 2005-2014), which is 50 days longer compared to 80-90 days at the end of 1970s (Grigoriev, 1987; Belova *et al.*, 2017). Sea depths are 4.5-5.5 m at 1 km and 7-8 m at 2 km offshore. The area is located in the zone of continuous permafrost, where deposits are frozen to a depth of 170 m and cooled to a depth of 260 m (Baulin *et al.*, 2003).

The Kharasavey gas condensate field is a unique site with about 2 trillion cubic meters of natural gas, condensate, and natural gas liquids. As part of the Yamal megaproject, the Russian President launched the development of Kharasaveyskoye in March 2019. Production start is planned for 2023 with reaching plateau production in 2027 (Launch of Kharasaveyskoye…, 2019). Its preparation has been ongoing since its discovery in May 1974. Today, after the construction and commissioning of a pipeline from the Bovanenkovo field in Central Yamal to the European part of Russia, new development opportunities emerged and a 100 km long southward pipeline from Kharasaveyskoye will link this new production area with the existing transportation infrastructure at Bovanenkovo. .

20% of the Kharasavey field is located offshore. To explore it, horizontal wells will be drilled from the coast. For optimal engineering solutions during the gas field development at the land-sea interface, knowledge of coastal dynamics is required.

METHODS

Employees of the Laboratory of Geoecology of the North, Faculty of Geography, Lomonosov Moscow State University, have been conducting field studies of coastal dynamics in the Kharasavey field area since 1981. However, direct measurements in those years were limited to repeated surveying of transverse shoreline profiles. Multitemporal remotely sensed data allows relatively precise estimation of coastal retreat along the whole segment, allowing comparative analysis of its spatial and temporal variability.

The aerial photographs and space images used for coastal erosion measurements were taken from 1972 to 2016 (Table 1). Previous studies included the Corona image of 1964 (Belova *et al.*, 2017, 2018), and we excluded it from this analysis because of its relatively low spatial resolution. The images were ortho-rectified on the basis of TanDEM-X 90m DEM. The cliff edge was visually traced within each image and further compared to the adjacent cliff edge line to calculate erosion rates for each respective period. The results were analyzed together with data on permafrost sediment composition obtained during field studies in 2008 and derived from archive reports since 1981, that are preserved in the archive of the Laboratory of Geoecology of the North. Hydrometeorological parameters such as freezing andthawing indexes, ice-free period duration, wind speed and direction, were obtained based on reanalysis and direct observations data (see Belova *et al*., 2017, 2018; Shabanova *et al*., 2018).

Table 1. *Characteristics of multitemporal aerospace imagery used in the study*

Sensor	Date	Resolution, m
Aerial	31.07.1972	1
Aerial	21.07.1977	1.5
Aerial	05.08.1988	0.5
ALOS PRIZM	16.07.2006	2
WorldView-2	15.06.2016	0.5

RESULTS

Coastal Sediments

The length of thermo-abrasional cliffs within the study area reaches 9 km, with heights of 7-12 m. Despite similar heights, sediment composition varies considerably, with loams and sands interchanging frequently along the 9-km segment. These deposits are interpreted as either marine sediments (Cryosphere of oil…, 2006; Baulin *et al.*, 2003), or glaciotectonic units:

Figure 2. Permafrost coast of 8 m height near Kharasavey settlement. Note block failure due to thermo-abrasional niches formation. Photo by Belova N.G., 2008

initially marine sediments deformed by a Pleistocene cover glacier that had moved from the Kara Sea shelf (Kaplyanskaya, 1982; Astakhov *et al.*, 1996; Svendsen *et al.*, 2004). Loamy cliffs have medium (up to 40%) and high (>40%) ice content with reticulate cryostructure (Figure 2). Sandy bluffs are less icy; in the north of the studied coastal segment they contain massive ice beds, on which small retrogressive thaw slumps develop.

Spatial Variability of Coastal Retreat

From the 9-km coast, only 6.8 km have a distinct cliff allowing precise interpretation. Of this segment, only 3.3 km experienced intense retreat in the last decades. Erosion rates for the 44-year period vary from 0.1 to 3.1 m/yr (Table 2; Figure 3). The largest retreat was observed on the 3-km coastal segment north of Cape Kharasavey. On average, these 3 km retreated at a rate of 1.8 m/yr over 44 years (1972-2016). Within the area, some coastal segments of 0.1-0.3 km length retreated at rates of 1.3-3.1 m/yr. The fastest erosion was observed at Cape Kharasavey (Figure 3, 1.8 m per year for 44 years) and at the 0.8-km section of the coast 2.5 km north of the Cape (Figure 2, 4), retreating at a rate of up to 3.1 m/yr.

