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COASTAL DYNAMICS OF THE PECHORA AND KARA SEAS UNDER CHANGING CLIMATIC CONDITIONS AND HUMAN DISTURBANCES

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, an up-to-date monitoring technology, which includes direct field observations, remote sensing and numerical methods, has been developed. The results of such investigations are analyzed on the example of the Ural coast of Baydaratskaya Bay, Kara Sea. The dynamics of thermal-abrasion coasts are directly linked with climate and sea ice extent change. A description of how the wind-wave energy flux and the duration of the ice-free period affect the coastal line retreat is provided, along with a method of the wind-wave energy assessment and its results for the Kara Sea region. We have also evaluated the influence of local anthropogenic impacts on the dynamics of the Arctic coasts. As a result, methods of investigations necessary for obtaining the parameters required for the forecast of the retreat of thermoabrasional coasts have been developed.

KEY WORDS: coastal dynamics, cryolithozone, thermoabrasion, monitoring, multitemporal imagery, climate change, ice extent, wave energy, human impact, Pechora and Kara Seas.

INTRODUCTION

The development of natural gas extraction and transportation facilities on the coasts and shelf of the Russian Arctic seas requires construction of sea ports, approach channels, artificial islands, drilling platforms, terminals, ground-surface and underwater pipelines. The knowledge of natural processes, particularly coastal dynamics, is necessary for the geotechnical and geoecological safety during their construction and operation. The coastal zone in the polar regions is extremely sensitive due to the contact with the cryolithozone. The coasts of Barents and Kara Seas composed of frozen deposits have poor resistance to erosion. Considering eventual human impact and the ongoing and forecasted climatic change, coastal retreat rates may significantly increase in the coming years. Technogenic disturbances activate trigger mechanisms of wave-induced coastal erosion. Under the conditions of global warming and sea ice cover reduction; this effect is enhanced by the increase of the wave fetch, together with the duration of the ice-free period, when waves act directly on the shores. As a result, local human impact and climate change form a synergetic effect, due to which coastal retreat rates can double and even triple.

In the present study, we describe the methods of the coastal retreat rates' determination, together with the assessment of the hydrometeorologic factors, mainly wind-wave energy, acting on the coasts. The key sites of investigations are the Varandey (Barents Sea) and Kharasavey (Kara Sea) industrial key areas, as well as the gas pipeline underwater crossing of the Baydaratskaya Bay, Kara Sea, 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 for coastal dynamics monitoring have been established there in the 80–90s of the XX century (Fig. 1). Coastal dynamics monitoring from constant benchmarks is executed by direct measurements and by trigonometric

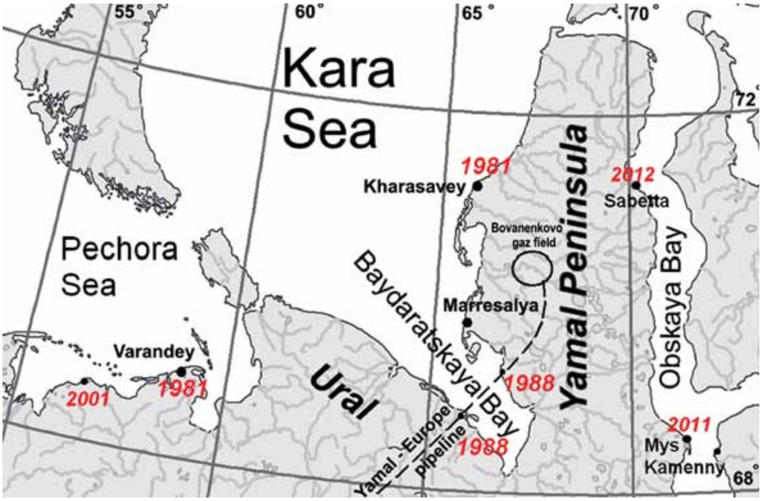

Fig. 1. Key sites of studies; years of the start of observations

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.

An example of the results of such investigations and the analysis of the reasons of changes in the coastal retreat rates are provided for the Ural coast of the Baydaratskaya Bay; the hydrometeorologic factors are analyzed based on the data of the Marresalya hydrometeorologic station. Apart from that, the consequences of the unreasonable technogenic exploration are observed based on the examples of the coasts of Baydaratskaya Bay and of Varandey Island, Barents Sea.

FACTORS OF THE ARCTIC COASTAL DYNAMICS

For the Russian Arctic coasts, one of the crucial dangerous processes is thermal abrasion. According to its definition, thermal abrasion is the destruction of coasts and underwater slopes composed by frozen sediments. For the seas situated in the cryolithozone, thermal and thermo-mechanical abrasion is caused, on the one hand, by mechanical abrasion induced by the wave action, and, on the other hand, by the thawing of the frozen grounds.

As a result of active thermal abrasion and thermal denudation, the coastline retreats up to several meters every year. Despite the short period of active dynamics, when the sea is ice-free, morpholithodynamic processes in the Arctic coastal zone are extremely intense because of the low stability of the cliffs composed by permafrost (Fig. 2). The mean multiannual retreat rates of thermal abrasion coasts vary from 0,5 to 2 m per year in natural conditions. Within sections with massive ice beds outcropping in the cliff, such destruction often reaches catastrophic velocities of up to 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. The increase of the ice-free period will lead to the rising impact of the wave action, which, in its turn, will cause mechanical abrasion intensification.

