SPE 166932

Investigations of Coastal Erosion Processes in Varandey area, Barents Sea

Anatoly Sinitsyn, UNIS, Emilie Guegan, NTNU, Osip Kokin, Aleksey Vergun, Leonty Udalov, Stanislav Ogorodov, MSU

This paper was prepared for presentation at the SPE Arctic and Extreme Environments Conference & Exhibition held in Moscow, Russia, 15–17 October 2013.

ABSTRACT

Knowledge on coastal processes is required for construction of robust coastal structures in the Arctic. Pechora sector of the Barents Sea is one of key areas for hydrocarbons production in the Arctic region. Description and analysis of erosion processes in coastal zone of Varandey area are presented. Three areas are considered – Pesyakov Island, Varandey Island, and Continental coastal zone of Malozemelskaya Tundra from Peschanka River to Western part of Medynskiy Zavarot Peninsula (further designated as Medynskiy segment). Varandey and Pesyakov Islands have close geomorphological structure, and present marine terraces from fine sand deposits. The former Island is exposed to erosion due to both, human and natural factors, while the erosion of the latter has only be associated to natural actions. Human factor in Varandey Island mainly consists in removal of sand deposits from avandune and intensive traffic of motorized vehicles on the beach and dunes. Natural factors of erosion on these islands are related to wave action, the deficiency of coarse-grained beach-forming material, the poorly developed profile of submarine coastal slope, and the high gradient of the avandune slopes. One can assess the human factor in erosion processes by comparison of erosion in these two areas. Medynskiy segment is marine terrace composed from dense ice and marine loams and clays. Thermoabrasion plays the main role in coastal erosion here. Techniques of erosion measurements and their results as well as some results of field campaign undertaken in 2012 are presented in the article. Results of preliminary analysis of satellite images from 1961-2012 has confirmed and extended known results on erosion rates in Varandey area obtained from filed surveys conducted between 1987-2012. Results show that erosion on Pesyakov Island was moderate, on Varandey Island – from moderate to rapid, and on Medynskiy segment from moderate to extremely rapid in 1961-2012. Presented results of research can be used as an element for quantitative and qualitative description of erosion over 1961-2012 in Varandey area and are data of primary importance for any further coastal research or coastal engineering designs undertaken in this area.

1. GEOMORPHOLOGICAL AND GEOCRYOLOGICAL STRUCTURE OF VARANDEY AREA

Contours of three areas considered in present research are presented in Fig.1, (image – SPOT data, presented by ISIS program).

