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USING MULTI-TEMPORAL AERIAL AND SPACE IMAGERY FOR COASTAL DYNAMICS INVESTIGATIONS AT KARA AND PECHORA SEAS, RUSSIAN ARCTIC

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ABSTRACT

The Arctic coasts are complex and actively changing systems, their erosion rates varying in time and space. Due to global warming and its thermal and wind-wave effects, there is a tendency of increase in coastal erosion rates. Understanding of the interaction between permafrost and sea is important to disclose the background of active development of natural resources in the Arctic coastal zone (construction of coastal facilities, offshore pipelines, etc). In the present study, coastal dynamics of the Western Russian Arctic coasts are studied, including Varandey (Pechora Sea), Ural and Yamal coasts near the underwater gas pipeline “Bovanenkovo-Ukhta” across Baydaratskaya Bay (Kara Sea). Kara Sea key-sites are characterized by continuous permafrost, with annual ground temperature of -4…-6 ºC and permafrost thickness of up to 50-100 m. Varandey key-site is located in the zone of sporadic permafrost. Estimations of coastal retreat rates were based on high resolution multitemporal space imagery analysis together with data of airborne surveys. All satellite images were orthorectified to decrease uncertainties. During fieldwork, DGPS mapping of some points with the constant position were made for accurate coastal erosion rates estimations. The study revealed that long-term (1960s-2010s) average annual retreat rates for coasts of different key-sites ranged from 0.5 to 2 m per year: at Varandey – 2.2 m/a; Ural coast of Baydaratskaya Bay – 2 m/a, and Yamal – 0.4 m/a. Coastal erosion rates were calculated for different time intervals, they depend on coastal morphology (cliff height, beach presence), slope exposure, permafrost features (sediment composition, ice content, etc). Studies on coastal dynamics and understanding their various aspects are very important for the attractive Arctic region under the conditions of climate change. The obtained results allow for a better understanding of coastal retreat processes and forecasting of Russian Arctic coastal dynamics in the future.

Keywords: coastal erosion, Russian Arctic, aerial and space imagery, permafrost

INTRODUCTION

Coastal erosion is influenced by a variety of environmental, climatic, geologic, biologic and anthropogenic factors (soils erodibility, fractures, adjacent bathymetry, cliff lithology, waves, wind, vegetation, etc). In addition, it depends on such factors as sea ice extension, permafrost thermal regime and cryostratigraphy of the area [4]. Arctic seas are covered by ice during about 9-10 month per year [3], [7]. During this period, sea ice protects coastal slopes from destruction. Frozen and thawed soils have different physical and mechanical properties, including erosion resistance. The presence of permafrost causes a lot of degradation processes, connected to thermal degradation of the soils, e.g. thermal abrasion, thermal denudation, thermokarst subsidence [1], [6].

Erosional processes induced by thawing permafrost are specific to Arctic region. Understanding of their drivers and development patterns is crucial to successful forecast of coastal degradation triggered by the current development of the northern territories, including construction of coastal facilities and offshore pipelines. The Arctic coasts are complex and actively changing systems. Rates of their erosion vary temporally and spatially. Due to global warming and its thermal and wind-wave effects, there is a tendency of increase in coastal erosion rates. Laboratory of Geoecology of the North of Geography Faculty of Lomonosov Moscow State University has been conducting monitoring of coastal dynamics at the key-sites of the Pechora and Kara seas since 1980s. By now, accumulated coastal dynamic data is enough to reveal impacts of different factors on coastal dynamics with a sufficient degree of confidence. The aim of this paper was to study coastal dynamics of the Western Russian Arctic coasts at the key sites and find out the influences of coastal morphology (cliff height, beach presence), slope exposure, permafrost features (sediment composition, ice content, etc) on erosion rates for different time periods.

SITES DESCRIPTION

To characterize coastal dynamics of the Western Russian Arctic coasts three key-sites were chosen (Figure 1) for investigation. Study area in the Pechora Sea is located on Pesyakov island near Varandey where Faculty of Geography of Lomonosov Moscow State University and N.N. Zubov's State Oceanographic Institute have been conducting research since 1980s. Ural and Yamal coasts near the underwater gas pipeline "Bovanenkovo-Ukhta" across Baydaratskaya Bay were investigated in the Kara Sea.

