Abstract

Coastal dynamics monitoring on the key areas of oil and gas development at the Barents and Kara Seas has been carried out by Laboratory of Geoecology of the North at the Faculty of Geography (Lomonosov Moscow State University) together with Zubov State Oceanographic Institute (Russian Federal Service for Hydrometeorology and Environmental Monitoring) for more than 30 years. During this period, a unique monitoring technology, which includes direct field observations, remote sensing and numerical methods, has been developed. The dynamics of thermal-abrasion coasts are directly linked with climate and sea ice extent changes. We have also evaluated the influence of local anthropogenic impacts on the dynamics of the Arctic coasts. As a result, a method of forecasting the dynamics of thermal-erosion coasts taking into account climate changes has been developed.

Introduction

The development of Russian sea coasts and shelf for natural gas mining requires construction of sea ports, approach channels, artificial islands, drilling platforms, terminals, ground-surface and underwater pipelines. Knowledge of natural processes, particularly coastal dynamics is necessary for geotechnical and geoecological safety of the facilities’ construction and operation. Natural geomorphic processes set the rules of oil and gas resources development in offshore and coastal areas in the Arctic. The coastal zone here is highly dynamic due to the contact with the cryolithozone. The coasts of Barents and Kara Seas which are composed of dispersive frozen deposits have poor erosion resistance qualities. In natural conditions such coasts may retreat with a rate of 0.5 to 2 m a year. Considering eventual human impact and forecasted climatic change, coastal retreat rate may significantly increase in the coming years. Technogenic disturbances activate trigger mechanisms of wave-induced coastal erosion. Under the conditions of global warming and ice cover reduce this effect is enhanced by the increase of the duration of the dynamic activity period and wave fetch. As a result, local human impact and climate change form synergetic effect due to which coastal retreat rates can double and even triple.
We are presenting here examples for Barents and Kara Seas where human impact has already brought in negative effects. To determine the speed of coastal retreat and shore zone profile deformations, approximately 120 permanent profiles have been established at the Varandey (Barents Sea) and Kharasavey (Kara Sea) industrial key areas, as well as at the gas pipeline underwater crossing of the Baydaratskaya Bay (Kara Sea) in the 80-90s of the XX century for coastal dynamics monitoring (fig. 1). Coastal dynamics monitoring from constant benchmarks is executed by direct measurements and by trigonometric leveling. An additional method of receiving an overview of multiannual coastal dynamics is studying multi-temporal aerial and satellite images of high and extra-high resolution.

One of the examples is Varandey Coast of the Barents Sea. From 1979 to 2012 a deliberate destruction of the dune chain of a barrier beach by vehicle traffic and beach material removal for construction needs led to quick intensification of the coastal retreat here. And now, storm surges penetrate inland for several kilometers without hindrance.

The second example of the negative impact of human activity has been documented at the sites underwater pipeline crossing on Yamal Coast of the Baydaratskaya Bay, Kara Sea. Designers and builders have not taken into account the negative experience of unsustainable management and sediment removal observed at Varandey and Kharasavey industrial areas. The construction of the pipeline, accompanied by the use of many technical devices and sediment removal from the beach and tide-flat, during the period from 2007 to 2012 led to significant increase in the rate of coastal erosion.

The features of Arctic coastal dynamics

According to the definition, thermal abrasion is the process of destruction of the coasts and underwater slope composed by frozen sediments. For the seas situated in the cryolithozone, besides mechanical abrasion induced by the wave action, thermal and thermo-mechanical abrasion caused by the thawing of the frozen ground can be selected.

The Russian Arctic coasts suffer from active thermal abrasion and thermal denudation. As a result, the coastline retreats up to several meters every year. Despite the short period of active dynamics, morpholithodynamic processes in the Arctic coastal zone are extremely intense because of the low stability of the cliffs composed by permafrost developing under the influence of thermal abrasion (fig. 2). The mean multiannual rates of thermal abrasion coasts destruction in natural conditions vary from 0.5 to 2 m per year. On sections with massive ice beds outcropping in the cliff, such destruction often reaches catastrophic velocities, reaching 5-10 m per year or more.