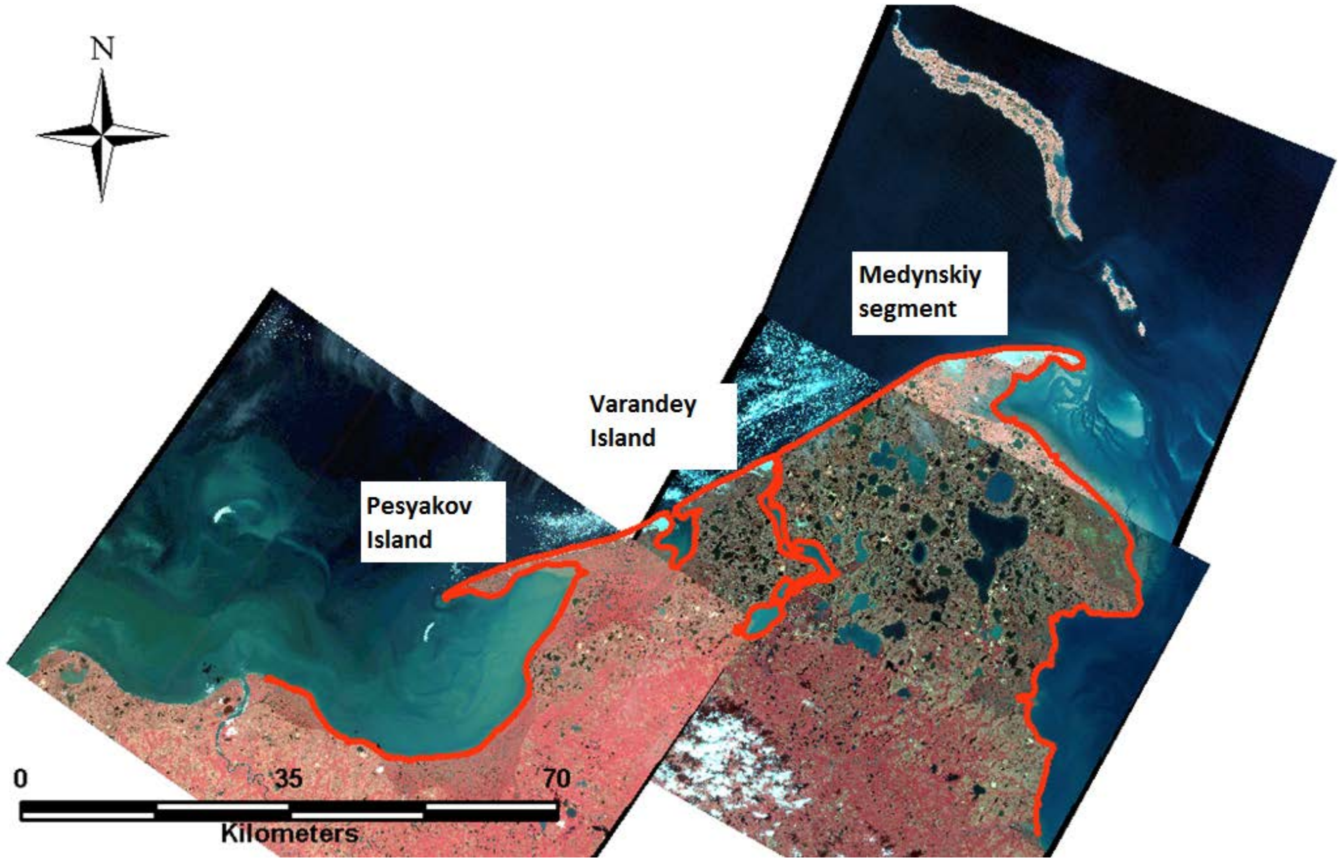

Fig. 1. Research areas in Varandey (SPOT image – ISIS program, CNES (Centre National d etudes spatiales).

Varandey and Pesyakov Islands have close geomorphological structure and belong to big barrier islands with an average height of 3-5 m, which was accumulated as a result of cross flow of fine sand sediments from submarine coastal slope during the period of climatic optimum at the final stage of the Holocene transgression, when both, duration of dynamically active period and hydrodynamic activity were the highest. Eolian processes have built a thick (up to 4-10 m) dune belt (avandune) over the barrier islands from the shoreface. Most part of eolian material removed from beaches and tidal flats is accumulated within the dune belt. Specific vegetation growing on avandunes protects it from deflation and favors intensive accumulation of eolian material. It should be noticed, that the extent of the opposite eolian transportation – from the dune belt to the beach and tidal flats – is considerably less due to high anti-deflation stability of the dune belt (Ogorodov, Kokin 2012).

In the zones of divergence of wave energy, an abrasion bluff formed on the marine slope of avandune and experiences relatively high rate of coastal retreat. At the places of sediment transit, marine slope of avandunes is relatively gentle (about 20-50°) due to less intensive wave activity and the influence of slope processes. However, during the years of extremely strong storms it could become steeper for a period of time due to abrasion. A relatively narrow beach (from 20-100 m to 100-300 m in the eastern part of Pesyakov Island) leaning against the marine slope of avandune gradually turns into the tidal flat.

At the distal parts of barriers, the avandune becomes lower and is replaced by a series of inactive coastal ridges marking certain stages in evolution of accumulative landforms. Coastal ridges have been considerably reworked by eolian processes. Where the storm surge overwashes the barrier, the well-developed active coastal ridge is formed. Laidas or high-water surge berms occupy the inner part of the barrier beach behind the dune belt. They are located at 2.5-3.0 m a.s.l., and present a low lying topography, very flat with multiple lakes. Two morphological levels correspond to wind surges of low and high recurrence.

The sediment sequence exposed in coastal bluffs of the barriers above 1.0-2.0 m is entirely represented by sub-aerial complex: fine-grained sands with abundant grass remains and traces of soil processes. They are devoid of any pebbles, gravel and other coarse-grained debris. On the contrary, deposits of beaches, active coastal ridges and high-water surge berms in the Pechora Sea consist of less sorted sands with numerous pebbles, gravel, rock debris and single bivalve shells. Coarse-grained material originates from numerous exposures of boulder clays and loams on the submarine coastal slope. No coarse debris was found in the barrier beach sediments from the cores recovered at considerable distance from the coastal bluffs. Laida deposits with characteristic peat-grass pillow are usually exposed below 1-2 m level. Laida deposits accumulated in the inner parts of barriers under the influence of storm surges up to 2.5-3.5 m high do not give any evidence either for higher than modern sea-level position or the Middle Holocene age of the overlying sand unit.

