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Coastal Dynamics, Permafrost, and Lithology of the Sharapov Shar Bay Shores, Kara Sea

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ABSTRACT

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The Arctic coast is a very sensitive system due to the interaction of the sea with the frozen coast under ongoing climate change. Our investigations were carried out within the northwestern part of the Yamal peninsula (Russia), Kara Sea. This region features continuous permafrost with annual ground temperatures ranging from -1.5°C to -6°C. Five key sites were selected for investigation. Four of them are located on the laida (low surface up to 1-2 m above the sea) with a high bluff (terrace) at a longer distance from the sea. Coastal dynamics for these four key areas were different. The northern site is stable, and no retreat was observed on either the laida or the terrace. Similar rates of retreat of about 0.4-0.6 m/year at sections of different height composed by sandy loams at key sites 2-5 reveal the significance of sediment composition as one of the factors of coastal erosion. A comparison of all the obtained coastal retreat rates shows that the presence of massive ice contributes to more rapid coastal destruction. In recent years, some areas of Sharapov Shar coast were unstable, although historical data shows their previously stable state, implying recent activation of coastal processes.

ADDITIONAL INDEX WORDS: *Coastal dynamics, massive ice, Kara Sea, erosion rates.*

INTRODUCTION

The Arctic region is particularly vulnerable to environmental changes, especially global warming (Nielsen *et al.,* 2022). Understanding the processes occurring in this unique ecosystem requires investigating the permafrost coasts (Martini *et al.,* 2019). The interaction of the atmosphere, sea, and terrain in the Arctic is complicated by the presence of permafrost, which composes coastal slopes and is sensitive to environmental changes. Arctic coasts form a multicomponent dynamic system, with stability dependent on several factors. The main factors affecting Arctic coastal destruction can be categorized into climatic, hydrodynamic, morphological, geological, and permafrost conditions. Climatic and hydrodynamic factors include air temperature and wave energy.

Climate change in the Arctic is progressing much faster than elsewhere, significantly impacting the sea ice regime, which covers the Arctic seas for 9-10 months per year (Dubikov *et al.*, 1997; Jones *et al*., 2009). Sea ice protects coastal bluffs from destruction and plays a critical role in coastal dynamics (Are, 2012; Ogorodov, 2013), but currently, ice-free period duration is increasing (Shabanov *et.al.,* 2024). During periods with positive air temperatures permafrost in coastal cliffs triggers erosion processes on high cliffs. The reduction of sea ice leads to the mechanical destruction of low coastal ledges by waves.

The features of the coastal zone, including lithology, morphology, and permafrost conditions, determine the resistance of the coast to erosion. This study focuses on permafrost unlithified coast in the Sharapov Shar Bay with different coastal types. The influence of geomorphological, lithological, and permafrost features on erosion patterns and rates is assessed, particularly considering grain size distribution and ice content impact on cliff morphology and erosion mechanisms.

Background

Coastal dynamics in various parts of the Kara Sea (Vasiliev *et.al.,* 2006) are systematically monitored due to the region's significant oil and gas industry development (Novikova *et.al*, 2018; Kazhukalo *et.al*., 2023). This monitoring is essential to understanding the impact of industrial activities and environmental changes on coastal erosion (Ogorodov *et.al*, 2023), sediment transport, and overall coastal stability.

Five key sites were selected within the coast of the Sharapov Shar Bay (Yamal peninsula, Russia) for the investigation of coastal dynamics, as illustrated in Figure 1. All study area is situated in the continuous permafrost zone with annual ground temperatures of -1.5...-6°C. The permafrost thickness ranges from 50-100 to 200-300 m. Closed and open taliks form under lakes and rivers (Badu *et.al.*, 2013). Frozen saline soils are widely distributed along the western Russian Arctic coast

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(Aleksyutina *et.al*., 2020), the cryopegs also occur (Dubikov *et al.*, 1997).

The study area features several geomorphological levels, including terraces (coastal plains), laida (flood plains), and beaches. The height of the coastal plain ranges from 5 to 8 meters in the northern part of the studied coastline and increases to 12-22 meters in the southern part. Laida is a low-lying coastal area in the northern and central parts of the studied coastline, typically 1-2 meters above sea level. Laida is often covered with tundra vegetation. It is subject to periodic inundation caused by storm surges. These coasts feature flat surfaces composed of fine-grained sediments such as sand, silt, and clay with peat layers (Romanenko *et al.*, 2014). Laida can extend several kilometers inland from the main shoreline (*Atlas*.., 2020).