Thermal abrasion of sea coasts has been studied relatively well in the XX century. However, in the XXI century, hydrometeorological features of the near-earth layer of the atmosphere will inevitably change under the conditions of global climate warming which will in its turn cause changes in the hydrosphere and lithosphere. Ice-free period will increase which will lead to the rising impact of the wave action which will cause mechanical abrasion intensification. Other changes of the hydrometeorologic characteristics, namely the occurrence of deep cyclones, changing wave action and storm surges increase will also appear, influencing coastal dynamics as well.

Dynamics of typical thermoabrasional coasts, in general, are determined by the combination and interaction of two factors: the thermal factor and the wave energy factor (Ogorodov, 2008, Ogorodov, 2011; fig. 3)
Thermal impact is expressed in energy transition to the permafrost composing the cliff as a result of its contact with air and water with the temperature above -1.8°C. Correspondingly, the higher the air and water temperature is, and the longer the duration of temperatures above zero as well as of the contact with sea water is, the more considerable the impact of the thermal factor on the coastal dynamics in permafrost areas is.

The impact of the wave energy factor is expressed in the direct mechanical impact on the coasts. Therefore the effect of this factor is determined by the intensity as well as the duration of storms. The intensity of storms, in its turn, considerably depends on the length of the wave fetch (of the border of the ice cover) and the duration of the active dynamic period, when the water area is ice free.

![Diagram of Hydrometeorologic factors of coastal dynamics](image)

Under the conditions of global climate change, and changes in the ice cover of the Arctic seas, forecasted for the XXI century, the influence of the thermal, as well as the wave energy factor on the coasts inevitably grows. Abrasion increase will occur due to the thermal factor as a result of intensive thawing of the frozen ground under the action of higher air and water temperatures, possible rise of precipitation, but also due to the increased impact of the wave action on the coast, the growth of which is determined by the repeated storm winds, widening of the active dynamic period and sea level rise.

The changes of the last decades are not unique. In the Holocene, and in the years 30-40 of the XX century there have been many cases when conditions in the Arctic area have been similar to the modern ones, with rising air temperature. Fluctuations in the rate of natural processes, including thermoabrasion, corresponding to warmer periods, often lead to damage of constructions projected without taking into account the features of coastal dynamics in the areas close to the coastline. These consequences are, in most of the cases, determined by the simple ignorance of the mechanism of the natural environment impact on the coasts in the cryolithozone, where, alongside with the cycles of natural processes, separate factors can be accentuated.

**Direct and remote sensing methods for coastal dynamics monitoring**

According to Russian construction code of practice, no industrial facility can be constructed without carrying out the monitoring of natural exogenous processes, including coastal dynamics. Geotechnical safety of petroleum infrastructure objects under development, as well as geoeconomic safety of surrounding areas, is highly dependent on the right choice of the most dynamically stable shore section, and implementation of the correct forecast of coastal dynamics for the facility lifetime.

A correct forecast of coastal dynamics at thermoabrasion shores is impossible without understanding the factors of its development. One of the most important parts of understanding the mechanisms of coastal dynamics for thermoabrasion coasts is, in turn, monitoring of the process of shore destruction (thermodenudation) and retreat (wave abrasion). Only a proper sequence of repeated monitoring data can help us reconstruct the conditions of thermoabrasion and improvise reliable correlations for active hydro- and meteorological factors that determine wave and temperature modes.

The benchmarks were attributed to the Baltic-77 (Russian) system of heights. Coastal dynamics monitoring from constant benchmarks is executed by direct measurements and by trigonometric leveling). Usually 3 benchmarks are set (fig. 4), this allows us to keep the range during leveling works, and allows more easy reconstruction of the profile in case of benchmark loss at actively retreating shores. The benchmark network for monitoring is usually set with respect to geomorphological and
cryolithological composition of the shore. This helps us to obtain more complex and sufficient data on spatial and temporal variability of the process of thermoabrasion at a prolonged section of a coast (fig. 5).

A reliable method of studying coastal dynamics on a prolonged time period is analysis of different times aerial and space images (Ogorodov, Belova et al., 2011). Among archived space imagery, declassified Corona images shot between 1961 and 1970 are of particular interest, since they have medium resolution (4 – 7 m per pixel), good enough for coastal investigations. Aerial photos are stored in paper format in different organizations and are usually inaccessible for purchase. For considerable part of the Arctic coast, modern space images of ultra-high resolution are available (Ikonos, QuickBird, Formosat 2).

