GROUND ICE AND ITS' INFLUENCE ON COASTAL EROSION OF KARA SEA REGION, RUSSIAN ARCTIC

Dr. Nataliya Belova\textsuperscript{1,2,3}

\textsuperscript{1} Lomonosov Moscow State University, Faculty of Geography, Russia
\textsuperscript{2} Earth Cryosphere Institute, Tyumen Scientific Centre SB RAS, Russia
\textsuperscript{3} University of Tyumen, Russia

ABSTRACT

This work aimed to define when high ice content in permafrost sediments becomes a leading factor of coastal dynamics of Kara Sea region and to determine the place of this parameter among other factors of coastal retreat. For three key sections of the Kara Sea coast (Kharasavey Cape, sites of underwater pipeline crossing of the Baydaratskaya Bay coasts), spatial variability of ground ice distribution was investigated in the field. Changes in ice content and the presence of massive ice (wedge ice, massive ice beds – a characteristic feature of the region) were studied. Studied coastal sections are also key sites of long-term field monitoring of coastal dynamics, conducted by the Faculty of Geography, Lomonosov Moscow State University since the 1980s. The average annual retreat rates were obtained based on field data and analysis of multitemporal aerospace imagery (from the 1960s till now). At the local level, the presence of ground ice leads to retreat rates about 2 times higher compared to adjacent coastal segments. The greatest retreat rates of ice-rich coasts (2-3 meters per year) were observed in years with a higher sum of positive air temperatures for Kharasavey Cape, west coast of Baydaratskaya Bay, Spindler Cape, Marre-Sale polar station. Climate warming observed in the Arctic is likely to affect primarily ice-rich coasts due to thermal denudation process development leading to their higher retreat rates. The role of ground ice in arctic coasts’ dynamics should be assessed only on a local scale. On a regional scale, the contribution of the ice content on coastal retreat rates is offset by the joint action of both hydrometeorological factors of coastal dynamics and features of the coastal structure.

Keywords: arctic coastal dynamics, thermal erosion, thermal denudation, ground ice, West Siberia

INTRODUCTION

Mainland coasts of the the Kara Sea are represented by retreating, accumulative and stable rocky coasts. Retreating coasts are composed of permafrost sediments and degrade with average annual rate 0.5 to 2 m per year [1-3]. As in other Arctic regions, retreat rates of permafrost coasts vary both spatially and temporally. This variability is determined by hydrometeorological factors, coastal morphology and permafrost features of coastal sediments. In particular, one of the important factors of coastal dynamics is massive ice bed occurrence, a distinctive feature of the region. An article aims to determine the ground ice contribution to the spatial and temporal variability of the coast retreat rates.
Factors determining coastal retreat rates variability

There is no agreement on the factors determining high retreat rates of eroding coasts among researchers. It is found that the dynamics of permafrost coasts is defined by a combination of the hydrometeorological factors (air temperature, sea wave activity, sea ice conditions, etc.) and parameters coastal structure (shoreline configuration, seabed morphology, bluff height, sediment type, permafrost parameters, etc.) [1-7]. However, researchers attribute different factors (or even different mechanisms of action of the same factor) to a decisive role in the coastal dynamics [8]. A.A. Vasiliev comes to the conclusion that for the shallow-water Kara Sea coastal retreat is determined by waves up to 1 m high, while and coastal destruction due to storms, as a rule, does not exceed 20% [1]. At the same time, S.A. Ogorodov with co-authors [3] indicate the leading role of storms in the destruction of the coasts of this region. It is suggested that the significance of each factor cannot be uniquely determined, but only taking into account the specific natural conditions of the study area [8].

By F.E. Are, the retreat of the above-water part of the coastal zone is a consequence of the development of the underwater coastal slope [4]. Thus, coastal dynamics is determined by the morphology of the underwater coastal slope and by wave activity, while sediment type and permafrost composition are secondary. However, under favourable conditions coastal sediments features determine the maximum retreat rates.

Ground ice is distributed extremely uneven in the permafrost zone; the spatial distribution of various types of ground ice is determined by the natural environment history of the region, including the permafrost formation conditions.

Contribution of ground ice to the rates of retreat is also uneven and is determined not only by the total ice content or the shape of ice bodies exposed in coastal bluffs [9], but primarily by a combination with other factors of coastal dynamics, especially with the thermal factor and features of the structure of the coastal zone.