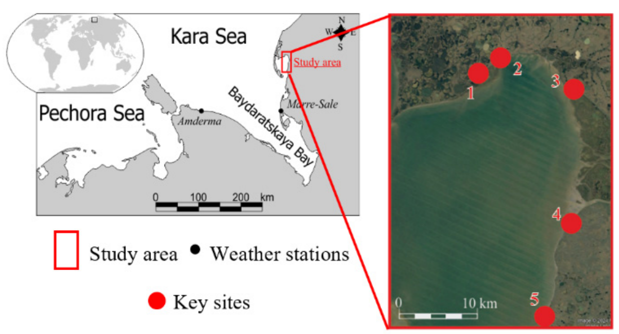

Figure 1. Study area location.

METHODS

The investigation of coastal dynamics included interpretation of satellite images obtained over various years. For our study area, the earliest available image was Corona satellite imagery from 1964, provided by the United States Geological Survey, with a resolution of up to 2.8 meters. Ultra-high-resolution images from WorldView-2, taken in 2010 with resolutions of 0.5 meters, were also employed. Additionally, to assess the dynamics of the coast, images obtained from a UAV in 2022 with a resolution of 0.1-0.3 meters were used. Key areas were surveyed using the Phantom 4 Pro, covering varying lengths along the coastline (see Table 1).

Table 1. *Length of the key site along the coastline.*

Key site	Segment lengths, meter
1	235
2	245
3	1590
4	1100
5	1330

Working with remote sensing data involves specific nuances and challenges. For instance, the 2010 satellite images were accompanied by reference files containing satellite orbit parameters. That is why both Corona and UAV images were georeferenced to the 2010 WorldView-2 images. However, in areas without significant human development, achieving absolute georeferencing is challenging due to the lack of spatially stable objects. Consequently, it is often necessary to use conditionally stable objects, such as the contours of lakes, which vary seasonally in water levels and outlines. This issue was mitigated by referencing a large number of control points. Unfortunately, the Corona satellite imagery was not suitable for three northern key areas, so the position of the coastline for these areas was determined for the period 2010-2022.

The estimation of coastal retreat rates at the key sites was conducted using satellite and UAV image analysis. The results were processed using ArcGIS 10.4 software and the Digital Shoreline Analysis System (DSAS), with transects placed every 10 meters. We estimated the position of terrace's bluff and laida ledge.

Lithological features and the permafrost structure were studied both at the outcrops and through laboratory tests. Key soil parameters, such as ice content and density were determined using commonly accepted standard methods. We aimed to analyze coastal retreat in zones both with and without massive ground ice.

RESULTS AND DISCUSSION

Lithological Features and Permafrost

On key sites 1-4, the laida exhibits varying widths, ranging from 450-400 meters at sites 1 and 4 to 70-20 meters at sites 2 and 3. The low laida features numerous channels and lakes, while the high laida has occasional thermokarst depressions. The laida is composed of sandy loam with peat layers (Figure 2). Due to the presence of organic material, the water content in the top sediments reaches 50-70%, and the ice content is 35-40% when ground frozen. Ice wedge polygons are widely developed on the terrace at key site 3.

The depth of seasonal thawing varies on different geomorphological levels. The thawing depth exceeds 1.4 meters at the low laida, while at the high laida, it ranges from 0.8 to 1.2 meters. On the terrace, the seasonal thawing thickness varies between 0.4 and 0.9 meters. The greatest depth is associated with microrelief depressions, where increased snow accumulation occurs (Bogatova et.al., 2021).

Figure 2. Low laida composed of sandy loams with a peat layers:
1 – view; 2 – sampling from the section.

There is no laida on the key site 5. This area is characterized by the greatest diversity of permafrost structures and lithological compositions of the sediments that form the coast. The sediment composition varies across the site 5 (Figure 3).

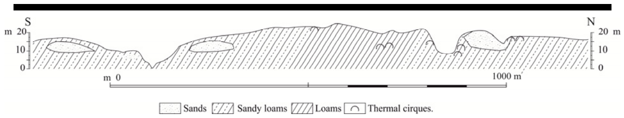

Figure 3. Lithological features on the key site 5.