The preparation of the obtained aerial and satellite imagery is the most important stage in the Arctic coastal dynamics investigations. Special attention should be paid to the spatial reference of the data. Ikonos and QuickBird images are provided with the world-files (reference files) created by the satellite’s orbit parameters. This kind of referencing is precise enough for coastal areas because the error between the heights on the terrain and the geoid level are negligible.

A more complicated task is referencing Corona satellite images which can only be obtained as a simple raster file. As benchmark data for these files, Ikonos and QuickBird images, as well as topographic maps and plans or field GPS-points can be used. Because of their considerable coverage, Corona images have trapeze-like deformations in their peripheral part. For their referencing, special methods allowing the curvature of initial data (polynomial transformations, “rubber sheet” method) should be used. The main problem regarding referencing of aerial and satellite imagery is the lack of stable points which is
caused by little anthropogenic presence in the explored region. Consequently, hydrographic objects are often used in georeferencing (rivers, lakes, ravines and hollows). By superimposing the received contours with the image we are referencing and their consequent matching by creating a set of verified reference points, precise enough correspondence can be reached.

After the referencing of all the multitemporal images available for the territory, the interpretation stage starts. One of the most spread and well decipherable signs for thermoabrasion and accumulative coasts is the cliff line and the border of the continuous vegetation cover. Based on the satellite imagery, the cliff edge (for abrasion sections) and the continuous vegetation limit (for accumulative sections) are digitized. By superimposing the limits of landforms, vectorised with the help of different time satellite images it is possible to assess the deformations of these forms, as such coastal retreat or progradation for a set time period. By satellite images, we can also determine the location and evolution of the underwater bars which are quasi-ephemeral landforms and can completely change their position during several years. Basing on analysis of different times imagery, interpretative maps of coastal dynamics are created (fig. 6).

![Fig. 6. The scheme of interpretation of the dynamics segment thermoabrasive coast (Ural Coast, Baydaratskaya Bay, Kara Sea): 1 - Corona image 1964, 2 - aerial photo -1988, 3 - QuickBird image - 2005, 4 - Formosat2 image -2012; coastal bluff in 2012; U8(110) - the number benchmark of the coastal dynamics monitoring network (the value of the coastal bluff retreat for 1964-2012, meters)](image)

**Coastal dynamics hydrometeorological factor**

Sea shore and underwater slope erosion intensity is determined by waves and excited currents action. As far as Russian Arctic seas waves are generated mostly by wind, wind conditions are to be crucial in wave energy flux formation. Shores are acted by waves during ice-free period. Seasonal shore retreat rate is determined by wave energy flux coming to the shoreline, which depends on the ice-free period duration. Storms provide the largest contribution to wind-wave energy total amount. Climate change of the latest decades reveals itself both in ice and wind conditions changes. Satellite and ground-based ice observation show Arctic ice cover reduction and ice free period extension (http://arctic.atmos.uiuc.edu/cryosphere, The Arctic ocean…, 2012).

These processes mentioned above are revealed at western Yamal region, which is good for the research for its long observation history: Marresalya station has held hydrometeorological observations (including ice monitoring) since 1914 and coastal dynamics monitoring is conducted from the beginning of the 80s (fig. 7).
As the climate of the Russian Arctic seas is characterized by a maximum of wind velocity and by the greatest number of storms in October-November, the shift of the end of the ice-free period towards winter would result in shoreline exposition to more and more severe storms. That would lead to coastal erosion intensification.

Popov-Sovershaev’s method (1980) was used for ice-free period wave-energy calculation. This value interannual variability analysis showed wave energy flux increase from 1977 to 2011 on the backdrop of ice-free period extension (fig.7). Also weak wind activity period of 1998 – 2004 was revealed (Ogorodov, 2011). Combined retrospective analysis of storm events and wave-energy flux interannual variability can establish the presence and nature of their relation and, as a result, coastal erosion potential.