Fig. 2. Typical thermoabrasional coast of the Kara Sea

Other changes of the hydrometeorologic characteristics, namely the occurrence of strong cyclones and storm surges, will also influence the coastal dynamics.

The dynamics of typical thermoabrasional coasts are generally determined by the combination and interaction of two factors: the thermal factor and the wave energy factor [Ogorodov, 2008, Ogorodov, 2011] (Fig. 3).

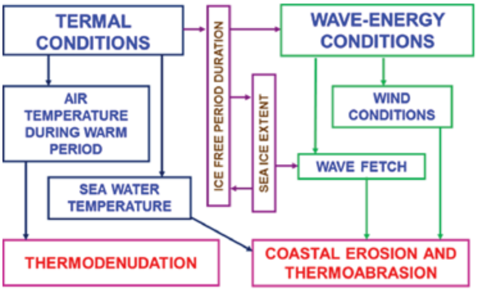

Fig. 3. Hydrometeorologic factors of coastal dynamics

The thermal impact is expressed in the transition of energy to the permafrost composing the cliff through 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 period with positive temperatures and the period of contact with sea water is, the more the thermal factor influences the coastal dynamics in permafrost areas.

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

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 both the thermal and wave energy factors on the coasts will inevitably grow. The increase of abrasion will occur not only due to the intensive thawing of the frozen ground under the action of higher air and water temperatures and possible 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, sea level rise and ice-free period prolongation.

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 were similar to the modern ones, with rising air temperature. Fluctuations in the rates of natural processes, including thermoabrasion, corresponding to warmer periods, often lead to the damage of constructions designed without taking into account the features of coastal dynamics in the coastal areas. These consequences are, in most of the cases, determined by the ignorance of the natural environmental mechanisms in the cryolithozone.

METHODS OF STUDY

Direct and remote sensing methods for coastal dynamics monitoring

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

A correct forecast of the coastal dynamics of thermoabrasional coasts is impossible without the understanding of the factors of their development. One of the most important parts is the monitoring of the cliff destruction due to thawing (thermodenudation) and retreat due to wave action (wave abrasion). Only a proper sequence of repeated monitoring data can help to reconstruct the conditions of thermoabrasion and establish reliable correlations for active hydro- and meteorological factors that determine wave and temperature conditions.

Coastal dynamics monitoring from constant benchmarks is executed by direct measurements and by trigonometric leveling. The benchmarks are attributed to the Baltic-77 (Russian) system of heights. As a rule, 3 benchmarks are set (Fig. 4). The benchmark network for monitoring is usually set with respect to geomorphological and cryolithological composition of the shore. This helps to obtain integrative data on spatial and temporal variability of the processes of thermoabrasion at a relatively long coastal section.

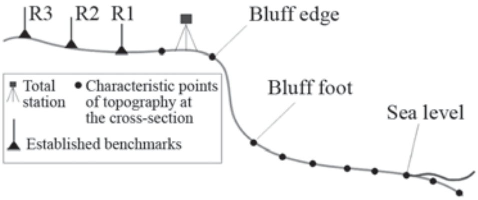

Fig. 4. Coastal dynamics monitoring by trigonometric leveling

A reliable method of studying coastal dynamics for relatively long time periods is the analysis of multitemporal aerial and space images [Ogorodov, Belova et al., 2011]. Among the archive space imagery, declassified Corona images shot between 1961 and 1970 are of particular interest, since they have medium resolution (4–7 m), good enough for coastal investigations. For a considerable part of the Arctic coast, modern space imagery of ultra-high resolution is 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 the referencing of Corona satellite images which can only be obtained as a simple raster file. Ikonos and QuickBird images, as well as topographic maps and plans or field GPS-points can be used as benchmark data for these files. 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 the 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 the georeferencing (rivers, lakes, ravines and hollows). By superimposing the received contours with the image and 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 wide-spread and well decipherable signs for thermoabrasion and accumulative coasts are 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. Sometimes, in case of aeolian processes influencing the beach and the littoral, for accumulative coasts, the border between the beach and littoral is digitized. It can either be determined visually by the difference in the color of these two landforms, or assessed based on the time and date when the image was taken, allowing calculating the height of the tide at that moment. By superimposing the limits of landforms, vectorised with the help of multitemporal 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 the analysis of multitemporal imagery, interpretative maps of coastal dynamics are created (Fig. 5).

Methods of the wind-wave energy assessment

The wave energy flux is calculated using the Popov-Sovershaev [1981, 1982] wind-wave energy method [Ogorodov, 2002]. The method is based on the theory of wave processes and applies correlations between the wind speed and the parameters of the wind-induced waves.

For deep-water conditions, when the sea floor does not influence the formation of waves, the wave energy flux per second (for 1 m of the wave front) at the outer boundary of the coastal zone is calculated using the equation similar to the one used in V.V. Longinov's method [1966]:

$$E_{0dw} = 3\cdot 10^{-6} V_{10}^{3} x, \qquad (1)$$

where V_{10} is the real wind speed measured by an anemometer at 10 m above sea level [m/s], x is the real or extreme distance of wave fetch [km] along the chosen wind direction. The dimension of the $3\cdot10^{-6}$ coefficient corresponds to the dimensions of ρ/g, where ρ is density [gr./m^3] (transformed into tons per cubic meter because of the big values, i.e. [t/m^3]), g is gravitational acceleration [m/s^2], i.e. is $\frac{t/m^3}{m/s^2}$. Thus, `E_{0dw} has the dimension of $\frac{tm}{ms}$, or t/s.