Ground ice as a factor of coastal dynamics at the regional scale

Researchers attempted to establish a correlation directly between the rates of retreat and the ice content of the coastal bluffs, it was assumed that the presence of ground ice would lead to an increase in the rates of retreat. However, for the Canadian coast of the Beaufort Sea, the rates calculated from the results of field monitoring and analysis of airphotos poorly correlated with the ice content of the sediments [10].

Based on the data collected within the framework of the Arctic Coastal Dynamics (ACD) international project, the researchers attempted to find a relationship between ice content and retreat rates for the entire Arctic coast [11]. From the 1,331 segments of the ACD database, 545 segments were selected for analysis. For each of them there were data on the rates of retreat, ice content and bluff height. Segments, whose bluffs are closed from wave action by pack ice, were also excluded from the calculations. Ground ice content and retreat rates are only weakly correlated statistically (r = 0.48, relationship statistically significant at $\alpha = 0.01$).

In the above-mentioned studies, the coasts extremely heterogeneous in terms of geological structure and hydrometeorological conditions were analyzed. The
relationship between the ground ice content and the rates of coastal retreat can be traced on a larger scale – under equal hydrometeorological conditions.

Another reason of weak correlation between ground ice content and retreat rates at regional scale is difficulties of proper assessment of volumetric ground ice content. This task is practically impossible without many years of field research combined with geophysical studies and drilling [9]. Modern models for assessing the ice content in coastal bluffs on a regional scale are based primarily on data on the genetic types of sediments and ground ice [12].

METHODS

Six key sections were chosen for consideration at the south-western coast of the Kara Sea (Fig.1). At most of them long-term observations of coastal dynamics were conducted and a considerable amount of data on coastal morphology, sediment composition and ice content is available. This makes it possible to consider estimates of ground ice types distribution and volumetric ice content to be reliable.

![Figure 1. Research area. GK – Gulf of Kruzenshtern](https://doi.org/10.5593/sgem2018/1.1)

For coastal retreat rate determination both remote methods (analysis of aerial and satellite multitemporal imagery) and results of field work were used.
RESULTS

Ground ice and local variability of coastal retreat rates

“Local variability of retreat rates” here is the unevenness of the rate of coastal destruction in coastal areas within a single lithodynamic region with a similar wave load on the coast. Sections with an extent of up to 45 km are considered. Erosional coasts make up less than 20% of the entire length of the Kara Sea coast [1], accumulative (depositional, receding and stable, >40%), rocky (30%) and icy coasts (2%) are also common. On the mainland, changes in erosional coasts are most pronounced. The characteristic rate of erosional coasts’ retreat at open coastlines of the Kara Sea varies from 0.8 to 2.0 m/year. The shorelines of narrow bays (the Ob Bay, the Yenisei Bay, etc.) are retreating at a much lower rate, from 0.2 to 0.7 m/year [1].

Shpindler, center of Yugorsky Peninsula coast

Kizyakov A.I. with co-authors have established that the interannual variability of the thermocircus growth rates at massive ice bed exposure near Spindler site on the Yugorsky Peninsula coast is determined by the difference in the annual sums of positive air temperatures [5]. The average annual growth rate of thermocircuses was only 0.6-1.0 m/year for the period 1947-2001, which is three or even more times smaller than the average rates of 1.6-4.2 m/year in 2001-2004, Stabilization periods associated with temporary burial of ice took place during the development of thermocircus from 1947 to 2001 [5].

Kharasavey Cape, Western Yamal Peninsula

On the coast of Western Yamal between the capes Kharasavey and Buruny (see Fig. 1) the coastal dynamics monitoring is conducted by the staff of the laboratory of Geocology of the North (NILGES), Faculty of Geography, MSU, since 1981. Based on the results of field observations and multitemporal satellite imagery analysis [13], it was found that on the 7-kilometer stretch of erosional coast the mean rate of retreat for 1964-2016 was 1.1 m/year. At the same time, the maximum mean annual velocities (> 2 m/year) were observed at the site where the bluff is composed of ice-rich fine sediments (marine loams). The average weighted long-term retreat of this 600-meter segment was 1.8 m/year in 1964-2006 and 2.7 m/year in 2006-2016, which is probably due to an increase in the amount thawing index in 2006-2016 in comparison with the period of 1964-2006. As in the area of Cape Spindler, the thermal factor affects the interannual variability of coastal rates at ice-rich coastal segments.