Territory of the investigation in Pechora Sea coast is situated on a barrier island with coastline 15 km long. This area is represented by beach with dune belt protecting laida (lowland surface flooded by tides). Varandey key-site is located in the zone of sporadic permafrost. Frequent layers of unfrozen highly saturated soil interbed the permafrost. Topsoil is represented by sand with water content values ranging from 20 to 38% [8]. Temperature regime varies between 0.3°C near shoreline and -1.9°C 500m inland [5]

Key site on the Ural coast is located on a 10-kilometer-long coastal segment between Torasavey and Levdiyev islands. To the northwest from Levdied, the laida continues to the pipeline. The pipeline is located on the high level surface with elevations 5.5-5 m above the beach and extension along the seashore 1.6 km. Further northwest surface starts to decline to transform into laida continuing 1.3 km along the sea coast with 1-2.5 m high berms. To northwest the laida surface level increases up 13-20 m elevation. Key site on the Yamal coast is located on a 15-kilometer-long coastal segment near the pipeline which is situated on the laida with coastal bar with 2 m elevation. To the north of the pipeline, the high surface levels have elevation 8-12 m, to the south – 22-28 m. [2]. Kara Sea key-sites are characterized by continuous permafrost, with annual ground temperature of -4…-6 ºC and permafrost thickness up to 50-100 m. Layers of unfrozen highly saturated soil also occur on the laida of Yamal coast. Interbedded silty clays, silts and silty sands compose coastal cliffs of the Baydaratskaya Bay coast.