A similar equation for the shallow sea zone looks as follows:

$$E_{0sw} = 2\cdot 10^{-6}\left(\frac{gH}{V_{10}^2}\right) V_{10}^{5}, \qquad (2)$$

where E_{0sw} has the same dimensions as in equation (1). Equation (2) is applied if two conditions occur: 1) the kinematic index of shallowness $\frac{gH}{V_{10}^2}$ is less than 3 (H is the sea depth along the current wind direction expressed in meters); 2) the wave fetch x min (in km) is great enough to generate waves:

$$\frac{x_{\min}}{H} \geqslant 6.5\left(\frac{gH}{V_{10}^2}\right)^{0,4}. \qquad (3)$$

At $\frac{gH}{V_{10}^2} < 3$ water depths hamper the formation of wind-induced waves. At $\frac{gH}{V_{10}^2} = 3$ equation (3) becomes the following:

$$\frac{g x_{\min}}{V_{10}^2} \geqslant 30. \qquad (4)$$

From (4), the value of the extreme wave fetch for deep-sea conditions is obtained:

$$x_{\lim} = 3V_{10}^2. \qquad (5)$$

If any object like an island or a curve of the coastal line is closer than x lim, the wave fetch is equal to the distance to this object, if not – it is determined by the formula (5).

Coastal wave abrasion is possible during the ice-free period. The longer it is, the greater the effect of wave action on coastal dynamics is. To calculate the energy coming to the shore from a given direction (Ed) during the ice-free period, the instantaneous flux E_0 is multiplied by the ice-free period duration expressed in seconds (n×86 400, where n is the number of ice free days) and by the current wind speed (v) and direction (d) frequency (p_{dv} calculated over the ice-free period):

$$E_{dv} = E_o \cdot n \cdot 86400. \qquad (6)$$

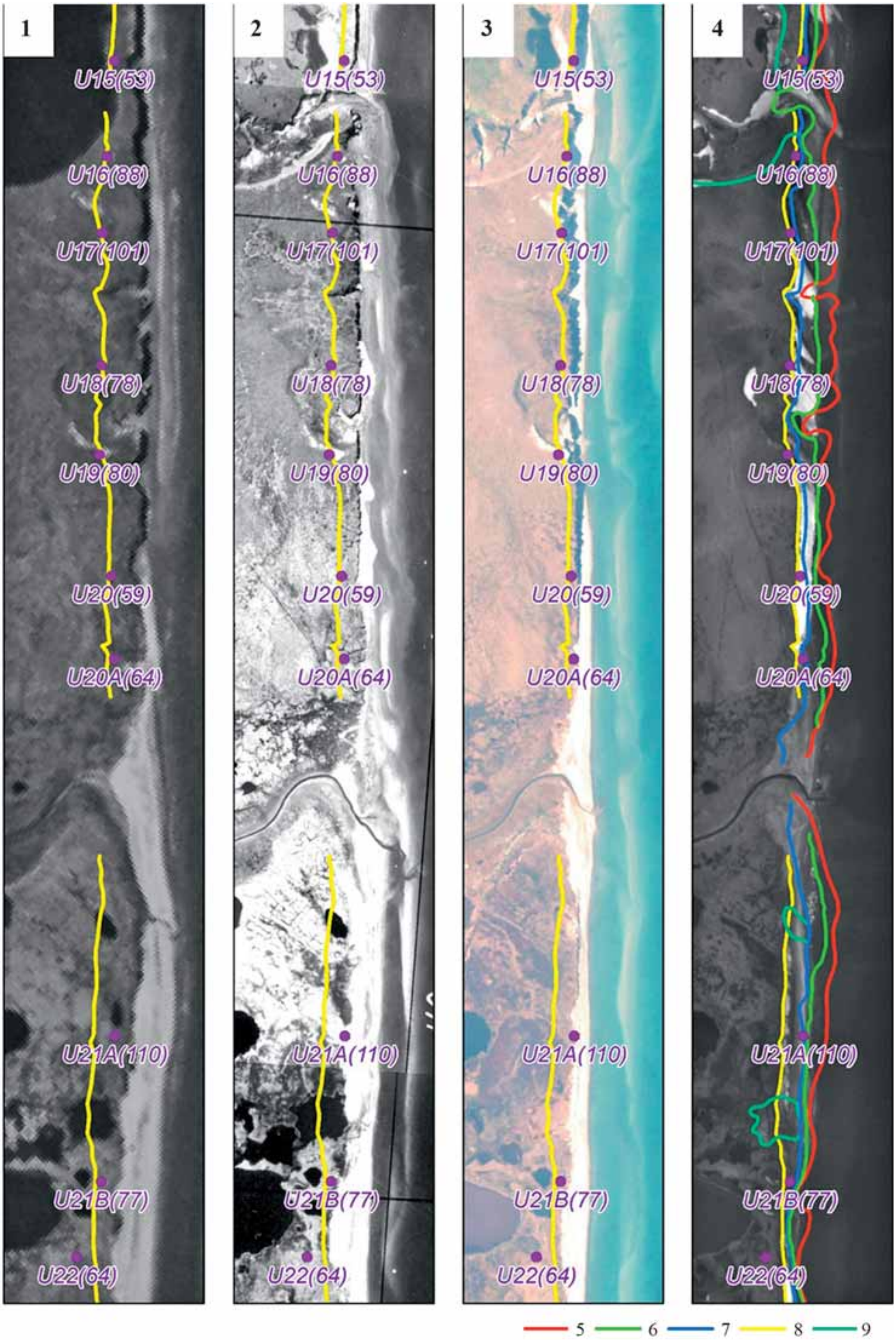

Fig. 5. Interpretative scheme of coastal dynamics for the Ural coast of the Baydaratskaya Bay, Kara Sea:

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), 5 – coastline in 1964; 6 – coastline in 1988, 7 – coastline in 2005, 8 – coastline in 2012, 9 – contours of drained lakes

After that, the winds with all speeds which occurred are summarized:

$$E_d = \sum_{\upsilon=6}^{p_{\max}} E_{d\upsilon}. \qquad (7)$$

It was shown in [Sovershaev, 1981, 1982] that the effect of weak winds (with velocities less, then 6 m/s) is negligible. That is why wind speeds higher than 5 m/s are taken into calculation.

The total amount of wind-wave energy (E) coming to a 1 meter long shore strap is calculated as the sum of Ed over all the wind-wave-dangerous directions, i.e. directions providing waves directed towards the coast:

$$E_d = \sum_{d=d_1}^{d_n} E_d = \sum_{d=d_1}^{d_n} \sum_{\upsilon=6}^{\upsilon_{\max}} E_{d\upsilon}. \qquad (8)$$

The total energy flux vector is calculated as a geometric sum of fluxes of wave-dangerous directions. It is divided into along- and across-shore components (Fig. 6).

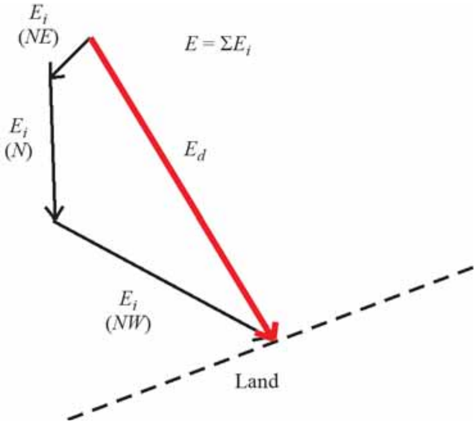

Fig. 6. The illustration of the total energy flux vector (being a geometrical combination of energy fluxes of the wave-dangerous directions)

RESULTS AND DISCUSSION

Wind-wave energy interannual variations (the hydrometeorologic factor of coastal dynamics)

The intensity of erosion of the sea shores and underwater slopes erosion is determined by the action of waves and excited currents. As far as waves in the Russian Arctic seas are generated mostly by wind, wind conditions are crucial in the formation of the wave energy flux. The waves act on the shores during the ice-free period. The seasonal coastal retreat rate is determined by the wave energy flux coming to the shoreline, which, in its turn, depends on the ice-free period duration. Storms provide the largest contribution to the total amount of wind-wave energy. The climate change of the latest decades is expressed both in ice and wind conditions changes. Satellite and ground-based ice observations show a reduction of the Arctic ice cover and an extension of the ice free period [http://arctic.atmos.uiuc.edu/cryosphere; *Obzor...*, 2012].

The western Yamal region is good for the investigation of these processes because of its long observation history: the Marresalya station has held hydrometeorological observations (including ice monitoring) since 1914 and coastal dynamics monitoring is conducted from the beginning of the 80s (Fig. 1). 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.

Using the Popov-Sovershaev's method [Sovershaev, 1980], the wind-wave energy of the ice-free period was calculated for the Marresalya station. The duration of the ice-free period in days is also shown on the graph (Fig. 7a). The analysis of the interannual variability of these values shows that the wind-wave energy flux generally increased from 1977 to the present day, while the ice-free period experienced an extension (Fig. 7). However, these two parameters do not always show a direct agreement. For instance, in spite of the increasing ice-free period duration in 1998-2004, the wind-wave energy during this period, on the contrary, dropped due to a revealed period of weak wind activity [Ogorodov, 2011]. Combined retrospective analysis of storm events and interannual variability of the wave-energy flux can establish the presence and nature of their relation and, as a result, the potential of coastal erosion. In some years, in spite of high wind-wave energy, the ice-free period doesn't include the time of the Autumn storms, and therefore coastal destruction is minimal. However, with the increase of the ice-free period, these storms can dramatically increase the energy of waves affecting the coasts.

In Fig. 7b, it can be seen that the annual maximum of the wind-wave energy is usually referred to spring and autumn. If the sea is free of ice at that moment, the energy reaches the coast. This happened in the years 2005–2010, when the heaviest September and October storms fell into the ice-free period. As a result, a maximum of the wind-wave energy interannual variability was observed in this period. This occurred due to the high frequency of winds blowing from the open sea, generating the biggest waves, during that time. The frequency of north-westerly and west-north-westerly winds, providing the most part of the wind-wave energy flux, increased twice during the period of 2005–2010 compared to the previous years. As the wind frequency is governed by atmospheric circulation, such an anomaly shows global circulation changes in the Kara Sea region connected with the climate change.