The coastal cliff at Cape Kharasavey is composed by sands. During periods of the site development (1970-80s and 2000s),

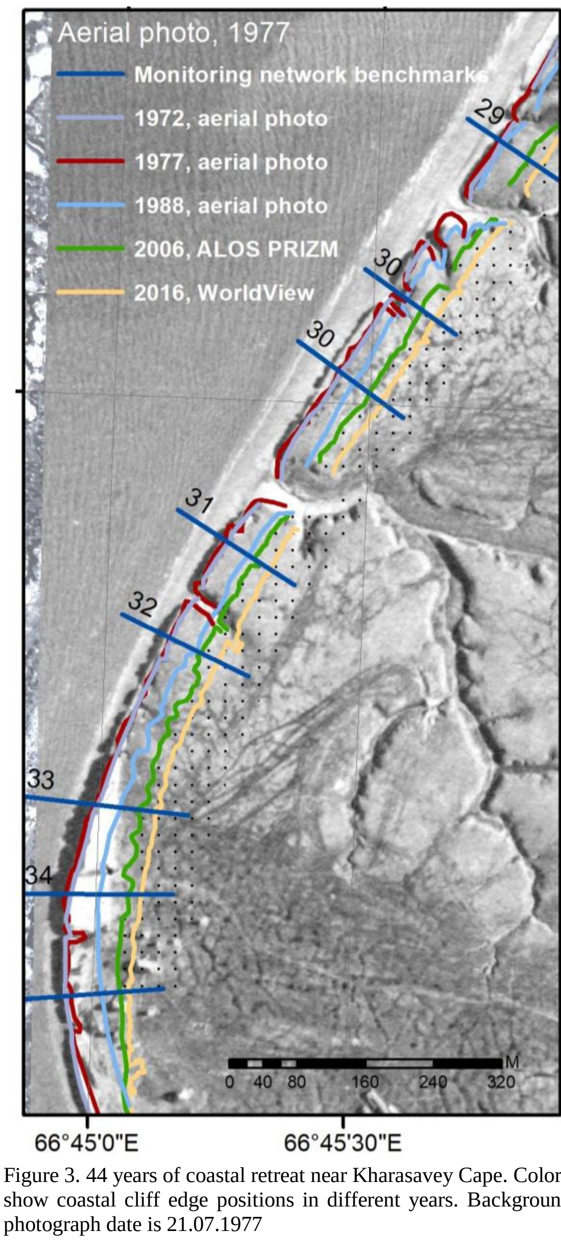

Figure 3. 44 years of coastal retreat near Kharasavey Cape. Colored lines show coastal cliff edge positions in different years. Background aerial photograph date is 21.07.1977