Geocryological structure was investigated at Pesyakov Island by drilling of boreholes at different geomorphological locations. The thickness of active layer varies from 0,8 m at high level of laida to 2,2 m at the flat surface of barrier and 4 m at the ridge of avandune. The average height of the top of barrier core permafrost fluctuates between 1 and 2 m a.s.l. rising under positive landforms (avandune – up to 2,5 m a.s.l.) and falling near the coast line under the sea level. The main peculiarity of geocryological structure of the Pechora Sea coast is cryopegs which are result of the saline sediments. Cryopegs was observed on the depth of 0.3 and 4 m under the sea level.

The geomorphology structure of the area between Varandey Island and Medynskiy Zavorot Peninsula differs from barrier islands. It is represented by a 5-15 m high, gently rolling lacustrine-alluvial plain with numerous lakes, usually referred to as the first terrace of Late Pleistocene-Holocene age (Novikov, Fedorova 1989). The surface of the terrace is covered with frost polygons and bogs. The base of the terrace is composed of dense ice (perhaps glacial) and marine loams and clays with inclusions (3-5%) of strongly weathered boulders, blocks, rock debris and gravel (three-fourths of the section). The layer of sands and peat represents the upper one-fourth of the terrace section. The terrace sediments include ice wedges and massive ice beds (Ogorodov 2004).

At location where the first terrace reaches the sea, the thermoabrasion coast has a cliff cut in frozen dense boulder loams. The height of this abrasion cliff ranges from 3 to 10 m. In contrast to the barrier islands, thermoabrasion plays the main role in coastal erosion here. At some places, typical thermoabrasion niches are present. Thermodenudation processes (thermoerosion, solifluction, slumping) considerably affect the coastal dynamics and supply sediment to the coast basement. The abrasion cliffs is surrounded by a narrow (10–20 m) pebbly-sandy beach that gradually turns into abraded tidal flats — the so-called ‘‘clayey bench’’. Due to the specific granulametric composition of the sediments, the amount of beach-forming material produced by thermoabrasion is insufficient. The presence of landslides and mudflows, as well as the small beach width, give evidence for relatively low coastal resistance. The average rate of thermoabrasive coastal retreat was estimated at 1.8–2.0 m/year (Novikov, Fedorova 1989).

2. ASSESSMENT OF EROSION RATES IN VARANDEY AREA ON THE BASIS OF SATELLITE IMAGES

Assessment of erosion rates in coastal zones can be performed with the use of satellite images and aerial photography. Reader can find detailed methodology of this approach in (Ogorodov et al., 2011). The idea of the method is to trace changes in a terrain by superposing images taken at different time. Changes in thermoabrasive and accumulative Arctic coasts can be traced by drawing crest of the coastal bluff, shore line (when time of image and hydrometeorological conditions are known), and by boundary of continuous vegetation. Superposition of images can be done by georeferencing or by projection of orthorectified images. ArcGIS software was used for alignment and collection of data.

Georeferencing is preferable approach, and can gather different sources of data: topographic and bathymetric maps, data from binding files for satellite images files (created by parameters of the satellite orbit). This method gives error less than 5 m for littoral areas, which is acceptable for research on dynamics of coastal zone (Ogorodov et al., 2011). In case where images do not have binding files (aerial photography, Corona images), their reference can be done on basis of: referenced maps, field points with known coordinates, already referenced images. Hydrographical objects can be used for certain methods of precise reference of Corona images.

Superposition of most of the images presented in this article is made manually. Orthorectified images were used for this purpose (not georeferenced), which means that images are correctly projected and that distances are conserved.

Assessment of erosion rates for three areas composing Varandey region is presented below.

Pesyakov Island

Images used for assessing the erosion rates on Pesyakov Island were made in 1961, 1968, 1998, 2004, 2010. The erosion rates were measured manually every 100 m along seawards side. Results do not reveal any obvious changes between 1961-1968-1998 years, due to images accuracy. Pictures resolutions for these years are 10 m, and it is hard to accurately delimitate the coast boundary, however one could not see any dramatic change (more than 20m) between the shorelines and coast in 1968 and 2010. However a noticeable change was found in the geometry of the Eastern end of the Island between 1961 and 2010 reflecting the development of a Spits.

