Monitoring and modelling issues of the thermoabrasive coastal dynamics

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Abstract. In view of the active development of the northern territories the study of the coastal dynamics of the Arctic seas remains very relevant. Despite the fact that scientists have been studying the coastal dynamics since the last century, there are many issues of monitoring of the dynamics of the coasts, complicating the creation of reliable models of this dynamics. Monitoring of the coast dynamics is carried out with the help of field and remote methods having their nuances, errors and conditions of applicability. There are some difficulties associated with the severity of the climatic conditions of the region and its inaccessibility. The main problems related to methodological approaches are considered in the article and some ways of solving these problems are offered, from the positions that seem to the authors to be feasible.

1. Introduction
The study of the northern seas and oceans coasts began in the 14th-16th centuries during the major geographical discoveries in the Arctic. Later in the 20th century, the stage of active economic development of the Arctic coast was connected to the exploration of raw material, the development of the Northern Sea Route, which was accompanied by research due to the construction of port facilities and other infrastructure on the coast.

The coastal zone of the Arctic seas is characterized by high dynamism due to the presence of permafrost, where the state and stability of soils depend on the temperature regime. Many environmental, climatic, geologic, biologic and anthropogenic factors influence the coastal erosion rates (soils erodibility, fractures, adjacent bathymetry, cliff lithology, waves, wind, vegetation, etc.). In Arctic region, additional factors relate directly to the presence of permafrost and cold weather conditions which influence the coastal destruction processes. According to Grigoriev [1], some of these additional factors include: the presence of sea ice, the permafrost (temperature) regime and cryostratigraphy of the area. The combination of hydrometeorological factors determines the conditions for soil thawing and removal of thawed material in the sea. Year by year these conditions change. Hydrometeorological factors of the Arctic coastal retreat include first of all the thermal regime of the territory (air temperature, sea water temperature, surface temperature) which determines the thermodenudation intensity, and the energy (wind-wave) regime that determines the thermal abrasion intensity and removal of thawed material from the beach. The wind-wave regime depends on the frequency and intensity of storms directing to the coast from the sea side and on the duration of the ice-free period [2, 3]. Arctic seas are covered by sea-ice during about 9-10 month per year [4, 5].
During this period, the sea ice cover protects the coastal slopes from destruction. Frozen and thawed soils have different physical and mechanical properties, including erosion resistance. The coastal erosion rate varies in time and space. The presence of permafrost causes a lot of degradation processes, linked to thermal degradation of the soils, e.g. thermal abrasion, thermal denudation, or thermokarst subsidience [6-9]. Every year the Arctic coastline composed by frozen unconsolidated deposits retreats into the continent by a value of several centimeters to several meters.

Despite the fact that scientists have been studying the Arctic coastal dynamics since the last century, still there are many problems [10] of coastal dynamics monitoring complicating the creation of reliable models of this dynamics. The purpose of the paper is to identify contemporary issues of Arctic coastal dynamics in order to attract attention of the scientific community to this and to solve these problems in the future.

2. Study area and background

Coastal dynamics monitoring on the key areas at the Western part of Russian Arctic (Barents and Kara Seas regions) has been carried out by Laboratory of Geoecology of the North at the Geography Faculty (Lomonosov Moscow State University) together with Zubov State Oceanographic Institute (Russian Federal Service for Hydrometeorology and Environmental Monitoring) for more than 35 years (figure 1). 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. Varandey key-site is located in the zone of sporadic permafrost. Frequent layers of unfrozen highly saturated soil interbed the permafrost.

![Figure 1. Key sites of studies; years of the start of observations [11].](image)

3. Monitoring of the coastal dynamic

Monitoring of the coast dynamics is carried out with the help of field work (geodetic survey) and remote sensing methods.

3.1. A subsection Geodetic survey

For better understanding the coastal retreat, approximately 120 profiles perpendicular to the coastline were installed in the 1980-s, the 2000-s, the 2010-s. From the start of the investigation period the monitoring technology has been developed. At the start of study the coastal retreat was investigated by tachometric measurements along profiles perpendicular to the coastline (figure 2). 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.
Currently, a reliable method of studying coastal dynamics for relatively short time periods by using the differential GPS (DGPS) with a Trimble GeoXH® (2008 series) rover connected to an external Zephyr® antennae [5] is used. For our research we utilized 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, which internal modem received the correction data. The using of the 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 leveling profiles, the operator installed a mobile receiver on the profile benchmark selected on the terrain. The survey was performed in real time kinematic (RTK) mode and was carried out in the WGS 84 UTM42N coordinate system.

The typical for tundra landscape peat moss vegetation covered the cliff making the identification of the exact position on the cliff edge complicated. The use of high-precision equipment in fields (levels, theodolites, DGPS, etc.) did not solve this problem. So, for example, on high coast during their retreat there is a gradual dangling and slipping of blocks of soil-vegetation cover up to several meters in diameter, which is close to the average annual rate of displacement of the edge of the coastal cliff (figure 3). At the same time, on the low shores, the mapping of the brow was complicated by the accumulation of sand resulting from wind impact and storm surges.

In addition, during field works there were some difficulties associated with the severity of the climatic conditions of the region and its inaccessibility. Episodic short-term periods of field work hampered the identification of a quantitative contribution of individual main factors that change during
one season of the coastal retreat (in the beginning of summer thermodenudation caused by the thermal exposure of positive air temperatures in the sea-blocked sea prevails, and in autumn period, thermal abrasion is caused by storm activity on the sea).