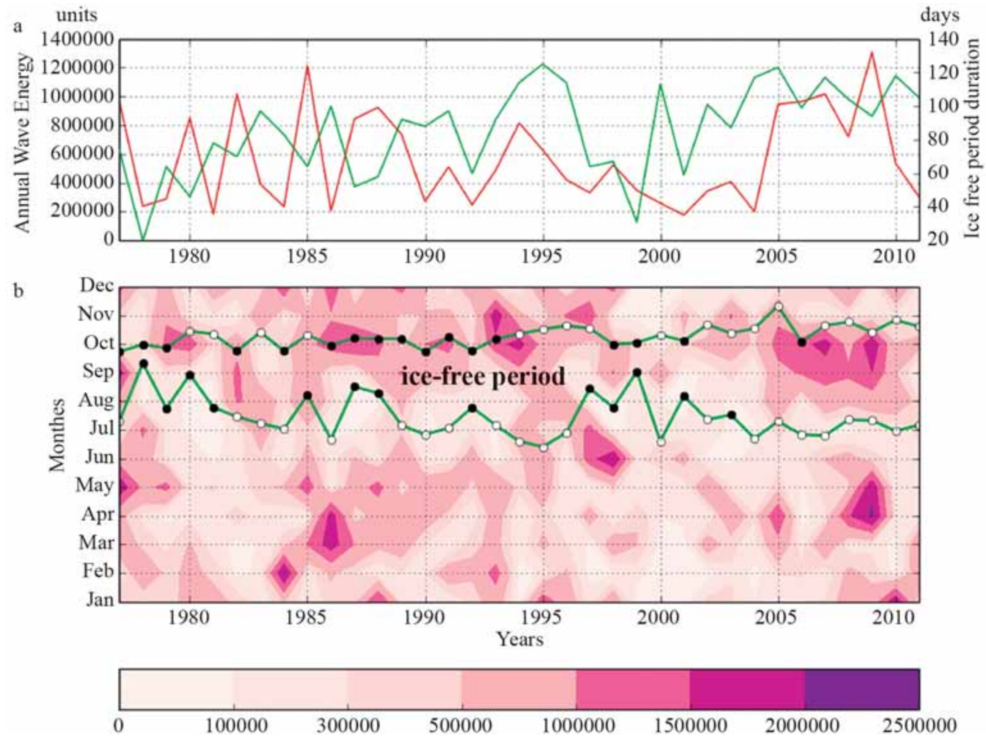

Fig. 7.

a) Marresalya annual wind-wave energy flux (standard units, red) and ice-free period duration (days, green);
b) values of potential wind-wave energy in standard units and ice-free period start and end dates (green line; black dot appears if the date reduces ice-free period duration in comparison to mean date, white – if extents)

The same patterns of wind-wave energy changes and consequent coastal retreat rates' increase were observed not only for the Kara Sea, but also for other parts of the Arctic, like the coasts of the Beaufort Sea in Alaska, where in 2007, in the conditions of an increased ice-free period, the rates of coastal retreat reached 25 m per ice-free season [Jones et al., 2009]. It has been noted that the duration of the open water season expanded from 45 days to 95 days during the period from 1979 to 2009 on the coasts of the Beaufort Sea, resulting in the fact that the exposure of the coastal cliffs to sea water increased by a factor of 2,5 [Overeem et al., 2011].

Climate change in the Arctic is also expressed in the wind speed decrease from the middle of XX to the beginning of XXI, especially noticeable at the Arctic shores [Vautard et al. 2010]. The reduction of the average wind speed occurs due to the decrease of strong winds frequency. At the same time, the number of calm days is getting lower too. At Marresalya station, changes in the ice-free period wind speed distribution are not related to the intensification or calming of the storm activity. There are periods of high and low storm activity (for the winds with the speed of more than 10 m/s). July–October of 1982–1996 are characterized by an increased number of storms. This is the case when the ice-free period end shifting towards winter extends the shore exposition to waves but does not necessarily result in the increase of the number of storms. The summers of 1997–2004 are the calmest. The wave energy minimum is caused both by small ice-free period duration (1998, 1999) and low storm frequency. The high values of wind-wave energy in 2000 appear because of high open water period duration and in 1980 – due to intensified storms in October. The same happened in 2005–2010, when, due to the extension of the ice-free period, the heaviest Autumn storms happened when the sea was ice-free. Data from the coasts of Alaska, based on time-lapse photography [Overeem et al., 2011] indicate that considerable erosion can happen even in one single storm; therefore this increase of the ice-free period in Autumn can significantly influence the rates of thermoabrasion. The frequency of wave dangerous wind directions in October is higher than in November and September, and the wave dangerous storms' activity and the wind-wave energy values are the highest in October. That's why the presence of October in the ice-free period is crucial. In this way, the wave-energy flux and the related coastal retreat depend on several interconnected factors which may act separately or jointly enhancing or weakening each other.

Interannual variations of coastal retreat rates (the Ural coast of the Baydaratskaya Bay)

The Ural coast of the Baydaratskaya Bay is composed by permafrost and is retreating with the average rates of 0,5–4 m/year. The stationary observations of the coastal dynamics have been conducted here by the Laboratory of geoecology of the North since 1988. In 2009, works on the construction of the underwater pipeline "Bovanenkovo-Uhta" crossing were made; therefore before that, coastal dynamics in natural conditions were observed, and after that they were affected by the influence of coastal constructions.