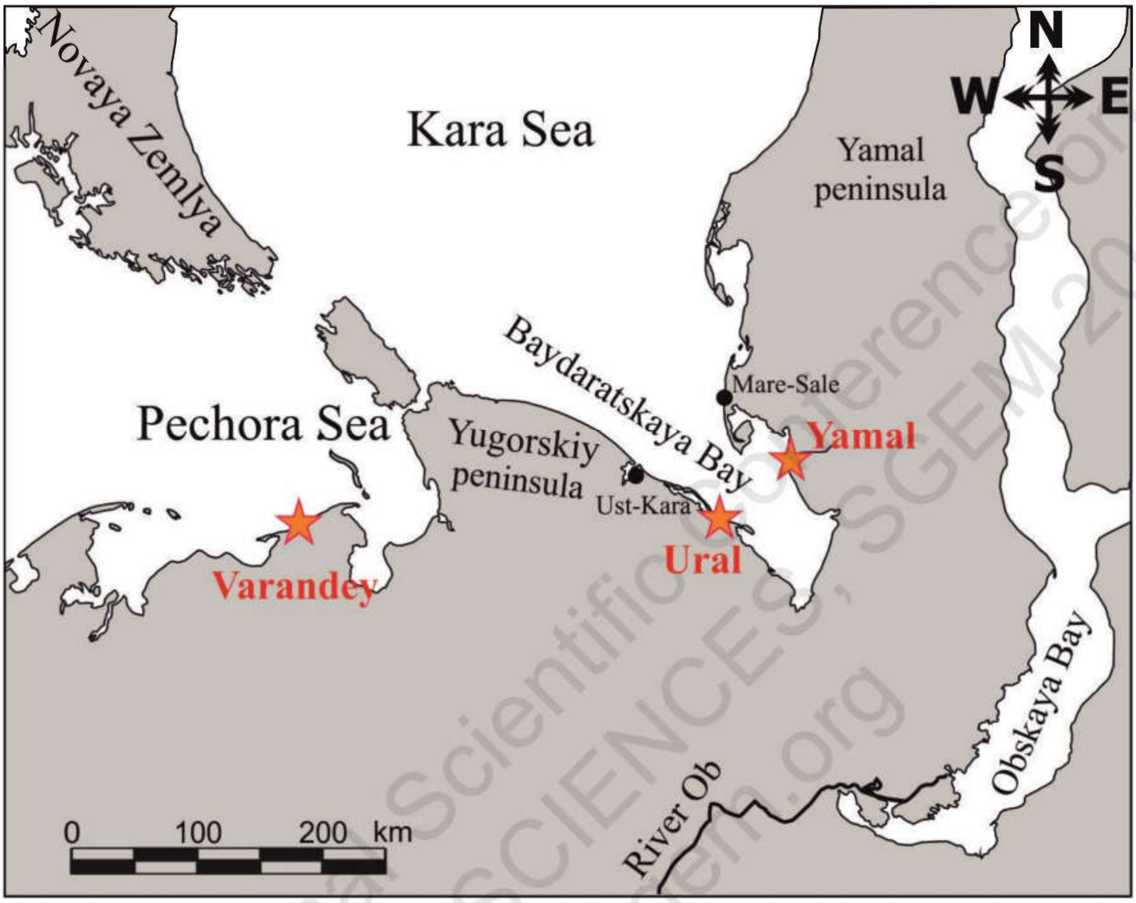

Figure 1. Study area (key sites are shown by red stars)

METHODOLOGY

Remote setting data

Archival remote sensing data is particularly important for investigation of coastal dynamics, since it allows analysing data over long-time period. For study area, the best and earliest available image is Corona from 1964 from United States Geological Survey with resolution 2-7 m. More recent images used in the coastal dynamics study were the aerial photographs obtained by the Geography Faculty in the late 1980s, which have resolution of 0.7 m. For short-term observation, ultra-high resolution images are needed. In our study we used QuickBird-2, WorldView-2 and WorldView-3 with a resolution of 0.7-0.3 m. These images were provided with reference files containing the satellite's orbit parameters, but the accuracy of georeference was not enough to analyse the annual variability of coastal dynamics. The images were georeferenced with ground control points, collected during the field work.

Geodetic surveys

In order to understand the coastal retreat in details, profiles perpendicular to the coastline were installed in the 1980-s. Currently, the coastal retreat is investigated by

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various geodetic methods, including survey of cliff-top and transverse profiles using the differential GPS (DGPS), as well as tachometric measurements along profiles perpendicular to the coastline. We used two-frequency satellite receivers Trimble (Trimble R8 GPS Receiver, Trimble tsc2 Controller, Trimble HPB450). Reference (base) station was installed, navigational data was collected and corrections using the known coordinates were performed. Together with the reference station, the Trimble HPB450 modem transmission equipment was installed, which broadcasted corrections in the CMR + format to a mobile satellite receiver, whose internal modem received the correction data. Using DGPS positioning in our conditions allowed estimating the accuracy of about 0.2 m both horizontally and vertically.

The operator moved close to the coastal edge and moved the receiver strictly above the cliff, then the track was recorded. When shooting profiles, the operator installed a mobile receiver on the profile benchmark selected on the terrain. The survey was performed in RTK mode (real time kinematic) and was carried out in the WGS 84 UTM42N coordinate system. Also, profile studies were conducted by tachometer Leica TCR802 power. Measurements were done on benchmark and on the distinctive relief points (coastal cliff position, position of coastline, beach berm, etc.), where repeated measurements were made in 10-15 cm increments for better accuracy.

In addition, during field work, high resolution images, available in the archive of Geography Faculty, were georeferenced at the control points. 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, etc.

Erosion rate estimations

Field work observations data and satellite imagery analysis were used for estimation of coastal retreat rates at the key-sites. Results 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 also to quantitatively estimate the coastal retreat rates at the different time periods. Interpretative schemes of cliff position for different time according to air and space images shows on the Figure 2 for Ural key-site.

For better understanding of the influence of morphology, lithological structure and permafrost features on coastal dynamics at the each key-site, study area was covered by virtual normal profile to shoreline with 10 m step. After that coastline classification was created according to selected factors and erosion rate was estimated. Based on obtained results and data from DGPS mapping we tried to estimate the volumes of removed sediments for each morphological segment of the coast composed by different soils and cryological structures.