Arctic climate change comes out also in wind speed decrease from the middle of XX to the beginning of XXI, especially noticeable at the Arctic shores (Vautard et al. 2010). Wind speed reduction goes due to strong winds frequency decrease. In the same time number of calms is getting lower too. At Marresalya station ice-free period wind speed distribution changes are not directed to storm activity intensification or calming. There are periods of high and low storm activity (wind speed higher then 10 m/s). Summers of 1997-2004 are the calmest. July-October of 1982-1996 are characterized by raised number of storms. Ice-free period end shifting towards winter extents the shore exposition to waves and does not result in storms number increase. Wave dangerous wind directions frequency in October is higher than in November and September and wave dangerous storms activity and wind-wave energy levels are the highest in October. That’s why October presence in ice-free period is crucial. The high values of wind-wave energy in the 2000-th appear because of high open water period duration and in 70-th – due to intensified storms in October. Wind-wave energy minimum in 1997 – 2004 is caused both by low ice-free period duration (1998, 1999) and low storm frequency. Thus wave-energy flux and corresponding shore dynamics depend on several interconnected factors which may act separately or jointly enhancing or weakening each other.

**Fig. 7. June-November wind velocity distribution and interannual variability of ice-free period start and end date (on the left) and interannual variability of wave energy flux (to the right) at Marresalya station (on the left wave-dangerous directions)**

**Coastal dynamics human-induced factor**

Varandey region is a negative example demonstrating the need for a well-developed, ecologically grounded approach to further exploitation of coastal regions. The main objects of oil transportation infrastructure here have been built on a marine terrace with an average height of 3-5 m formed during the Holocene transgression. The terrace is represented by a series of barrier islands and barrier beaches. Its width reaches 2-6 km. The terrace is composed of fine sand unit underlain by peat-grass pillow. The cryogenic structure of the terrace sediments is characterized by low ice volume (Novikov and Fedorova, 1989). Frontal and seaward, part of the terrace is covered by an avandune (ridge-like dune belt) reaching 5-12 m asl. At the distal parts of the barrier beaches, the avandune turns into a series of ancient and young barrier ridges corresponding to different
stages of the evolution of barrier beaches and barriers-spits. Barrier ridges have been considerably reworked by eolian processes. The inner parts of the terrace behind the dune belt represent a layda (surge flood plain) up to 2.5-3 m high with two levels corresponding to the low and high surge.

At present, under natural conditions, most of the First terrace is being eroded at a rate of 0.5-2.5 m per year. The abrasion coast has an erosion scarp cut in eolian-marine fine sands. During years with extraordinarily strong fall storms, the slope is eroded and becomes steeper for a short period of time. Thermoabrasion does not, in fact, erode slopes of the Holocene terrace. The latter is destroyed due to relatively high average annual ground temperatures, small ice volumes and a considerable thickness of the layer of seasonal melting. Coastal erosion is determined by a combination of different factors including deficit of coarse-grained beach-forming material (the discrepancy between the grain size and hydrodynamic conditions), a poorly developed profile of the submarine coastal slope, and high gradient of the avandune slopes.

Active exploitation of the Varandey industrial area started in the seventies. Varandey Island was subjected to the strongest human impact. Here, the main industrial base was formed, and a new settlement for 3 thousand inhabitants, was built (fig. 8). The well-drained dune belt of the Holocene terrace, composed of sand beds with low ice content, was chosen as the place for the settlement, oil terminal and storehouses, because it seemed to be more stable from the engineering-geological point of view than the surrounding swampy tundra lowland.

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Construction of the settlement and industrial base practically at the edge of the abrasion cliff demanded repeated withdrawals of sand and sand-pebble sediments from the avandune and beach. This is extremely dangerous for the zones of wave energy divergence (Popov et al. 1988), especially in zones that have been eroded before. Within the zone of industrial exploitation, the coastal bluff and the coastal zone experienced considerable mechanical deformations of the landforms because of transport ramps, mechanical leveling of coastal declivities and other human disturbances (Ogorodov, 2005). Uncontrolled use of transport and construction techniques including caterpillars caused degradation of soil and plant covers of the whole dune belt of Varandey Island. Under the conditions of deep seasonal melting, the dune belt formed of fine sands is subjected to deflation and thermoerosion. The extent and rate of these processes has been so great that in several places the surface of the island became 1-3 m lower than before the period of exploitation. Deflation hollows became widespread. Numerous deflation-thermoerosional gullies were formed in the bluff. As a result, the bluff became lower, its homogeneity was disturbed, the amount of sediments supplied to the coastal zone decreased and, finally, the coasts became less stable, and the rate of retreat increased. Coastal protection at the Varandey settlement caused a decrease in sediment supply to the adjacent areas and, hence, their erosion.