Varandey Island

Images from 1961, 1968, 1982, 1990, 1998, 2004, 2005, 2009, 2010, 2012 were used for assess of erosion rates on Varandey Island. The following observations of erosion rates can be drawn:

- 1961-1968: difficult to see any changes due to images resolution;
- 1961-1990: some shore recession (not coastal erosion) can be observed between 0,7 and 6,1 km (here and further distances are measured from the Western end of the Island). With maximum retreat of 100 m, and average of 46,7 m in 29 years or 1,6 m/yr;
- 1990-1998: no obvious changes;
- 1998-2004: no obvious changes except in both ends of the Island;
- 2004-2005: coastal crest recession (some segment are undergoing erosion, up to 11 m, but with average of 3,6 m/yr for the first 6 km);
- 2005-2010: 28 buildings have been destroyed, erosion up to 7,4 m/yr, with average erosion of 13,7 m in 5 years or 2,7m/yr (from 1,1 till 6,7 km));
- 2010-2012: the first kilometer of coast presents a low gradient coast where no clear boundary can be drawn. Afterwards the coastal bluff in 2010 (and before) has been covered by transgressive dunes (until kilometer 3), and also unable one to draw a coastal boundary. Coastal erosion up to 46 m in 2 years (23m/yr) but with average rates of 12,5 m/yr (from 3rd till 6,6 km). Fence protection put along the airstrip were already destroyed between 2010 and 2012.

Analysis of georeferenced images from 1961, 1982, and 2009 gives the following:

- 1961-1982: retreat was at about 50-80 m, which gives in average 3,1 m/yr;
- 1982-2009: retreat was from 15 to 60 meters, which gives in average 1,4 m/yr.

Continental coastal zone of Malozemelskaya Tundra from Peschanka River to Eastern part of Medynskiy Zavorot Peninsula

Aerial and satellite images available for Medynskiy segment were made in 1961, 1968, 1990, 1998, 2009, 2010, 2011; analysis of images gives the following (location of the crest of coastal bluff was monitored):

- 1961-1968-1990: No visible changes due to images resolution;
- 1990-1998: coastal erosion measurable until kilometer 21 (from Peschanka River towards Medynskiy Zavorot Peninsula) with maximum of 55 m in 8 years (6,8 m/yr), but average erosion of these 21 km is 2,8m/yr. The resolution of the 1990 and 1998 images are not great but visible and consistent over the full length of the bluff differences could be observed;
- 1998-2010: active coastal erosion, up to 50 m with average of 19,2 m in 12 years (1.6 m/yr);
- 2010-2011: very active, spectacular erosion, up to 60 m (6,6 km from Peschanka River) in one year, with average of 19,6 m/yr (from 4,1 till 24,3 km), see Fig.2.