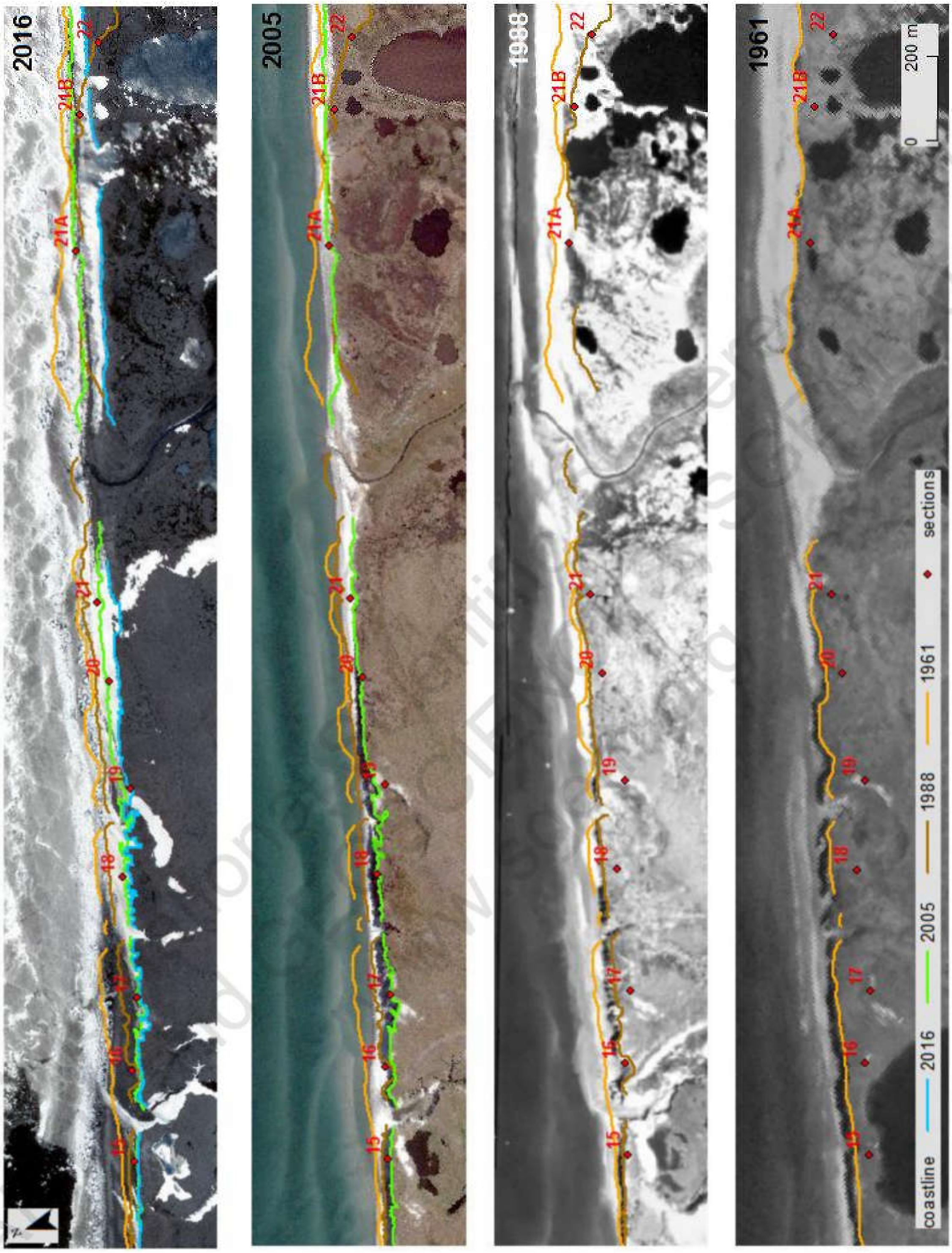

Figure 2. Interpretative scheme of coastal dynamics for the Ural coast of the Baydaratskaya Bay, Kara Sea (from left to right): WordView 2 image (2016); QuickBird image (2005); aerial photo (198); Corona KH-4A satellite image (1964). 18 - number of benchmarks of the coastal dynamics monitoring network

RESULTS AND DISCUSION

The study revealed that long-term (1960s-2010s) average annual retreat rates for coasts of different key-sites ranged from 0.5 to 2 m per year: at Varandey – 2.2 m/a; at; Ural coast of Baydaratskaya Bay – 2 m/a, and Yamal – 0.4 m/a.