In the southern part, the bluffs are composed of sandy loams with interlayers of loams, and in some places, sand lenses up to 2-3 meters thick and several meters to several tens of meters in length. In the central part of the study area, the shores are composed of loamy soils, which contain massive ice deposits. The northernmost part is also composed by loamy sediments with massive ice, the thawing of which creates unique relief forms known as thermocirques (Figure 4). A total of eight thermocirques were noted on the slope of the terrace in the study key site. Most of the thermocirques have a well-like shape with a narrow channel for the outflow of thawed thixotropic sediment, primarily composed of loamy material. The removed material from the larger thermocirques forms debris fans, which extend into the sea for a few tens of meters. The top of the massive ice lies at varying depths based on the location of the thermocirques. There were two series of massive ice beds in Amderma, which melting forming thermocirques (Kizyakov *et.al.,* 2006). The size of cirques ranges from 8 to 172 m. Baranskaya *et.al.* (2021) documented thermocirques with diameters ranging from 10-20 meters up to 100-150 meters in summer 2016.

Figure 4. Two thermocirques are present at the site 5, one massive ground ice (white color) is seen.

Coastal Dynamics

Image resolutions and georeferencing accuracy do not allow evaluating coastal dynamics at the key site 1. We think that the stability of the laida shoreline is due to the protection offered by a cape to the southwest. The considerable width of the laida, which extends up to 450 meters, shields the terrace from strong surges and storms. The completely overgrown slope of the terrace indicates this. The terrace of key site 2 is also stable from 2010 to 2022, however, the retreat rate of laida in some places can reach 1 m/year, with average values of 0.2-0.4 m/year (Figure 5).

The opposite behavior is observed in key site 3, where the laida position is stable, but erosion processes are noted on the terrace slope, as evidenced by the devoid of vegetation slope. Most likely, this is due to the thermal erosion activity of meltwater or rapid solifluction, which carries out the material, or perhaps this is due to the sea activity when the abrasion of the lower part of the slope. The erosion rate for this key site varies from 0.1 to 1.1 m/year with a median value 0.65 m/year (Figure 6). The normal distribution of coast retreat rates indicates the homogeneity of factors (the same lithological composition and permafrost structure, the same impact of waves on the lower part of the scarp, etc.).

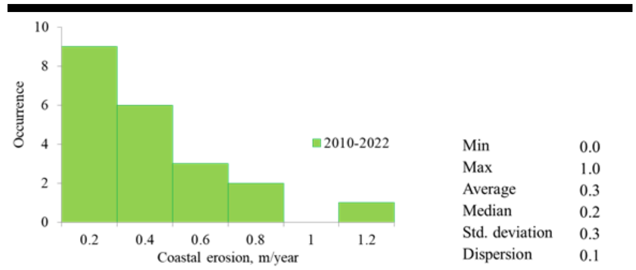

Figure 5. The distribution of laida retreat rates for key site 2.

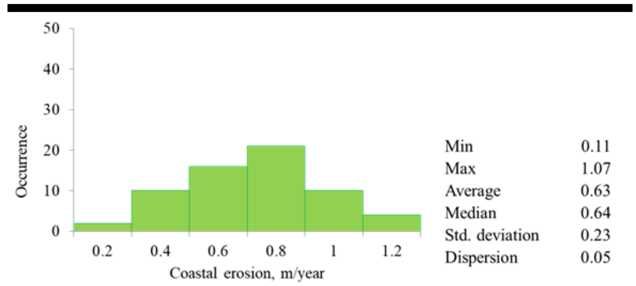

Figure 6. The distribution of coastal bluff retreat rates for key site 3 from 2010 to 2022

The retreat rate of laida on key site 4 ranges from 0.1 to 0.65-1.45 m/year for different periods (Figure 7). The average long-term (over 46 years) coastal erosion rates are comparable with the last decade's rates (from 2010 to 2022). At the same time, for the period 1964-2010, about 70% of the coastline did not change its position, only a 300 m long section. Perhaps this is due to the low resolution of Corona images. Erosion rates for 2010-2022 occurred along the entire length of the considered coastline, i.e. evenly in plan.

The obtained values are significantly lower than those recorded for the laida and accumulative shores of the Yamal Peninsula (Ogorodov *et al.,* 2016; Romanenko *et al.,* 2014). This discrepancy is likely due to the absence of industrial development in the study area, which means there is less anthropogenic impact compared to other regions of the Yamal Peninsula. Industrial activities, such as oil and gas exploration, often accelerate coastal erosion (Belova *et.al.,* 2023) through increased human presence, construction, and associated environmental disturbances. In contrast, the lack of such activities in the current study area has likely contributed to the relatively lower erosion rates observed, allowing natural processes to dominate without significant interference.