3.2. Remote setting data

Archive remote sensing data is particularly important for investigation of coastal dynamics, since it allows analysing data over a long-time period. A reliable method of studying coastal dynamics for relatively long time periods is the analysis of multitemporal aerial and space images [13, 14]. For our study area, the best and earliest available image was Corona from 1964 or 1968 from the United States Geological Survey with a 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 had resolution of 0.7 m. For short-term observation, ultra-high resolution images are needed. QuickBird-2, WorldView-2 and WorldView-3 with a resolution of 0.7-0.3 m were used.

However, work with remote sensing data also has its own nuances and features. Space images were provided with the reference files containing the satellite’s orbit parameters, but the accuracy of the georeference was not enough to analyse the annual variability of the coastal dynamics. The images should be georeferenced with ground control points, collected during the field work. However, in territories outside of the technogenic development there is the problem of absolute georeferencing of images, due to the lack of objects with spatially stable outlines, as a result, it is necessary to use conditionally stable objects (for example, the contours of lakes which water level, and, accordingly, the planned outlines vary from season to the season). Part of this problem is solved by referencing a lot of control points, thereby reducing the error.

Another issue with remote sensing data is recognising the position of the coast line. There are not many of images of Russian Arctic coast ready for analysis. For example, this may be due to the snow covering the ledge (figure 4). Also, the visual border of the edge cannot always be identified on the low terraces, which are covered with sand under surges. The difficulties described above in the identification of the cliff position (when the block are sliding) occurs also during field works.

![Figure 4. Snow cover on top of the marine terrace at relief settling the Ural coast, complicating coastline digitization on image (2016).](image)

Also space image reflects a one-time moment with specific characteristics that can change during one season (for example, the width of the beach changes during tides and autumn storm surges). In addition, remote sensing does not allow assessing the changes in the coastal profile, but only the planned outlines of the edge of the cliff. This problems can be solved with help of new approaches and methods, like the stereomultilpairs from drone mapping or survey by 3D laser scanner. Among other things, the human factor is another problem: even with experienced researchers who work with remote
sensing data and know preliminary methodological agreements, researchers decode the images in different ways.

3.3. Erosion rate estimations
Field work observation data and satellite imagery analysis were used for estimation of coastal retreat rates at the key-sites. Results processing are usually performed using ArcGIS 10.2 software [Kricuc, 2014]. 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. To estimate the cliff position changes Thieler et al. [15] produced Digital Shoreline Analysis System (DSAS), available as an extension to ArcGIS. The program automatically creates transections perpendicular to the general direction of the shorelines (which is chosen) with an optional spacing along the baseline. However, another problems associated with remote sensing data do not allow analyze two neighboring years of space images, because coastal retreat is not very large and determinations coincide and sum up errors.

4. Modeling of Arctic coastal dynamic
Currently, there are a lot of models trying to predict the arctic coastal dynamics. However, these models, as a rule, are regional and are focused on modeling the shoreline for particular part of the selected coast. Early studies with the prediction of the coastal dynamics were conducted for the regions outside the permafrost, and did not take into account the permafrost characteristics. F.A. Are [16] proposed a model for processing the frozen coast of water-collecting area based on thermophysical calculations of the subsidence of frozen sediment during the thawing. Vasiliev et al. [17] considered the modeling of the dynamics of thermal abrasion from the position of a stochastic model when the natural process of retreat of the coast was partly random. The morphodynamic model of development of the Arctic coasts of Russia developed by Leontiev [18, 19] made it possible to quantify the transport of material influencing the rate of destruction of the coast while the model described in detail the characteristics of the storm impact and only the sediment during ice thawing in frozen soil. For the shores of the East Siberian Sea, mathematical model of the sandy accumulative bar dynamics under the conditions of long-term changes in open water and sea level but under unchanged permafrost, geological conditions and atmospheric circulation have been developed and tested [20]. S. O. Razumov [21, 22] developed models for the development of thermal abrasion of ice banks with a stationary indicator of abrasion activity and a stable sea level, as well as under a changing climate conditions.

All the models considered were calibrated for specific parts of the coast, for example, for Alaska and the Canadian part of the Beaufort Sea with specific features of coastal destruction [23]. Coastal cliffs of these areas are exposed to active erosion which entails virtually no beaches on the shore, and the retreat of the edge of the coastal ledges is associated with a "block" collapse of frozen rocks. In connection with such conditions the Kobayashi model [24] taking into account the thermal characteristics of water, sea level, time of impact, estimates the rate of penetration of the thermoabrasive niche along the base of the frozen cliff, which is always in contact with a constant sea water level. In addition, the thawing of frozen soil blocks falling into the sea water was evaluated by various researchers [25, 26, 27] based on empirical equations for the Alaska coast, which took into account the height of the cliff, the period wave, water temperature and freezing point of water. Further development of the Kobayashi model showed the need to take into account the convective heat flux which depends on the rate of sea water movement and its temperature which strongly affect the frozen soil [28, 29]. This approach was embodied in the COSMOS program [30], which is still used for modeling [31].

Thus, the above mentioned features of monitoring the coastal dynamics complicate the possibilities of comparing and analyzing the data obtained. In that context there are many problems in simulating and modeling the process of coastal retreat which associated with a lack of conditioned factual
material, which compels modeling on empirical dependencies. The ambiguity of the leading factors complicates the creation of an universal model that takes into account all parameters of the retreating shore, so at this stage only a description of the qualitative characteristics of the coastal dynamics is possible. In addition, the coasts of the Western sector of the Russian Arctic are composed of unconsolidated sediments with varying cryolithological composition, which additionally complicates the modeling.

5. Conclusion
Thus, the paper considers the main problems which have scientists involved in the Arctic coastal dynamics. Some problems could be solved now with a thoughtful approach and with the use of modern technologies.

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