We present the data and its analysis for Ural coast in detail, because it was the most representative key site including a lot of geomorphological levels composed by different soils type with varied cryogenic structure.

Based on obtained data it was established that bluff retreat was very irregular for different coast segments. It corresponded to the features of geocryological structures of the coast. Coastal erosion rates varied from 0.5 to 4 m/year for different time periods. We estimated the coastal erosion rates between 2005 and 2015 at the different geomorphological levels. South-eastern part of the Ural coast situated on low laida which affected by sea tide and accumulation of sand on the surface, therefore it was not possible to analyze the dynamics from remote data. At the center part of the study area of the Ural coast average erosion rates between 2012 and 2015 were estimated as 2-4 m/year for the high surface, 1.2-1.4 m/year for laida and 2.5-4 m/year for the low terrace. Obtained data on erosion rates for different periods demonstrated the slowing of coast destruction. Average erosion rates for time interval 2012-2015 were slightly lower than average erosion rates between 2005 and 2015. Ogorodov et.al [9] also reported two periods: from 2005 to 2012, when thermoabrasion increased; and from 2012 to 2016, when a decrease in coastal erosion was observed.

The present analysis of coastal bluff retreat showed a relationship between the erosion rates and the average elevation of each coastal segments (Figure 3). The figure demonstrates that the maximum of coastal erosion rates was observed on laida. It could be explained by the prevailing wave factor in long-term period.

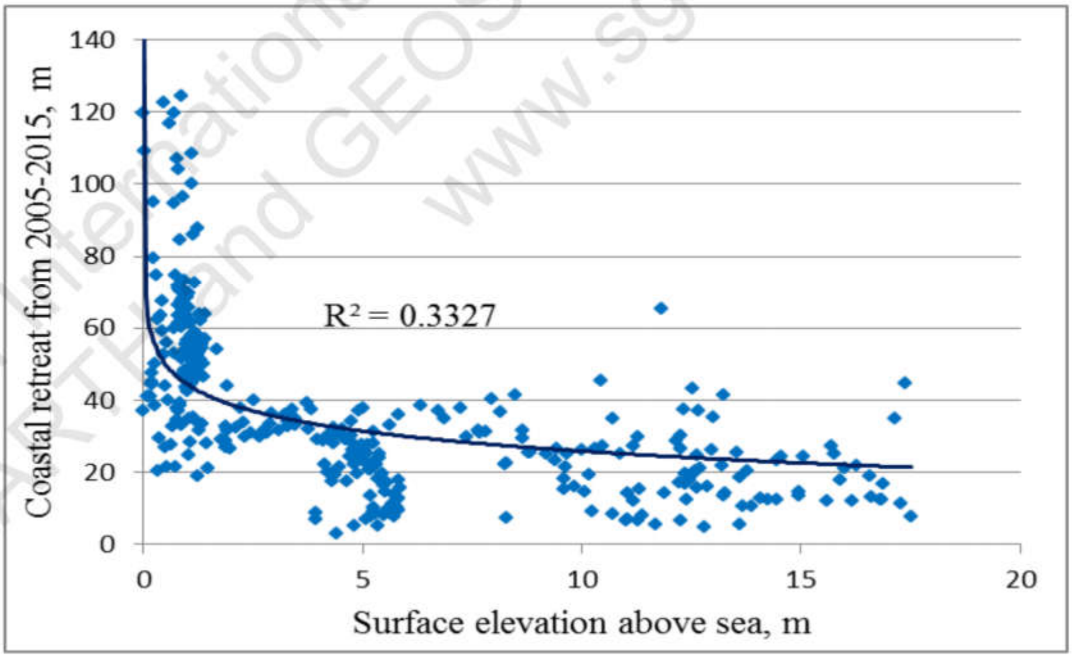

Figure 3. Coastal cliff retreat versus surface elevation

Volumes of eroded and removed sediments were calculated for 2005-2015 period (Figure 4). The maximum volume of sediment removed was noted for the high level. The peaks observed on the plot, especially on the high surface, could be related with a massive ice or ice wedges, which were recognized during field studies 2012.