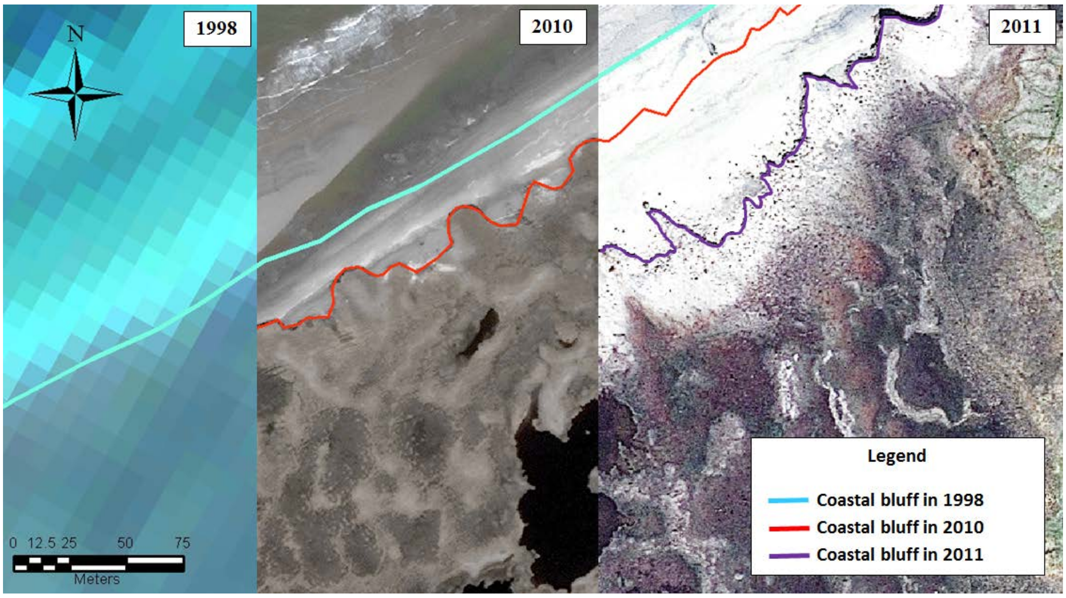

Fig. 2. Outline of coastal bluff in Medynskiy segment in 1998, 2010, 2011.

Images from 2010-2011 give possibility to observe the difference of coast morphology (from perfectly linear, to heavily curved) between different coastal segment but also within different years (for the same segment). Also the erosion mechanisms of block failure, that looks closely related with ice wedge thermokarst can be seen on images from 2010-2011.

Large destruction on the coastal bluff in 2010-2011 most probably associated with catastrophic storm, which took place on 24th of July, 2010; image from 2010 was taken on 5th of July. Water pileup was up to 3,5 m, what caused such retreat of a crest of the coastal bluff towards the shore. It should be noticed that such retreat took place just one single time (in 2010-2011), and it is not a recession of shore line. Therefore one should notice, that very high erosion rates found in Medynskiy Segment between 2010 and 2011 do not reflect a long term trend. If these rates would have been stable since 1961, it would be definitely possible to identify it on the images 1961-1998 (even though they do not have high resolution).

Analysis of satellite images can give one an opportunity to see a difference in morphology (and then most likely difference of soil and/or ice content) from the West to East of Varandey area (from Pesyakov Island to Medynskiy Zavorot Peninsula). It is definitely difficult to accurately use old images from 1961 to 1998 due to their poor resolution, however what one can say is that there have not be any dramatic changes since over the last 50 years. The modern erosion rates also reveal a change of erosion rates from West to East. Pesyakov Island looks relatively stable with formation of the Spits (accumulation of sediments) and dunes; Varandey Island has higher erosion rates (human activity most probably has large impact in it); Medinsky Zavorot Peninsula is experiencing very intense erosion in 2010-2012, that we can associate with its geomorphological structure and catastrophic storm event in July 2010.

3. ASSESSMENT OF EROSION RATES IN VARANDEY AREA ON THE BASIS OF TOPOGRAPHICAL SURVEY AND DIRECT MEASUREMENTS

Repeated topographical survey is used in order to determine erosion rate, and deformations of coastal profile. Newly established or already existing benchmarks with known coordinates are used as basis for measurements. The benchmark network for monitoring is usually set with respect to geomorphological and cryolithological composition of the shore. This helps to obtain complete data on spatial and temporal variability of the erosion processes on prolonged sections of a coast. Used benchmarks should be located on sufficient distance from shore line in order to avoid destruction of it during catastrophic storm events. If possible, benchmarks of state geodetic net should be used. Geodetic leveling is the method used for measurements. Measurements are performed in perpendicular to the shore line direction; orientation of geodetic instrument is usually done visually (with use of two additional benchmarks situated in 10 m between each other). Walls of buildings, other fixed objects can be used as well for keeping the direction for survey. Besides geodetic data itself, the following has to be noted during survey: time, water level, locations of distinctive zones of coastal area (boundary of beach, foot of dune, etc.), locations of distinctive objects (line of drift wood, vegetation boundary).

Results of topographical survey in coastal zone can be also compared with topographical maps. Such comparison is usually done when measurements are carried out on newly established profiles, and no other data, except topographical maps, is available.

Direct distance measurements from benchmarks till crest of coastal bluff are used for erosion assessment on thermoabrasive coasts.

Erosion measurements in Varandey area were launched in mid 1980ies by laboratory "Geoecology of the Northern Territories", Moscow State University. Description of networks for topographical survey and direct measurements for erosion assessment in Varandey region is presented below (measurements were conducted in summer seasons). Data from some early years are not mentioned in description below due to its inaccessibility to present time.

Pesyakov Island

Method - repeated topographical survey, number of profiles for 2012 – 12. Topographic survey measurements took place in 2000, 2011, 2012; analysis of some results gives the following:

- 1968-1969 (topographical map)-survey 2000: retreat of shore line with rate 1-2,5 m/yr (Ogorodov 2005);
- 2011-2012: Western part of island shows retreat of crest of dune slope (seaward side) for 0,7-1,2 m/yr.