The profiles for the coastal dynamics monitoring are set in different geomorphological conditions (Fig. 8). In the north-west of the key area, a terrace with the heights of 10–18 m comes to the coast. In its central part, a low terrace of 4–10 m height with relatively high ice content is divided into several fragments by river valleys. In the south-eastern part, low laida (high water surge berm) with numerous lakes is situated. This laida can be covered by water during the highest surges and floods. As it can be seen from the retreat rate diagrams in Fig. 8, the coasts of the low terrace and laida generally experience a faster retreat. This retreat can be especially noticed in the last several years, with the increase of the wind-wave energy coming to the shores due to the prolongation of the ice-free period and changes in the wind patterns. The low coasts are, with all

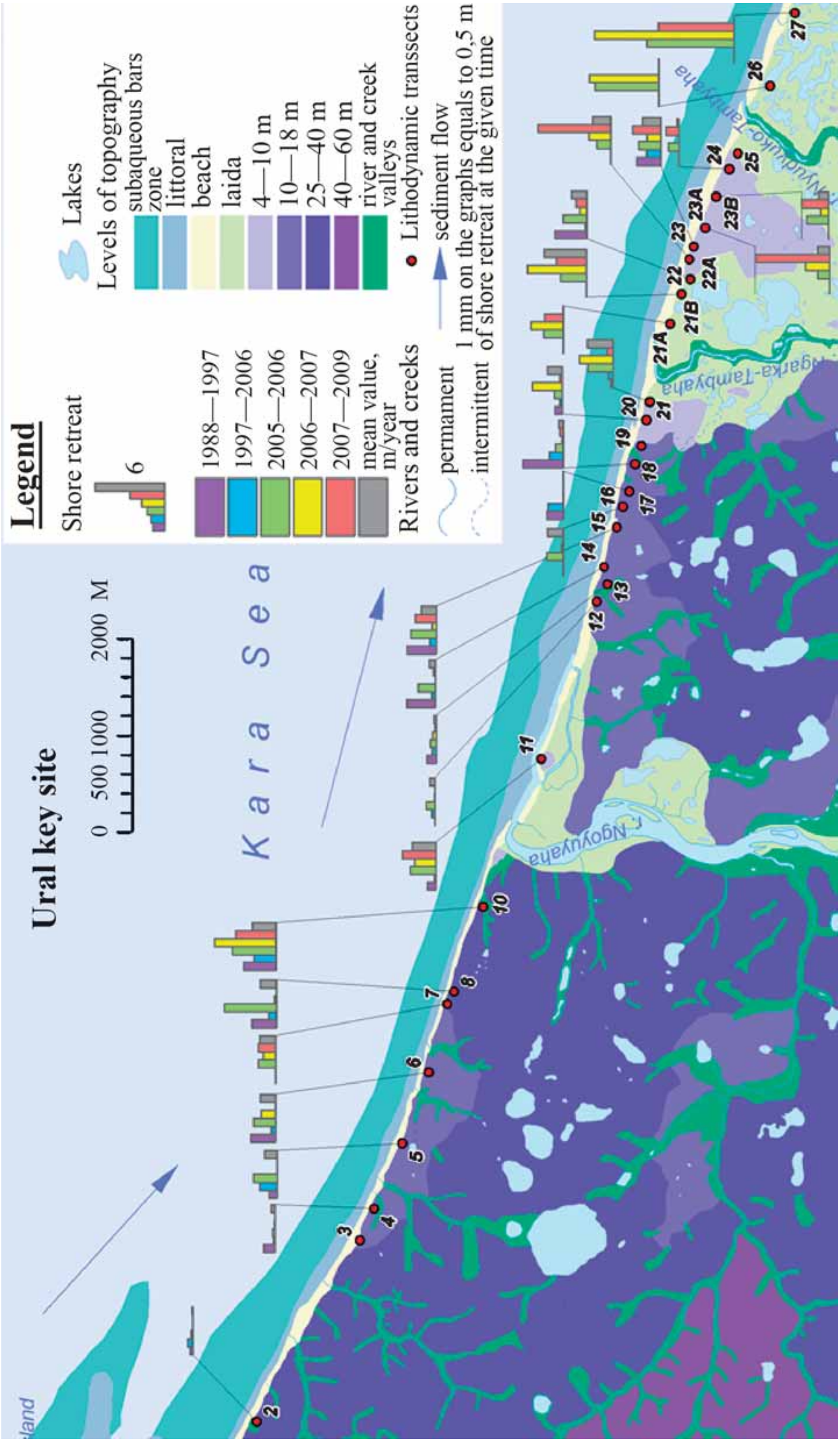

Fig. 8. Schematic map of the spatial and temporal variability of thermal abrasion coast of the Ural key area of Baidaratskaya Bay coast

other conditions being equal, less resistant to erosion than the high ones because with the same volume of material removed, the coast of, for instance, 20 m height will retreat by 1 m, while the coast of 1m m height will retreat by 20 m.

Not only spatial, but also temporal variability is characteristic for the retreat rates of the Ural coast. In general, two peaks of increase in retreat rates are observed: in 2005–2007 and in 2009–2012 (Fig. 9, 10).

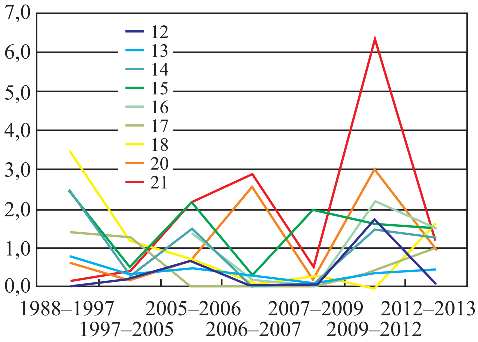

Fig. 9. Average rates of coastal retreat (m/year) for coastal dynamics monitoring profiles 12–21 within the Ural coast of the Baidaratskaya Bay key area (Y-axis – meters per year, X-axis – years)