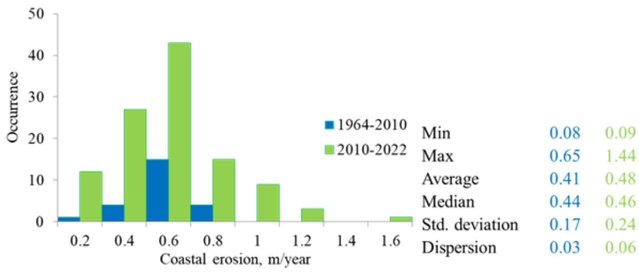

Figure 7. The distribution of laida retreat rates for key site 4.

The highest rates of cliff destruction were observed at key site 5. The rate of coastal retreat varies from 0.2 to 4-6 m/year, with the most common values being 0.4-0.8 m/year (Figure 8).

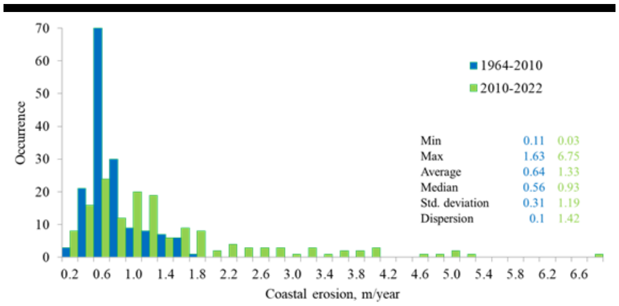

Figure 8. The distribution of coastal bluff retreat rates for key site 5.

The rate of coastal retreat for areas composed of sandy and sandy loam soils without massive ice is significantly lower compared to area with ground ice (Figure 9). The higher rates of coastal erosion observed during shorter-term are associated with thawing of massive ice beds (Belova, 2018; Kizyakov, 2005).

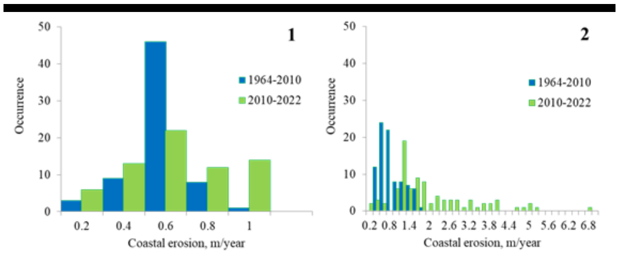

Figure 9. The distribution of coastal bluff retreat rates: 1 – without massive ice; 2 – with massive ice

In our study from 2010 to 2022, the average retreat rates were between 1.5 and 2 meters per year, with the most frequent rates ranges between 1.2 and 1.8 meters per year. In contrast, during the period from 1964 to 2010, the retreat rates ranged from 0.4 to 0.8 meters per year, with average values around 0.65 to 0.8 meters per year.

Over the long-term period of 46 years, the average rate of coastal cliff retreat is lower compared to the more recent period from 2010 to 2022. Specifically, in areas without massive ground ice, the retreat rates are nearly identical, approximately 0.5 to 0.55 meters per year. However, in areas with ground ice, the retreat rates differ significantly, by two times or more. This discrepancy is likely due to the reduced presence of ice in sections destroyed earlier and the limitations in the accuracy of the Corona images, which have lower resolution and less georeference.

Additionally, our analysis of remote sensing data indicated that the thawing of ground ice and the formation of thermocirques is not directly dependent on the cliff position. It means for a thermocirque to develop some time is required after the coastal bluff retreat.

CONCLUSIONS

Each study site is characterized by unique permafrost structures, distinct morphological features, and varied lithological compositions of the soils that form the coastal ledges. These variations influence the dynamics and stability of the coastal regions. The permafrost at each site has different characteristics, such as the thickness of the active layer (the surface layer that thaws in summer) and the presence and distribution of ground ice. These factors significantly affect the thermal stability and erosion rates of the coastal areas. The coastal morphology varies from site to site, including differences in elevation, slope gradient, and the presence of features like laida (low surfaces) and marine terraces. These morphological distinctions impact how each site responds to environmental forces like wave action and thermal erosion.The soil composition at each site includes varying proportions of materials such as sands, silts, loams, peat, and interbedded sediments. The lithology determines the erodibility and mechanical stability of the coastal ledges, with some soils being more prone to erosion than others.

For example, the northern site remains stable with no observed retreat, likely due to its specific morphology protected by a cape in the southwest. In contrast, key site 4, with its sandy loamy soils interbedded with peat, shows active retreat due to abrasion. Key site 5 is characterized by intense erosion due to complex cryogenic structure and lithology, including significant ground ice presence.

These site-specific characteristics illustrate the diverse and dynamic nature of Arctic coastal systems, emphasizing the importance of tailored approaches to studying and managing coastal erosion in these sensitive regions.

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