Varandey Island

Method – repeated topographical survey, number of profiles for 2012 – 17. Measurements took place in 1981, 1982, 1984, 1986, 1987, 1999, 2000, 2002, 2003, 2011, 2012; analysis of some results gives the following:

- 1969 (topographical map)- survey 1987: retreat of shore bluff 3,9-6,5 m/yr (Novikov, Fedorova 1989);
- 1981-1987: retreat of shore bluff was 2-3 m/yr (Ogorodov 2005);
- 1987-2000: retreat of shore bluff 3 m/yr (Ogorodov 2005);
- 2000-2003: no changes (associated with natural factors) in coastal zone (Ogorodov 2004);
- 2011-2012: almost no shore erosion was revealed , only one profile on Western end of island demonstrate loses of ground for about 0,5 thickness of on seaward part of coastal slope on distance of about 200 m.

Continental coastal zone of Malozemelskaya Tundra from Peschanka River to Eastern part of Medynskiy Zavorot Peninsula (Polar cape)

Method – direct distance measurements, number of profiles for 2012 – 12; measurements took place in 1987, 2000, 2003, 2012; analysis of some results gives the following:

- 1968-1969 (topographical maps)-survey 1987: retreat of shore bluff) ≈2 m/yr (Ogorodov 2004).

4. CORRELATION OF HYDRIMETEOROLOGICAL FACTORS AND EROSION RATES IN VARANDEY AREA

As it was noted in section two, that two types of coast are presented in Varandey area. Pesyakov and Varandey Islands presents the first type of coast, and composed from sand sediments with low ice content (Ogorodov 2004). Sediments composed such coasts don't manifest settlements after thawing, and are not prone to landslide processes, thermoerosion and thermokarst. As expected comparison of average monthly temperatures and coastal dynamics doesn't reveal any correlation between these parameters. Wave action believed to play the main role in dynamics of such coasts. Influence of wave action can be assessed by calculation of stream of wave energy, which generated by wave-induced wind from directions suitable for wave generation. Calculations can be based on wind-energetic method of Popov-Soversiaev (Soversiaev 1980; Ogorodov 2002). Such calculations were performed for Varandey area, taking into account ice concentration in Pechora Sea, the latter parameter which determines the fetch, which large defining total value of wave energy coming to external boundary of coastal zone. Standard three hour-observation data for wind values was used, data with resolution of 1-3 days were used of ice concentration (http://arctic.atmos.uiuc.edu/cryosphere), period from 1981 till 2009 was considered. Comparison of calculations of wave energy and data on coastal erosion shows that wave-energy factor plays major role in dynamics of coasts composed form sand sediments with low ice content (Ogorodov 2011), value of correlation coefficient was 0,8 (Fig. 3).

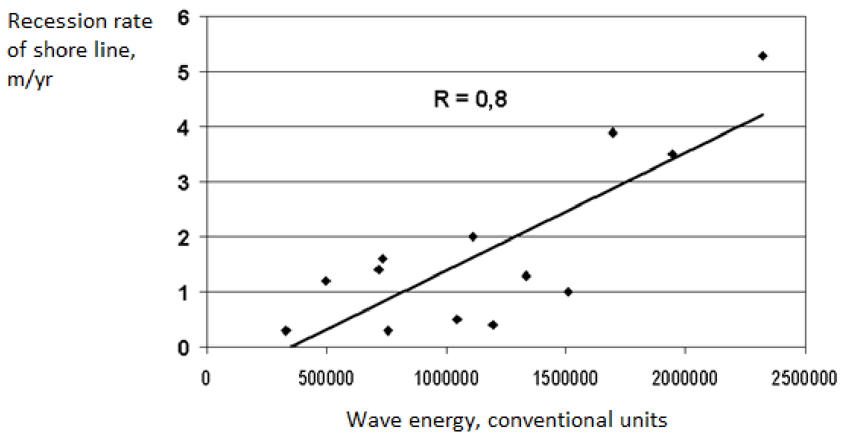

Fig. 3. Relationship between coastal retreat rate at Varandey Island to wave energy (Ogorodov, 2008)

Thermoabrasive coast (or so called abrasive-thermodenudative coast) of Medynskiy segment represents the second type of sea coast in Varandey area. Such type of coast is under influence of whole complex of active hydrometeorological factors, which includes both thermal and waves action.