Marre-Sale weather station

Since 1978, coastal dynamics investigations are conducted near the Marre-Sale weather station [1]. Here the maximum averaged annual retreat rate of 4.5-km section was observed; the bluffs 10-30 m in height retreated at the maximum for the Western Yamal rate of 1.7 m / year [1]. The presence of massive and wedge ice affects the rate of thermal denudation and the rate coastal retreat as a whole: with an increase in volumetric ice content of the sediments from 25 to 45%, the total retreat of the upper edge of the coast has increased approximately in 2 times in 1978-2002 [1].

Ural coast of Baydaratskaya Bay, Ouyachya River mouth (CS-2 Yarynskaya)

Coastal erosion monitoring the between Torasovay and Levdiyev islands (30 km) was started by the staff of NILGES in 1988. In different years, the study of coastal dynamics
involved the staff of NILGES, N.N. Zubov State Oceanographic Institute (SOI) and Faculty of Geology of Moscow State University [14].

Several geomorphological levels are presented at the area:

- a surface 10-29 m high composed by sandy strata with massive ice beds and ice wedges, which has been significantly lowered by the thermokarst of several generations;
- surface 6-10 m high composed by sands with ice wedges and loams at the base;
- laidas of 1.5-3 m high, composed of ice-rich loams with ice wedges, covered from the surface by dense sod;
- low laidas (up to 1.5 m high), composed of loamy-sandy deposits with plant detritus.

Based on the analysis of multitemporal aerial and satellite imagery the period of intensification of coastal destruction was singled out – from 2005 to 2012.

The growth of maximum retreat rates occurred primarily due to the destruction of laida and bluffs up to 10 m height. At both of these segments ground ice content is quite high due to the ice wedges network (> 50% volumetric ice content for laida and 30-40% for bluffs up to 10 m high). At laida, fine sediments and high ice content facilitate the erosion of low bluffs. Thermoerosion gullies are formed along the ice wedge on the surface 6-10 m high, which contribute to the growth of the coastal retreat rates.

The segments of sandy bluffs 12-27 m height retreat with highest rates at sections with massive ice beds exposures (mean annual rate 2 m per year) due to thermocirques formation.

**Yamal coast of Baydaratskaya Bay, Yarayacha River mouth (CS-1 Baydaratskaya)**

Key site is characterized by low retreat rates (0.3-0.7 m per year) first of all due to the low ice content of sandy bluffs 7-25 m height. Local increase in retreat rates is due to anthropogenic impact.

The coast for 14 km to the south of Cape Mutny includes both erosional and accumulative types of coasts [14]. The rates of retreat are determined on the basis of the analysis of multitemporal satellite imagery analysis, as well as the results of joint field research conducted by the staff of the NILGES and SOI. Unlike the Ural coast of the Baydaratskaya Bay, sandy bluffs of 7-25 m high have less volumetric ice content (20-40%). Erosional coasts are developed in the northern and southern parts of the investigated coast, they are separated by accumulative barrier. Retreat rates increased in 2005-2016 compared to 1968-2005 (in ~2 times in the southern part and in 4.5 times in the northern part). The average weighted rate along the coast is 0.4 m per year for 48 years, under such low retreat rates it is difficult to single out the influence of individual factors of coastal dynamics.

**Gulf of Kruzenshtern**

The coasts of shallow Gulf of Kruzenshtern at Western Yamal Peninsula (see Fig.1) are partly protected by Sharapovy Koshki Islands from high waves generated at Kara Sea. For a 45-kilometer coastline, based on space images analysis, the coast retreat rates were determined [15]. Bluffs of 20-35 m in height retreat at an average annual rate of 0.6 m/year (1967-2010), but the rates of up to 1.6 m/year were observed at the sections with massive ice beds occurrence.
CONCLUSION

For several key sites at the south-western coast of the Kara Sea, the growth of retreat rates of ice-rich coasts was observed during the periods of enhanced hydrometeorological forcing on the coast at the end of XX – beginning of the XXI century. At Cape Kharasavey, Spindler, Marre-Sale weather station, western coast of Baydaratskaya Bay the retreat of ice-rich coastal segments have increased during the periods of the thawing index growth. Climate warming observed in the Arctic [7], probably will first of all be reflected in the growth of ice-rich coasts retreat rate.

The role of ground ice in the dynamics of the Arctic coasts should be assessed only on a local scale. In the Arctic as a whole and in certain regions, the contribution of parameter of the ice content is offset by the joint action of other factors of coastal dynamics, both hydrometeorological parameters and coastal zone features. To model the coastal dynamics on a regional scale, there is yet insufficient data on the sediment composition and ground ice content.

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REFERENCES