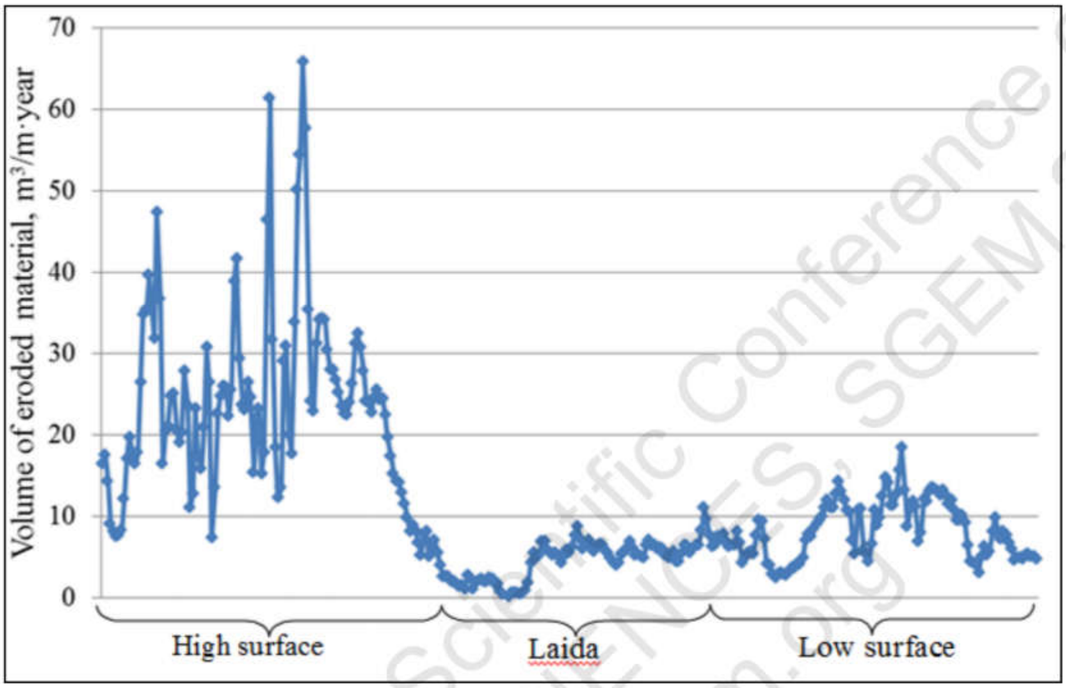

Figure 4. Annual volume of removel material for different coastal segment

CONCLUSION

Coastal dynamics in the Western sector of Russian Arctic was described for three key areas: Varandey settlement (Pechora Sea), sections on Ural and Yamal coasts, where underwater gas pipeline "Bovanenkovo-Ukhta" rises on land (Kara Sea). It was established that sections of low terrace and laida (high water surge berm), sections composed by icy fine-dispersed sediments, sections with outcrops of massive ground ice generally experience a faster retreat.

The method of coastal dynamic monitoring was tested on the key-sites of the Western sector of Russian Arctic according to analysis of the multi-temporal remote sensing data (Corona KH-4 of 1960-1970s and ultra-high resolution QuickBird, WorldView 2000-2010s space imagery and aerial imagery of 1980s). Successful application of different aerial and space materials has great perspectives for studying Arctic coastal dynamics and allowed providing considerable amount of data. However, as showed in this paper, remote sensing data alone is insufficient. For understanding and thoroughly estimation of impacts of geomorphology, lithology and permafrost conditions on coastal erosion rates, remote sensing data must be accompanied with complete field observation data, obtained by modern and accurate methods.

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