Thermal factors have influence mainly in summer time, and cause thermodenudation processes destroying coastal bluff. Waves, in turn, remove material moved to foot of coastal bluff by thermodenudation. Development of thermodenudation becomes slower if waves don't remove products of thermodenudation. Waves don't destroy coast so efficiently if it is in frozen, not reworked by thermodenudation, state. Correlation of erosion rates in Medynskiy segment with thermal and wave factors will be performed in further works.

CONCLUSIONS

Description and some results of investigations of coastal erosion processes in Varandey area are presented. Coastal processes were investigated by topographical surveys, direct measurements, comparison of topographical maps, and analysis of aerial and satellite images. Some results elaborated by topographical surveys were previously available in the literature, but for the first time investigations are gathered all together. For the first time analysis of satellite images for long time span was performed, nevertheless resolution of most of them were not high, results have added good supplement data for field surveys.

On the basis of available data one can assess erosion processes in Varandey area in 1961-2012, which reveal that Pesyakov Island is relatively stable (average erosion rates 1-2,5 m/yr); Varandey Island was exposed to higher erosion rates (more than 3 m/yr), human activity plays sufficient role here; Medynskiy segment has undergone to erosion rate of about 2 m/yr, acceleration of erosion in recent years is believed to be caused by catastrophic storm event.

Further steps include creation of shore classification and segmentation maps, which consider different features of coastal morphology, dynamics, and formation, obtained from both field investigations and remote sensing data analysis.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Research Council of Norway through the Centre for Sustainable Arctic Marine and Coastal Technology (SAMCoT) at NTNU, UNIS, SINTEF; to Federal Target Program "Scientific and academic teaching staff of the innovative Russia" at MSU; to providers of satellite imagery – *View from a star* (GeoEye images), *Digital Globe* (Worldview images), Centre National d'Etudes Spatiales (*CNES*), ISIS program (SPOT images); we would like to express special thanks to all staff of laboratory “Geoecology of the Northern Territories”, Moscow State University and State Oceanographic Institute conducted expeditions in Varandey.

REFERENCES

Novikov, V.N., Fedorova, E.V., 1989. Destruction of costs in the southern Barents Sea (in Russian). Vestnik MGU, series 5, Geografiya, №. 1, pp. 64-68 (In Russian).

Ogorodov, S.A. 2002, Application of wind-energetic method of Popov-Sovershaev for investigation of coastal dynamics in the Arctic. In: Arctic Coastal Dynamic. Report of an International Workshop. Potsdam (Germany) 26-30 November 2001. Reports on Polar and Marine Research. Edited by V. Rachold et al. Bremerhaven. Vol. 413, 37-42.

Ogorodov, S.A., 2004. "Morpholitodynamics of coastal zone of Varandey area in Pechora Sea under man-made impact." Geoecology, Engineering Geology, Hydrogeology, Geocryology 3: 1-6 (In Russian).

Ogorodov, S.A. 2005, Human impacts on coastal stability in the Pechora Sea // Geo-Marine Letters, Vol. 25, N 2-3, P. 190-195.

Ogorodov, S.A. 2008, Effects of Changing Climate and Sea Ice Extent on Pechora and Kara Seas Coastal Dynamics // Proceedings of the Ninth International Conference on Permafrost, Fairbanks, Alaska, US, Vol. 2, P. 1317-1320.

Ogorodov, S.A. 2011, The Role of Sea Ice in Coastal Dynamics. – Moscow University Press, 173 p. ISBN 978-5211-06275-7. (in Russian)

Ogorodov, S.A., Belova, N.G., Kuznetsov, D.E., and Noskov. A.I., 2011. “Using Multi-Temporal Aerospace Imagery for Coastal Dynamics Investigations at Kara Sea”, Earth from Space - the Most Effective Solutions, Vol. 10, pp. 66-70 (in Russian).

Ogorodov, S.A., Kokin, O.V., 2012. Geomorphological structure and dynamics of barrier islands in the Barents Sea. INQUA SEQS 2012 Meeting, pp. 74-75 (In Russian).

Soversiaev, V.A., 1980. *Coastal forming factors and zoning of the Laptev, East Siberian and Chukchi Seas Coast under dynamic principle.* Dissertation, Moscow State University, 212 p. (in Russian).