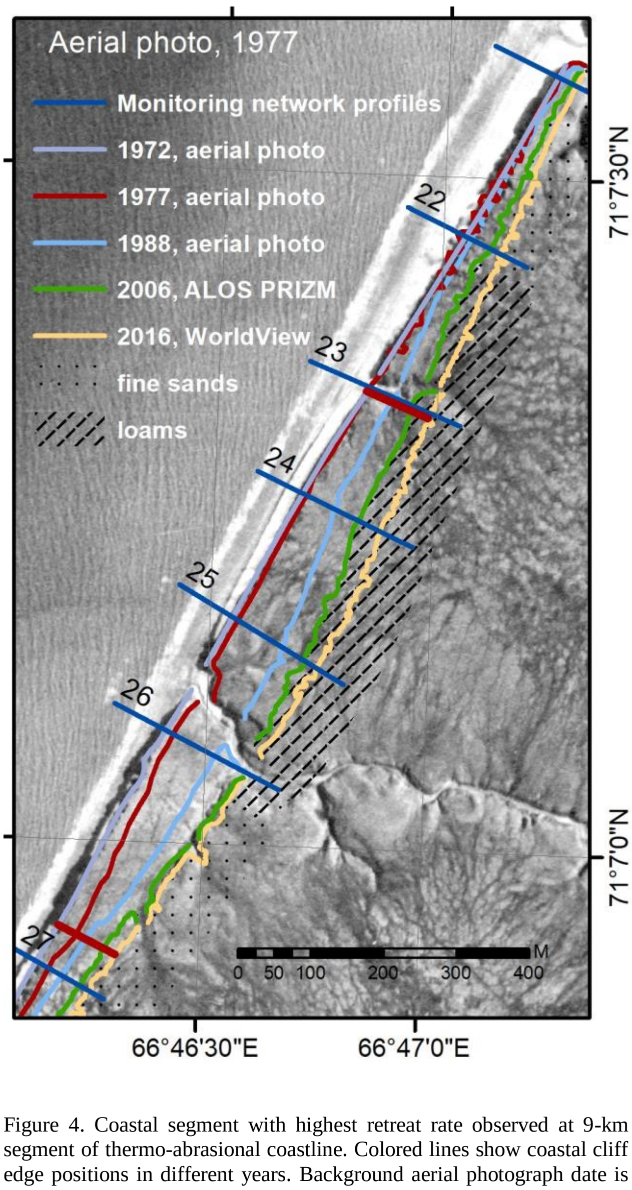

Figure 4. Coastal segment with highest retreat rate observed at 9-km segment of thermo-abrasional coastline. Colored lines show coastal cliff edge positions in different years. Background aerial photograph date is 21.07.1977

Table 2. *Retreat of a 6.8-km coastal segment north of Cape Kharasavey estimated from multi-temporal aerospace data*

Period	Duration, yrs.	Length of retreating segment	Weighted average retreat rate for 6.8 km of the coast, m/yr	Maximum rate, m/yr
1977-1988	11	3.3	1.3	6.5
1988-2006	18	5.3	0.9	2.3
2006-2016	10	6.8	1.2	3.7
1977-2016	39	6.8	1.1	3.2
1972-2016	44	6.8	1.1	3.1

Figure 5. Sand excavation near Cape Kharasavey. Photo by Belova N.G., 2008

Figure 6. Blocks of icy loams are quickly eroded by waves, 1976 (Here, at Kharasavey, 1978).

sand for construction has been removed from the beach and tidal flats (Figure 5).

The most intensively retreating 0.8-km long coastal segment is composed of icy heavy loams (Figure 2). Severe storms resulted in the formation of thermo-abrasional niches in the

Temporal Variability of Coastal Retreat

The strongest erosion rates at Cape Kharasavey were observed in the earliest analyzed period of 1977-1988 (See Table 2 and Figures 3, 4). Then, coastal retreat slowed down during the following 18-year period from 1988 to 2006, characterized by the lowest rates. Rates then again increased between 2006 and 2016, but did not reach the 1977-1988 level. Before our analyses starting point in 1977, the average coastal retreat rate between 1972-1977 was slow and below our accuracy threshold and has therefore not been included in the dataset.

DISCUSSION

The retreat rates in the Kharasavey area are close to the maximum values in the southwestern Kara Sea. Similar rates of up to 1.7 m/yr in 1978-2010 and up to 1.2 m/yr in 1964-2016 were documented near the Marresalya weather station on West Yamal (Vasiliev *et.al.*, 2006, 2011) and at the western junction of the subsea pipeline built from the Bovanenkovo field through the Baydaratskaya Bay (Novikova *et al.*, 2018), respectively.

In contrast to the mentioned sites, the coast of Kharasavey had the strongest retreat rates between 1977 and 1988, when the hydrometeorological load was relatively low, with neither elevated air temperatures nor a long ice-free period (see Belova *et al.*, 2018), in contrast to the period of 2006-2016, when both of these parameters dramatically rose (Shabanova *et al.*, 2018). Most likely, intense erosion in the 1970s-1980s was caused by human impact. The period of enhanced retreat coincides with the beginning of development, when construction of the settlement was in progress, and sediments were excavated from the littoral. Deficiency of sandy beach-forming material led to erosion of the adjacent shore segment composed by icy heavy loams, resulting in fast bluff retreat.

CONCLUSIONS

In the Kharasavey area, Western Yamal coast, local anthropogenic impact in the last four decades had a greater impact on the rate of coastal retreat than the variability in hydrometeorological parameters caused by climate change. Considering the current industrial development, sustainable solutions need to be found and applied to ensure reliable construction and safe operation of natural gas production facilities.

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