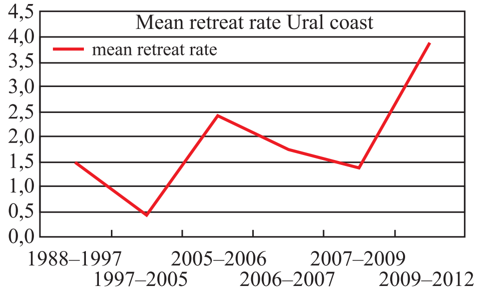

Fig. 10. Mean rates of coastal retreat (m/year) for all coastal dynamics monitoring profiles within the Ural coast of the Baidaratskaya Bay key area (Y-axis – meters per year, X-axis – years)

In 1997–2005, a negative peak is seen for all the profiles. It coincides with a minimum in wind-wave energy due to little occurrence of storm events, in spite of an increase of the ice-free period. After that, in 2005, 2006 and 2007, the increase of the ice-free period continued and coincided with an increase in the wind-wave energy flux, which resulted in periods of Autumn storms and winds falling into the ice-free period, as mentioned above. As a result, most of the profiles show a 1,5–2 times increase of retreat rates compared to the average. The most affected were profiles 20 and 21, which showed a rate of 2,6 and 2,9 m/year in 2006–2007, respectively. These profiles are situated on a low terrace, which is, in natural conditions, destroyed quicker than the higher terraces. Probably, during the autumn storms of 2005 and 2006, most part of the low (4–10 m) cliff was directly affected by waves.

In 2007–2009, all the profiles show a negative peak in destruction rates again, although the wind-wave energy remained high. The negative peak, characteristic for the Ural coast for these years (unlike the Yamal coast, where higher retreat rates were observed) was caused by relatively low temperature during these years, which prevented ground ice and permafrost from thawing.

In 2009–2012, after the construction of the underwater pipeline crossing, a new, even more dramatic, peak of retreat rates is observed. The biggest retreat values were from 6 to 18 m/year, which is a record for the observations within the Ural coast. Profile 21, situated on low laida, reached a maximum retreat rate in 2009–2012, after the constructional works. Profile 28, which is situated within the coast of accumulative type and didn't retreat at all before 2009, showed a dramatic jump in the destruction rates in 2009–2013. The coast retreated by 55 m, which corresponds to an average rate of 18 m/year. The reason of such dramatic change lies in the road which came through the beach at this segment, with several heavy vehicles a day passing on the beach and littoral. In 2012–2013, this segment didn't retreat more than 3 m.

In general, there was a slight increase in the wind-wave energy in 2009–2012; however, it didn't exceed the typical values. Therefore the reason of erosion activation lies in processes connected with the technogenic impact.

In the last period of 2012–2013, rates of coastal retreat were, for most of the profiles, lower that the average values. Profile 17, 20 and 26 are an exception. The activation of abrasion for profile 20 is not extreme: the coast has already retreated here quicker in 2009–2012. In general, alteration of periods with high and low rates is characteristic for these profiles. For low rate periods (1988–2006, 2007–2009), typical values are 0,2–0,7 m/year, while for high rate periods (2006–2007, 2009–2013), 2,6–3,0 m/year are observed. It can be noted that average values were never observed. Such behavior is probably caused by the lithology of the coast within profile 20. Fine-grained sands here are overlain by peat. During "usual" years, the peat cover protects the bluff from erosion; this is why low retreat rates are observed. However, once every several years, a layer of peat falls from the edge of the cliff, which retreats several meters at once, providing a high erosion rate.

For profile 17, rates of retreat, close to those observed in 2012–2013, were noted before 2005. In 1991–1997, the average rate here was 1,4 m/year, and in 1997–2005 – 1,3 m/year. As both of these periods cover several years and an average rate is provided, it is highly probable that the retreat rate during some of these periods exceeded 1,6 m/year.

Therefore, the only area for the Ural coast of the Baidaratskaya Bay which experienced extreme retreat rates in 2012–2013, was profile 26. The coast retreated 12 m during 1 year, despite that, before, annual retreat rates didn't exceed 6 m/year. The coast here is accumulative, and the retreat is expressed not in cliff abrasion, but in displacement of the beach-slope landwards. Unlike the beach of full profile, which can migrate both seawards and landwards, a beach-slope retreats inevitably. The reason is that from the landward side, such beach transits into a laida, and therefore a washaway of such a beach will result in the laida destruction, not always even visible morphologically. It should be noted that retreat was observed here even before the technogenic impact in 2005–2009. This testifies that coastal destruction is a natural process for this area, in spite of its accumulative morphology (the so-called retreating accumulative shore). However, the rate of retreat observed in 2012–2013, is not characteristic for the natural conditions of this coast. Such active retreat was caused by technogenic impact, and namely vehicles constantly driving on the beach as well as on adjacent laida.

It should be noted, that since the construction of the underwater pipeline, for areas where extreme abrasion rates were observed in 2009–2012, this trend didn't continue further on neither of the profiles. Interestingly, profiles 26, 27 and 28, situated in an area of alternation of thermoabrasional and accumulative coasts, are continuing to retreat in 2012–2013. This behavior can be connected with the movement of vehicles, because, before the latest time, coastal stability prevailed.