Under the existing conditions of intensive human impact, the coastal erosion rate increased considerably in the mid to late seventies. In some years in some sites it was up to 7-10 m/year. The rate of coastal retreat slightly decreased, down to 1.5-2 m/year, after the coastal-protection construction was built near the Varandey settlement. However, it remained high in the adjacent areas. Recent measurements have shown that the rate of coastal retreat in the region around the settlement increased and reached 3-4 m/year: that is twice and more as high as in the regions that are not affected by human activity. Acceleration of shore and underwater slope erosion has contributed to the output to the surface of the underwater pipeline. As a result, it was pulled out from the bottom by sea ice impact (Chernikov, 2006). After an earth-dam and a bridge were constructed in the eastern part of the Varandey Island, the height of storm surges increased. The latter is an important factor of coastal dynamics.
Previously, during high surges corresponding in time with tides, water was partly flowing into the branches and channels, thus lowering the surge height and decreasing its influence upon the coast. July 24, 2010 extreme storm surge completely flooded the Varandey Island, and penetrated several kilometers inland. Enormous damage was done for oil infrastructure.

The negative experience of Varandey industrial area development has not been considered for the construction of gas transportation facilities on the coast of the Kara Sea. As an example is the section of the coast of the Yamal Peninsula at the underwater crossing Yamal - Europe. The following types of direct human impact on the relief within the landfall of the underwater transition of the gas pipeline that is under construction have been documented: construction of large artificial positive landforms, which leads to additional sediments income to the coastal area in the given place; construction of artificial concave landforms, removal of sand material from the beach, tide flats (fig. 9) and from the underwater shore slope, which leads to erosion and narrowing of tide flats and of the beach as well as to reconstruction of submerged bars system; deformation of the surfaces of mud flats, beach, coastal barrier and of laida during construction and during motion of heavy track machines or heavy vehicles as well as destruction or disturbance of soil and vegetation cover, which leads to intensification of erosion.

Among the indirect kinds of human impact, the following ones are distinguished: appearance of anthropogenic accumulative forms in the coastal area connected with the change in the sediments drift (e.g. filling of the re-entrant corners formed with buildings); appearance of concave landforms on the beach and on tide flats caused by the intensification of erosion resulting from the disruption of the sediments transportation or from the change in the cross profile of the beach; intensification of deflation at the disturbed surfaces.

Due to the fact that the places of extraction of construction materials that are safe from the perspective of morpholithodynamic situation were not considered in advance, the extraction of sand material for construction purposes is carried out without a certain plan and without consideration of the consequences. The sand material is most actively extracted from the surface of the barrier and the beach between the nearest river mouth and the cofferdam. The surface deformation and the vegetation destruction at the coastal barrier leads to intensification of deflation, which means that it intensifies the process of extracting sand material from this area. This creates sediments deficit in this coastal area, which leads to its erosion. During the construction of a harbor the following operations were carried out: dredging of the fairway for construction of an approach channel and aggradation of coasts for harbor construction at the surface. This created the sediments deficit at the river mouth, which led to a partial interception of the sediments drift coming from the south, and, as a result, to the increase in the sediments deficit and to the shore erosion between the nearest river mouth and the cofferdam.

Cofferdam construction resulted in the accumulation of sediments in the re-entrant corner to the south of the cofferdam and in the erosion of the coast to the north from it. In natural conditions, the coastal barrier completely absorbs the wave energy even during extreme storms (Kamalov et al. 2006). The change in the coastal barrier morphology entails the change in the conditions of wave’s destruction and, therefore, the entire change in the morpholithodynamic regime that can cause unfavorable and hazardous consequences. The coastal system will tend to reach a new equilibrium, which will cause reformation of the coasts and of the floor with the rates that were not considered in the construction project. In order to reduce the impact of the pipeline construction on coastal systems, it is first of all necessary to stop the removal of sediments from the area of the coast between the river mouth and the cofferdam. Extraction of sand material without the risk of coastal erosion activation in the pipeline construction area can be done in the discharge zone of the alongshore sediments drift.
Conclusions

A truly responsible decision-making towards the strategy of developing the northern coasts of Russia and constructing new facilities has to be based on integrated knowledge of the ongoing environmental processes, in particular coastal dynamics. The ignoring of this issue may cause irreversible damage to both the coastal geosystems and the facilities themselves, which, once they are destructed, may drag in enormous environmental implication.

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