Average rates of coastal retreat on the coasts of the Kara Sea show steady growth (from 0,5 to 4 m/year on the average for all profiles, and up to 6 m/year for separate profiles). Similar values and trends were also noted for the eastern part of the Russian Arctic: erosion rates on Muostakh island, Laptev Sea increased from –1,8 ± 1,3 m/year since 1951 to 3,4 ± 2,7 m a–1 on average during the 2010–2013 observation period [Guenther et al., 2015]. However, in the American Arctic, greater velocities of coastal destruction were noted: the mean annual erosion rates at some locations of the Beaufort Sea coasts increased from 6,8 m/year in 1955–1979 to 13,6 m/year in 2002–2007 [Jones et al., 2009].

The human-induced factor of coastal dynamics

The 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 content [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 aeolian processes. The inner parts of the terrace behind the dune belt are laidas (surge flood plains) of 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 aeolian-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 the slopes of the Holocene terrace. The latter is destroyed due to relatively high average annual ground temperatures, small ice content and a considerable thickness of the layer of seasonal melting. Coastal erosion is determined by a combination of different factors including the 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 1970s. The Varandey Island experienced the strongest human impact. The main industrial base was formed here, and a new settlement for 3 thousand inhabitants, was built (Fig. 11). 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.

The construction of the settlement and industrial base practically at the edge of the

Fig. 11. Aerial photo of the Varandey settlement at 1985; coastline of 2013

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 vehicles including caterpillars caused the degradation of soil and plant cover of the whole dune belt of Varandey Island. Under the conditions of deep seasonal melting, the dune belt formed of fine sands experienced 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 formed in the bluff. As a result, the bluff became lower, its homogeneity was disturbed, the volume of sediment supplied to the coastal zone decreased and, finally, the coasts became less stable, and their rates of retreat increased. Coastal protection at 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 at some sites it reached up to 7–10 m/year. The rates of coastal retreat slightly decreased, down to 1,5–2 m/year, after the coastal-protection construction was built near the Varandey settlement. However, they 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. The acceleration of coastal and underwater slope erosion has contributed to the self-excavation of the underwater pipeline to the surface. As a result, it was pulled out from the bottom by the 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 on the coast. On July 24, 2010, an extreme storm surge completely flooded the Varandey Island, and penetrated several kilometers inland. Enormous damage was made for oil infrastructure.

The negative experience of Varandey area development was not taken into account during the construction of gas transportation facilities on the coasts of the Kara Sea. The section of the coast of the Yamal Peninsula (Baydaratskaya Bay) at the underwater crossing Yamal-Europe can be an example. The following types of direct human impact on the relief have been documented: construction of large artificial positive landforms, which leads to additional sediment income to the coastal area in a given place; construction of artificial concave landforms, removal of sand material from the beach, tide flats (Fig. 12) and from the underwater shore slope, which leads not only to erosion and narrowing of tide flats and of the beach, but also to changes in the position of submerged systems of bars; deformation of the surface of mud flats, beach, coastal barrier and 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 results of human impact, the following changes are distinguished: appearance of anthropogenic accumulative forms in the coastal area connected with the change in the sediments drift; appearance of hollow forms on the beaches and tidal flats caused by the intensification of erosion

Fig. 12. Yamal Coast of the Baydaratskaya Bay: traces of sandy sediment removal from the tide flat and beach

resulting from the disruption of sediment transportation or from the change in the profile of the beach; intensification of deflation at the disturbed surfaces. Due to the fact that the places of extraction of constructional materials were not considered in advance from the perspective of morpholithodynamic situation, the extraction of sand material for constructional purposes is carried out without a certain plan and without consideration of the consequences. Sandy material is most actively extracted from the surface of the barrier beach between the nearest river mouth and the cofferdam. The surface deformation and the vegetation destruction at the barrier beach leads to the intensification of deflation. This creates sediments deficit in this coastal area, which leads to its erosion. The construction of the cofferdam where the pipeline lies resulted in the accumulation of sediments in the entrance corner to the south of the cofferdam and in the erosion of the coast to the north from it. In natural conditions, the barrier beach completely absorbs the wave energy even during extreme storms [Kamalov et al., 2006]. Changes in the barrier beach morphology cause the changes in the conditions of waves' destruction and, therefore, changes in the entire morpholithodynamic regime that can lead to unfavorable and hazardous consequences. The coastal system will tend to reach a new equilibrium, which will cause off- and onshore topography reforming with the rates that were not considered in the construction project. In order to reduce the impact of the pipeline construction on coastal systems, the first required thing is stopping the removal of sediments.

As the Ural coast mentioned above, the Yamal coast also experienced an increase in the retreat rates in 2005–2010, right after the removal of sediments and the increase of the traffic of heavy vehicles of the beach. Unlike these two sites, at the Kharasavey area, where no considerable constructional works were executed in 2005–2010, the rates of retreat experienced only a slight increase. This proves again that such a dramatic peak in abrasion of the Ural and Yamal coasts of the Baydaratskaya Bay was caused not only by natural processes connected with climate change and wind-wave energy increase, but were enhanced by unreasonable human activity, which strengthened the negative natural effect.

CONCLUSIONS

During the last decades, the Arctic coasts have experienced relatively quick changes. On the one hand, they are caused by the changing climate leading to higher summer air temperatures and longer ice-free period duration leading to sometimes dramatic increases of the wind-wave energy affecting the shores. On the other hand, unreasonable human activity can easily enhance the negative effect of the climate change, leading to redistribution of the natural morpholithodynamic systems causing catastrophic coastal retreat. Among this negative impact, the removal of sediment from the beach, tidal flat and laida, especially at low coasts, can be considered the most dangerous process.

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 lead to enormous environmental implication.

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